Ninth International Workshop on Tropical Cyclones

Honolulu, Hawaii, USA, 3–7 December 2018
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Participants attending the Ninth International Workshop on Tropical Cyclones (IWTC-9), Honolulu, Hawaii, USA, 3-7 December 2018
INTRODUCTION

The International Workshop on Tropical Cyclones (IWTC) was conceived in the early 1980’s by a small group of tropical cyclone meteorologists led by Professor William Gray who was also at the time engaged as a WMO project consultant. The goal was to organize a forum for forecasters and researchers from all regions affected by tropical cyclones (TC) to examine current knowledge, forecasting and research trends on this weather systems from an integrated global perspective. The idea was endorsed by WMO’s ninth Congress (1983) and it’s thirty fifth (1981) and thirty sixth (1984) Executive Council. Consequently, the first truly global gathering of all types of TC specialists representing all five TC regional bodies (currently with 85 Members) was held in Bangkok, Thailand in 1985. After 33 years, IWTC is now considered as one of one of WMO’s major quadrennial workshop series. It is a special and unique gathering of TC researchers and forecasters from all regions affected by tropical cyclones.

The subsequent IWTCs followed a well-established model where an International Committee was set up to develop the workshop programme, select main topics to be discussed during the workshop and put together a group of experts to produce a pre-workshop report.

The International Committee for IWTC-9 is co-chaired by Dr Mike BRENNAN (USA) and Prof. Yuqing WANG (Australia with membership: Linda ANDERSON-BERRY (Australia), Lixion AVILA (USA), Andrew BURTON (Australia), Philippe CAROFF (France), Esperanza CAYANAN (Philippines), Johnny CHAN (HK, China), Jing CHEN (China), Yihong DUAN (China), Shishir DUBE (India), Phil KLOTZBACH (USA), Tom KNUTSON (USA), Ravind KUMAR (Fiji), Zhiyu LIU (China), M. MOHAPATRA (India), Chiashi MUROI (Japan), Robert ROGERS (USA) and Raymond TANABE (USA)).

This extensive report of the workshop, one of the hallmarks of the IWTC, was prepared by a team composed of topic chairs and rapporteurs ably assisted by working groups Rapporteur reports includes forecast issues, examples of difficult forecast situations and recommendations on future research directions. The report also serves as the basis for the breakout discussions during the workshop.

The IWTC has, through the years, essentially served to channel scientific advances and emerging technologies into operational tropical cyclone forecasting. Another noteworthy outcome of this workshop series is the establishment of better communication between tropical cyclone researchers and forecasters. More often than not, plans for future international co-operation between individuals and governments dealing with the tropical cyclone problem were also developed during the workshop. The in-depth exchange of both practical and theoretical information and extensive discussions on the complex problems of tropical cyclones resulted in a number of useful recommendations concerning tropical cyclone forecasting, warning and research.

A special tribute session was held at IWTC-9 for the late William Gray, organizer of the 1st IWTC in Bangkok and who was a professor in the Department of Atmospheric Science at Colorado State University (CSU) for over 50 years. The session featured three of Prof. Gray’s Ph.D. graduates: Johnny Chan, John Knaff and Phil Klotzbach. Prof. Lianshou Chen, head of the Chinese Academy of Meteorological Sciences and close friend of Prof. Gray, also delivered
some personal remarks and remembrances. Prof. Gray was an enthusiastic proponent of these meetings that bring together tropical cyclone forecasters and researchers together from around the world. The tribute session highlighted many of Prof. Gray’s contributions to tropical meteorology, including fundamental discoveries regarding tropical cyclone movement, structure and genesis. Prof. Gray pioneered Atlantic basin seasonal hurricane prediction, which was underpinned by his discovery that El Niño reduced Atlantic hurricane activity. These forecasts have been issued by CSU every year since 1984. Prof. Gray also noted multi-decadal variability in Atlantic hurricane activity and tied this variability to the strength of the Atlantic thermohaline circulation and the Atlantic multi-decadal oscillation. In addition to being an extremely productive scientist, Prof. Gray also served as advisor for over 70 M.S. and Ph.D. students. While Prof. Gray passed away in 2016, his contributions to the field of tropical meteorology will live on forever.

IWTC-9 was like previous workshops in the series provided an international opportunity for forecasters and researchers from around the world to summarize progress, discuss needs and requirements, and plan future advances primarily aimed of improving tropical cyclone forecasting and warning systems.
1.0 Introduction

Tropical cyclone genesis (TCG) continues to be an area of active research due at least in part to its multiscale nature and various pathways to development. Forecasting TCG from a few days to a few weeks in advance remains an operational challenge due to areas of sparse surface data, subjectivity in the Dvorak satellite intensity estimate, and inconsistent definitions of TCG across basins.

Despite the challenges, progress has been achieved toward several of the recommendations made during IWTC-8. Specifically, from the research perspective, there have been additional studies on: the pathways to TC genesis via baroclinic development and tropical waves; aggregation of convection via radiative-convective equilibrium and feedbacks; and, further tests to the marsupial paradigm. Gains have also been made in understanding internal TCG processes, such as the convective and thermodynamic evolution. From the forecasting perspective, additional RSMCs/TCWCs have started issuing operational TCG forecasts to the general public, TCG guidance tools continue to be developed and enhanced, and pre-genesis
advise, and forecasts have become operational. This report provides an overview of the recent advances made to TCG understanding and forecasting.

1.1 Synoptic, mesoscale, and convective scale aspects of cyclogenesis

TCG is the result of a series of complex interactions between spatial scales, successive events, and different physical processes, analysed through combinations of observations, numerical modeling, and theoretical approaches. This report examines recent developments relative to environmental and internal mechanisms controlling TCG.

While the environment in the tropics is frequently favourable for the development of convection, the presence of synoptic scale features can help induce or inhibit TCG. Tropical waves (mixed Rossby–gravity, easterly, equatorial Rossby, Kelvin, and the Madden–Julian oscillation) with different spatial and temporal characteristics modulate vertical motion, moisture, low-level vorticity and vertical wind shear. TCG is strongly related to wave activity in the different basins (e.g. Frank and Roundy 2006). These interactions are still the subject of intense research, with a focus on the influence of interactions between waves of different categories and refining the influence of certain wave types on TCG. Recent research has also emerged on how Rossby wave radiation may be an important contributing factor to Multiple Tropical Cyclogenesis Events (MTCEs). Rossby wave radiation may also impact mid-latitude cyclogenesis, especially in the Mediterranean.

The Inter-Tropical Convergence Zone (ITCZ) and the monsoon systems are the most prominent meteorological features in the tropics, with significant influence on TCG. Many studies have been devoted to the western North Pacific monsoon trough where shear lines, confluence regions, monsoon gyres, easterly waves and Rossby energy dispersion can favour TCG. Recent studies have examined the distribution of where in the monsoon trough region TCG occurs and when the trough is more likely to provide an environment more favourable for TCG. Extension to other basins and monsoon systems remains limited. In the ITCZ, barotropic instability of the low-level flow and breakdown associated with synoptic-scale wave trains are responsible for the genesis of vortices that eventually develop into tropical cyclones.

TCG via tropical transition represents a relatively small, but non-trivial fraction of global TCG events. Recent studies indicate that measures of bulk tropospheric stability (e.g. coupling index) may be more suitable for diagnosing the potential for TCG via tropical transition compared to more traditional metrics (e.g. SSTs > 26°C). Studies also suggest that anticyclonic wave breaking may contribute to the development of upper-tropospheric features that are associated with subtropical cyclone development. Forecasting TCG via tropical transition remains a challenge, with a recent study suggesting that tropical transition may be less predictable than other genesis pathways.

Although it is well known that strong vertical shear of the horizontal wind is detrimental to TCG and further cyclone evolution, TCG can occur in a sheared environment, particularly if the low-level and mid-level vortexes can vertically align. While there is an incomplete understanding of the factors resulting in vortex alignment, recent studies have identified environments where TCs are better able to resist shear. Studies have also been devoted to the processes through which dry air entrained from the mid-troposphere interferes with the developing convection and cyclonic circulation.
Convection is the leading energetic process, driving TCG through latent heat released by condensation of water vapor in liquid water and ice. Recent studies have shown that convection’s spatial organization and proximity to the circulation center are more important factors than its spatial expanse or intensity alone. Developing disturbances are indeed more frequently associated with very deep convective towers concentrated in the inner-core region. But the relationship between such convective outbursts and cyclonic vorticity remains largely elusive, even if new paradigms and diagnostic methods have been proposed.

The marsupial paradigm states that the critical layer of a tropical wave (the pouch), a region of closed circulation protected from dry air intrusion and shear deformation, is a favourable place for TCG through system-scale convergence in the lower troposphere and vorticity aggregation. Several authors have tested this concept for developing storms over the Atlantic, the western North Pacific and the North Indian oceans. Complementary theoretical refinements have been proposed to generalize this approach.

How the incipient vortex acquires its warm-core structure is still largely an open question. The relative roles of upper-level warming by latent heating and adiabatic warming by dry subsidence in the lower troposphere are not yet clear. Likewise, the column moistening of the inner-core region probably results from sequential influences of moderately developed convection first in the low to mid-troposphere, followed by deep convective outbursts near the circulation center. Interactions between the thermodynamic structure and the three-dimensional circulation complicate the TCG framework. The vertical heating profile controls the secondary circulation which leads to vortex amplification, which in turn will modify the temperature field through the associated thermal wind balance.

The extraction of moisture by strong winds flowing over the ocean surface is the real energy source of mature storms, but its role in TCG is less certain. For storms at the earliest stage of their development, it is unclear whether local evaporation through wind-induced surface heat exchange (WISHE) is sufficient to produce enough water vapor to feed the convective developments, or whether moisture rather comes from the outer regions via low-level convergence.

A reliable parameterization of microphysical processes is important to correctly reproduce latent heating. Therefore, it is necessary to correctly account for ice microphysics, which controls the diabatic exchanges in the upper troposphere, and allows a realistic representation of hydrometeors distribution. However, its influence on TCG has not been clearly established.

Important and new results concern radiative feedbacks. Idealized simulations in radiative-convective equilibrium have revealed that moist convective clouds spontaneously organize into one or several clusters surrounded by dry subsiding air. On an f-plane, this self-aggregation process leads to the formation of a single vortex that eventually intensifies to tropical cyclone stage. Also, differential heating between the cloudy regions and their dry surroundings favours upward motion and moistening in the convective clusters. The diurnal cycle amplifies this process due to the destabilization caused by nighttime radiative cooling aloft.

1.2 Cyclogenesis: Operational forecasting perspectives

Continuing the trend noted during IWTC-8, considerable progress has been made with respect to the skill and lead time of operational TCG forecasts from RSMCs/TCWCs. Additional RSMCs/TCWCs have started to issue categorical and/or probabilistic TCG forecasts to the
general public, typically in a graphical format that indicates the location of the disturbance of interest. Many of the current operational TCG forecasts focus on the 0-5 day time frame. However, there are now forecasts that provide a more qualitative assessment of TCG potential in the week 1-2 to week 4 time range. These longer-range forecasts often use forecasts of tropical waves, including the MJO, and convectively-coupled Kelvin waves to assess whether the environment will be modulated to favour TCG. While the recent advances have been encouraging, TCG forecasting and declaration remain a difficult and subjective task due in part to differences in the definition of TC genesis among RSMCs/TCWCs and a paucity of observational data.

Much of the improvement in TCG forecasting has been attributed to the continued improvement of numerical model guidance. This improvement may be due in part to model assimilation of satellite data with greater spatial and temporal resolution, increased model resolution, and improved model parameterization schemes. The result is that global models from various countries and institutions have demonstrated the ability to predict TCG with several days’ lead time. TCG forecast false alarm ratios have decreased, but detection of smaller systems and systems forming outside of the deep tropics remain challenging. Ensemble prediction systems and multi-model ensembles have proven useful for obtaining quantitative probabilistic estimates of TCG.

The development and enhancement of TCG guidance tools has continued since IWTC-8. An extension of the Dvorak technique for pre-T1.0 disturbances and an objective method for determining the relative contribution of genesis pathways is being used in the western North Pacific basin. Statistical-dynamical guidance products using model output fields as predictors for probabilistic TCG forecasts are available for the North Atlantic, eastern and central North Pacific, and North Indian Ocean basins. Another statistical-dynamical technique that uses model output, sea-surface temperature analyses, and satellite data provides TCG guidance globally.

A new development is the operational issuance of pre-genesis advisory and forecast packages for disturbances with a high probability of genesis that are located near land. These new operational products include pre-genesis track and intensity forecasts as well as watches and warnings. They have been an effective method for communicating the hazards associated with a potential TC to the general public.

1.3 Recommendations

The following recommendations – many of which are included in the Rapporteur reports, and some of which are similar to recommendations from IWTC-8 – are proposed for discussion at IWTC-9:

- Investigate multiscale influences on TCG, including STC formation, in different environments and background flows to continue building understanding of the global diversity of TCG.
- Examine MTCEs in all basins, including the role of individual TCs and large-scale flows in favouring MTCEs, together with predictability/forecasting challenges of MTCEs.
- Study how nonlinear interactions of environmental factors (for example, shear, dry air, SST, etc.) affect TCG, particularly how these factors influence convection and vortex alignment.
- Test the sensitivity of observational results to different tracking, areal averaging, and
compositing methods, considering the constraints of the data/instruments being used.

- Utilize the increased temporal and spatial resolution from the latest generation of geostationary satellites, along with next-generation/current polar-orbiting satellites and in-situ data, to increase our understanding of cloud and precipitation structure evolution in developing and non-developing disturbances.
- Explore the TCG helicity framework and rotating convection paradigm, including the effects of system-scale vertical shear.
- Develop and apply novel ways to analyse the flow structure of disturbances, building upon recent Galilean-invariant and Lagrangian frame-independent variables, that can be applied broadly to all disturbances.
- Analyse the role of the midlevel vortex, and associated thermal perturbation effects on convection, on TCG.
- Investigate the role of the spatial structure and time evolution of surface fluxes, gross moist stability, and radiative fluxes/feedbacks in controlling TCG, which should include gathering and analyzing observations of these processes.
- Make use of radiative-convective equilibrium as an idealized framework for investigating the intrinsic properties of TCG.
- Clarify the role of microphysics and microphysics parameterizations in numerical models, including aerosol effects, on modulating TCG.
- Future studies should re-examine how the distribution and frequency of lightning may be associated with TCG, using new satellite-based lightning detection systems.
- Future studies should further quantify the role of the oceanic surface and mixed layer during TCG using in-situ and satellite data as well as numerical modeling studies.
- The research community should develop and/or enhance forecast guidance tools for predicting the track, intensity, and size of pre-genesis TCs.
- The research community should develop and/or enhance guidance tools that provide calibrated probabilistic forecasts of TC genesis globally.
- RSMCs/TCWCs should continue to explore issuing probabilistic forecasts of TC genesis to the general public.
- RSMCs/TCWCs should explore extending their operational probabilistic TC genesis forecasts to days 6-7.
- RSMCs/TCWCs should continue to explore issuing pre-genesis TC track, intensity, and size forecasts for tropical disturbances with a high likelihood of genesis near land.
- RSMCs/TCWCs should continue to explore issuing pre-genesis TC watches and warnings for tropical disturbances with a high likelihood of genesis.
- To more easily intercompare results from multi-model ensembles, the community should explore the use of a common TC tracking algorithm, including a way to commonly track pre-genesis disturbances in model output.
- The community should explore the possibility of creating a standard definition for TC genesis across all basins.
TOPIC 1.1 - SYNOPTIC, MESOSCALE, AND CONVECTIVE SCALE ASPECTS OF CYCLOGENESIS

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Abstract
Significant advances have been made in our understanding of tropical cyclogenesis (TCG), ranging from the microscale to synoptic scales, along with interactions among scales. TCG is a nonlinear process involving the interplay of convection, environmental influences, waves and vortices at various scales, and the accompanying dynamic and thermodynamic processes. Studies have furthered our understanding of these processes, using observations from field campaigns and satellites, numerical model simulations (both idealized and real cases), and theoretical treatments.

We review the latest research on TCG, focusing on environmental influences and internal processes important to TCG. Environmental features that can affect TCG include intraseasonal oscillations, monsoon circulations, the intertropical convergence zone (ICTZ), midlatitude troughs/cutoff lows, which can provide precursor disturbances or help/hinder TCG. Additionally, the roles of various internal processes have been further investigated, such as the organization of deep, precipitating, rotating convection; the evolution of the pouch structure; the role of friction; the development of the moist, warm core; the importance of surface fluxes; and the role of the midlevel vortex. A relatively recent class of idealized, numerical simulations of TCG in radiative-convective equilibrium have highlighted the potential importance of radiative feedbacks on TCG.

1.1.0 Introduction

TCG is a multiscale process involving cooperative interaction between processes from the synoptic scale to convective scale. Since IWTC-8 in 2014, continued progress has been made in understanding a number of aspects of TCG. We summarize recent progress on TCG research.
1.1.1 Environmental influences on TCG

1.1.1.1 Intraseasonal wave interactions

The role of intraseasonal oscillations (tropical waves), including the Madden-Julian Oscillation (MJO), on TCG continues to be an area of active research. The importance of tropical waves in modulating TCG has been further quantified (Xu et al. 2013; Yoshida et al. 2014; Yuan et al. 2015; Hsieh et al. 2017; Bian et al. 2018; Chen et al. 2018; Wu and Takahashi 2018). Schreck (2015, 2016) argued that Kelvin-wave-induced wind anomalies favour the formation of tropical cyclones (TCs) days after a Kelvin wave’s convection has passed. The westward tilting wind anomalies persist longer than the Kelvin wave’s period. Westerly anomalies can reach up to 500 hPa days after the convection has moved away (Fig. 1), which can help close the circulation necessary for TCG. By analysing a TCG potential index, Zhao and Wu (2018) showed equatorial Rossby waves are effective in modulating the midlevel moisture and low-level vorticity. In addition to the direct impacts mentioned above, tropical waves also exert indirect effects on TCG via modulating synoptic wave trains (Xu et al. 2014). TCG can evolve from more than one tropical wave (Park et al. 2015). Chen and Chou (2014) and Ching et al. (2015) found that the MJO and tropical waves can cooperatively act to intensify the local circulation by modulating vertical wind shear, and by increasing upward motion and low-level vorticity at the genesis location.

Numerical model simulations have been widely used to quantify the role of tropical waves in TCG. Extended-range forecasts that have skill in predicting intraseasonal oscillations are able to capture TCG events up to two weeks prior to genesis (Nakano et al. 2015; Xiang et al. 2015). Additional numerical experiments of case studies of TCG offer quantitative descriptions of the contribution of various wave types to TCG (Shu and Zhang 2015; Fang and Zhang 2016; Yang et al. 2018).

![Figure 1. Composite longitude–height cross sections of semi-Lagrangian total zonal wind (shading) and Kelvin–filtered zonal wind anomalies (contours) averaged 0–10°N for (a) 4, (b) 2, and (c) 0 days before genesis. Values that are not 95% statistically significantly different from climatology are grayed out. Contours are drawn every 0.2 m s\(^{-1}\) with westerlies in red and easterlies in blue. Line graphs show the associated Kelvin–filtered rainfall anomalies averaged 0–10°N. Longitudes are relative to genesis and are shown for reference only. Vertical dashed line identifies the estimated easterly wave trough. Adapted from Schreck (2016).](image-url)

Multiple tropical cyclogenesis events (MTCEs), TCs forming in the presence of at least one preexisting TC in the same basin, are associated with tropical waves. Schenkel (2016, 2017) presented a climatology of MTCEs and found that Rossby wave radiation may contribute to a substantial fraction of MTCEs in all basins, and strong intraseasonal anomalies may favour
MTCE occurrences in the eastern Pacific. Hu et al. (2018) also emphasized the role of Rossby wave radiation in a MTCE event. They found that anomalous warming in the tropical central Pacific and cooling in the tropical Indian Ocean favours TC energy dispersion and subsequent MTCEs in the western North Pacific.

1.1.1.2 Monsoon and ITCZ interactions

The monsoon trough is an important synoptic-scale system for TCG. The definition of the monsoon trough and the criteria of TCG within the monsoon trough in the western North Pacific were ambiguous in previous studies. Zong and Wu (2015) proposed a definition for the western North Pacific monsoon trough and criteria for identifying TCG within the monsoon trough based on the daily observations. The percentage of TCG within the monsoon trough is much smaller than that in previous studies. Compared to the confluence zone, more TCs formed in the shear region. Cao et al. (2014a, b, 2016) compared TCG within the monsoon trough in numerical simulations with different monsoon trough strengths. They found that in years with a strong monsoon trough, the monsoon trough provides more favourable environmental conditions for vortex development. Feng et al. (2014) suggested that TCG within the monsoon trough is highly associated with barotropic energy conversion, while barotropic energy dispersion is not the main mechanism for the increase of eddy kinetic energy for TCG in monsoon gyres and easterly trade winds. Wu and Duan (2015) compared simulations of TCG events developing from a synoptic-scale wave train within the monsoon trough, using unfiltered winds and low-frequency, background winds. They found that simulations initialized with only low-frequency winds were able to simulate synoptic-scale waves and TCG successfully. Hsieh et al. (2017) found that the larger, low-frequency vorticity over the western North Pacific is more capable of capturing TCG processes than the smaller, low-frequency vorticity. Akter (2015) highlighted a combination of southwesterly and northwesterly winds in the Bay of Bengal (BoB), associated with the monsoon trough over the BoB, as synoptic flow patterns favourable for triggering BoB bimodal TCG events.

Several studies have focused on TCG mechanisms within the monsoon gyre in the western North Pacific. Wu et al. (2013) found that most TCs tend to form in the center and the eastern part of monsoon gyre. Liang et al. (2014) simulated TCG within ideal monsoon gyres and found that there are Rossby wave energy dispersions to the southeast of the monsoon gyre, which is important to TCG. The genesis location of TCs within monsoon gyres depends on the size of the monsoon gyre.

The ITCZ may also be important for TCG in some circumstances. Cao et al. (2013) simulated TCG due to ITCZ breakdown, and found that a synoptic-scale wave train in the ITCZ contributed to ITCZ breakdown. Yokota et al. (2015) analysed the TC formation process due to ITCZ breakdown in both ideal and real case simulations. They found that barotropic instability of the low-level flow associated with the ITCZ is responsible for the precursor vortices. Conversion from cumulus-scale kinetic energy into TC-scale kinetic energy is significant during the ITCZ breakdown.

1.1.1.3 Midlatitude interactions and tropical transition

Although many TCs form in the deep tropics far removed from the influence of midlatitude systems, about 16% of global TCG events from 1948–2010 form via tropical transition (TT; Davis and Bosart 2003, 2004; McTaggart-Cowan et al. 2013). TT TCG events typically develop poleward of 25° latitude, and their frequency of formation varies between and across
individual ocean basins (Fig. 2). TCs forming via the TT process can develop over SSTs < 26.5°C (e.g. Tory and Dare 2015) due to the reduction of bulk tropospheric stability beneath the upper-tropospheric disturbance that steepens lapse rates and facilitates the development of deep convection. A better indicator of the potential for a TC to form via the TT process is the value of the coupling index (CI), a measure of bulk tropospheric stability (Bosart and Lackmann, 1995), in the vicinity of the cyclone. McTaggart-Cowan et al. (2015) suggested that CI ≤ 22.5°C are required for TT to occur.

According to Galarneau et al. (2015), TCs forming in the presence of an upper-tropospheric disturbance develop from either the favourable interaction of a preexisting lower-tropospheric cyclonic vorticity center with an upper-tropospheric trough or the TT of a subtropical cyclone (STC) (e.g. Bentley et al. 2016). González-Alemán et al. (2015) and Bentley et al. (2017) used cyclone-relative composite analysis to examine the upper-tropospheric features associated with North Atlantic STC formation. These studies reveal that the structure of the upper-tropospheric features associated with North Atlantic STC formation can vary, often identified as cutoff lows, meridional troughs, or zonal troughs. As suggested by McTaggart-Cowan et al. (2013) and Galarneau et al. (2015), the upper-tropospheric features associated with North Atlantic STC formation typically form in conjunction with anticyclonic wave breaking (e.g. Thorncroft et al. 1993).

Recent case studies have identified TCs forming via the TT process in a variety of basins, including the South Atlantic Ocean (e.g. Dias Pinto et al. 2013), Northeast Pacific Ocean (e.g. Bentley and Metz 2016), South China Sea (e.g. Yuan and Wang 2014), and Mediterranean Sea (e.g. Mazza et al. 2017). In the future, the predictability of such TCs should be examined using ensemble prediction systems (EPSs). González-Alemán et al. (2018) recently clustered members of the 51-member European Centre for Medium-Range Weather Forecasts EPS according to their depiction of the evolution of TC Alex (2016) through the extratropical transition process. A similar approach could be used to investigate the predictability of TCs forming via the TT process, as well as the features and processes associated with their formation.
1.1.1.4 Vertical wind shear

There is increased understanding of how vertical wind shear affects TCG, particularly the sensitivity in different environments. The alignment of the low-level vortex and midlevel vortex is associated with genesis and subsequent intensification (Fig. 3; Tao and Zhang 2014; Nasuno et al. 2016; Yoshida et al. 2017). Failed genesis in high shear occurs when convection is advected farther away from the low-level center, leading to reduced secondary circulation strength and weakening precession (Tao and Zhang 2014). TCs at higher latitudes (Zhou 2015) and at higher SSTs (Tao and Zhang 2014) are able to better resist shear and align. Further understanding of the mechanisms responsible for aligning a vortex in a moist, convecting environment is needed.

Vertical wind shear can also enhance entrainment of environmental dry air into convection, which can reduce diabatic heating and have negative effects on genesis (Tao and Zhang 2014), particularly if the midlevel vortex is weak or misaligned from the low-level vortex, leading to a pathway for the dry air to enter the tropical disturbance “pouch” (see section 1.1.2.2; Fritz and Wang 2013; Gjorgjievska and Raymond 2014; Penny et al. 2015; Freimuth et al. 2016; Rajasree et al. 2016b; Fowler and Galarneau 2017; Rutherford et al. 2017). Drier midlevels imply a greater entropy deficit, which increases the spinup time (Zhou 2015; Tang et al. 2016). It remains to be fully clarified the importance of the following in inhibiting the spinup of the low-level vortex: downdrafts, and the flushing of the boundary layer with low-entropy air (Tao and Zhang 2014; Penny et al. 2015); feedbacks, whereby an initial dry-air intrusion weakens convection and the midlevel vortex, leading to greater susceptibility to more dry-air intrusions (Gjorgjievska and Raymond 2014; Freimuth et al. 2016); and the relative roles of subsidence and lateral mixing in drying midlevels (Fritz and Wang 2013).

Figure 3. Sea-level pressure (contour), surface wind (vector), and maximum reflectivity (shading) at 24, 36, 42, 54, and 78 h for simulations with (top row) 5 m s⁻¹, (middle row) 6 m s⁻¹, and (bottom row) 7.5 m s⁻¹ of westerly shear. All simulations have a SST of 27°C. Adapted from Tao and Zhang (2014).
1.1.2 Internal processes during TCG

1.1.2.1 Convective evolution

The convective evolution ahead of and during TCG, and how it differs from nondeveloping disturbances, has been an important focus of TCG research. Using infrared brightness temperature data, Wang (2018) investigated the convective evolution of > 150 TCG events. There are three distinct clusters (Fig. 4), which differ substantially in convective intensity, area, and asymmetry. Such differences can be attributed to environmental effects. Convection is most effective in strengthening a proto-vortex when its maximum occurs near the circulation center. These findings suggest that organized convection near the circulation center is the key overall feature for TCG, and that the spatial pattern of convection is important to consider, not just convective intensity or area alone.

The distributions of convective and stratiform clouds/precipitation have been compared in observations of developing and nondeveloping disturbances. Park and Elsberry (2013) found a sharp latent heating maximum in the region of a strong updraft in the pre-Nuri (2008) disturbance during the TCS-08 experiment. In contrast, nondeveloping tropical disturbances had deeper layers of more vertically uniform heating and cooling rates, and some evidence of more shallow cloud tops, which distinguished them from the developing cases. Fritz et al. (2016) examined the evolution of precipitation and cloud populations using TRMM data. They found that precipitation increases substantially within 36 h before genesis, and suggested that genesis is the outcome of the collective contribution of different types of precipitation (including stratiform precipitation). Case studies of a coastal TCG event by Park et al. (2015, 2017) identified vigorous convective towers (reaching above 15 km height) in TRMM observations just prior to the genesis of Mekkhala (2008) (Fig. 5).

Figure 4. Composite mean of infrared brightness temperature (°C) superimposed on 700-hPa wave-relative streamlines for three distinct convective clusters embedded in different environments at the time of tropical cyclogenesis. Adapted from Wang (2018).
Figure 5. Horizontal distributions from TRMM at 1235 UTC 25 Sep 2008, which is within a convective burst just prior to Mekkhala formation, of (a) PR reflectivity (dBZ) at 6 km, (b) PR storm height (km), (c) VIS infrared brightness temperature (K), and (d) TMI 85-GHz PCT (K) with LIS lightning flashes (black points) in each panel. (e) Vertical cross-sectional distributions of reflectivity (shading), TMI PCTs at 85 and 37 GHz (thick solid and dashed lines, respectively, with the right axis), and near-surface rain rates from TMI and PR (thin solid and dashed with the left axis in 10 mm h\(^{-1}\)) along the lines in (a)–(d).

Adapted from Park et al. (2015).

The roles of convective bursts and the persistence of convection have been studied in developing and nondeveloping disturbances. Chang et al. (2017) found that consecutive convective bursts are observed in many nondeveloping disturbances, as well as developing ones. Using geostationary satellite measurements, Kerns and Chen (2013) followed cloud clusters lasting more than 8 h, and they found many nondeveloping systems exist in seemingly favourable environments. Further investigation of null events would be valuable in assessing why vigorous convection does not lead to TCG in certain cases. Leppert et al. (2013a, b) found that the coverage of low IR brightness temperatures provides the best distinction between
developing and nondeveloping African easterly waves (AEWs). Interestingly, there is little difference in convective intensity between developing and nondeveloping AEWs, suggesting that updraft intensity is less important than the areal coverage of persistent convection near the circulation center. Based on multi-satellite microwave observations, Zawislak and Zipser (2014) showed that developing disturbances have a larger raining area than nondeveloping disturbances but a clear trend in raining area was not found prior to genesis. The discrepancies are likely due to different tracking and composite methods. Wang (2018) showed that convective intensity and frequency both increase with time in the meso-β-scale inner-circulation region but change little, or even weaken slightly, in the outer-circulation region. The trend becomes much weaker, or is even lost, if the averaging area is too large or does not closely follow the circulation center.

The rotating convection paradigm (Kilroy and Smith 2012, 2016; Montgomery and Smith 2017) has been applied to TCG by Kilroy et al. (2017a). They found that cyclonic vorticity, generated by deep convection, can gradually organize into a monopole at relatively low wind speeds. The authors suggested that the processes involved in genesis are not fundamentally different from those involved in intensification, and that genesis does not require the prior existence of a midlevel vortex. This paper offers a seamless view of genesis and intensification without the need to invoke separate mechanisms. Further work is required to expand the rotating convection paradigm to include the effects of system-scale vertical shear. A novel diagnostic method for genesis involving helicity was offered by Levina and Montgomery (2014), who claimed that it may provide an answer to the question of when genesis will occur. This method and claim require further investigation.

1.1.2.2 Marsupial paradigm

Dunkerton et al. (2009) originally proposed the marsupial paradigm for TCG, and the paradigm continues to be used to study TCG in different ocean basins. Lussier et al. (2014) applied the ideas of the marsupial paradigm in the TCG of Nuri during TCS-08, concluding that the Kelvin cat’s eye (or “pouch”) region is favourable for mesoscale vorticity organization by convection and low-level spinup. Rajasree et al. (2016a) discussed the applicability of the marsupial paradigm in the North Indian Ocean, using high-resolution analysis. In another study, Rajasree et al. (2016b) discussed the similarities and differences in TCG sequences in the North Indian Ocean and Atlantic Ocean from the perspectives of the marsupial paradigm. Asaadi et al. (2016a, b, 2017) used a potential vorticity framework to study the formation of the Kelvin cat’s eye in AEWs, reiterating the importance of the wave critical layer for TCG.

In the North Atlantic, AEWs are known to be the main source of TCs. Russell et al. (2017) showed that about 70% of Atlantic TCs directly or indirectly originate from AEWs. Developing AEWs have large low-level moisture and vorticity (Chen and Liu 2014; Brammer and Thorncroft 2015). This favourable environment promotes convective bursts, and results in upper-level warming. This warming contributes to a storm-scale surface pressure drop (Cecelski and Zhang 2013; Cecelski et al. 2014). However, Zhu et al. (2015) argued that even if a pouch exists at midlevels, TCG cannot occur until the low-level circulation/pouch is closed.

There have been refinements of diagnostics and methods to monitor and study pouches. Tory et al. (2013) introduced the OWZ, a Galilean-invariant metric that is the product of absolute vorticity and a normalized Okubo-Weiss parameter, and used the OWZ to define a genesis parameter. Rutherford et al. (2017) developed Lagrangian frame-independent variables to
study the structure and strength of disturbances, particularly disturbances that do not have a straightforward frame of reference (e.g. non-AEW disturbances).

### 1.1.2.3 Friction

The role of friction in TCG had been thought to be relatively unimportant at low wind speeds during TCG (Ooyama 1982). Kilroy et al. (2017b) performed idealized numerical simulations, which showed that, even with a very weak initial vortex, boundary-layer convergence produced by friction plays a crucial role in organizing deep convection near the circulation center. The strength of the frictional boundary-layer convergence and the location where the air exits the boundary layer are dependent also on the size of the initial vortex. Kilroy and Smith (2017) showed that the smaller the initial vortex, the sooner TCG occurs.

### 1.1.2.4 Thermodynamic evolution

#### a) Warm core development

Compared to that in mature TCs, the evolution of the warm-core structure in incipient TCs is less well documented. A few recent studies examined this issue. Using dropsonde data from the PREDICT field campaign, Komaromi (2013) revealed a progressive development of warm anomalies from 500 to 200 hPa. Using microwave temperature profiler data from the PREDICT field campaign, Davis et al. (2014) also showed upper-level warm anomalies near the circulation center (or a negative radial gradient of temperature) in developing disturbances. The authors attributed the warm anomalies to organized convection near the center of the circulation.

The development of the warm-core structure in the lower troposphere was examined by Kerns and Chen (2015). They emphasized the role of stratiform precipitation, and suggested that the lower tropospheric subsidence associated with stratiform precipitation may induce net warming in regions of light precipitation, where adiabatic warming exceeds evaporative cooling. It was also suggested that the vertical alignment of the subsidence warming with the middle to upper tropospheric warming induces substantial surface pressure fall and is a critical step for TCG. This mechanism, however, has to rely on the deep convection and the associated low-level convergence to spin up the low-level circulation. A coherent picture is incomplete, as the development of the dynamical structure (i.e. an intense low-level vortex) and thermodynamic structure (i.e. a warm core) is realized separately by two competing processes (convective vs. stratiform precipitation). In addition, the secondary warm core in the lower troposphere likely develops after the formation of a tropical storm (Wang et al. 2010; Gao et al. 2017), or is much weaker than the primary warm core, even if present (Komaromi 2013).

#### b) Moistening

Another aspect of the thermodynamic evolution is the column moistening. Wang and Hankes (2016) showed that a nonlinear relationship between humidity and precipitation rate exists in incipient TCs. Therefore, saturation fraction can be more or less regarded as an on-off switch for sustained deep convection. Several recent observational studies showed moistening of the inner-circulation region about two days prior to genesis (Wang 2012; Komaromi 2013; Zawislak and Zipser 2014; Helms and Hart 2015), which precedes a sharp increase in precipitation or low-level vorticity (Wang and Hankes 2016; Komaromi 2013). Using numerical model simulations, Wang (2014a) proposed a two-stage conceptual model for TCG. The first
stage is a gradual process of moisture preconditioning and low-level spinup, in which cumulus congestus plays a dominant role (Fig. 6). The second stage commences with the rapid development of deep convection in the inner-pouch region after the air column is moistened sufficiently, whereupon the concentrated convective heating near the pouch center strengthens the transverse circulation and leads to the amplification of the cyclonic circulation over a deep layer. Since column moistening occurs preferentially in the inner-core region, convection and vorticity intensify near the circulation center, but are strongly modulated by the diurnal cycle in the outer-circulation region (Wang 2014b).

c) Surface fluxes

The role of wind-induced surface heat exchange (WISHE) in TCG has been debated. Using an idealized model simulation, Murthy and Boos (2018) tested the hypothesis that a negative radial gradient of surface enthalpy flux is necessary for TCG. It was shown that sustained spinup does not occur if the surface enthalpy flux is homogenous even when the surface enthalpy flux is set to a high value. The strong surface enthalpy flux near the circulation center can be realized via two mechanisms: 1) the wind-dependence of the surface enthalpy flux (or the conventional WISHE mechanism); 2) the enhanced air-sea enthalpy disequilibrium if the surface wind speed is capped to a constant value. Murthy and Boos (2018) suggested that a negative radial gradient in the surface enthalpy flux fosters greater convective instability near the circulation center and is a necessary condition for TCG. However, a water vapour budget analysis by Fritz and Wang (2014) showed that an incipient TC draws moisture from large radii via low-level convergence, and local evaporation only makes a small contribution to the total precipitation.

![Figure 6](image)

**Figure 6.** (a) A schematic showing the approximate water budget above the boundary layer: total moistening (local moistening + horizontal moisture divergence/detrainment) = vertical moisture convergence – net condensation. (b) The net vertical moisture flux (solid curves) and the total net condensation (dashed curves) between 2–8 km within 100 km radius. Black curves are for cumulus congestus regions, and red for deep convective regions. The net vertical moisture flux exceeds (is slightly less than) the total net condensation for cumulus congestus (deep convection), contributing to column moistening (drying). Adapted from Wang (2014a).

1.1.2.5 **Dynamic-thermodynamic interactions**

The constructive interaction between dynamical and thermodynamical processes is critical to TCG. A “bottom-heavy” vertical mass flux profile, one that has a maximum vertical mass flux at lower to middle levels of the troposphere, is more conducive to an increase of near-surface vorticity (Gjorgjievska and Raymond 2014). A midlevel vortex, and its associated balanced
thermal structure, is associated with a smaller normalized gross moist stability and bottom-heavy vertical mass flux profiles, along with an increase in precipitation rates (Fig. 7; Raymond et al. 2014). A positive radial gradient of (normalized) gross moist stability may be important for creating a synergy between surface fluxes, advection by the developing secondary circulation, and the emerging meso-beta-scale proto-vortex (Tang 2017a, b). A stronger midlevel vortex is also better able to preserve the heating and moistening by vortical hot towers, increasing the available potential energy, which can then be converted to the kinetic energy of the secondary and primary circulations (Xi 2015; Wang et al. 2016).

Figure 7. Normalized gross moist stability vs. instability index (saturation entropy difference between $z = 1$–3 km and 5–7 km) for tropical disturbances observed during T-PARC/TCS08 and PREDICT. Cases represented by large green (small red) dots developed into tropical storms (failed to undergo genesis) within 48 h of the observations. Developing TCs also had higher saturation fractions and stronger midlevel vortices (not shown).

Adapted from Raymond et al. (2014).

1.1.2.6 Microphysics

TCG in numerical models is sensitive to the choice of microphysics scheme. Cecelski and Zhang (2016) found in numerical model simulations of Hurricane Julia (2010) that when the latent heat of fusion due to depositional growth is removed, no TCG occurs. Penny et al. (2016) showed that vortex development in numerical models is highly sensitive to the representation of convection and diabatic heating, and that larger heating rates lead to overdevelopment. More sophisticated microphysics schemes do not necessarily produce better TCG simulations.

Another effect of ice microphysics is to produce a midlevel vortex. Kilroy et al. (2018) showed that a midlevel vortex forms in the presence of ice, namely enhanced diabatic heating rates at midlevels due to ice processes. They showed also that a midlevel vortex is not necessary for genesis to occur, and that a systematic lowering of the vertical mass flux maximum can still occur without a prior midlevel vortex, in contrast with the hypothesis offered by Raymond et al. (2014). The interactions of two identical midlevel vortices in an idealized framework were described by Schecter (2016), who found that when the initial vortices are located close to one another, TCG can be inhibited.

1.1.3 Radiative-convective equilibrium and feedbacks

Radiative-convective equilibrium (RCE) is an idealization of the tropical atmosphere in which there is a balance between radiative heat-loss of the atmosphere and heating by convection. RCE is attractive as a background state for TC studies (e.g. Nolan et al. 2007; Khairoutdinov
One phenomenon that has emerged from studies of RCE is convective self-aggregation, in which convection spontaneously organizes into one or several persistent clusters. Self-aggregation is the result of interactions between clouds, moisture, radiation, surface fluxes, and circulation (Bretherton et al. 2005; Wing and Emanuel 2014), and when simulated on an f-plane, takes the form of spontaneous TCG (Nolan et al. 2007). In such RCE simulations, moist cyclonic vortices form, while other regions of the domain become drier, eventually forming a single dominant vortex that subsequently develops into a TC (Davis 2015; Wing et al. 2016). Davis (2015) found that the approach to saturation within a mid-tropospheric vortex accelerates the genesis processes. One result that has emerged is that radiative feedbacks, which are essential to self-aggregation, aid in the development of coherent rotating structures and accelerate TCG (Davis 2015; Nicholls 2015; Wing et al. 2016; Muller and Romps 2018). Radiative feedbacks result not simply from the existence of radiative processes, but from interactions between spatially and temporally varying radiative heating and cooling and the developing TC. Differential heating between deep convection and the surrounding cloud-free region favours rising motion and moistening in the region of deep convection, which promotes clustering of convection and continued moistening of the atmosphere (Wing et al. 2016). Differential heating also can generate a circulation response that favours TCG (Nicholls 2015; Muller and Romps 2018). Both mechanism denial experiments and column moist static energy variance budget diagnostics indicate that these radiative feedbacks, while not strictly necessary, significantly accelerate TCG, and are at least as important as WISHE feedbacks in the early stages of genesis (Wing et al. 2016; Muller and Romps 2018). Once the TC has formed, WISHE plays a dominant role in its subsequent intensification (Tang 2017b). These results from idealized simulations were also found in analysis of radiative feedbacks during TCG and intensification in historical high-resolution climate model simulations (Wing et al. 2018).

These recent results add to a growing body of evidence of the importance of radiation for TCs. Of particular relevance for the role of radiative feedbacks on TCG, the diurnal cycle has been found to accelerate TCG and intensification through a destabilization of the local and large-scale environment (promoting deep convection) due to strong nighttime longwave cooling (Melhauser and Zhang 2014; Ge et al. 2014; Tang and Zhang 2016). In case studies of Hurricane Karl (2010) and Hurricane Edouard (2014), TCG was suppressed in the absence of nighttime cooling (Melhauser and Zhang 2014; Tang and Zhang 2016).

Future research should continue to make use of RCE as an idealized framework for investigating the intrinsic properties of TCG. Future work should also further investigate the role of radiation in TCG, which, despite recent studies, has historically been underappreciated. Observational analyses of radiative feedbacks would be particularly valuable.

1.1.4 Recommendations

We summarized recent progress on TCG research. General research themes are the complexity of interactions between scales that may lead to TCG, comparisons of cloud/precipitation and pouch structures between developing and nondeveloping disturbances, and nonlinear feedback mechanisms that may be important for TCG.
We list the following recommendations for future TCG research:

- Investigate multiscale influences on TCG, including STC formation, in different environments and background flows to continue building understanding of the global diversity of TCG
- Examine MTCEs in all basins, including the role of individual TCs and large-scale flows in favouring MTCEs, together with predictability/forecasting challenges of MTCEs
- Study how nonlinear interactions of environmental factors (e.g. shear, dry air, SST, etc.) affect TCG, particular how these factors influence convection and vortex alignment.
- Test the sensitivity of observational results to different tracking, areal averaging, and compositing methods, considering the constraints of the data/instruments being used
- Utilize the increased time and spatial resolution from the latest generation of geostationary satellites, along with next-generation/current polar-orbiting satellites and in-situ data, to increase our understanding of cloud and precipitation structure evolution in developing and nondeveloping disturbances
- Explore the TCG helicity framework and rotating convection paradigm, including the effects of system-scale vertical shear
- Develop and apply novel ways to analyse the flow structure of disturbances, building upon recent Galilean-invariant and Lagrangian frame-independent variables, that can be applied broadly to all disturbances
- Analyse the role of the midlevel vortex, and associated thermal perturbation effects on convection, on TCG
- Investigate the role of the spatial structure and time evolution of surface fluxes, gross moist stability, and radiative fluxes/feedbacks in controlling TCG, which should include gathering and analysing observations of these processes
- Make use of RCE as an idealized framework for investigating the intrinsic properties of TCG
- Clarify the role of microphysics and microphysics parameterizations in numerical models, including aerosol effects, on modulating TCG

**Acronyms**

AEW – African easterly wave  
BoB – Bay of Bengal  
CI – coupling index  
EPS – ensemble prediction systems  
ITCZ – Intertropical Convergence Zone  
LIS – Lightning Imaging Sensor  
MJO – Madden-Julian Oscillation  
MTCE – multiple tropical cyclogenesis event  
OWZ – Okubo–Weiss–Zeta  
PCT – polarization corrected temperature  
PR – precipitation radar  
PREDICT – Pre-Depression Investigation of Cloud-Systems in the Tropics  
RCE – radiative-convective equilibrium  
STC – subtropical cyclone  
TCG – tropical cyclogenesis  
TCS-08 – Tropical Cyclone Structure – 2008  
TMI – TRMM Microwave Imager  
T-PARC – THORPEX (The Observing System Research and Predictability Experiment) – Pacific Asian Regional Campaign
TRMM – Tropical Rainfall Measuring Mission
TT – tropical transition
VIS – Visible and Infrared Scanner
WISHE – wind-induced surface heat exchange

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TOPIC 1.2 – CYCLOGENESIS: OPERATIONAL FORECASTING PERSPECTIVES

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Abstract
Operational tropical cyclogenesis monitoring and forecasting for different ocean basins is assessed. Improvements in terms of both the skill and the lead time of cyclogenesis forecasts have occurred primarily due to the improvement of skill of global numerical models. The improvements of global numerical models as well as post-processed products (dynamical-statistical) of global models are providing very useful guidance to the issuance of cyclogenesis forecasts operationally.

1.2.0 Introduction

This report summarizes the operational activities in the field of tropical cyclogenesis forecasting at RSMCs and TCWCs worldwide. Note that much of the information in sections 1.2.0 – 1.2.2 has not changed since IWTC-8, and is therefore adapted from Landsea (2014).

Accurate tropical cyclone genesis forecasting is important because of:

- The need to provide extended community response planning, especially in remote or large communities.
- The need to provide advisories at extended forecast ranges for offshore and onshore commercial activities.
- The requirement for National Meteorological Services to manage forecasting and reconnaissance resources.
- The potential to reduce future track, intensity, and size errors by more accurately defining the likely genesis location.

At present:
- Both Ensemble Prediction Systems (EPS) and deterministic Numerical Weather Prediction (NWP) models capture TC formation reasonably well, although both struggle with smaller systems.
- Improvement in cyclogenesis forecasts of operational numerical models are due to advances in various aspects of numerical weather prediction systems, which includes increased
resolution, improved parameterization schemes, and improved use of observations, especially satellite data to improve initial conditions.

- Although tropical cyclone genesis forecasts continue to remain a challenging task, significant improvement in the skill of global numerical models has become very useful for monitoring and forecasting tropical cyclogenesis.

1.2.1 Definition of tropical cyclogenesis

The definition of tropical cyclogenesis from RSMC Miami/Honolulu (North Atlantic and Northeast/North Central Pacific Oceans) is as follows:

“A warm-core, non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and closed surface wind circulation about a well-defined center.”

Note that this definition has no lower bound on the intensity (maximum sustained wind speed). The other regions have similar, but not identical definitions. RSMC La Reunion (Southwestern Indian Ocean) additionally specifies that the maximum of the average wind speed has to be at least 28 kt before a tropical disturbance can be considered a tropical depression. RSMC New Delhi likewise indicates a minimum threshold of maximum winds to be 17 kt. The RSMC and TCWCs of the Southeastern Indian Ocean and Southwestern Pacific Ocean) require maximum winds to reach a minimum threshold of 34 kt before the system is considered a tropical cyclone. RSMC Tokyo, like RSMC Miami/Honolulu, does not have a lower bound wind speed threshold. Such differences make intercomparisons of tropical cyclogenesis across basins somewhat problematic as well as developing and verifying various forecasting methodologies. Regardless of whether a wind speed threshold is used or not, identifying when a TC has formed is a challenging and subjective determination. Even with the benefit of hindsight and post-analysis, the frequent lack of sufficient data and the inherent ambiguity in the definition of a TC introduce ambiguities into the analysis of tropical cyclogenesis. The above definition allows for a wide range of subjective interpretation allowing the forecaster some latitude as far as designating a system a TC.

1.2.2 Genesis forecast tools

Observations and analyses

In preparing a prediction for tropical cyclogenesis, forecasters typically assess the large-scale conditions and other characteristics associated with TC formation including the following necessary but not sufficient aspects (following Gray 1968, Dvorak 1975, Zehr 1992):

- A pre-existing disturbance containing abundant deep convection
- Latitudes poleward ~5°
- Adequate ocean thermal energy: SST > 26°C extending to a depth of 60 m
- A "sufficiently” unstable atmosphere and deep layer of moist air
- Small vertical shear of the horizontal wind
- Upper-tropospheric anticyclonic outflow over the area
- Enhanced lower tropospheric relative vorticity
- Appearance of curved banding features in the deep convection
- Falling surface pressure: 24-hour pressure changes (falls) of usually 3 hPa or more.
1.2.3 Forecasting Tropical Cyclogenesis (Central North Pacific Ocean): RSMC Honolulu

This section describes techniques used at RSMC Honolulu/Central Pacific Hurricane Center (CPHC) to forecast tropical cyclogenesis (TCG) at seasonal, intraseasonal/monthly, and short-to-medium time ranges.

Average environmental conditions make TCG a somewhat unusual event in the central north Pacific (CNP), with the majority of tropical cyclones (TCs) entering the basin from the much more active eastern North Pacific basin. One of the primary inhibitors to TCG within the CNP is the vertical wind shear provided by the combination of prevailing westerly flow aloft, and a nearly permanent easterly trade wind flow. Another inhibiting factor is the climatologically vertical moisture profiles in the CNP in the mid- and upper-levels of the troposphere. However, when environmental conditions shift away from climatology, especially during an El Nino event, TCG becomes more likely in the CNP. In coordination with the Climate Prediction Center (CPC), CPHC issues a seasonal forecast that indicates the number of TCs that are expected to occur within the basin.

On the monthly scale, knowledge of large scale conditions and anomalies can help provide the context for evaluating the likelihood of TCG. One such large scale factor is the Madden-Julian Oscillation (MJO), which is increasingly examined by forecasters, with Phase 7 being the preferred stage for TCG in the CNP. Additionally, on shorter time scales, convectively-coupled Kelvin waves (CCKW) can also affect TCG by temporarily making large-scale environmental conditions more conducive for TC formation. Pre-existing disturbances have a greater likelihood of developing into TCs after the passage of a CCKW or the MJO, especially in ENSO warm events. This was particularly true during the extremely active 2015 TC season in the CNP. The analysis of a CCKW and/or MJO impact on TCG is subjectively applied by forecasters, and usually results in small adjustments to genesis probabilities. The CPC leverages these improvements, and collaborates with national and international partners to produce a Global Tropics Hazards and Benefits forecast (Figure 1). This graphical forecast indicates areas of potential TCG, and provides unified situational awareness to forecasters that can be quickly and easily referenced.

In the short to medium range, CPHC indicates the probability of TCG through the issuance of a regular Tropical Weather Outlook (TWO) during the designated TC season (1 June - 30 November). This text and graphical product is updated every 6 hours, gives a general assessment of activity in the CNP, and provides probabilities (to the nearest 10%) of TCG over the next 5 days. The forecast is split into three categories indicating a low (<40%), medium (40-60%) and high (>60%) chance of TCG. Figure 2 contains forecast verification for the 48 hour TCG CPHC forecasts. The primary conclusion is that CPHC has a small high bias for TCG in the medium probability range.
Global Tropics Hazards and Benefits Outlook - Climate Prediction Center

Figure 1. An example of the Global Tropics Hazards and Benefits Outlook produced by the Climate Prediction Center, in collaboration with a variety of national and international partners.

Figure 2. CPHC 2-day forecast verification of tropical cyclone genesis for the period 2009-2017.
Oceanic heat content, vertical wind shear and the vertical moisture profile fields are analysed to determine the likelihood that an existing disturbance or suspect area will further develop. Deterministic and ensemble GFS and ECWMF guidance are the primary models used at CPHC for predicting the fields that lead to TCG. Guidance from the UKMET/MOGREPS, NAVGEM and Canadian (CMC) global models is also reviewed, typically in those cases where both the GFS and ECMWF are indicating TCG. Recent model advances have led to an increased number of correctly forecast TCG events, with longer lead times.

Recent studies suggest that a consensus of the available model guidance usually outperforms any single model. Additionally, a single model run will not result in dramatic changes to the TCG forecast. Forecasters prefer to evaluate deterministic and ensemble model performance over a series of runs, looking for consistency between models, and for run-to-run consistency of the same model. The probabilities of formation are also modulated by the amount of development indicated by model guidance. For example, if the guidance is unanimous in indicating TCG, but limits development to a weak system that only lasts a few days, then forecasters will temper their forecasts for TCG. On the other hand, if the guidance indicates a more intense TC that lasts for a significant amount of time, forecasters will tend to increase the probability that TCG will occur. However, these subjective analysis techniques can vary amongst forecasters, and this aspect of forecasting TCG can make it a somewhat contentious forecast issue at times.

Objective guidance is available to assist operational forecasters, with a Joint Hurricane Test bed project at Florida State University providing bias-corrected probabilistic TC genesis forecasts based on GFS, UKMET and CMC model output (Halperin et al., 2017). These forecasts provide disturbance-based probabilities of TCG in the 2- and 5-day periods that correspond to CPHC’s Tropical Weather Outlook (TWO). A recent example of the graphic is presented in Figure 3.

![Experimental 0-120 h TC genesis probability](http://moe.met.fsu.edu/modelgen)

**Figure 3.** Tropical cyclone (TC) genesis probabilities based on global numerical models. The genesis probabilities are based on logistic regression models that were developed for each model and each basin.
Additional objective guidance is available through the Tropical Cyclone Formation Probability Guidance Product (Schumacher et al., 2009), developed by the Regional and Mesoscale Meteorology Branch (RAMMB) at the Cooperative Institute for Research in the Atmosphere (CIRA). This product is operationally maintained by NOAA’s National Environmental Satellite, Data, and Information Service (NESDIS), and utilizes global model forecasts, Reynolds weekly sea surface temperature, and satellite imagery to estimate the global probability of tropical cyclone formation within the next 48 hours. An example of the forecast graphic is presented in Figure 4.

Figure 4. The Tropical Cyclone Formation Probability Guidance Product, indicating the probability of TC formation over the next 48 hours

1.2.4 Forecasting Tropical Cyclogenesis (Western North Pacific Ocean and South China Sea): RSMC Tokyo

In this section, some incipient efforts toward the development of tropical cyclogenesis forecasts that have been made at the RSMC Tokyo are briefly described.

1.2.4.1 Early Dvorak Analysis

The Dvorak technique (Dvorak, 1984) provides a measure of tropical cyclone intensity and has been extensively used worldwide in weather centers responsible for operational tropical cyclone analyses and forecasts. In 2007 the RSMC Tokyo expanded the sphere of applicability of the original Dvorak technique and initiated the Early-stage Dvorak Analysis (hereafter “EDA”), where the scale of T-numbers, beginning at 0.0 instead of 1.0, is assigned to cloud systems yet to reach the stage of tropical depression. In the EDA scheme, an organized convective cloud system is given a T-number of 0.0 and 0.5 when it meets three and four, respectively, out of the five prescribed conditions below:

- The convective cloud system persists for over 12 hours.
- Location of the cloud system center (CSC) can be determined with a margin of error less than 2.5 degrees.
- The CSC persists for over 6 hours.
- A well-developed, dense and cold (-31°C or colder at the cloud top) cloud system exists
within a 2.0 degree of radius of the CSC.
- The extent of the said dense cloud system is larger than a 1.5 degree of radius.

The EDA scheme enables operational forecasters at the RSMC Tokyo to spot a prospective precursor to a typhoon (tropical storm intensity or higher) at earlier stages and to examine the likelihood of its growth into a full-fledged typhoon. The results of the EDA are provided on the RSMC Tokyo’s Numerical Typhoon Prediction website (hereafter “the NTP site”) dedicated to the Typhoon Committee members (Figure 5).

During the nearly 10-year period from January 2009 to September 2018, forecasters at the RSMC Tokyo have analysed a total of 553 EDA cloud systems, and 404 of these were assigned a T-number of 0.5. Our analysis shows that the EDA cloud systems assigned T=0.5 eventually evolve into a full-fledged typhoon around 60% of the time, with 239 of the systems developing. This means that the EDA scheme can effectively serve as a tropical cyclogenesis forecast with a typical lead time of up to 48 hours.

![Figure 5. Typhoon AMPIL (T1810), a tropical depression and two EDA disturbances in the western North Pacific analysed at 12UTC July 21, 2018, superposed on an infrared image from Himawari-8. Figures seen under the cross marks indicate a T-number assigned to the disturbance.](image)

### 1.2.4.2 Ensemble prediction-based TC genesis prediction

In 2017 the Japan Meteorological Agency (JMA) has joined the other leading forecast centers in running operationally a global ensemble prediction system dedicated for short-range forecasts up to several days. The JMA Global Ensemble Prediction System (hereafter “GEPS”) runs 6-hourly with 27 ensemble members, and produces forecasts up to 132 hours ahead. The 40km horizontal resolution of the GEPS makes it possible to represent a tropical cyclone over its lifecycle starting from an embryonic cyclonic vortex. Moreover, the forecast range of 132 hours provides an adequate lead time and the 27 ensemble members are large enough to constitute a viable probabilistic genesis prediction.
A probabilistic forecast of tropical cyclogenesis up to 5 days produced from the GEPS has been available since June 2018 on the NTP site under “Tropical Cyclone Activity Prediction”. Juxtaposed with this on the NTP site are similar probabilistic genesis forecasts produced from the ensemble prediction GPVs of the ECMWF, the UK Met Office and the NCEP, and these four genesis forecast constitute a multi-center grand ensemble (Figure 6).

1.2.4.3 Typhoon Genesis Environment Analysis

Although the EDA-based and the GEPS-based forecasts described in the previous sections combine to allow a TC genesis outlook of fair accuracy up to 5 days, they give little or no insight whatsoever into the background atmospheric conditions that are closely related to the intra-seasonal variability of TC genesis occurrences. If forecasters are to weigh the reliability of a TC genesis forecast and to be accountable for the forecast they produce, they need to be informed of the atmospheric environment in the genesis area and to be able to give a valid explanation of the causal links leading to the genesis event.

Ritchie and Holland (1999) (hereafter RH99) examined large-scale circulation conditions associated with tropical cyclogenesis in the western North Pacific basin based on eight years of genesis events and extracted five characteristic patterns favourable for cyclone development: (1) shear line, (2) confluence region, (3) monsoon gyre, (4) easterly waves and (5) Rossby energy dispersion from a pre-existing typhoon (Figure 7).

Inspired by this result, Yoshida and Ishikawa (2013) and Fudeyasu and Yoshida (2018) devised an objective analytical system for the atmospheric environment conducive to TC genesis (Tropical cyclone Genesis Scoring; hereafter “TGS”). Given the location of cyclogenesis, the TGS analyses the surrounding atmospheric circulation field 72 hours prior to genesis and determines to what extent the five patterns identified in RH99 (plus an upper tropospheric trough pattern) might have been involved in the genesis process. The level of contributions from these patterns is represented individually in terms of normalized objective scores ranging from 0 to 1 and can be compared with each other (Figure 8).

An analytical tool like the TGS is very informative and will be indispensable when an operational tropical cyclogenesis forecast is initiated in the future. With this in mind the RSMC Tokyo has been examining the feasibility of bringing the TGS into operational use.
Figure 7. A conceptual image depicting the five atmospheric flow patterns associated with TC genesis events in the western North Pacific based on Ritchie and Holland (1999). (From Fudeyasu and Yoshida 2018)

Figure 8. An analysis of the atmospheric environment associated with the genesis of SHANSHAN (T1813). “SL”, “CR”, “GY”, “EW”, “PT” and “UL” in the below-left inset denote “shear line”, “confluence region”, “monsoon gyre”, “easterly wave”, “preexisting typhoon” and “upper tropospheric trough”, respectively.

1.2.4.4 Notable TC genesis events since IWTC-8 - A case study on the tropical cyclone activity in August 2016

Seven typhoons formed in the NW Pacific basin in August 2016, and four of those, Chanthu, Mindulle, Lionrock and Kompasu, made landfall in rapid succession on the Japanese mainland. This ties with August 1962 and September 1954 as the largest number of typhoon landfalls over the country in a single month since records began in 1951. This pattern of typhoon activity is peculiar given that all the four typhoons headed north instead of west or northwest.
and eventually hit the Pacific coast of northern Japan (Figure 9), where it is rare, though not unprecedented, to experience even a single typhoon landfall. Primarily due to rainfall from these typhoons, the regional average monthly precipitation total in the Pacific side of northern Japan for August was the highest on record since 1946 at 231% of normal. More than 20 fatalities and substantial damages to houses, infrastructure and agriculture were reported due to a recurrence of heavy precipitation events that led to river overflows and flooding.

The active genesis of typhoons in August was associated with large cyclonic circulation anomalies in the lower troposphere encompassing much of the northwestern tropical Pacific. The pronounced cyclonic circulation, which persisted through much of the month and served as a reservoir of positive vorticity, resemble the well-known pattern of the Matsuno-Gill response to an anomalous heating source and may be linked to significantly active convection to the southeast (Figure 10). This intensified convection in turn was ignited and sustained in relation to repeated intrusions of high potential vorticity air associated with the persistent upper-tropospheric trough over the mid-latitude Pacific.

Figure 9. The best tracks for typhoons Chanthu (upper left), Mindulle (upper right), Lionrock (lower left) and Kompasu (lower right). The four typhoons made landfall on the Pacific coast of northern Japan in a single month.
1.2.5 Forecasting Tropical Cyclogenesis (South-West Indian Ocean): RSMC La Reunion

For many years the risk of cyclogenesis has been monitored daily by the TC forecasters at RSMC La Reunion. Five-day genesis forecasts are disseminated through a bilingual daily advisory (delivered in English and French) text bulletin called “Bulletin for cyclonic activity and significant tropical weather in the Southwest Indian Ocean”. Since November 2016, this outlook has been supplemented by a new graphical product called “Cyclogenesis risk prognosis map for the South-West Indian Ocean” (Figure 11). One important point to take note of is the change made to the criteria considered for the cyclogenesis assessment: from now on the risk considered is that of the formation of a tropical storm over the next five days (instead of tropical depression).

If tropical storm genesis is forecast at short-range (<2 days), a solid contour appears on the map, and if it is at long range (2-5), a dashed contour is used on the map. The map is colour-coded so that a high risk (>50%) is shaded in red, 30-50% is shaded in orange, and probabilities less than 30% are indicated in yellow. If the risk changes between the short and long range outlooks, the map shows the highest risk colour and the appropriate contour type for that colour.
Figure 11. Cyclogenesis risk prognosis map with two suspect areas

The main elements considered by the TC forecaster for prognosis of cyclogenesis come from the NWP guidance. Both deterministic and ensemble products are looked at but the most informative are the ensemble products, like the genesis products provided by the European Centre, in particular the strike probability maps which offer very valuable information not only on the potential area of cyclogenesis, but also of the level of risk (probability of occurrence) and of the ensuing general motion anticipated.

Although there are no procedures established for the verification of performances for genesis forecasts, the consensus feeling in the office is that in most cases the information provided by the models is now of very good quality. Compared to the situation 10 to 15 years ago, genesis prediction appears to be the field where the greatest improvements have been achieved by the models. The non detections and false alarms rates have been highly reduced and in some occasions storms have been correctly anticipated to form up to 10 days in advance.

Nevertheless, in some occasions spurious vortices are still generated by the models. However, in general the ensemble does not follow with very few members going the same way, which helps to discard the unrealistic behavior of the deterministic model. Conversely, some tropical cyclones are still missed. Interestingly both situations generally correspond to small systems and low circulations.
1.2.6 Forecasting Tropical Cyclogenesis (North Indian Ocean-NIO): RSMC New Delhi

The average life period of a Cyclonic Disturbance (CD) over the NIO is about 3-5 days only in contrast to larger life periods over other oceanic basins. If a depression (Maximum Sustained Surface Wind Speed (MSW): 17-27 knots and two closed isobars at the interval of 2 hPa in a 5°x5° latitude / longitude box) forms over the NIO from a pre-existing low-pressure area, cyclogenesis is said to have occurred. Recent advances in monitoring and prediction of cyclogenesis over the NIO is presented and analysed in the following sections.

1.2.6.1 Operational monitoring and prediction of cyclogenesis

The standard procedure for monitoring and prediction of cyclogenesis is presented below. The basic inputs for monitoring of cyclogenesis include satellite and synoptic data and guidance from Numerical Weather Prediction (NWP) models and is comprised of the following steps:

(i) Monitoring of the convective cloud clusters using INSAT-3D and Kalpana satellites
   (a) The areal extent, depth, number of cloud clusters with high reflectivity and cloud top temperatures < -40°C and organisation of cloud clusters
   (b) Animation of cloud clusters for past 24 hrs is closely watched for their persistence, areal expansion, increase in depth and improvement in organization. IR/WV/Microwave imageries of various geostationary and polar orbiting satellites are also closely monitored for the above purpose.

(ii) In case of prevailing favourable convection over the sea, the Low Level Cyclonic Circulation (LLCC) is monitored using scatterometer wind data (OSCAT / ASCAT winds) and available buoy and ship observations. Wind speed, temperature and moisture in the vicinity of the LLCC are also regularly monitored using WINDSAT and SSMI data.

(iii) The LLCC is then matched with surface-derived pressure and circulation patterns. When cyclogenesis occurs close to the coast, radar observations take the highest priority to find out the LLCC (Raghavan, 2013).

(iv) The environmental factors governing cyclogenesis (e.g. section 1.2.2) are monitored using satellite-derived products from NOAA-AOML, Co-operative Institute of Meteorological Satellite Studies (CIMSS) University of Wisconsin, INCOIS (Indian National Centre for Ocean Information Services), and Indian and numerical models analyses in addition to buoy, ship, coastal observations.

(v) Climatological inputs are taken from India Meteorological Department’s (IMDs) Cyclone eAtlas [a tool for depicting tracks and statistics of CDs over the NIO in graphical / map form - developed during 2008 in CD form (IMD, 2008) and later hosted in the web during 2012 at the URL: www.rmcchennaieatlas.tn.nic.in)]. Monthly frequency of CDs over the NIO for a specified period from the year 1891 onwards are generated using this tool in 2.5°x2.5° grid map and the same is utilized to determine the climatological probability for the grid corresponding to the region of the pre-existing low pressure area.

(vi) Dynamical and statistical models guidance
A genesis potential parameter (GPP), for the NIO basin has been developed (Kotal et al., 2009; Kotal and Bhattacharyya, 2013) as the product of four variables, namely vorticity at
lower levels, middle-tropospheric relative humidity, middle-tropospheric instability, and the inverse of vertical wind shear. The GPP is used for predicting cyclogenesis at their early development stages (when T-number is 1.0, 1.5, 2.0). The grid point analysis and forecast of the genesis parameter up to seven days are generated in real time. Grid point analysis and forecast of GPP for a typical Cyclonic storm ‘MAARUTHA’ over the Bay of Bengal during 15-17 April 2017 (Figure 12) below shows the analysis and predicted zone of cyclogenesis for 48 hr, 72 hr and 96 hr.

**Figure 12.** Predicted zone of cyclogenesis

(vii) Dynamical model analysis
NWP-based Mean Sea Level Pressure (MSLP), wind, moisture and temperature fields are analysed regularly to compare the model analyses with actual observations for selecting the model with best initial conditions and hence to follow the guidance from that model. The forecaster may also follow the numerical model with better performance in the past for predicting genesis. NWP analysis and forecast fields include outputs from various models such as IMD-GFS, GEFS, NCMRWF(India)-GFS, NCEP-GFS, ECMWF, UKMO, JMA, ARP (MeteoFrance), IMD-WRF, HWRF and IMD coupled model for extended range (up to 4 weeks) forecast (joint effort of IITM, NCMRWF, INCOIS). Figure 13 shows the predicted 4-week zone of cyclogenesis probability from a multi-model ensemble (MME).
(viii) Consensus based monitoring and forecast of cyclogenesis

Depending upon the number of models predicting genesis and based on the past performance of these models and prevailing synoptic climatological and conditions, the probability of cyclogenesis is estimated by the forecasters. Further the dynamical-statistical guidance and synoptic and environmental conditions are also considered by the forecasters while making the final decision.

Thus, the official forecast is based on a consensus forecast determined from NWP, synoptic, environmental, statistical, and dynamical-statistical inputs. It provides probability of cyclogenesis during next 120 hrs based on the observations through 0300 UTC and issued at 0600 UTC. This probabilistic forecast is issued in terms of nil, low, fair, moderate and high probability corresponding to 0, 1-25, 26-50, 51-75 and 76-100% probability of occurrence. After considering guidance from all NWP models, extended range official outlooks (two weeks) for cyclogenesis have also been recently implemented (as shown in Figure 14).

![Cyclogenesis Probability (%) from MME](image)

Figure 13. Predicted zone of cyclogenesis probability by multi-model ensemble (MME)
1.2.6.2 Difficult situations

When a TC forms close to the coast, it leads to operational problems of issuing 120 h forecasts. For example, TC Ockhi developed from a low over the southwest Bay of Bengal and adjoining areas of south Sri Lanka & equatorial Indian Ocean at 0300 UTC of 28 November 2017, becoming a Depression at 0000 UTC of 29 November, Deep Depression at 2100 UTC of same day and Cyclonic Storm at 0300 UTC of 30 November 2018. Most of the models including GFS, JMA, NCUM & NEPS indicated limitation in predicting genesis and intensification of Ockhi. There was over warning of other areas of the Bay of Bengal during formation of Ockhi over the Comorin area. The models predicted weakening of the system over Comorin (actually rapid intensification occurred) and the intensification of a system over the Bay of Bengal (false alarm) which was a challenging task for the forecasters.

1.2.7 Forecasting Tropical Cyclogenesis (Southwest Pacific and Southeast Indian Ocean): Bureau of Meteorology, Australia

Broadly, a similar cyclogenesis forecasting process (periods less than one week) is followed across all of the Australian TCWCs, located in Perth, Darwin and Brisbane. Longer term (out to 28 days) cyclogenesis forecasting is done from our Perth office to service needs of various clients.

The cyclogenesis forecasting process is quite systematic and most forecasters within the Australian TCWCs use checklists, similar to Figure 15, to derive their tropical cyclone outlook policy for their respective regions. The checklists are thorough and ask for forecasters to analyse and assess the following:
Figure 15. Example of an Australian cyclogenesis checklist

- Longer-term assessment of the tropical environment
  - analysis of active tropical waves around the region (MJO and other)
  - interpretation of long term NWP guidance (mainly ensembles)
- Identify the location of any existing or potential tropical cyclones (using any available observations).
- Broad-scale analysis (evaluation of MSLP/low level winds, SSTs, upper level winds/shear and available moisture).
• Circulation analysis (satellite interpretation and analysis of all available observations)
• NWP and forecast (assessment of deterministic and ensemble NWP, including output from ECWMF, ACCESS, GFS, UKMO and other global models).

Although a systematic forecast process is followed within the Australian TCWCs, the analysis and assessment conducted within this process is very subjective depending on the duty forecaster. Forecasters are encouraged to strongly bias the tropical cyclone outlook policy towards the current assessment of the environment in the short term (i.e. day 0 and 1) and to trend towards the NWP assessment beyond that. Consistency in tropical cyclone outlook policy is strongly encouraged from day to day.

1.2.7.1 Tools

Visual Weather is the primary software used in the visualisation of observational data and NWP guidance across all of the Australian TCWCs. Figure 16 provides an example of one of the templates used by forecasters, which shows the multi-view functionality of being able to assess different meteorological fields and levels at the same point in time. The diagnosis of vertical wind shear during the forecast period has historically been an issue for forecasters, but this has been alleviated with the development of a spatially average 850-200hPa shear field (over a 5 by 5 degree, and 10 by 10 degree domain), which can also be seen in Figure 16.

Figure 16. Visualisation of NWP guidance in Visual Weather (top left: 950hPa winds, top right: 500hPa winds and relative humidity, bottom left: 250hPa winds and MSLP and bottom right: average shear in a style similar to the CIMMS output).

Interpretation of ensemble guidance is done largely through custom web sites created for the purpose that show vortex location and intensity for each ensemble member as well as aggregated percentages of members reaching various thresholds. Figure 17 shows an ensemble track viewer that is used to interrogate ensemble guidance. It can show up to the
four most recent runs from the ECMWF, UK and GFS models, with intensity, wind distribution and percentage information easily viewed. Basin risk can also be assessed using similar tools. Figure 18 shows output from a web viewer that displays the percentage of ensemble members that have a vortex reaching user determined wind thresholds. The use of different vortex tracking algorithms on different ensembles complicates the interpretation of these plots. Some trackers, such as that used by ECMWF, calculate the maximum wind speed with in a large radius of the system centre. For weak systems, this can lead to gale force intensity being indicated for a weak circulation when there are gales in the monsoon flow. Hence the raw probabilities tend to have a high bias, despite the overall low bias in intensity amongst ensemble members.

Figure 17. Ensemble track viewer showing tracks, location and intensity of vortex (main panel), percentage of members reaching wind thresholds (lower centre panel), distribution of max wind around vortex centre (lower right panel), and distribution of ensembles by pressure and wind (lower left panel).

Figure 19 provides an example of an ECMWF strike probability viewer that has been created, offering the following benefits to forecasters:

- No need to log in to the ECMWF website and find the product from the forecast menu.
- Provides a view of the entire Australian region.
- Offers the ability to toggle between model runs and therefore provides a trend in the model guidance.
- Allows for quick scrolling through the forecast period.
1.2.7.2 Research

An analysis of the daily and weekly probability of tropical cyclone occurrence in all the Australian basins has been conducted to ascertain the probability of having a tropical cyclone in the region at any time during the tropical cyclone season (Figure 20 shows the Coral Sea example).
For the purposes of formulating a tropical cyclone outlook policy this research is largely used for information purposes, but at times it may provide the forecaster with some guidance for the outlook days (particularly when assessing risk out to 28 days).

![TC probability (%) - Coral Sea (1972/73 - 2015/16)](image)

**Figure 20.** Daily probability of a tropical cyclone in the Coral Sea (142E to 160E, 5S to 29S) based on 44 seasons from 1972/73 to 2015/16 inclusive (for the period between November 1 - April 30 in each season).

1.2.8 **Forecasting Tropical Cyclogenesis (Caribbean Sea, Gulf of Mexico, North Atlantic and eastern North Pacific Oceans): RSMC Miami-National Hurricane Center/NOAA/NWS**

The National Hurricane Center (NHC) continues to make 2- and 5-day genesis forecasts, 4 times daily for the eastern Pacific and Atlantic basins. While many of the tools remain the same from the last IWTC, one of the biggest service enhancements since that time is the ability to issue TC watches/warnings before a system becomes a tropical cyclone (Figure 21). The entire suite of products (including genesis, track, intensity, etc.) is issued when NHC forecasters indicate that the threat of genesis is high enough near land that a watch or warning is necessary. Prior to 2017, there was no way to issue these watches or warnings before a tropical cyclone had formed.
The longest-range input that NHC provides is to the Climate Prediction Center for their week 1 and week 2 forecasts (see section 1.2.3-CPHC for more details). At these long ranges, the GFS, UKMET and ECMWF model ensembles are the primary tools used, in addition to considering the phase of the MJO and if any CCKWs are forecast to be in the basin.

The primary tools used for operational 2- and 5-day genesis forecasts continue to be the global models, specifically the high-skill ECMWF, GFS and UKMET models and their ensembles, and to a lesser extent the CMC and the NAVGEM models. A consensus of the high-skill models usually works better than any individual solution, although this can be extremely variable in a season. Calibrated probabilities for a 20 kt “Tropical Depression” and a 35-kt Tropical Storm (e.g. Figure 22) are available from ECMWF, and these probabilities are used as guidance for the 2- and 5-day NHC predictions. NHC also uses the explicit probabilities calculated from http://moe.met.fsu.edu/modelgen/ (see section 1.2.3-CPHC for more details) as part of its forecast process, and these probabilities have become the primary explicit forecast probability aid.
The use of ensembles in operational genesis forecasting has increased during the past few years with the easier availability of the ensemble members from the ECMWF model. Clustering of ensemble lows, persistence of these features, and the number and trend of ensemble members below 1008 mb is used to supplement the deterministic model output, as well as the run-to-run consistency of the model.

The reliability of the 5-day genesis forecasts in the Atlantic basin is shown in Fig. 23. The NHC forecast reliability has improved since the last IWTC, with only a small low bias noted, which is a little higher in the eastern Pacific (not shown). The refinement distributions are also becoming closer to the ideal (similar number of cases for all bins), although there is still a spike at 10%, likely due to operational procedures of usually introducing disturbances at that value.
1.2.9 Forecasting Tropical Cyclogenesis (South-West Pacific Ocean):
RSMC Nadi-Tropical Cyclone Centre/Fiji Meteorological Service

The RSMC Nadi area of responsibility (AOR) is from 0-25°S, 160°E-120°W covering over 20 million square miles of ocean. Apart from few ship reports and land-based observations, it is a data sparse region. For numbering a low pressure system to a disturbance (TD01F, TD02F...) it has to meet the criteria "has the potential to develop into a tropical cyclone or persist to cause significant impact to life and property in RSMC Nadi AOR and persistently analysed on the MSLP charts for the last consecutive 24 hours".

During the initial stage of development, the 3 day outlook is based mostly on the ECMWF and GFS models. Other diagnostic tools are also used like the CIMSS page for shear, vorticity, divergence, upper air streamline analysis. The Dvorak normal development of one T-number per day is also considered.

The RSMC Nadi issues a 3-day Tropical Cyclone Outlook every day at 0400 UTC from 1 November to 30 April. Here is an example product:

“Tropical Disturbance 07F and Tropical Disturbance 08F were expected to lie in the shaded region. The potential for TD07F and TD08F to develop into a Tropical Cyclone is LOW. The potential for formation of a Tropical Cyclone in the region from another system is VERY LOW (Figure 24).”
Figure 24. The potential for formation of a Tropical Cyclone

References


TOPIC 2 - TROPICAL CYCLONE TRACK

Abstract

The advances in tropical cyclone track forecasting and understanding the science of TC motion are reviewed. Emphasis is on how these advances have addressed the challenges identified in the last IWTC. The fundamental theories of TC motion, which are well accepted by the research community, have been applied to study topographic effects, those from land-sea contrast and interactions with synoptic and mesoscale systems. Besides improvements in dynamic core and physical processes, global models that produce forecasts out to 7 days are now available. Regional models have demonstrated added value to the driving global models. Evaluation of ensemble prediction systems show mostly good spread-skill relationship and reliability in probabilistic forecasts, which form the basis of expression of forecast uncertainties for impact assessment. There is a tendency for operational forecasting centers to apply multi-model ensemble systems for track forecasting that demonstrate superior performance than single-model ensembles. Various selective consensus methods have been developed to address the limitations of simple or unweighted consensus. Nevertheless, there are still cases with very large forecast track errors, which impose great difficulties on forecasters. A typical deformation synoptic flow pattern is found to be associated with many of these difficult cases. Several techniques have been developed to diagnose the error sources and large ensemble spread of these difficult cases. Overall, the challenges identified four years ago have been well addressed by the advances in research and operations. However, a more consistent way to estimate and express forecast uncertainties across operational forecasting centers is desired, which would help future evaluation of the ensemble systems, consensus methods and uncertainty communication.

2.0 Introduction

Elliot and Yamaguchi (2014) reported the advances in tropical cyclone (TC) motion and track forecast studies for the IWTC-VIII, which is the basis of reference here. Several major challenges in TC track forecasting were identified four years ago. A summary of our rapporteur reports with respect to the three subtopics (2.1 to 2.3) is provided with emphasis on how progresses in research and operations since 2014 have addressed the earlier challenges identified. These challenges are summarized here for reference.
A. Forecast skill for weak or at the initial stages of TC development is usually low and needed to be improved. This situation also applies when the analysed intensities in numerical models are weak.

B. To minimize the track variability (i.e. increase the track forecast ‘steadiness’) without sacrificing accuracy or timeliness.

C. The consensus approach to track forecasting sometimes leads to short-term motions that are consistently faster or slower than that observed.

D. There were still TC cases with large forecast errors, in which the observed track was totally outside the ensemble envelope. Our knowledge of the sources of these large forecast errors is still poor.

E. There is still no consistency in uncertainty estimation across the operational centers. Standardization within agencies on best practices will enable consistent messaging.

2.1 Recent progress in fundamental and theoretical studies on tropical cyclone motion

In IWTC-VIII, it was reported that although there was almost no new research on TC motion for many years and our existing theories on TC motion are satisfactory to many, there are still significant track forecast errors. In the past few years, there were a substantial number of studies that obtained further understanding of the existing TC motion theories, development of new mechanisms on topographic effects, as well as those during interactions with synoptic and mesoscale systems.

Under the barotropic framework, the theoretical basis of TC motion is the environmental steering flow and that contributed by the beta-gyre effect. When there is diabatic heating associated with convection, the potential vorticity (PV) tendency budget equation explains TC motion well. While the beta effect and PV tendency theory have been developed for years and are well understood, in recent years they have been applied to study topographic effects, those from land-sea contrast and interactions with other synoptic and mesoscale systems.

2.1.1 Barotropic framework

Further studies have been conducted under the barotropic framework. For example, based on the barotropic nondivergent model the beta gyre effect can be interpreted in terms of a wavenumber-1 vortex Rossby wave propagating via the outer-region waveguide. Thus, the beta gyre would depend on the radial profile of the basic vorticity field. Singular vectors (SVs) of the barotropic model were developed to study how perturbations grow under either cyclonic or anticyclonic horizontal shear.

In most of the previous studies, the barotropic model is applied to the steering level or a layer. However, the horizontal advection of planetary vorticity by the TC circulation at different vertical levels would generate vertical wind shear (VWS) known as the beta shear. Such latitude-dependent (via the Coriolis parameter) beta shear results in asymmetric convection. Consideration of the PV equation due to convective heating then leads to higher tendency of recurvature for TCs at higher latitudes, which is an intrinsic property even under no mean flow.
2.1.2 Topographic effect

When a TC approaches topography such as an island, track deflection, especially the upstream type with respect to the terrain, often causes large forecast error and needs better understanding. In the past few years, the following mechanisms have been proposed to explain such upstream track deflection: (1) advection by orographically blocking flow, (2) channelling effect, (3) asymmetric latent heating, (4) asymmetric mid-level steering flow, (5) terrain-induced gyres and (6) approaching angles and landfall location.

Studies showed that all these mechanisms may be interacting, but some of them are more important in specific periods. Terrain such as Taiwan and the Philippines induce a pair of gyres, which rotates cyclonically within the TC circulation. The flow associated with the gyres would provide additional steering to the TC. It was found that near landfall, horizontal advection of PV and diabatic heating are both important.

The low-level channeling effect and the modification of the background flow by topography (when the TC is still upstream of the terrain) has been proposed in earlier studies to explain the southward track deflection. Recently, more mechanisms responsible for the track deflection have been investigated. These include the orographically generated high pressure, inner-core dynamics and the azimuthally asymmetric tangential wind at middle levels as reported in several studies. When inner-core convection is modified, the associated asymmetric diabatic heating would cause deflection. In general, track deflection is most prominent when the translation speed (i.e. background flow) is slow.

2.1.3 Interaction with other systems

Besides TC intensity forecasts, atmosphere-ocean coupling was found important to track forecast as well. The vertical extent of a TC was found to be different in numerical models with or without atmosphere-ocean coupling. The vertical extent of the TC then determines the vortex’s sensitivity to steering flow. A weaker and shallower TC may be more sensitive to the low-level steering. On the other hand, atmosphere-ocean coupling would change the upper-level anticyclone. Depending on the location of the upper-level anticyclone, asymmetric convection may be promoted such that the associated diabatic heating contributes to a steering component that changes the track. Although the impact is not substantial, indeed it has been reported that slight improvement in track forecasts was obtained in coupled models versus uncoupled atmospheric models.

Studies found that the background flow pattern largely determines the predictability of TC track. In particular, it was reported that often the largest ensemble spread was from a steering flow pattern with a saddle point of strong deformation. Under such flow pattern, a small perturbation would result in drastically different TC track direction.

Studies have also been conducted on interactions with large-scale features such as monsoon gyre (MG), upper-tropospheric cold low (UTCL) and subtropical high (SH). For MG, it was found that factors of initial TC structure, vertical and intensity of the MG are all important to the TC track. A noticeable case to study was Typhoon Megi (2010) that made a sharp northward turn around the MG.
The interaction between UTCL and TC track has been studied statistically. Unlike previous results through case studies, it was found that the interaction distance between the UTCL and TC has to be as small as 5 degree for significant impact to the TC track. When there is interaction with the UTCL, usually the TC slows down during the abrupt directional change.

The issue of TC size and its interaction of the SH, especially for cases over the western North Pacific (WNP), has been studied. Often, TCs with larger size were able to break into the SH and turned northward. Studies showed that TCs with a large vortex have increased mass flux over the outer region, which decreases the midlevel geopotential height there and leads to a break in the SH.

2.2 Recent progress in tropical cyclone track forecasting and expression of uncertainties

2.2.1 Global models

Compared with the IWTC-VIII report on TC track (Elliot and Yamaguchi 2014), the major advancement in track forecast is the extension of lead time to 7 day (168 hours) in some of the operational forecasting centers. Besides computational resources, a lot of changes in model configurations have to be implemented for realizing 7-day forecasts. The encouraging news is that operational numerical weather prediction (NWP) centers such as the ECMWF has demonstrated skill in their 7-day operational forecast comparable with that from the same model driven by ERA5 reanalysis.

Most operational NWP centers still show a decreasing trend of track forecast error from about 4-5 years ago. For example, the downward trend in the UKMO MetUM’s forecast error has accelerated since the major model upgrade in 2014. In other words, there is still room for improvement in TC track forecasting, although studies have investigated the associated predictability limits.

There have been changes in the global model configurations that are relevant to address the challenge A with respective to weak TCs. It was reported that coupling to the ocean in the ECMWF HRES and ENS system had a significant impact in improving TC intensity, which may improve the sensitivity of weak systems to the steering flow. Also note that within the US Next Generation Global Prediction System, the identified model GFDL fvGFS (or the FV3-GFS) has a dynamically active mixed-layer ocean model.

To represent the TC circulation well in the model, especially for the weak TCs, initial condition is critical to track forecast. Model cycles in the ECMWF will also allow more ‘late’ observations to enter the system during the assimilation process. In NCEP, GFS model uses a special technique for relocating TC position in the model background. JMA will start all-sky microwave radiance assimilation and improve the method of assimilating high-resolution atmospheric motion vectors derived from Himawari-8. For the US Navy’s NAVGEM, the TC synthetic wind profile assimilation technique will be improved to consider the higher model resolution compared with that decades ago.

2.2.2 Regional models

In general, the skill of TC track forecasts from regional models is comparable to those from the driving global models. However, two points are noteworthy. One is that the track forecasts
from regional models are dependent on the global model driver. This has been demonstrated for the COAMPS-TC system. There is significant difference in the track mean error when COAMPS-TC is driven by the NOAA/GFS versus that by the Navy NAVGEM.

Secondly, although most of the regional models have track characteristics similar to that in the driving model, there are circumstances when the regional model would behave differently. It has been demonstrated that the regional version of the MetUM has significantly different storm positions compared with the global driving model, meaning that the inherited steering flow has been modified. In addition, the Météo France AROME, convection-permitting models for their overseas domains perform much better than their driving model for TC track forecast.

Synthetic observation scheme is performed in some regional models. This is the case for the Australian ACCESS-TC2 (and the forthcoming ACCESS-TC3) system. Synthetic observations in addition to the normal in-situ and satellite observations are applied to help define the TC vortex.

In general, the regional models still have better track forecasts for the more intense TCs compared to the weak systems. Nevertheless, the regional models usually have better intensity estimates than the driving global models and would be beneficial to forecast the tracks of the weak TCs.

2.2.3 Ensemble prediction systems (EPSs)

The details of the EPSs and their recent upgrades in the operational NWP centers can be found in the rapporteur report. The emphasis here is that whether the perturbation and post-processing techniques in the EPSs can address the challenge B and C identified in the IWTC-VIII. Namely, whether an accurate motion vector can be estimated from the EPS, this is especially critical in the short term when the TC is steered in a particular direction. At the same time a steady forecast is desirable from the forecaster perspective.

Various kinds of selective consensus have been developed for EPSs in the operational centers. In the UKMO, storm-based verification has been performed for their multi-model ensemble system. The ensemble that displays the highest skill varies from storm to storm. Although the multi-model ensemble usually has comparable skill with the strongest performing individual member, it would be good if we have understanding about why some ensembles perform better for some storms but not the others.

The Météo France operates the mesoscale EPS (Arome-Ensemble). Case studies from applications of the Arome-Ensemble showed that the system may add value to the global ensembles. For example, in some fast-moving TCs Arome-Ensemble simulated tracks with consistent speeds and closer to observations, thus having less track variability compared with the global ensembles. This would give higher forecast confidence to the forecasters.

The UKMO’s global ensemble MOGREPS-G is going to adopt an ensemble data assimilation system En-4DEnVar (from the previous Kalman filter method). The new En-4DEnVar has shown much faster growth of ensemble spread and better match to errors (i.e. a better spread-skill relationship). Moreover, a technique to partially re-center the TC around deterministic analysis gives an additional increase in skill and reduces jumpiness. The latter will be able to address the challenge B.
Reliability diagrams have been applied to evaluate ensemble systems. Strike probability evaluation for the ECMWF ENS shows that their 10-day forecasts are slightly over-confident. However, for 7-day forecasts, the ECMWF ENS has near perfect reliability for all probabilities. Comparatively, the UKMO MOGREPS-G and the NCEP GEFS show over-forecasting for probabilities over 60%, but GEFS also has under-forecasting for 0-20% probabilities. The JMA had their GEPS replacing the old Typhoon-EPS. The new GEPS provides useful information on the reliability of TC track forecasts with its ensemble spread.

A relevant development to better spread-skill relationship is the stochastic perturbation technique in the new NCEP GEFS based on the FV3 dynamic core. The technique involves stochastic perturbation of physical tendencies, kinetic energy backscatter and humidity. The overall good evaluation on spread-skill relationship and reliability of these global ensemble systems is the basis of providing consistent uncertainty estimates for TC track, which is our challenge E.

2.2.4  Operational forecasting centers

Most operational forecasting centers apply multi-model ensembles for their operational forecasts, and their detailed configurations can be found in our rapporteur report. Again, the issue here is that whether a simple consensus is applied for operational forecast, or whether kind of optimized / weighted / corrected / selective consensus is developed. The Florida State University Super-ensemble (FSSE) is an example from the U.S. NHC. FSSE combines its individual components on the basis of past performance and attempts to correct biases in those components. Certainly, availability of ensemble members is an issue. The NHC has been experimenting in extending the forecasts out further in time to 7 days, however, not all models run out to this lead time.

The JTWC utilizes an internally generated, non-weighted, consensus forecast track aid named the CONW. The 10-member ensemble consists of both global and regional models. The model members are evaluated annually before they are included as the CONW members.

The JMA introduced multi-model ensemble forecasts in 2015. They are also working on the selective consensus method and seeking the best combination of NWP models. It was reported that TC position error from 72-hour forecasts can be reduced up to 150 km by the best model combination. However, such best combinations differ each time and for each storm, and an objective method to identify it has yet to be identified.

It is noteworthy that the JMA reported reduction in the forecast circle radii as a remarkable improvement in performance related to track forecast since the IWTC-VIII. The official radius of forecast circle (with about 70% probability within the circle) has been reduced by 20-40% depending on TC direction and speed. The IMD also reported the radii of the cone of uncertainty based on past five years average track forecast error have been reduced by about 20-25% since 2014. These changes address the issue of over-dispersiveness of the warning areas.

The NHC has been forecasting based on the GFS model with a sophisticated 4D hybrid ensemble-variational global data assimilation system. A special technique of relocating TC position in the model background is also applied. While the short-term track errors have been quite steady in the last few years, the 3-day to 5-day forecasts still have clear decreasing trends of track errors for hurricanes in the Atlantic and East Pacific since 2014. One exception
is over the East Pacific when the average track error in 2017 was higher than that in 2016 for all lead times. The average track error for Atlantic hurricanes in 2015 was also higher than that in 2014.

2.3 Advances in understanding difficult cases of track forecasts

Our subtopic 3 has exactly addressed the challenge D about the TC cases with large forecast errors. In many of these cases, the ensemble forecast tracks all or mostly missed the observed TC track, thus leading to serious issues in impact preparation. Although the operational models have been improving significantly throughout the past decades, the WMO WGNE project on intercomparison of TC forecasts still showed that for all operational NWP centers there were extremely large errors that deviated far from the mean/medium errors.

Studies to improve our understanding of these cases with large errors are urgently needed. Reviews associated with this subtopic have shown substantial advances in the diagnostic techniques of the difficult cases, which are briefly summarized in the following. A number of studies analysed the difficult case Hurricane Joaquin (2015). This case can be applied as a reference to collectively identify error sources from the operational models and ensemble systems worldwide.

2.3.1 Forecast busts

Difficult cases in TC track forecasts are known as 'forecast busts’ or 'drop-outs’. These cases can be grouped into those with large forecast bias (e.g. track error of ensemble mean forecast is larger than a certain percentile in the annual track error distribution). The second group consists of those with large forecast spread (e.g. with ensemble spread larger than a certain percentile of the annual spread distribution of the ensemble members). These two groups of forecasts would pose challenges to researchers and forecasters. We need to understand the sources of errors in the first group, while for cases in the second group propagation of uncertainties would be very fast.

2.3.2 Diagnostic tools to understand difficult cases

In the last few years, diagnostic tools have been developed to understand the error sources in the difficult cases. These tools include: diagnostics of the environmental flow, ensemble sensitivity, masked ensemble perturbations, adjoint sensitivity and nudging (relaxation) experiments.

Diagnosis of the operational model simulations of Hurricane Joaquin (2015) showed that they did not forecast well either the intensity or track of the hurricane. Hurricane Joaquin’s actual track avoided a region of large VWS, and it was able to rapidly intensify even over less warm SST. The large track errors from the operational models may be related to how the intense storm core interacted with the steering environment. Diagnosis of the tracks within the ECMWF ensemble also showed sensitivity to the subtropical ridge to the east and the trough over U.S.

Ensemble sensitivity technique have been applied to study track variability within the ECMWF ensemble. The initial southwestward motion of the Joaquin was associated with more northerly ensemble perturbation steering winds. The hurricane then entered a region of
deformation steering environment, thus position variability increased quickly. It was found that such variability was mostly sensitive to steering winds near the TC core.

In the masked ensemble perturbation technique, initial perturbations can be withdrawn from inside the TC, in the vicinity, and/or remote from the TC. Applying this technique to Hurricane Joaquin it was also found that perturbing the core of the hurricane created the largest ensemble spread. The greatest sources of track errors originated 600-900 km from the center, while those around 300 km from the TC contributed to the intensity spread.

The US Navy's COAMPS-TC ensemble was applied to study the intensity and track simulation of Hurricane Joaquin by performing re-runs with only vortex perturbations or only synoptic and lateral boundary perturbations. The discrepancy between intensity and track forecasts can be explained by these re-runs.

Based on the COAMPS-TC ensemble, Hurricane Joaquin was also found most sensitive to an anticyclonic wavebreaking event that occurred north of the cyclone. Furthermore, the adjoint modelling system of COAMPS and adjoint sensitivity diagnostics highlight the importance of an upper-level trough to the northeast that provided the steering flow for the poorly-predicted initial movement of the hurricane to the southwest.

2.3.3 Lessons learned

As discussed in section 2.1.3, a steering flow pattern featuring a saddle point with strong deformation is often associated with large track forecast error. Such a pattern was identified for storms with large forecast errors over the western North Pacific (WNP). In the case of Typhoon Hagupit (2008), diagnosing the outer circulation structure is important. In the deformation pattern the steering flow is not clear. However, after the primary (azimuthal wavenumber-0) component is removed, a cyclonic gyre is identified providing the easterly steering flow for Typhoon Hagupit to move northeast toward Luzon.

Typhoon Debby (2012) and Typhoon Lionrock (2016) over the WNP were also located in a deformation wind field. Studies showed that forecast variability increases via a two-stage process. In the early forecast, small differences in near-storm steering flow would advect the storm onto one side or another of the axis of contraction within the deformation flow pattern. Afterward, the storm experiences different ensemble-mean winds and is advected farther away from the ensemble mean position, resulting in a very large ensemble spread.

Some operation centers have developed techniques to reduce forecast errors due to the forecast busts or outliers. For example, the CMA has developed their OBEST (and the Super-OBEST based on multi-model super-ensemble) system that constructs a subset of ensemble members based on their 12-hour error. This super-ensemble subsetting method has been used operationally at the CMA Typhoon and Marine Forecast Center since 2015. The reason for this ensemble subset’s good performance is that when the TC is close to a bifurcation point, the error could be sharply reduced when new information is taken into account.

Recommendations

Since the average error of track forecast has been decreasing for years, the physical processes that were considered ‘minor’ previously have become ‘substantial’ as the expected accuracy becomes higher than ever. Thus, further research should be performed on the physical
processes discussed in 2.1, including topographic effect, land-sea contrast, interactions with synoptic and mesoscale systems.

(2) It is recommended that initiatives such as The International Grand Global Ensemble (TIGGE) and the collection of global models’ forecast tracks by the WGNE shall continue. With these collections, ensemble sensitivity can be conveniently applied without additional resources for model simulations to diagnose large forecast track errors.

(3) The investigations on difficult forecast cases should feedback into the observation community through field-based projects with targeted observations. The locations of the most important errors can provide strategies of observations such as dropsondes.

(4) The difficult cases with large ensemble spreads should be used to improve communication of uncertainties, and training of forecasters to better understand forecast uncertainties.

Acknowledgments

The topic co-chairs would like to thank all the rapporteurs named at the top of the report for writing their subtopic reports and providing valuable information used in the compilation of this report.

Acronyms used in the report

ACCESS - Australian Community Climate and Earth-System Simulator
COAMPS – Coupled Ocean/Atmosphere Mesoscale Prediction System
ECMWF – European Centre for Medium-range Weather Forecast
EPS – Ensemble Prediction System
ERA – ECMWF Reanalysis
FSSE - Florida State University super-ensemble
GEFS – Global Ensemble Forecast System
GEPS – Global Ensemble Prediction System
GSM – Global Spectral Model
HRES – High Resolution
IMD - India Meteorological Department
IWTC – International Workshop on Tropical Cyclones
JMA – Japan Meteorological Agency
JTWC – Joint Typhoon Warning Center
MetUM – Met Office Unified Model
MOGREPS – Met Office Global and Regional Ensemble Prediction System
MG - Monsoon Gyre
NCEP – National Center for Environmental Prediction
NHC – National Hurricane Center
NOAA – National Oceanic and Atmospheric Administration
NWP – Numerical Weather Prediction
OBEST – Observation-Based Ensemble Subsetting Technique
PV – Potential Vorticity
SH - Subtropical high
SST – Sea Surface Temperature
SV – Singular Vector
TIGGE – The International Grand Global Ensemble
TC – Tropical Cyclone
UKMO – United Kingdom Meteorological Office
UTCL - Upper-Tropospheric Cold Low
VWS – Vertical Wind Shear
WNP – Western North Pacific

References

TOPIC 2.1 - RECENT PROGRESS IN FUNDAMENTAL AND THEORETICAL STUDIES ON TC MOTION

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Abstract
This report summarizes the recent advances in the fundamental understanding of the movement of TC. Although this area is quite mature, there are still considerable progresses. This report summarizes new concepts and updates on existing fundamental theories on TC movement obtained from simplified barotropic models, full-physics models, and data analysis. It also reviews the interaction with environment and discusses the fundamental aspects of predictability related to the TC movement. The conventional concepts of the steering flow, β-gyre, and diabatic heating remain important. However, sophisticated understanding of various mechanisms serves as an important basis toward the further improvement of track forecast.

2.1.1 Introduction

Amongst all the elements of TC forecasting, the track forecast has always been the most important, because the intensity, rainfall, and storm surge become less meaningful if the track forecast is wrong. Basically, a TC is influenced by the surrounding flow, but its motion is also modified by the β-gyre effect and the diabatic heating. Because of the importance of the TC track, the effects of topography, land-sea contrast and the interaction with other systems on the TC motion have also been intensively studied.

However, there are still considerable progresses in the understanding of the movement of the TC. With the errors in track forecast being decreased, the considerations of the physical processes that were previously thought of as "minor", have become more important. It is also worth mentioning that updated understandings of well-known mechanisms and the important target regions. This report does not repeat detailed discussions on the concepts mentioned earlier in Elsberry (1995), Chan (2010, 2017), and the latest one on the TC track in IWTC-VIII (Elliot and Yamaguchi, 2014). Rather, this report focuses on the recent findings from numerical models and data analysis.
2.1.2 Barotropic Models

Recently, Gonzalez et al. (2015) have shown that a barotropic non-divergent model has replicated the linear $\beta$-gyres as a stream function dipole with a uniform southeasterly ventilation flow across the vortex. The $\beta$-gyre effect can be interpreted in terms of a wave number-1 vortex Rossby wave. Because the positive mean radial gradient of the vorticity in the outer region constitutes an outer waveguide that supports very-low-frequency vortex Rossby waves, the reproduced structure of $\beta$-gyre clearly depends on the radial profile of the basic vorticity field. They also show that although the simulated storm with the linear model accelerates to unrealistically fast speed (8.5 m/s), the introduction of non-linearity yields the forced wavenumber-1 gyres, that have opposite phase of the linear gyres. In this way, their ventilation flow counteracts the advection by the linear gyres, to limit the overall vortex speed up to approximately 3 m/s.

Scheck et al. (2014) investigated the structure and evolution of SVs for stable TC-like vortex in background flows with horizontal shear using a non-divergent barotropic model (Fig. 2.1.1). In anti-cyclonic shear with westerly wind to the north, the leading initial SV for a stable TC-like vortex is aligned with streamlines connected to stagnation points. The singular value for the leading SV for anticyclonic shear is larger than that for the cyclonic shear. The evolved SV indicated a southwest-northeast displacement of the vortex. This is associated with the efficient advection by the outer perturbation.

Figure 2.1.1. Vorticity distribution of the initial (a),(b) and the evolved (c),(d) SVs for a single stable vortex: an optimization time interval of 2 days and background (left) cyclonic shears and (right) anticyclonic shears. The thin black contours are streamlines. In the anticyclonic shear case, the thick lines are the streamlines connected to the stagnation points (small circles) north and south of the vortex. The singular value is shown by sigma at the upper left in each panel. (after Scheck et al., 2014)

2.1.3 Recurvature

The recurvature is basically explained by the change of the environmental flow that steers the TC. Recent works have shown that the occurrence and location of the recurvature are sensitive to the SST field and the size of TC, as discussed in sections 2.1.5 and 2.1.7 below. Notably, it has been found that a TC initiated at a higher latitude can recurve by itself even in the absence
of background flow (Chan and Chan, 2016; Fig. 2.1.2). Differential horizontal advection of the planetary vorticity by the TC circulation at different vertical levels leads to the development of vertical wind shear known as the $\beta$-shear. The flow associated with the upper tropospheric anticyclone on the equatorward side of the TC and the diabatic heating associated with the asymmetric convection combine to cause the intrinsic recurvature of the TC. The knowledge is important in forecasting the movement of the TC, when, in particular, the environmental flow is weak. The anticyclonic outflow in the upper troposphere and Rossby wave dispersion, gradually propagate the upper tropospheric anticyclone equatorward and westward such that it displaces from the southeast to southwest of the TC in general (Wang and Holland, 1996). Given that a TC located at a higher latitude has a slower development (Li et al., 2012) and a greater Coriolis force, the anticyclonic outflow of a higher-latitude TC therefore advects the upper tropospheric anticyclone less outward (see Fig. 3 of Chan and Chan (2016)). As a result, the upper tropospheric anticyclone of a TC at higher latitude is located closer to the vortex and thus has a greater influence on the TC movement through the horizontal advection of potential vorticity. It subsequently leads to the diabatic heating asymmetries to cause the intrinsic recurvature at higher latitudes.

### 2.1.4 The Influence of Topography

The interaction between terrain, basic flow and the TC is non-linear. Recent studies have made efforts in further understanding of the mechanisms leading to TC track deflection (Lin et al., 2016). The following mechanisms have been proposed to explain the upstream track deflection: (1) Advection by orographically blocking basic flow, (2) Channeling effect, (3) Asymmetric latent heating, (4) Asymmetric steering flow in middle levels, (5) Terrain induced gyres, (6) Approach angles and landing location.
Tang and Chan (2014) analysed the terrain effect in the Taiwan and the Philippines. The terrain induced gyres are found over both Central Mountain Range of Taiwan and the mountains of Luzon. A pair of terrain-induced gyres rotate cyclonically around the TC, and the flow associated with the gyres starts to push the TC northward. As the TC is about to make landfall, the anticyclonic gyre is located north and the cyclonic gyre south of the TC. Furthermore, the height of a terrain controls the strength of the terrain-induced gyre, with weaker gyre in the Philippines terrain simulation. PVT diagnosis showed that while horizontal advection played a major role, the importance of diabatic heating became comparable during the landfall period.

Different from the mechanism of track deflection proposed by Jian and Wu (2008) and Huang et al. (2011), which had suggested that low-level channeling effect is the main contribution of the track deflection. Wu et al. (2015) investigated the effect of sudden track changes of TCs approaching Taiwan. An important finding in this study, is that the robust flow characteristics identified during the southward turn of a TC is the azimuthal asymmetric tangential wind at middle levels, but not the channeling winds at low levels. The azimuthal changes in the wind speed is connected to the changes in vertical velocity. Sensitivity experiments with respect to different parameters are also conducted in this study. The results demonstrate that the southward track deflection of the TC, is a common phenomenon prior to landfall. The results also suggest that when the altitude is higher, the TC approaches the northern part of the terrain, or when the translation speed is lower, the track deflection of the TC, would be prominent. Other parameters such as the width and length of the mountain, and the RMW have limited effects on the track of the TC.

Lin et al. (2016) investigated a series of idealized experiments to examine the influences of orography on TC track. These influences include mean flow advection, cyclonic circulation, channeling, asymmetric flow steering, asymmetric latent heating, and vertical wind shear effects. The VT is utilized to examine the southward deflection of TC. When the TC was upstream the mountain, the easterly basic flow became sub-geostrophic as a result of orographic blocking. The TC decelerated and deflected to the south, with the VT primarily dominated by the horizontal advection. After that, the TC passes over the mountain clockwise, steered by the orographically generated high-pressures. During this time period, the VT is mainly contributed by horizontal advection and stretching term. The diabatic heating is linked with the northwestward movement over the lee-ward slope. The enhanced advection of eyewall convective clouds associated with diabatic heating contributes to the abrupt turning of the TC, to the northwest.

Both the channeling effect and the asymmetries in the mid-levels, contribute to the southward track deflection of a TC. Huang and Wu (2018) investigates the motion of a TC that is deflected southward while moving westward toward an idealized terrain similar to that in Taiwan. The analyses of both the flow asymmetries and the PVT demonstrate that horizontal advection contributes to the southward movement of the TC [see Fig. 9 of Huang and Wu (2018)]. The track deflection is examined in two separate time periods, with different mechanisms leading to the southward movement. The changes in the background flow induced by the terrain, first cause the large-scale steering current to push the TC southward, even the TC is still far from the terrain. As the TC approaches the idealized topography, the role of the inner-core dynamics becomes important, and the TC-terrain-induced channeling effect results in further southward deflection of the track. The asymmetries in the mid-level flow also develop during this period (Fig. 2.1.3), in part associated with the effect of vertical momentum transport. The combination of the large-scale environmental flow, low-level
channeling effect and the asymmetries in the mid-level flow all contribute to the southward deflection of the TC track.

![Figure 2.1.3. Asymmetric flow at different levels calculated within 100 km of the vortex. The x-axis shows the integration time (h), and y axis is the vertical levels in terms of atmospheric pressure (hPa) (after Huang and Wu 2018).](image)

### 2.1.5 The role of atmosphere-ocean interaction

Recent researches suggest that initial SST can affect TC tracks. Katsube and Inatsu (2016) and Sun et al. (2017) have shown that the warm SST tends to yield the earlier northward recurvature of the TCs in some cases in WNP. Sun et al. (2017) ascribed this result to the retreat of the subtropical high in their warm run. With a simplified linear baroclinic model, Katsube and Inatsu (2016) interpreted this track change as the well-known subtropical thermal response documented by Hoskins and Karoly (1981).

The coupling of the atmospheric model with the ocean model has become more common in recent years, because atmosphere-ocean coupling can be an important factor in intensity forecasts. The impact of the oceanic feedback on the track is less obvious. However, secondary influences of ocean coupling on the track via changes in intensity may be possible. For example, the coupling could change the vertical extent of the tropical cyclone, so that it is sensitive to different steering flow. A weakening and shallower cyclone may be more sensitive to lower level flow so that the effective steering flow may change (to lower height) as the coupling reduces the intensity (Lin et al., 2018). Coupling with the ocean could indirectly change the cyclone upper level anticyclone through intensity (diabatic heating) changes and the symmetry of the convection which could also have an impact on the flow.

Model studies do not show a strong impact of atmosphere-ocean coupling on the track of tropical cyclones. There have been a range of studies showing a marginal or no effect: idealized tropical cyclone studies with and without ocean coupling (e.g. Zhu et al, 2004, Duan et al., 2013), the role of adding wave coupling (Liu et al. 2011), individual case studies in the
Atlantic (e.g. Winterbottom et al., 2012). Ito et al. (2015) examined 34 TC cases (281 runs) near Japan and found a minor effect of the atmosphere-ocean coupling. They report that the atmosphere-ocean coupling slightly (of the order of 20 km) deflects the TC position to the left because sea surface cooling on the right-hand side is not favourable for the storm (Fig. 2.1.4). A study of six tropical cyclones for the Bay of Bengal showed some improvement in the track forecast in the coupled model of less than 14% for the best initial SST distribution (Srinivas et al. 2016). They attributed the improved track to improved location of net vorticity generation to which cyclones tend to move. A more recent complete climatological study of the entire Indian Ocean shows no significant impact of coupling on track density (Lengaigne et al. 2018).

Figure 2.1.4. TC center position at T+36 h for each experiment with the non-hydrostatic atmospheric (red) and coupled (blue) models relative to the RSMC best track. Vertical axis is the along-track distance in the direction of the modeled TC motion from T+ 30 to 36 h, while the horizontal axis is the cross-track distance. Triangles indicate the mean positional bias in the same colour (adopted and modified after Ito et al., 2015).

It is important to distinguish among the role of coupling in short-term weather forecasts, the initial condition of SST and its impact on the longer seasonal or climate time-scale. In addition to the recent works mentioned above regarding to the impact of initial SST, there is no doubt that coupling with the ocean can modify the large-scale SST patterns and hence the winds of the steering flow on longer time scales (e.g. Ogata et al. 2016; Sun et al. 2017). The seasonal forecast and climate projections of track densities will therefore be sensitive to atmosphere-ocean coupling.

2.1.6 Dynamics of Low-Predictability TC Tracks

There remain occasional stark disruptions in forecast skill in which ensemble spread is abnormally large, but only for a limited window of initialization times. The theoretical reasons behind such large track errors were explored by Torn et al. (2018). Using ensemble sensitivity analysis, the authors concluded that the foremost factor in creating large ensemble spread was a steering flow pattern with a saddle point of strong deformation (Fig. 2.1.5) downstream of the current location of the TC. In this pattern, small perturbations to the initial state have drastic consequences for the track prediction 2-4 days later.
2.1.7 Large Scale Features

An MG is identified as a low-frequency cyclonic (or anticyclonic) circulation in the lower (or upper) troposphere with the diameter of about 2000-2500 km. When a TC is initially located in the eastern semicircle of an MG, several types of TC tracks can be identified (Liang and Wu, 2015). Liang and Wu (2015) showed that the different structure and relative distance affect the track pattern. Bi et al. (2015) showed that the sharp northward turn of the Typhoon Megi (2010) was induced by the strength of the TC in the initial field, as no sharp turn was observed when the initial TC was weakly implemented. Ge et al. (2018) indicated that the sharp northward turn can also be influenced by the vertical structure and the intensity of an MG. In their idealized simulation with a deeper and stronger MG, the total vorticity tendency of TC’s wavenumber-1 component has become almost absent by the vorticity advection of the MG and the TC has exhibited a sharp northward turn (Fig. 2.1.6). In contrast, a TC experiences nearly constant northwestward track with a shallower MG. They also showed, that the differences in the radial gradient of the relative vorticity also yield the similar track differences in a simple barotropic model.

Wei et al. (2016) statistically investigated the relationship between the UTCL and the TC tracks over the WNP during 2000-2012. They found that for all the TCs and the UCTLs within the 15-degree interaction distance, there is little impact of the UTCL on the average directional change of the TC track, unlike the results obtained by the previous case studies. Albeit with the lower frequency, most of the left-turning TCs within a 5-degree distance experienced abrupt left-turning as much as 50 degrees in 12 hours. The TCs tended to be slowed down when undergoing abrupt directional changes.
Sun et al. (2015) investigated the interaction between a TC and a subtropical high on the WNP, focusing on the initial size of the TC for the case of TC Songda (2004) and the Megi (2010). With the increase of initial storm size, the main body of subtropical high tends to withdraw, and the TCs, which are initially located on the south western edge of the subtropical high, tend to turn northwards earlier. The increase in the mass flux with the larger vortex, decreases the geopotential height of the middle troposphere in the outer region of the TC and thus it leads to a break of the subtropical high on the WNP.

Figure 2.1.6. Simulated 3-hourly TC tracks with a deep intense MG (SG04) and a shallow weak MG (SG05). (Ge et al., 2018)

2.1.8 Summary and Recommendation

The highly idealized models still provide an important perspective for the forecasting of the TC track. Recent works suggest that the TC track forecasting is sensitive to the radial profile of the relative vorticity in the outer region of the TC because it is related to the β-gyre and the faster developing mode. Recent idealized simulations with a full-physics model have brought the deeper understanding of the existing mechanisms and the finding of previously known mechanisms: the intrinsic recurving nature, the channeling effect in the middle troposphere, the atmosphere-ocean interaction and the impact of large-scale features. They suggest that the horizontal and vertical structure of a TC can impact on their own track through the interaction with other systems or as its own nature. It seems that the state-of-the-art models have, to some extent represented some of these effects. However, these findings are important for understanding the mechanism of the change of the TC tracks, particularly, when TC track was changed according to the use of finer mesh, new physical scheme, topography and coastal line. More accurate implementation of these components is highly desirable.

The fundamental aspects of the movement of the TC, are also important because it can facilitate the design of observations and data assimilation systems. Recent works suggest that the uncertainties along streamlines connected to stagnation points for TCs in a cyclonic shear should be reduced. The realistic-model-based ensemble sensitivity analysis detected the foremost factor in large track forecast errors was a steering flow pattern with a saddle point of strong deformation. These locations presumably correspond important regions to watch in terms of the track forecast.
Thanks to the sophisticated numerical model and observations, the TC position forecast errors have been decreasing to <100 km for T+24 and 200-300 km for T+72. In turn, the physical processes that were previously considered to be “minor” have become “substantial” in importance, as the required accuracy has become higher than ever. Although the conventional concepts of the steering flow, the $\beta$-gyre, and the diabatic heating remains important, the better understanding of various physical processes should be regarded as an important step for disentangling the complicated dynamics associated with the movement of the TC in the real world.

**Acronyms used in the report**

CWB - Central Weather Bureau  
ECMWF - European Centre for Medium-Range Weather Forecasts  
IWTC - International Workshop on Tropical Cyclones  
MG - Monsoon Gyre  
NCAR - National Center for Atmospheric Research  
NTU - National Taiwan University  
PVT - Potential Vorticity Tendency  
RSMC – Regional Specialized Meteorological Center  
SST - Sea Surface Temperature  
SV - Singular Vector  
T+XX - Forecast time of XX hours TC - Tropical Cyclone  
UTCL - Upper Tropospheric Cold-Low  
VT - Vorticity Tendency  
WNP – Western North Pacific

**References**


Elloitt, G. and M. Yamaguchi, 2014: Motion - recent advances. 7th International Workshop on Tropical Cyclones.  
http://www.wmo.int/pages/prog/arep/wwrp/new/documents/Topic1_AdvancesinForecastingMotion.pdf  


TOPIC 2.2 - REVIEW OF RECENT PROGRESS IN TROPICAL CYCLONE TRACK FORECASTING AND EXPRESSION OF UNCERTAINTIES

Rapporteurs: Julian Heming (Met Office, UK), Fernando Prates (ECMWF)


Abstract
The forecasting of tropical cyclone (TC) track has seen significant improvements in recent decades both by numerical weather prediction models and by regional warning centres who issue forecasts having made use of these models and other forecasting techniques. Heming and Goerss (2010) gave an overview of forecasting techniques and models available for TC forecasting, including evidence of the improvement in performance over the years. However, the models and techniques used for TC forecasting have continued to develop in the last decade. This presentation gives an updated overview of many of the numerical weather prediction models and other techniques used for TC track prediction. It includes recent performance statistics both by the models and the regional warning centres.

1. Introduction

In 2010 the World Scientific book Global Perspectives on Tropical Cyclones: From Science to Mitigation was published (Chan and Kepert, 2010). This included a chapter on track and structure forecasts of TCs (Heming and Goerss, 2010). The aim of this subtopic report is to provide an update on some aspects of this chapter. Many of the Numerical Weather Prediction (NWP) models used for tropical cyclone (TC) track forecasting are described (deterministic and ensemble) together with recent performance statistics. Contributions are also included from Regional Specialized Meteorological Centres (RSMCs) and other operational TC forecasting centres, including usage of NWP models and other forecast aids such as consensus forecasts.

An outline of the structure of the report is as follows:

Global Models
- European Centre for Medium-Range Weather Forecasts (ECMWF)
- Met Office (UK)
- National Centers for Environmental Prediction (USA)
- Japan Meteorological Agency
- US Navy
- Canadian Meteorological Centre
- National Centre for Medium-Range Weather Forecast (NCMRWF, India)
- WGNE Intercomparison of Global Models

Regional Models
- Met Office (UK)
- National Centers for Environmental Prediction (USA)
• US Navy
• Météo France
• Bureau of Meteorology (Australia)

**Ensemble Prediction Models**
- European Centre for Medium-Range Weather Forecasts (ECMWF)
- Met Office (UK)
- National Centers for Environmental Prediction (USA)
- Japan Meteorological Agency
- Canadian Meteorological Centre
- Météo France

**Operational Forecasting Centres**
- RSMC Miami (National Hurricane Center, USA)
- Joint Typhoon Warning Center (USA)
- RSMC Tokyo (Japan Meteorological Agency)
- Bureau of Meteorology (Australia)
- RSMC La Réunion (Météo France)
- RSMC Nadi (Fiji Meteorological Service)
- RSMC New Delhi (India Meteorological Department)
- Canadian Hurricane Centre

2. **Global Models**

   a) **European Centre for Medium-Range Weather Forecasts (ECMWF)**

   **Model Formulations**

   Several ECMWF Integrated Forecasting System (IFS) model cycles have been implemented since 2014 with many technical and scientific upgrades, including an increase of horizontal resolution in March 2016 of both the High-RESolution (HRES) and ENSemble (ENS). In the same year the ocean model was upgraded from one degree to a quarter-of-degree resolution, and from 42 vertical levels to 75. With the implementation of IFS cycle 45r1 on the 5 June 2018, HRES became a coupled ocean-atmosphere system, as was then already the case for the ENS for the medium/extended and long-range forecasts. The coupling to the ocean had a significant impact in improving the intensity forecast errors of TCs (not shown). Table 2a.1 contains the main model features relevant to forecasting TCs.

### Table 2a.1. Configuration of the ECMWF HRES and ENS systems

<table>
<thead>
<tr>
<th></th>
<th>HRES/ENS</th>
<th>ERA5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>Tco1279 (0-10 days)/Tco639 (0-15 days)/Tco319 (16-46 days)† Equivalent to 9 km/18 km/32 km 137 levels/91 levels to 1 Pa</td>
<td>31 km (TL639)</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>137 levels to 1 Pa</td>
<td>137 levels to 1 Pa</td>
</tr>
</tbody>
</table>
### Atmospheric Data Assimilation Window for 0000 and 1200 UTC

12-hourly 4D-Var for the HRES, and with the 25 low-resolution members of the Ensemble Data Assimilation (EDA) providing perturbed analyses for the ENS.

<table>
<thead>
<tr>
<th>Ocean analysis system (OCEAN5)</th>
<th>Provide ocean and sea-ice initial conditions for HRES and ENS (including 5 members with perturbed initial conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-D Ocean model (NEMO)</td>
<td>0.25° horizontal resolution with 75 vertical layers. Coupled with the HRES and ENS. Provides SST to HRES and ENS.</td>
</tr>
<tr>
<td>Ocean wave model (ECWAM)</td>
<td>0.125°/0.250°/0.5° resolution. Provides surface stress, Stokes drift and turbulent energy flux at the ocean surface. Coupled with HRES and ENS.</td>
</tr>
<tr>
<td>Model error (only ENS)</td>
<td>Stochastic Perturbed Parametrization Scheme (SPPT) in the ENS and EDA.</td>
</tr>
</tbody>
</table>

† run Mon & Thu only.

‡ random perturbations to observations and to model physical tendencies. Current configuration allows an additional 6 hours of observations to be used in the assimilation window than ECWMF operational.

### Recent Performance

The annual average of HRES TC position forecast errors (all TC basins) over the past decade are shown in Figure 2a.1 (blue lines). The performance of the 10-day TC position forecasts from the ERA5 reanalysis system (run in forecast mode) for 0000 and 1200 UTC has been computed recently using the same TC tracking software as in operations and the result is included in Figure 2a.1 (red lines). The ERA5 reanalysis is based on IFS cycle 41r2, which was operational between March and November 2016 (see table 2a.1 for details). This dataset provides a useful benchmark against which to compare the HRES operational run, and helps us to identify the year-to-year variability in TC predictability across the world. Overall there is a good correlation over the year of the annual mean position errors between HRES and ERA5 forecasts, at all lead times.

Mean TC position errors for HRES at 120-hour and 168-hour forecast lead times have decreased by 25% and 40% respectively since 2008. Successive model upgrades have been responsible for the decrease of the mean position errors over recent years. The differences between HRES and ERA5 forecasts became smaller following the model resolution upgrade in 2010, following continual improvements in model physics and following the addition of new observation systems alongside improvement to the assimilation that include using the EDA background information in 4DVAR HRES analysis. At shorter forecast lead times the improvement in mean error has been less pronounced in recent years.

### Future Developments

The plan for the next model cycle (46r1) is to allow more 'late' observations to enter the system during the assimilation process, without changing the delivery time of the forecasts. There are also longer-term plans to investigate how information from TC near real-time reports (storm position) or the ‘2-D minimum divergence’ method, can help better resolve the wind direction ambiguities, intrinsic to scatterometer wind data, near the centre of TCs. This will reduce errors in the analysed TC position (Figure 2a.1), and, one would expect, in the forecasts also.
Web Links to model information and further verification
Model upgrades in chronological order, with links to extra information:
https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model

The latest confluence page for model cycle 45r1 includes relevant information on the scientific and technical upgrades. It also contains the score card summarizing the positive/negative impacts of that model cycle, including a short summary of the forecast performance for TCs:
https://confluence.ecmwf.int/display/FCST/Implementation+of+IFS+cycle+45r1

![Figure 2a.1](image)

Figure 2a.1. Annual average of the TC position errors (km) at analysis time, and in three-, five- and seven-day forecasts from the operational HRES (blue), and with 41r2 forecasts initialised with the ERA5 reanalysis (red) shown as a reference. Verification is against the estimates of observed position reported in near real time. All TC basins are included. Bars indicate 95% confidence intervals based on the bootstrap method.

b) Met Office (UK)

Model Configuration

The Met Office Unified Model (MetUM) is a numerical model of the atmosphere used for both weather and climate applications. The MetUM is suitable for NWP, seasonal forecasting and climate modelling with forecast times ranging from a few days to hundreds of years. Furthermore, the MetUM can be used both as a global and a regional model.

The MetUM’s dynamical core solves the compressible non-hydrostatic equations of motion with semi-lagrangian advection and semi-implicit time stepping. Sub-grid scale processes such as convection, boundary layer turbulence, radiation, cloud, microphysics and orographic drag are represented by parameterizations. The global NWP configuration has a spherical latitude-longitude grid with spacing 0.140625° x 0.09375° (about 10 km at mid-latitudes) and 70 levels in the vertical. More details of the latest model configuration can be found in Walters et al. (2017). For data assimilation, the model uses a hybrid incremental 4D-Var scheme with 44
short forecasts from the Global Ensemble (Clayton et al., 2013). TCs are initialised by assimilating central pressure estimates from regional TC warning centres issued in real time (Heming, 2016).

The global NWP version of the MetUM is run four times per day out to 168 hours (0000 and 1200 UTC) and 69 hours (0600 and 1800 UTC). TCs are tracked after the 0000 and 1200 UTC runs of the model (Heming, 2017) and forecast guidance messages issued both on the Global Telecommunications System and the Met Office web site for use by TC warning centres.

**Forecast Performance**

Figure 2b.1 and 2b.2 show the 5-year running mean of TC track forecast errors from the global MetUM for the northern and southern hemispheres. This shows a long term downwards trend in forecast errors which has accelerated since the introduction of a major model change in 2014 (Walters et al., 2017; Heming, 2016). 5-day forecast errors are now lower than 2-day errors were 25 years ago.

![Figure 2b.1](image1.png)

*Figure 2b.1. Met Office global model 5-year running mean TC track forecast error for the northern hemisphere.*

![Figure 2b.2](image2.png)

*Figure 2b.2. Met Office global model 5-year running mean TC track forecast error for the southern hemisphere.*
Future Plans

The next major change to the global NWP MetUM is coupling to the ocean which is expected to be operational by 2020. This is not expected to improve TC forecast track significantly, but in trials produces much better predictions of TC intensity in cases where ocean feedback is important, such as slow-moving TCs.

In the longer term a completely new modelling framework known as LFric is being developed to overcome the challenge of weather and climate prediction on the next generation of supercomputers: https://www.metoffice.gov.uk/research/modelling-systems/lfric

c) National Centers for Environmental Prediction (USA)

NCEP Operational Models

NOAA’s National Centers for Environmental Prediction (NCEP) provides real-time deterministic and ensemble based TC forecast guidance across the globe, primarily to the forecasters at the National Hurricane Center (NHC), the Central Pacific Hurricane Center (CPHC), U.S Navy Joint Typhoon Warning Center (JTWC) and various public and private forecast agencies across the world. The deterministic models include operational Global Forecast System (GFS) and two exclusive high-resolution TC specific models – the Hurricane Weather Research and Forecast System (HWRF) and the Hurricanes in Multi-scale Ocean-coupled Non-hydrostatic (HMON) models. The ensemble based forecast guidance comes from NCEP Global Ensemble Forecast System (GEFS) and the North American Ensemble Forecast System (NAEFS) that includes multi-model ensembles using Canadian and U.S. Navy ensembles.

Forecast Performance from Operational GFS

NCEP operational GFS is the cornerstone of NCEP Production Suite. GFS is based on Global Spectral Model (GSM) dynamic core and employs a sophisticated 4D Hybrid Ensemble-Variational (4D EnVar) Global Data Assimilation System (GDAS). GFS uses a special technique for relocating TC position in the model background. Apart from providing medium range forecast guidance for global TCs, it also provides initial and boundary conditions for various downstream models including HWRF and HMON. GFS is one of the main model used in NHC’s track forecast consensus, and has shown significant improvements in the forecast skill over the past several years in the North Atlantic and North Eastern Pacific basins. Figure 2c.1 shows track forecast errors since 2001.

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Figure 2c.1. Annual mean GFS TC track errors for Atlantic and east Pacific for 2001-2017
After serving US National Weather Service for 38 years, the spectral dynamic core based GFS is being replaced with Next Generation Global Prediction System (NGGPS) selected Finite Volume Cubed Sphere (FV3) dynamical core in early 2019.

The GFDL FV3 dynamical core (Putman and Lin, 2007) is the dynamical core (Figure 2c.2) of choice for many global models in the United States, having been implemented in the GFDL suite of global weather and climate models, the NASA GEOS modelling system, and other systems around the world. FV3 was selected as the dynamical core for the US National Weather Service's Next-Generation Global Prediction System (NGGPS), on the basis of its superior accuracy, forecast skill, computational performance, conservation properties, and numerical stability. The FV3 dynamical core has been transferred to the National Weather Service’s (NWS) National Center for Environmental Prediction (NCEP) as the replacements for the NWS’s Global Forecast System (GFS) and is scheduled to become operational at NCEP in January 2019.

FV3 uses the forward-in-time scheme and Lagrangian vertical coordinate of Lin (2004), based on the Lagrangian dynamics of Lin and Rood (1997) and the finite-volume pressure gradient force of Lin (1997). FV3 is distinguished from its predecessor, FV (Lin 2004), through the discretization on a quasi-uniform cubed-sphere grid, which avoids the singularity at the poles of the earlier latitude-longitude grid. FV3 has the capability to locally-refine its global cubed-sphere grid by either two-way interactive nesting (Harris and Lin, 2013) or stretching (Harris et al., 2016) using a Schmidt transformation.

The version of the FV3 that is run in near real time by scientists at GFDL is referred to as fvGFS. It uses the operational GFS initial condition (cold start), compared to the parallel version now being run and evaluated extensively at NCEP using a cycled data assimilation that has been developed for FV3-GFS. In order to test the robustness and skill of their version of fvGFS, scientists at GFDL have performed retrospective forecasts for most of 2015, 2016 and 2017, cold started from the GFS initial condition. The TC track performance were evaluated in all ocean basins (Figure 2c.3) for this three year sample, which provided a robust sample size of slightly over 2000 cases. Overall the track performance was found to be as good as the operational GFS, with some reduction in track error, particularly in the Northwest Pacific where the 48-hour and 72-hour track error was reduced 8%.
An improved version of fvGFS has been developed at GFDL and has been run daily in real time since July 2018. The new 2018 GFDL version of fvGFS introduces the Yonsei University (YSU) planetary boundary layer scheme and a dynamically-active mixed-layer ocean model. The 2018 GFDL fvGFS also includes a revised positive-definite tracer advection scheme and the number of vertical levels is increased from 64 to 91. Also in this new version, the GFDL microphysics has the capability to be called in-line directly from the dynamics, allowing a much faster calling frequency to the microphysics.

So far, the results for the 2018 TC seasons are showing superior track performance with the 2018 GFDL fvGFS compared with both the current operational GFS, the version run in parallel at the Environmental Modelling Center (FV3-GFS) scheduled for operational implementation in January 2019 and most of the other operational numerical guidance.

Forecast plots from GFDL’s fvGFS model are available in real time in the following web site:
https://data1.gfdl.noaa.gov/fvGFS/?MODEL=fvGFS

More details on FV3-GFS development and evaluation can be found at these web sites:
https://vlab.ncep.noaa.gov/web/fv3gfs
http://www.emc.ncep.noaa.gov/users/Alicia.Bentley/fv3gfs/
JMA runs several NWP models for various purposes; the Global Spectral Model (GSM), the Meso-Scale Model (MSM), the Local Forecast Model (LFM), the Global Ensemble Prediction System (GEPS) based on a low-resolution version of GSM, an ensemble prediction system based on an atmosphere-ocean coupled model and other NWP models for specific targets such as ocean waves and sea ice extents. For TC information, GSM and GEPS are mainly used. The specifications of the GSM and GEPS for the new supercomputer system are as follows. More detailed information for the models is available at JMA’s website: https://www.jma.go.jp/jma/en/Activities/nwp.html.

Table 2d.1: Specifications of GSM and GEPS

<table>
<thead>
<tr>
<th>Model</th>
<th>Resolution (Grid Spacing)</th>
<th>Vertical Levels</th>
<th>Forecast Range (Initial Time)</th>
<th>Initial Condition</th>
<th>Number of Ensemble Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM</td>
<td>TL959 (0.1875°, 20 km)</td>
<td>100 layers (top: 0.01 hPa)</td>
<td>132 hours (0000, 0600, 1800 UTC) 264 hours (1200 UTC)</td>
<td>4D-Var Analysis</td>
<td>-</td>
</tr>
<tr>
<td>GEPS</td>
<td>TL479 (0.375°, 40 km)</td>
<td>100 layers (top: 0.01 hPa)</td>
<td>132 hours (0600, 1800 UTC) 264 hours (0000, 1200 UTC)</td>
<td>Global analysis with ensemble perturbations</td>
<td>27</td>
</tr>
</tbody>
</table>

Forecast Performance

Figure 2d.1 shows GSM annual mean position errors since 1997. The annual mean errors for 30-, 54- and 78-hour predictions in 2017 were 106, 182 and 300 km, respectively. All were better than those in 2016. 30-, 54- and 78-hour GSM predictions are verified as these are used as primary information by forecasters creating 24-, 48- and 72-hour operational forecasts, respectively.
Future Plans

JMA will increase the horizontal resolution of GSM from the current 20 km to 13 km and enhance its physical processes optimized for the increased resolution, aiming at enhancing the representation of smaller scale features of meteorological phenomena including TCs. This will lead to the higher forecast accuracy.

JMA will start all-sky microwave radiance assimilation. In addition, JMA will also improve the assimilation method of high-resolution atmospheric motion vectors derived from Himawari-8. Increase in accuracy of the initial fields of cloud/precipitation areas and initial wind fields is expected with these improvements, which will also result in the higher prediction accuracy of meteorological phenomena including TCs.

e) US Navy

Model Configuration

The Navy Global Environmental Model (NAVGEM) is the U. S. Navy’s global weather prediction system, developed by the Naval Research Laboratory (NRL) and run operationally at Fleet Numerical Meteorology and Oceanography Center (FNMOC). NAVGEM deterministic forecasts are made four times per day out to 180 hours and there is also a 20-member NAVGEM ensemble that produces 384-hour forecasts twice per day.

NAVGEM is a spectral model utilizing a Semi-Lagrangian/Semi-Implicit dynamical core. The operational model, as of September 2018, has a horizontal resolution of 31 km (spectral triangular truncation of T425) and 60 vertical levels. The model uses a sea-surface temperature analysis performed by FNMOC, and is held fixed throughout the forecast. Deep convection is parameterized using the Simplified Arakawa-Schubert scheme (Moorthi et al., 2001). Turbulent mixing in the boundary layer and shallow convection are parameterized using an eddy- diffusivity/mass flux approach (Suselj et al., 2014). Further details about the model can be found in Hogan et al. (2014).
The data assimilation system used to define the initial state for NAVGEM is the NRL Atmospheric Variation Data Assimilation System – Accelerated Representer (NAVDAS-AR). NAVDAS-AR uses a hybrid background error covariance matrix combining ensemble-based and static components. For TCs, synthetic wind profiles are assimilated in to represent the TC. The synthetic wind profiles are based on the real-time analysis of position, intensity, and surface wind radii performed by JTWC, NHC or CPHC.

Forecast Performance

Figure 2e.1 shows track mean absolute error for a homogeneous comparison of NAVGEM, GFS, and UKMO global model (UKMET) forecasts for the Atlantic, Northeast Pacific and Northwest Pacific TCs in 2018 up to the end of August. For this sample, NAVGEM track forecast error is comparable to UKMET and GFS. However, for a sample of Atlantic, Northeast Pacific and Northwest Pacific TCs in 2017, NAVGEM track forecast errors are clearly larger than those of GFS and UKMET.

In recent years, NAVGEM track predictions tend to perform best with respect to other global models in the Northwest Pacific basin (as compared with Atlantic and Northeast Pacific basins), particularly at later lead times. The track mean absolute error statistics for the 2018 Northwest Pacific season-to-date are shown in Figure 2e.2. For this sample, NAVGEM has similar error statistics to UKMET, which has been one of the best-performing track prediction models in the Northwest Pacific basin over the past few years.

Figure 2e.1. Upper panels show track mean absolute error for NAVGEM, GFS, and UKMET global models. The sample consists of TCs in the Atlantic, Northeast Pacific, and Northwest Pacific basins in 2017 (left) and 2018 up to the end of August (right). Sample size as a function of lead time is shown in the lower panel.
Future Plans

Two major upgrades are planned for NAVGEM to greatly increase the horizontal resolution of the model. The first upgrade, planned for late 2018, increases the horizontal resolution to 19 km, implements a two-time level semi-Lagrangian scheme to replace the current 3-time level scheme, and includes refinements to the model physics and how the physics are coupled with the dynamics. A follow-on upgrade, planned for 2019, will feature another increase to horizontal resolution (from 19 to 13 km), an increase in the number of vertical levels from 60 to 100, and additional physics improvements.

Some of deficiencies in NAVGEM track predictions are thought to be related to the TC synthetic wind profile assimilation technique discussed earlier, which was designed for a much lower resolution model and less sophisticated data assimilation system than contemporary NAVGEM and NAVDAS-AR. Work is underway to develop new techniques for TC initialization that depend more heavily on satellite observations and the model background state rather than TC synthetic observations. With improved initialization of TCs alongside the planned increases in NAVGEM resolution, we expect that the model will make substantial progress in TC track prediction in the coming years.

Finally, an initial operational capability at FNMOC for the new Navy Earth System Model (NESM) is planned for 2019. NESM is a coupled atmosphere-ocean-ice-wave model designed for multi-week deterministic prediction and multi-month probabilistic prediction. The deterministic short-term forecast is planned to run once a day out to 16 days lead time, using a 19 km horizontal resolution NAVGEM atmospheric model, 4.5 km HYCOM ocean model, 4.5 km CICE ice model, and 14 km WW3 wave model. NESM will provide an exciting new capability for air/ocean/wave coupled predictions of TCs.
Canadian Meteorological Centre (CMC)

Model Configuration

The CMC’s Global Environmental Model (GEM) is a global grid point model that solves the hydrostatic governing equations on a pair of latitude-longitude Yin-Yang limited area grids (Qaddouri and Lee, 2011). The global deterministic prediction system has a horizontal grid spacing of approximately 25 km with 80 staggered log-hydrostatic-pressure levels in the vertical with a top at 0.1 hPa (Girard et al., 2014). The initial conditions for global forecasts are obtained from an ensemble-variational analysis as described by Buehner et al. (2015). No vortex initialization scheme or synthetic observations are used in the analysis cycle. Details about the model configuration and physical parameterizations used in the global system are documented by Zadra et al. (2014a). The CMC global deterministic system is coupled to the NEMO ocean model for the full length of its integration (Smith et al., 2018).

Forecast Performance

The GEM model has a well-known over-prediction bias for TCs, most notable in the model’s elevated false alarm rate (Zadra et al., 2014b). A modernization and rebalancing effort for the model physics is currently under way at the CMC, with a focus on improving the representation of the tropical atmosphere. TC tracking results from the new physics package are promising, with a highly significant reduction in the false alarm rate and threat score as shown in Figure 2f.1. These changes are scheduled to be implemented in the global modelling system in the summer of 2019.

Figure 2f.1. The left panel shows, the number of tracked TCs over a two month period in summer 2016 in IBTrACS (black), a system close to the current CMC operational global model (blue) and an equivalent global forecast system with the proposed CMC physics modifications (red). The right panel shows the threat score for the two modelling systems with a consistent colour scheme. None of the integrations shown here use a coupled ocean model.
NCMRWF Operational Models

NCMRWF NWP models are based on the Met Office’s Unified Model (MetUM) and abbreviated as NCUM.

1. **NCUM Global Deterministic Model**: In the latest upgrade of NCUM, the horizontal resolution of the model was increased from ~17 km (N768L70) to ~12 km (N1024L70).

2. **NCUM Regional Model**: The regional configuration of the model has resolution of 4 km and includes explicit convection.

3. **NCMRWF Ensemble Prediction System (NEPS)**: NCMRWF global Ensemble Prediction System (NEPS) was upgraded from ~33 km and 44 members (N400L70) to ~12 km (N1024L70) resolution with 23 members.

**TC Tracker Implemented at NCMRWF**

The Met Office bi-variate approach to tracking TCs is used in the real-time to track TCs in the North Indian Ocean. This method is in contrast to the earlier NCEP method which used any or all of MSLP, 850 mb and 700 mb relative vorticity and geopotential height to track TCs (Marchok, 2002). The bi-variate method identifies TCs by examination of the 850 mb relative vorticity field but then fixes the TC centre to the nearest local MSLP minimum (Heming, 2017). The key advantage of the method is that it gives a strong signal of the approximate centre of the TC even for weak systems and does not depend on the current position information for tracking.

**Forecast Products and Performance for Recent Cyclonic Storm Daye**

Cyclonic Storm Daye evolved from a depression which developed over the Bay of Bengal in September 2018. Daye made landfall near southern Odisha, also impacting the adjoining north Andhra Pradesh coast, resulting in heavy rains and strong wind. Figure 2g.1 shows example track forecast products for the NCUM global and NEPS models.

*Figure 2g.1. Forecast tracks for Cyclonic Storm Daye. Right panel also shows ensemble forecast (NEPS) strike probabilities.*
Figure 2g.2 shows mean track forecast errors for the NCUM global and regional models and NEPS ensemble mean for both 0000 UTC and 1200 UTC tracks. All verification for the track forecasts uses the IMD track data. This shows that particularly at longer lead times the NEPS ensemble mean shows the lowest track forecast errors.

![Graph showing direct position error in forecasts for Cyclonic Storm Daye (September 2018)](image)

**Figure 2g.2. Direct positional errors in forecasts for Cyclonic Storm Daye (September 2018)**

**h) WGNE Intercomparison of Global Models**

**History**

The Working Group on Numerical Experimentation (WGNE) was established by the World Climate Research Programme Joint Scientific Committee and the World Meteorological Organization Commission for Atmospheric Sciences. The group works to foster the advancement of NWP models, with a membership consisting of representatives from operational NWP centres and research organizations. One of WGNE’s many activities is its intercomparison of TC track forecasts, which it has conducted using operational global NWP models since 1991 (Tsuuyuki et al., 2002). This work is undertaken annually by JMA and includes a large number of both global and regional models used for TC prediction.

**Forecast Performance**

Due to the large amount of work involved to collect NWP model data from agencies around the world and calculate and publish statistics, results for each calendar year are usually published about 22 months after the end of the year. Thus currently results up to 2016 are the latest available. Large amounts of verification data are available from the WGNE TC Intercomparison web site: [http://nwp-verif.kishou.go.jp/wgne_tc](http://nwp-verif.kishou.go.jp/wgne_tc). A few examples have been selected for this report.
Figure 2h.1 shows track forecast errors for various NWP models in 2016 for three regions: the Northwest Pacific, North Atlantic and Australian region. These show that for the Northwest Pacific the ECMWF model was the best performer followed by the KMA and UKMO models. In the North Atlantic the UKMO model was mostly the best performer with KMA and ECMWF also performing well. In the Australian region the NCEP (GFS) model was the best performer with ECMWF being the second best.

Figure 2h.1. Track forecast errors from NWP models in 2016. Top left: Northwest Pacific. Top right: North Atlantic. Bottom: Australian region.

Figure 2h.2 shows a long time series of 72-hour forecasts for the same three regions. In the Northwest Pacific the ECMWF model has mostly been the best performer since the start of the intercomparison. There is a clear downwards trend in track forecast errors for many of the models. In the North Atlantic the ECMWF and NCEP (GFS) models have shown to be good performers, particularly in the last decade. The Australian region has only been part of the intercomparison for the last decade and in this region the ECMWF and NCEP (GFS) models perform well.
3. **Regional Models**

   **Met Office (UK)**

   **Model Configuration**

   The Unified Model (MetUM) is the Met Office’s weather and climate prediction model. It solves the full, deep-atmosphere, non-hydrostatic, Navier-Stokes equations using a semi-implicit, semi-Lagrangian numerical scheme (see Wood et al., 2014 for details). Model prognostic fields are discretized on to a regular latitude/longitude grid with Arakawa C-grid staggering (Arakawa and Lamb 1977), whilst the vertical discretization utilizes a Charney-Phillips staggering (Charney and Phillips 1953) and a terrain-following hybrid-height vertical coordinate.

   The MetUM is used at the Met Office to produce global and regional, deterministic and ensemble forecasts for TCs. Convection-permitting tropical regional models currently being run at the Met Office include:

   1. A deterministic 4.4 km grid length model spanning Southeast Asia, with a 1.5 km model for the Philippines nested inside this. This system is run twice a day (0000/1200 UTC) out to 120 hours.
   2. An 18-member, 4.5 km ensemble system for a domain covering the Philippines, also run out to 120 hours twice a day.
3. A re-locatable 18-member, 4.4 km ensemble system used to produce on-demand forecasts for major Atlantic TCs.

All of these models have 80 vertical levels, the spacing of which increases quadratically with height up to a fixed lid 38.5 km above sea level. Initial and boundary conditions are supplied by the Met Office operational global model (either deterministic or ensemble system, as appropriate), which uses the Global Atmosphere (GA) 6.1 science configuration (Walters et al. 2017). There is no data assimilation or vortex specification in the regional models; initial conditions are derived by simple interpolation of global model fields. Regional models are one-way nested inside the driving global model and there is no atmosphere-ocean coupling (the sea-surface temperature is held fixed throughout a forecast).

The science configuration of the MetUM used in the tropical regional models is known as RA1T (where RA stands for Regional Atmosphere). The most important difference between RA1T and GA6.1 is that the convection parametrisation is switched off in the former. From a TC modelling perspective, another key difference is that frictional heating due to the dissipation of turbulence in the surface layer is not included in RA1T.

**Forecast Performance**

As part of RA1T testing, a 4.4 km regional model of the Philippines (domain shown in Figure 3a.1) was used to rerun all 2015 TC cases (a particularly active El Niño year). Figure 3a.2 shows the mean error in storm position relative to observations (as measured by the direct positional error, DPE) as a function of lead time. Corresponding mean track errors derived from Met Office global model (GA6.1) and HWRF operational forecasts are also displayed. Note that the storm sample has been homogenised across the models.

![Figure 3a.1. Philippines regional model domain and orography. The dashed black line shows the portion of the Philippines Area of Responsibility (PAR) inside the domain.](image-url)
Figure 3a.2. Error in forecast storm position relative to observations (direct positional error, DPE) as a function of lead time for the RA1T regional and GA6.1 global models, for (a) all storms in the sample, (b) storms of category 3 and above, and (c) storms below category 3. The solid lines with error bars represent the mean error and 95% confidence intervals on the mean, respectively. The mean track error from the HWRF model is also displayed. The solid grey lines indicate the number of storm cases (see the right-hand axis of each plot).

It is clear that track errors are comparable in the RA1T and GA6.1 models (any differences are not statistically significant). The DPE increases by approximately 36 km per day of forecast, reaching a maximum of around 200 km at 120 hours. On average, both models are able to forecast the position of more severe storms (category 3 and above, CAT35) better than weaker storms (below category 3, <CAT35). Although mean track errors relative to observations are similar, Short & Petch (2018) showed that storm positions in the two models are typically different, implying that the steering flow inherited from the driving global model is modified by the convection-permitting model.

HWRF gives similar mean track errors to the two MetUM configurations out to 48 hours or so, but the rate of error growth increases beyond this, leading to a larger mean track error in the latter stages of the forecast.

**Future Plans**

The future development of regional configurations of the MetUM for TC forecasting will be targeted at improving intensity, rather than track, predictions. A change that has recently gone into the models described above is a cap on the air-sea drag coefficient at high wind speeds, as motivated by observational data. Trials have demonstrated this considerably reduces the weak bias in TC surface winds seen in regional and (to a lesser extent) global configurations of the MetUM. Looking further ahead, there are plans to improve the initialisation of TC forecasts (at present, the regional model is somewhat handicapped by having to spin-up strong storms from relatively weak global analyses) and to implement some form of air-sea coupling in the model (along with frictional heating in the surface layer).
**b) National Centers for Environmental Prediction (USA)**

**Forecast Performance from High-Resolution HWRF**

Lately, NCEP's HWRF model has been one of the top performing operational track prediction models. Improvements to model resolution (3 km in 2012, 2 km in 2015 and 1.5 km implemented in 2018), physics and initial conditions enhanced with aircraft observations, have led to steep-step progress in improved numerical guidance. Figure 3b.1 below illustrate the progress of operational HWRF in forecasting track with significantly reduced errors for the year 2017 as compared with 2015. During the 2017 season, track skills of HWRF were comparable to operational GFS for most lead times.

![Graph showing operational HWRF track errors for the Atlantic Basin from 2015 (top left), 2016 (top right) and 2017 (bottom).](image)

**c) US Navy**

**Model Configuration**

The COAMPS-TC system (Doyle et al., 2014 and 2012) is a high-resolution regional dynamical model designed for prediction of TC track, intensity, and structure and run by Fleet Numerical Meteorological and Oceanography Center (FNMOC). The COAMPS-TC atmospheric model features a non-hydrostatic dynamical core and physical parameterizations for cloud microphysics, boundary layer and free-atmospheric turbulent mixing, surface fluxes, radiation,
and deep and shallow convection. The atmospheric model is fully coupled to the Navy Coastal Ocean Model (NCOM, Martin, 2000; Martin et al., 2006) in order to represent the interaction of a TC with the underlying ocean (Chen et al., 2010).

For the 2018 operational version of COAMPS-TC, the atmospheric model consists of a fixed outer grid mesh at 36 km resolution and two storm-following inner grid meshes at 12 km and 4 km resolution. The atmospheric model uses 40 vertical levels, with a top at 10 hPa. The NCOM ocean model is run on a single 7.5 km fixed mesh with 40 levels in the vertical.

The COAMPS-TC atmospheric model is cold started from a global model analysis. In the case of the CTCX version of COAMPS-TC (run in real-time by NRL) the initialization is from the NOAA GFS system, and the Navy NAVGEM system is used to initialize the operational COTC version of COAMPS-TC.

A balanced synthetic vortex is inserted in the storm-following 12 km and 4 km grid meshes and replaces the global model analysis in these regions.

*Forecast Performance*

Figure 3c.1 shows a homogeneous comparison of COTC and CTCX configurations. The retrospective forecast sample consists of 381 cases from TCs that occurred in 2015, 2016 and 2017 mostly in northern hemisphere basins. The track mean absolute error (MAE) for CTCX is far lower than that of the COTC tracks, especially between 24 and 96 hours, when the MAE improvement is 20-30%. This illustrates the strong dependence of regional model TC track forecast performance on the parent global model.

2017 real-time track MAE statistics for the western Atlantic, eastern Pacific, and western Pacific are shown in Figure 3c.2 for a number of regional and global models including COTC and CTCX. The close relationship between the global model track forecast performance and the track performance for COAMPS-TC can also be seen here, as the COTC track MAE closely follows that of NAVGEM and likewise, CTCX closely follows GFS.

![Full Sample: Track](image)

Figure 3c.1. Full retrospective sample track MAE for COTC and CTCX (left panel) and track MAE percent improvement for CTCX w.r.t. COTC (right panel).
Figure 3c.2. Track MAE for 2017 operational models including the CTCX (GFS-based) and COTC (NAVGEM-based) COAMPS-TC versions. Other models shown include HWRF, GFS, and NAVGEM. The CTCX sample size is shown in the right panel.

Future Plans

Future upgrades are being planned for the COAMPS-TC modelling system. We anticipate moving towards a cycling 4D-Var or ensemble-based data assimilation system for model initialization in the next several years. Upgrades to the physical parameterizations (especially boundary layer and microphysics) and an increase in the vertical resolution from 40 to 60 levels are anticipated within 3 years. An increase in inner-most nest horizontal resolution from 4 km to 2 km is planned in ~2021 and then on to 1 km after that as operational computing resources permit. The air-ocean coupled model will utilize a coupled data assimilation system, NCODA (Cummings, 2005), and a wave model (WWIII) will be added to the coupled system to better represent the air-sea interface. We are also developing a high-resolution COAMPS-TC ensemble system to characterize state-dependent track and intensity forecast uncertainty. An 11 member ensemble with 4 km horizontal resolution (and not coupled to an ocean model) is being transitioned to operations at FNMOC later this year.

d) Météo-France

Model Configuration

Météo-France operates five convection permitting models, centred on main French overseas Territories, which have been in operations since February 2016. These versatile systems, used both for daily weather and TC forecast, have static domains (Figure 3d.1).

- Horizontal resolution of 2.5 km, with 90 vertical levels (from 5m); 60s time step; explicit deep convection.
- No data assimilation scheme; their initial and lateral conditions are derived from ECMWF HRES model. For the surface, use of data from Arpège (for continents) and Mercator- Ocean global model PSY4 (1/12°) for the ocean.
Coupled with the surface model SURFEX, along with a 1D ocean model.

Four runs per day, up to 42 hours (78 hours on demand, when there is a TC threat for instance).

Further details of the Arome model configuration can be found in Seity et al. (2011), Brousseau et al. (2016) and Termonia et al. (2018).

Forecast Performance

At Météo-France, the main verification of TC track predictions is focused on Arome Overseas models. Since they don't have movable domains, the verification sample is small, even when gathering all domains. Nevertheless, these models have shown good skill in TC track forecasts, at least on par with their driving model (ECMWF HRES model), as shown on Figure 3d.2.

Occasionally Arome Overseas models perform much better than their driving model for TC track prediction. This ability appears as a positive feedback of better intensity on track. The better representation of the TC intensity and structure during the forecast leads to a more accurate steering flow and then a better track prediction.
**e) Bureau of Meteorology (Australia)**

**Model Configuration**

The Australian Bureau of Meteorology’s ACCESS models are based upon the Met Office Unified Model (MetUM) system. ACCESS-TC2 is the current tropical prediction model configured at a resolution of 0.11° x 0.11° in the horizontal and 70 levels in the vertical. Forecasts out to 72 hours are produced from 0000 UTC and 1200 UTC base times and are triggered by the existence of one or more TC within the Asian Tropical domain (covering the South Pacific, East Indian and Northwest Pacific ocean basins), with up to three domains available (for three concurrent TCs). For each domain, five high-resolution analyses are performed every six hours from T-24 (cycle-1) through to T-0 (cycle-5), with a final 72-hour forecast run in cycle-5. First guess fields for cycle-1 are derived from the global ACCESS-G2’s initial conditions, and reconfigured to the TC domain; the boundary conditions are obtained from ACCESS-G2 forecasts. For cycles 2 to 5, the system is warm run, i.e. the first-guess input files for these cycles are obtained from forecast data from the previous cycle of ACCESS-TC2.

Unlike the other ACCESS NWP systems, ACCESS-TC2 uses a synthetic observation scheme (Davidson et al., 2014) in addition to the normal in-situ and satellite observations to help define the TC vortex. Based on estimates of present and past locations, central pressure and storm size, vortex specification is used to filter the analysed circulation from the original analysis, construct the inner-core of the storm, impose motion asymmetries consistent with the past motion of the storm, merge the synthetic vortex with the large-scale analysis at outer radii, and relocate the vortex to its observed position. Synthetic observations are extracted from the idealized vortex at a resolution sufficient to resolve the maximum wind at the radius of maximum wind. In ACCESS-TC2, synthetic observations for surface pressure only are then merged with the conventional observations in the ACCESS Observation Processing System (OPS) module.

A comparison of the system specifications of current and upcoming versions of ACCESS-TC2 are listed in Table 3e.1 below.

**Forecast Performance**

Long term time series plots showing the annual mean track and central pressure errors (verified against JTWC best track data) for the Bureau's dedicated TC NWP systems since 2005 are shown in Figure 3e.1 below. Between July 2001 and August 2010, the model was the locally developed TCLAPS (Davidson and Weber, 2000), initially with a 15 km model horizontal resolution but increased to 10 km in June 2008. The MetUM-based ACCESS-TC0 was introduced in Nov 2011, with subsequent minor upgrades in December 2013 (ACCESS-TC1) and December 2016 (ACCESS-TC2). All versions of ACCESS-TC to present have been configured with a model horizontal resolution of 12 km.

Track errors showed a dramatic improvement following the introduction of ACCESS-TC in 2011. Since then, performance has been fairly static, although the 2017 ACCESS-TC2 results were the best yet at almost all forecast ranges.

ACCESS-TC has shown a consistent positive bias in the central pressures, i.e. the modelled pressure is not as deep as the best track estimate. This is expected to improve significantly when we move to a higher horizontal resolution in the next model upgrade.
Future Developments: ACCESS-TC3

An upgraded, higher resolution version of ACCESS-TC is currently undergoing development trials, with a target implementation date of mid-2019. The most significant changes involve an increase in resolution to 0.036°x0.036° (approximately 4 km) in the horizontal and 80 levels in the vertical and use of explicit convection (i.e. not parameterised convection). It uses TC specific background error covariances derived from a training set of paired forecasts for TC instances between July 2015 and February 2016, generated by the CVT method. Software upgrades include the use of more recent versions of the UKMO software components and the UKMO ‘RA1T’ physics configuration.

ACCESS-TC3 will nest within initial and lateral boundary conditions from the upcoming 12 km ACCESS-G3 system. ACCESS-G3 will also commence assimilating hourly-interpolated TC central pressures derived from international TC advisory bulletins, as is done in the UKMO global model (Heming, 2016).

Table 3e.1. ACCESS-TC System Specifications

<table>
<thead>
<tr>
<th></th>
<th>ACCESS-TC2</th>
<th>ACCESS-TC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain</td>
<td>33.0°x33.0°, relocatable anywhere within 3° of the ACCESS Tropical domain, i.e. boundary extremes within 42.0°S to 52.875°N, 63.0°E to 145.875°W.</td>
<td>Same</td>
</tr>
<tr>
<td>Geographical limits for initial vortex location</td>
<td>Minimum 3° from ACCESS-TC boundary, i.e. 39.0°S to 49.875°N, 66.0°E to 148.875°W</td>
<td>Same</td>
</tr>
<tr>
<td>Geographical limits for vortex tracking program</td>
<td>Minimum 2.25° from ACCESS-TC boundary, i.e. 39.75°S to 50.625°N, 66.25°E to 148.875°W</td>
<td>Same</td>
</tr>
<tr>
<td>UM horizontal resolution (lat x lon)</td>
<td>300x300 (0.11°x0.11°)</td>
<td>920x920 (0.036°x0.036°)</td>
</tr>
<tr>
<td>Analysis horizontal resolution (lat x lon)</td>
<td>100x100 (0.331°x0.331°)</td>
<td>320x320 (0.102°x0.102°)</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>L70, top level at 80km</td>
<td>L80, top level at 38.5km</td>
</tr>
<tr>
<td>Observational data used (6hr window)</td>
<td>AIRS, ATOVS, CrIS, ATMS, IASI, ASCAT, AMV, SYNOP, SHIP, WINDPROFIL, BUOY, AMDARS, AIREPS, TEMP, PILOT, GPSRO,</td>
<td></td>
</tr>
<tr>
<td>Synthetic Surface Pressure Observations</td>
<td>As before plus also SSMIS, ScatSat, increased AMV (possibly 10 minute)</td>
<td></td>
</tr>
<tr>
<td>Sea surface temperature analysis</td>
<td>Daily global 0.25° SST analysis</td>
<td>Same</td>
</tr>
<tr>
<td>Soil moisture analysis</td>
<td>N512 soil moisture field. SURF interpolates to the targeted resolution.</td>
<td>N1024 soil moisture field. SURF interpolates to the targeted resolution.</td>
</tr>
<tr>
<td>Internal model time step</td>
<td>5 minutes (288 time steps per day)</td>
<td>2 minutes (720 time steps per day)</td>
</tr>
<tr>
<td>Analysis time step</td>
<td>15 minutes</td>
<td>6 minutes (240 time steps per day)</td>
</tr>
<tr>
<td>Nesting</td>
<td>ACCESS-G2 (N512L70, 25 km)</td>
<td>ACCESS-G3 (N1024L70, ~12 km)</td>
</tr>
</tbody>
</table>
4. Ensemble Prediction Models

a) European Centre for Medium-Range Weather Forecasts (ECMWF)

Details of the Formulation of the ECMWF ensemble system (ENS) are given under Section 2 (Global Models) of this report.

To assess one aspect of the performance of the ENS TC position forecasts, for the medium range, the annual average of the forecast error of the ENS mean position is compared with the corresponding ensemble spread. If the sample size is large, both measures should match in a well-tuned ensemble forecast system. Figure 4a.1 shows the evolution of the ensemble mean and spread in five-day forecasts. Gradually the differences between the two have become smaller, especially in recent years, attesting to a well-calibrated ensemble. Similar results can be seen for the six and seven-day forecasts (not shown).

Based on the strike probability product available on the ECMWF website (the probability at a given location that a reported TC will pass within a 120 km radius in the next 10 days) a probability verification is routinely computed. Figure 4a.2 shows reliability curves for the last three 12-month periods ending on 30 June. These results indicate the strike probability forecasts are somewhat over-confident at this lead time.
Figure 4a.1. Annual average of the position forecast error of the ensemble mean (dashed red) and the ensemble spread (solid orange) of the five-day forecasts. Position errors for HRES are shown as well. Verification is against the estimates of observed position reported in near real time. All TC basins are included. Bars indicate 95% confidence intervals based on the bootstrap method.

Figure 4a.2. Probability verification of the 10-day strike probability forecast product (inset box shows an example). Reliability diagram for three 12-month periods; Jul 2015-Jun 2016 (green), Jul 2016- Jun 2017 (blue) and Jul 2017- Jun 2018 (red). Forecast probabilities and observed frequencies are shown as percentages.
**Met Office (UK)**

**Formulation of the Met Office Global Ensemble (MOGREPS-G)**

MOGREPS-G is the global component of the Met Office Global and Regional Ensemble Prediction System (MOGREPS). It runs four times a day, at 0000/0600/1200/1800 UTC, at a resolution of N640L70 (~20 km), out to a forecast lead time of 8 days (192 hours), with output every 6 hours. Each run has 18 members (a control and 17 perturbed members), but the last two runs are time-lagged so that products from each run use a 36-member time-lagged ensemble. MOGREPS currently uses an Ensemble Transform Kalman Filter (ETKF) to perturb the initial conditions in the perturbed members, and includes two schemes, Stochastic Kinetic Energy Backscatter (SKEB) and Stochastic Perturbation of Tendencies (SPT), to account for model error. Soil-moisture, deep-soil temperature and sea-surface temperatures are perturbed to improve near-surface ensemble spread.

**Verification Results**

At the Met Office, TC tracking (Heming, 2017) is run in real time on the Met Office MOGREPS-G ensemble, and the ECMWF ENS and NCEP GEFS ensembles. The three ensembles are also combined in to a 108-member multi-model ensemble. A range of products, including track and intensity forecasts for both named and forming storms, are produced and distributed to several operational TC forecasting centres. The probabilistic forecasts from each global ensemble, and the various multi-model combinations, are evaluated using a probabilistic verification framework. A range of probabilistic verification statistics are calculated to assess the skill, reliability and value of the forecasts, including the Relative Operating Characteristic (ROC), reliability diagrams, relative economic value and Brier Skill Score. See [http://www.cawcr.gov.au/projects/verification/](http://www.cawcr.gov.au/projects/verification/) for more details of these verification metrics.

Verification results for the strike probability forecasts (the probability that a storm will pass within 120 km within the next seven days) for all named storms in every basin in the 12 month period July 2017 to June 2018 are shown in Figures 4b.1 and 4b.2 for the three ensembles and the multi-model ensemble combination. The reliability diagram in Figure 4b.1 displays good reliability for all models, with ECMWF ENS showing near perfect reliability for all probabilities. MOGREPS-G and NCEP GEFS both show over-forecasting for probabilities 60% and greater, with NCEP GEFS contrastingly showing slight under-forecasting for 0-20% probabilities. In the relative economic value plot, the multi-model ensemble value curve fully encompasses the three individual models showing the multi-model ensemble combination gives the greatest economic value for all cost-loss ratios. All the models display the greatest relative economic value (over 0.7) for very small cost loss ratios (0 to 0.1). For TCs, users’ cost-loss ratios vary significantly but are often very low due to high potential losses.

Figure 4b.2 compares the Brier Skill Score for the strike probability forecasts between models for all storms and for the storms in each TC basin. ECMWF ENS is the most skilful of the three included global ensembles in most basins, apart from the Northwest Pacific and the Southwest Indian Ocean basins where MOGREPS-G and NCEP GEFS respectively have the greatest skill. However, in all basins additional skill is gained using the multi-model ensemble.

Further verification statistics, including storm-based verification, and the results for TC activity verification, can be found in Titley and Stretton (2018). The storm-based verification further demonstrates the value in the multi-model ensemble as the ensemble that displays the highest
skill varies from storm to storm, with the multi-model ensemble shown to be of comparative skill to the strongest performing model (which would not be known at the time of the forecast).

Figure 4b.1. Verification plots comparing MOGREPS-G, ECMWF ENS, NCEP GEFS and multi-model ensemble forecasts of named storm strike probability, from July 2017 to June 2018: Reliability diagram (left) and relative economic value plot (right).

Figure 4b.2. Brier Skill Score of MOGREPS-G, ECMWF ENS, NCEP GEFS and multi-model ensemble forecasts of named storm strike probability: All storms from July 2017 to June 2018 and split by TC basin.

Planned Developments

A major change to the MOGREPS-G ensemble is scheduled to go live in summer 2019, as the ensemble perturbation system used in MOGREPS-G is changed from Ensemble Transform Kalman Filter (ETKF) to an ensemble of data assimilations (En-4DEnVar, Bowler et al., 2017). In the new system, data assimilation is performed for each member, creating increments
relative to its own background trajectory. Figure 4b.3 shows that for 850hPa winds in the tropics, although in the current ensemble system ETKF gives good spread at initial time, this spread grows too slowly compared to the root mean square error. Comparative trials of the new En-4DEnVar have shown much faster spread growth, with a much better match to errors. A partial re-centring around the deterministic analysis gives an additional increase in skill and reduces jumpiness. The effect on TC track and intensity is currently being evaluated using trial data, but it is hoped that it will lead to a significant improvement in the ensemble spread.

Figure 4b.3. RMSE (solid) and spread (dashed) of wind at 850hPa for the tropics from the current MOGREPS-G ensemble with ETKF perturbations (red), and the planned MOGREPS-G upgraded ensemble using En-4DEnVar (blue). Both are verified against ECMWF analyses.

A relocatable regional ensemble system is also under development and has been tested on several high profile TCs. This involves taking the initial perturbations from the MOGREPS-G ensemble and running them forward with a 4 km resolution version of the model similar to that described in section 3a). The system is currently being evaluated to assess whether it provides benefit over and above that of MOGREPS-G.

c) National Centers for Environmental Prediction (USA)

Forecast Performance

NCEP operates a 21-member Global Ensemble Forecast System (GEFS) to provide probabilistic guidance based on ensemble perturbations from GDAS Ensemble Kalman Filter (EnKF) initial conditions and Stochastic Total Tendency Perturbations (STTP) in the forecast model. In addition, multi-model ensembles based from NOAA (GEFS), Navy (FNMOC), ECMWF, and Canada are routinely produced in operations. Figure 4c.1 shows comparison of track forecast errors from various ensemble means for 2017 Atlantic hurricane season. Multimodel ensemble products are also generated in real-time using GEFS and ECMWF ensembles, which are generally more skillful than individual ensemble means or deterministic forecasts, as shown in Figure 4c.2.
NCEP is developing the next generation GEFS based on FV3 dynamic core with more advanced stochastic perturbation techniques including Stochastic Perturbation of Physical Tendencies (SPPT), Stochastic Kinetic Energy Backscatter (SKEB) and Stochastic Humidity (SHUM) perturbations. Figure 4c.3 shows that the FV3 version of GEFS reduces track error, but increases spread relative to the operational GEFS.

In addition, GEFS will include high resolution (25 km) 31 member ensembles and will provide sub-seasonal (35-day) forecast guidance with this upgrade scheduled for operational implementation in early 2020. The GEFS development also includes production of 20-year reanalysis and 30-year reforecast datasets for calibration and evaluation.
High-Resolution Regional Ensembles

It is well known that the track and intensity forecasts made by deterministic dynamic hurricane model systems have limitations due to various uncertainties existed in both observations and model, including: (1) the errors introduced by the use of imperfect initial conditions, due to observation errors, amplified by the chaotic nature of the evolution equations of the atmosphere, this is often referred to as sensitive dependence on the initial conditions; and (2) errors introduced because of imperfections in the model dynamics and model physics, such as the approximate mathematical methods to solve the equations. Ensemble Prediction System (EPS) is capable of accounting for all kinds of the uncertainties, and hence reducing track/intensity forecast errors by averaging over the ensemble members. HWRF based EPS has been running in real time parallel for the past four years with support from NOAA’s Hurricane Forecast Improvement Project (HFIP).

During 2017 multi-model regional ensemble experiment, three model ensembles are used: the HWRF, Navy’s COAMPS-TC and the HMON. A 41-member, multi-regional model ensemble system consisting of HWRF (20 members), COAMPS-TC model (10 members) and HMON model (11 members) was run in real-time.

d) Japan Meteorological Agency

Forecast Performance

GEPS took over the role of JMA’s previous ensemble system (Typhoon Ensemble Prediction System - TEPS) and has been providing ensemble forecasts for TC since January 2017. GEPS and TEPS annual mean position errors since 2008 are presented in Figure 4d.1. In 2017, the annual means of ensemble mean position errors for 30-, 54-, 78-, 102- and 126-hour
predictions were 114 km (106 km with the GSM), 193 km (182 km), 314 km (300 km), 436 km and 542 km, respectively.

Figure 4d.1. GEPS and TEPS annual mean position errors since 2008

Although position errors of GEPS ensemble mean forecasts were larger than those of GSM in short-range forecasts, GEPS provides useful information on the reliability of TC track forecasts with its ensemble spread. Figure 4d.2 shows the relation between 6-hourly cumulative ensemble spreads in TC position forecasts and ensemble mean forecast position errors in 126-hour prediction. In an ideal ensemble prediction system with a large number of samples, a large position error is observed when the ensemble spread is large. The figure shows that large position errors were seen in 2017 only when GEPS predicted large spreads.

Figure 4d.2. Relation between 6-hourly cumulative ensemble spread in TC position forecasts and ensemble mean forecast position errors in 126-hour predictions in 2017.

Multi-Model Ensemble Forecasts

JMA introduced multi-model ensemble forecasts in 2015, which consist of ECMWF, UKMO, NCEP and JMA’s ensemble systems. These multi-model ensemble forecasts have been available
on the RSMC Tokyo’s dedicated Numerical Typhoon Prediction (NTP) website since June 2016 in order to help forecasters of the National Meteorological Services of Typhoon Committee Members.

Recently, JMA has been working on the selective consensus method and seeking for the best combination of NWP models. The research so far reveals that the position error can be reduced by up to 150 km in 72-hour forecasts with the best combination. However, what is best differs each time and it is not yet possible to find the best combination on an operational basis.

Therefore, it can be said that the future tasks for track forecast are the improvement in accuracy of each model as well as consensus methods.

**Future Plans**

JMA will increase the horizontal resolution of GEPS from the current 40 km to 27 km and the ensemble members from 27 to 51. This will also enhance the ability to explain meteorological phenomena including tropical cyclones and achieve higher accuracy of forecasts as well as probability information.

**e) Canadian Meteorological Centre**

The Canadian Meteorological Centre (CMC) produces 20 ensemble members twice daily at ~39 km resolution and 45 vertical levels using the GEM, to a forecast lead time of 16 days. Once a week, these runs are extended to 32 days to provide monthly guidance. The 20 members are integrated using a multi-physics approach to ensure sufficient ensemble spread (Du et al., 2018) and are initialized using perturbations on a sub-sample of the 256 different analyses that have been generated by the Ensemble Kalman filter (EnKF) assimilation system (Houtekamer et al., 2014). The EnKF uses both perturbed observations and a set of homogeneous, isotropic perturbations to the atmospheric state to represent uncertainty within the assimilation context. The ensemble system is currently not coupled to the ocean, but will become coupled in a change planned for mid-2019.

**f) Météo-France**

Météo-France operates an Arpège Ensemble (PEARP), composed of 35 members and run 4 times a day. Like its deterministic counterpart, this Arpège ensemble system has a stretched grid, with a focus on Europe (TL798C2.4, 90 vertical levels from 14 m to 1 hPa). There is currently no routine evaluation for TC track prediction.

An Arome-Ensemble system, based on the one operational over France (12 members), has been developed and tested over the Indian Ocean on a few cases of TC during 2018 season (LACy and CNRM laboratories joint work). The 12 initial conditions and lateral coupling are chosen from a global ensemble (ECMWF EPS or PEARP) by clustering. Like its deterministic version, it has shown interesting added value for TC track forecasting, thanks to a more realistic simulation of TC structure. Figure 4f.1 shows the added value of the mesoscale ensemble compared to the ECMWF EPS: the fast moving motion of TC Fakir is more accurately forecasted by Arome ensemble than by ECMWF EPS.

The Arome Ensemble will be run on demand in real time during 2018-2019 Southwest Indian Ocean TC season at the LACy laboratory.
5. Operational Forecasting Centres

a) RSMC Miami (National Hurricane Center, USA)

The National Hurricane Center (NHC) has made tremendous improvements over the past couple of decades in lowering the error of the official track forecasts for TCs. Figure 5a.1 shows a time series of NHC’s 24 hour through 120 hour track errors since 1990. The 24–72 hour track forecast errors have been reduced by 70 to 75% since 1990 and error reductions of about 60% have occurred over the past 15 years or so for the 96- and 120-hour forecast periods. In 2017, records for accuracy were set at all time periods and the errors were about 15% lower than the previous records at several forecast times. The primary reason for this success are the advancements in technology, specifically the improvements in the observing platforms and the various modelling systems that NHC uses to make forecasts. The horizontal and vertical resolution, and physics in the models today are far superior to what forecasters had available in the 1990s or prior decades. In addition, NHC has found ways to outperform the individual dynamical models by using a balance of model consensus approaches and experience.

Consensus models are not true forecast models per se, but are merely combinations of results from other models. One way to form a consensus is to simply average the results from a collection or ensemble of models, but other more complex techniques can also be used. The Florida State University Super-ensemble (FSSE) for example, combines its individual components on the basis of past performance and attempts to correct for biases in those components (Williford et al., 2003). A consensus model that considers past error...
characteristics can be described as a weighted or corrected consensus. On average, these consensus models have been the most accurate track forecast aids over the past several years and NHC forecasters value these models most when making a track prediction. An evaluation over the three years 2015-17 (Figure 5a.2) indicates that the HFIP Corrected Consensus Approach (HCCA), FSSE, and NHC’s Track Variable Consensus model (TVCN) were the best-performing models. Table 5a.1 lists all of the models that NHC uses.

Looking ahead to the future, there are a few anticipated challenges in terms of track forecasting. NHC has been experimenting in extending the forecasts out further in time to day 7 (currently 5-day forecasts are made). However, not all of the models are run out to 7 days, which reduces the guidance to NHC and limits the utility of the current consensus model composition at days 6 and 7. The global model ensembles have proven to be quite useful for longer range track prediction. However, it has been shown that the GFS ensemble suite is not dispersive enough to fully capture the uncertainty and possible scenarios. Another issue is how to communicate 7-day track forecasts. The NHC currently uses a combination of deterministic forecasts (i.e. cone graphic) and probabilistic graphics (i.e. wind speed probabilities, storm surge probabilities) to display their prediction and TC hazards. However, it is not known if the current methodology would be appropriate to extend in forecast time.

A recent study (Landsea and Cangialosi, 2018) discussed the potential limits of TC predictability and how these limits could be reached in the near future. Although it remains unknown when this might occur, it is agreed upon that perfect forecasts are not possible.

### Table 5a.1. National Hurricane Center forecasting aids

<table>
<thead>
<tr>
<th>Tracker Name</th>
<th>Forecast Aid Description</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFCL</td>
<td>Official NHC forecast</td>
<td></td>
</tr>
<tr>
<td>HWRF</td>
<td>HWRF Model</td>
<td>Regional model</td>
</tr>
<tr>
<td>HMON</td>
<td>HMON</td>
<td>Regional model</td>
</tr>
<tr>
<td>GFSO</td>
<td>NWS/Global Forecast System</td>
<td>Global model</td>
</tr>
<tr>
<td>AEMN</td>
<td>GFS ensemble mean</td>
<td>Global model</td>
</tr>
<tr>
<td>UKM</td>
<td>UK Met Office model, full resolution tracker</td>
<td>Global model</td>
</tr>
<tr>
<td>EGRG</td>
<td>UK Met Office model, reduced resolution tracker</td>
<td>Global model</td>
</tr>
<tr>
<td>UEMN</td>
<td>UKMET ensemble mean</td>
<td>Global model</td>
</tr>
<tr>
<td>NVGM</td>
<td>NAVGEM</td>
<td>Global model</td>
</tr>
<tr>
<td>CMC</td>
<td>Environment Canada global model</td>
<td>Global model</td>
</tr>
<tr>
<td>NAM</td>
<td>NWS/NAM</td>
<td>Regional model</td>
</tr>
<tr>
<td>CTCX</td>
<td>COAMPS-TC using GFS initial and boundary conditions</td>
<td>Regional model</td>
</tr>
<tr>
<td>EMX</td>
<td>ECMWF global model</td>
<td>Global model</td>
</tr>
<tr>
<td>EEMN</td>
<td>ECMWF ensemble mean</td>
<td>Consensus</td>
</tr>
<tr>
<td>TABS</td>
<td>Beta and advection model (shallow layer)</td>
<td>Single-layer trajectory</td>
</tr>
<tr>
<td>TABM</td>
<td>Beta and advection model (medium layer)</td>
<td>Single-layer trajectory</td>
</tr>
<tr>
<td>Code</td>
<td>Model Name</td>
<td>Trajectory Type</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>TABD</td>
<td>Beta and advection model (deep layer)</td>
<td>Single-layer trajectory</td>
</tr>
<tr>
<td>CLPS</td>
<td>CLIPERS (Climatological and Persistence model)</td>
<td>Statistical (baseline)</td>
</tr>
<tr>
<td>TCLP</td>
<td>Trajectory-CLIPER model</td>
<td>Statistical (baseline)</td>
</tr>
<tr>
<td>OFCI</td>
<td>Previous cycle OFCL, adjusted</td>
<td>Interpolated</td>
</tr>
<tr>
<td>HWFI</td>
<td>Previous cycle HWRF, adjusted</td>
<td>Interpolated-dynamical</td>
</tr>
<tr>
<td>HMNI</td>
<td>Previous cycle HMON, adjusted</td>
<td>Interpolated-dynamical</td>
</tr>
<tr>
<td>CTCI</td>
<td>Previous cycle CTCX, adjusted</td>
<td>Interpolated-dynamical</td>
</tr>
<tr>
<td>GFSI</td>
<td>Previous cycle GFS, adjusted</td>
<td>Interpolated-dynamical</td>
</tr>
<tr>
<td>UKMI</td>
<td>Previous cycle UKM, adjusted</td>
<td>Interpolated-dynamical</td>
</tr>
<tr>
<td>ESGI</td>
<td>Previous cycle ESSR, adjusted</td>
<td>Interpolated-dynamical</td>
</tr>
<tr>
<td>NVGI</td>
<td>Previous cycle NVGM, adjusted</td>
<td>Interpolated-dynamical</td>
</tr>
<tr>
<td>EMXI</td>
<td>Previous cycle EMX, adjusted</td>
<td>Interpolated-dynamical</td>
</tr>
<tr>
<td>CMCI</td>
<td>Previous cycle CMC, adjusted</td>
<td>Interpolated-dynamical</td>
</tr>
<tr>
<td>AEMI</td>
<td>Previous cycle AEMN, adjusted</td>
<td>Consensus</td>
</tr>
<tr>
<td>UEMI</td>
<td>Previous cycle UEMN, adjusted</td>
<td>Consensus</td>
</tr>
<tr>
<td>FSSE</td>
<td>FSU Super-ensemble</td>
<td>Corrected consensus</td>
</tr>
<tr>
<td>GFEX</td>
<td>Average of GFSI and EMXI</td>
<td>Consensus</td>
</tr>
<tr>
<td>TCON</td>
<td>Average of ESSR, GFSI, and HWRF</td>
<td>Consensus</td>
</tr>
<tr>
<td>TCCN</td>
<td>Version of TCON corrected for model biases</td>
<td>Corrected consensus</td>
</tr>
<tr>
<td>TVCN</td>
<td>Average of at least two of GFSI EGRI HWFI EMXI CTCI</td>
<td>Consensus</td>
</tr>
<tr>
<td>TVCA</td>
<td>Average of at least two of GFSI EGRI HWFI EMXI CTCI</td>
<td>Consensus</td>
</tr>
<tr>
<td>TVCE</td>
<td>Average of at least two of GFSI EGRI HWFI EMXI CTCI HMNI EMNI</td>
<td>Consensus</td>
</tr>
<tr>
<td>TVCX</td>
<td>Average of at least two of EMXI (double weight) GFSI EGRI HWFI CTCI</td>
<td>Consensus</td>
</tr>
<tr>
<td>TVDG</td>
<td>Average of at least two of GFSI (double weight) EMXI (double weight) EGRI (double weight) CTCI HWFI</td>
<td>Consensus</td>
</tr>
<tr>
<td>TVCC</td>
<td>Version of TVCN corrected for model biases</td>
<td>Corrected consensus</td>
</tr>
<tr>
<td>HCCA</td>
<td>Weighted average of AEMI, GFSI, CTCI, DSHP, ESSR, EMNI, EMXI, HWFI, LGEM</td>
<td>Corrected consensus</td>
</tr>
</tbody>
</table>
b) **Joint Typhoon Warning Center (USA)**

*Consensus Forecast Aids*

JTWC was one of the first TC forecasting sites in the world to implement consensus forecasting in the late 1990s (Sampson and Schrader, 2000). At that time, limitations in model availability meant that the consensus was fairly limited. However, over the years, the availability of high-quality NWP models capable of generating a high confidence track forecast has dramatically increased. Beginning in the early 2000s, JTWC began to have access to increasing numbers of these models and started to use the consensus methodology to improve track forecasts.
Today, the JTWC utilizes an internally generated, non-weighted, consensus forecast track aid, (CONW), consisting of 10 individual members, including a mix of global, regional and ensemble models (Table 5b.1).

<table>
<thead>
<tr>
<th>Tracker Name</th>
<th>Model Name</th>
<th>Type</th>
<th>Date in CONW</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVNO</td>
<td>GFS</td>
<td>Global</td>
<td>2002</td>
</tr>
<tr>
<td>NVGM</td>
<td>NAVGEM</td>
<td>Global</td>
<td>2002</td>
</tr>
<tr>
<td>AFUM</td>
<td>USAF GALWEM</td>
<td>Global</td>
<td>2017</td>
</tr>
<tr>
<td>EGRR</td>
<td>UK Met Office</td>
<td>Global</td>
<td>2002</td>
</tr>
<tr>
<td>ECMF</td>
<td>ECMWF</td>
<td>Global</td>
<td>2007</td>
</tr>
<tr>
<td>JGSM</td>
<td>Japan GSM</td>
<td>Global</td>
<td>2002</td>
</tr>
<tr>
<td>HWRF</td>
<td>HWRF</td>
<td>Regional</td>
<td>2014</td>
</tr>
<tr>
<td>CTCX</td>
<td>COAMPS-TC</td>
<td>Regional</td>
<td>2017</td>
</tr>
<tr>
<td>AEMN</td>
<td>GEFS ensemble mean</td>
<td>Global</td>
<td>2014</td>
</tr>
<tr>
<td>EEMN</td>
<td>ECMWF ensemble mean</td>
<td>Global</td>
<td>2016</td>
</tr>
</tbody>
</table>

The JTWC consensus requires a minimum of two of the 10 members be present in order to generate the CONW tracker. NRL and JTWC annually review the performance and reliability of various models to assess the sensitivity of CONW accuracy to each member and to optimize overall accuracy of the consensus. For instance, in 2017, the USAF Global Air-Land Weather Exploitation (GALWEM) model (AFUM) replaced the JMA TC ensemble mean track forecasts (JENS) in the track forecast consensus. An example of the current CONW members as displayed in the Automated Tropical Cyclone Forecast (ATCF) system is shown in Figure 5b.1.

![Figure 5b.1. Example of current CONW trackers in ATCF display](image-url)
**Forecast Performance**

The JTWC provides TC track, intensity, and wind field forecasts for U.S. Government customers in the North Pacific, South Pacific, and Indian Ocean basins. Figure 5b.2 shows the mean track errors for the Northwest Pacific (since 1970) and Southern Hemisphere regions (since 1985). JTWC began producing 120-hour forecasts for the Northwest Pacific in 2000, and in the Southern Hemisphere in 2010. In 2000, mean track error at 72 and 120 hours were near 400 km and 600 km. In 2017, mean track errors at 72 and 120 hours were near 250 km and 415 km. The same general trends are evident in the southern hemisphere as well. Taking into account intra-seasonal variability, the implementation of consensus track forecasting at JTWC along with great improvements in numerical modelling capabilities has significantly and steadily reduced forecast track errors, particularly in the later forecast periods.

![Figure 5b.2. JTWC TC forecast errors (km) for the Northwest Pacific (top) and Southern Hemisphere (bottom).](image)

c) **RSMC Tokyo (Japan Meteorological Agency)**

**Forecast Performance**

Annual mean errors in TC track forecasts covering 24-, 48-, 72-, 96- and 120-hour operational track forecasts have steadily reduced in the long term (Figure 5c.1). Results for 2016-17 were
affected by the characteristics of TCs in those seasons since the forecast skill against persistence (not shown) mostly continued increasing compared to 2015.

Reduction of Forecast Circle Radii

The reduction of forecast circle radii is a remarkable improvement in performance related to track forecasts since IWTC-8. Based on TC track forecast improvements made in recent years via NWP model enhancement and other forecast techniques, JMA reduced the radius of forecast circles in its official forecasts by 20 - 40% (depending on TC direction and speed) in June 2016. This change addresses the issue of over-dispersiveness of warning areas. The size of forecast circles is determined so that forecast track falls within the circles in a probability of about 70%. For each forecast time, circle size is defined based on the speed and direction of movement. Furthermore, for forecast times 96 and 120 hours, circles are dependent on the forecast reliability estimated by the results of GEPS for each TC. Changes in forecast circle size in typhoons with two directions are shown in Figure 5c.2.

Figure 5c.1. Annual mean position errors in JMA 24-, 48-, 72-, 96- and 120-hour operational track forecasts

Figure 5c.2. Changes in forecast circle size; blue: old circles; black: new circles. Left: Northeastwards moving Typhoon Chan-hom (2015). Right: Northwestwards moving Typhoon Vongfong (2014)
Consensus Forecasting

Research on a selective consensus technique for TC track forecasts using multi-model ensembles was conducted in 2014 by the Meteorological Research Institute of JMA (Nishimura and Yamaguchi, 2015). Based on this, JMA verified the accuracy for track forecasts from 2012 to 2014 using four NWP models (JMA, ECMWF, UKMO, NCEP) and proved the effectiveness of the simple consensus method, with the combined four NWP model consensus achieving the highest accuracy at all forecast times (24, 48 and 60 hours). Therefore, this method has been adopted for JMA’s operational TC forecasts as the first guess since 2015. In addition, JMA has started improving a model and method to use in the following season by conducting verification at the end of every year.

JMA’s operational forecasts were mainly based on GSM until 2014, so accuracy was almost the same as GSM. In 2015, the four NWP model consensus was adopted for JMA’s operational tropical cyclone forecasts as the first guess. Figure 5c.3 shows that operational forecasts (black bars) had lower errors than GSM (pink bars) and the four model consensus (GEUA; red bars) gave the most accurate results.

![Figure 5c.3. Track errors (km) for combinations of the four NWP models for 2015, with operational errors (black bars). Forecast times 24, 48 and 60 hours.](image)

d) Bureau of Meteorology (Australia)

Forecasting Method and Performance

Performance of Bureau of Meteorology (BoM) in operational track forecasting is summarized in Figure 5d.1 and Table 5d.1, with values averaged over the past five years. The BoM issues a forecast track out to 120 hours with ‘uncertainty areas’ which represents the range of possible tracks between analysis time and a certain time.
Figure 5d.1. Mean forecast track error (great circle distance) based on best track or operational best track for seasons 2013/14 to 2017/18 inclusive.

Table 5d.1. Percentage of times the analysis position at the forecast hour was within the uncertainty area for seasons 2013/14 to 2017/18 inclusive (preliminary results). BoM has only been doing 120-hour uncertainty areas since November 2015.

<table>
<thead>
<tr>
<th>Forecast Hour</th>
<th>Number in area</th>
<th>Total number</th>
<th>Percentage in area</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>614</td>
<td>750</td>
<td>81.9</td>
</tr>
<tr>
<td>48</td>
<td>516</td>
<td>641</td>
<td>80.5</td>
</tr>
<tr>
<td>72</td>
<td>395</td>
<td>510</td>
<td>77.4</td>
</tr>
<tr>
<td>120</td>
<td>90</td>
<td>106</td>
<td>84.9</td>
</tr>
</tbody>
</table>

The BoM’s standard track forecast process involves a consensus of model guidance, shifting to the analysis position and using average motion to generate a track. Once a system has developed, the standard consensus is the latest (deterministic run) from ECMWF, GFS, UKMO, HWRF, ACCESS-TC (3-day high resolution) or ACCESS-TCX (5-day high resolution), COAMPS (CTCX), JMA, and optionally ACCESS-G or ACCESS-R. When or if available, ECMWF and UKMO ensemble means are also used. The shifting to analysis position and then average track motion avoids jumps in the consensus track when/if model guidance stops being available. The uncertainty areas (for 24-, 48-, 72- and 120-hour forecasts) are initially based on radii calculated from the consensus tracks and climatological track error. The forecasters then have the option to adjust the shape of the uncertainty areas based on guidance (deterministic and ensemble).

The BoM has a requirement, in some cases to start issuing tropical system forecasts prior to a tropical disturbance forming. Due to limited guidance at that time range, the usual consensus is two or more runs of the ECMWF, GFS, UKMO, JMA and ACCESS-G models. Depending on the situation, the inclusion of models and past runs is based on comparison to how well the resulting spread matches ensemble guidance. Due to uncertainty in analysis position (or no analysis position at all) the track is generally based on average guidance position or average initial position and average motion (not shifted to analysis). The included models and ensemble guidance is used to inform the uncertainty areas. These early tracks generally
exhibit greater forecast error due to errors in where the system develops compounding with errors in track forecasting.

Forecasting Challenges

The BoM’s main challenging scenarios are:

- Small systems with different steering flows depending on depth of the system, particularly since the small systems can be under forecast by the lower resolution global models.
- Small, well structured systems which could move offshore and then rapidly intensify.
- Two or more systems interacting which increases forecast error.
- Bifurcation and representing that in a forecast track. We generally try and forecast the most likely scenario and then modify the uncertainty area (which is initially uniform in all directions) to show the remainder of the risk, with the risk being based on guidance.

Future Developments

In the future, we’d like to move to a forecast method which uses a ‘super ensemble’ (multiple deterministic models, ensemble models and multiple runs) to generate the track and uncertainty areas. The uncertainty area for a specific time would be based on a contour of a heat map, with the contour value having been calibrated on past events and representing the area the system should be in some percentage of the time.

With improving NWP skill and availability of ensemble guidance, BoM aims to increase automation of the track generation process but there is still concern at how to interpret outliers and to identify scenarios requiring forecaster scrutiny. This includes cases of both high and low model spread.

In line with an increased focus on hazard rather than the TC, forecasters are focussing on the occurrence of wind thresholds for example point based onset of gales. While track is a key element, this approach requires a more sophisticated method of combining track, structure and intensity details rather than viewing these parameters in isolation.

e) RSMC La Réunion (Météo-France)

TC track forecasting at RSMC La Réunion essentially relies on the track forecasts provided by the main NWP models available at the Centre. Indeed, while a TC forecaster can beat any numerical model for an individual forecast at a given time, it has become virtually impossible to statistically beat them for a large sample of forecasts, like for a whole cyclone season.

Given this reality, the challenge for the TC track forecasting is then to optimize the forecasts provided by the models. The best that can be done is to follow the currently deemed ‘best performers’ or the consensus of the models that have been assessed to outdo the individual best models. A few years ago, during a certain period the ECMWF HRES model outperformed the other models by such a margin that any consensus built by adding one or several other models just degraded the performance of the track forecast. Currently, this situation does not prevail anymore, as the GFS model has caught up with the ECMWF model in the Southwest Indian Ocean basin. Therefore the outputs from these two models form the base of the track
forecasts for a more or less weighted consensus, the main adjustment variable being the weight given to each in the consensus.

However, in certain circumstances a consensus would not be appropriate. This is the case when there is a too large discrepancy between the models with track forecasting options that really differ. In such a situation it is the role of the TC forecaster to 1) try to understand the origin of the differences by examining the different fields and 2) to make a choice (with no guarantee of making the right one despite his expertise).

While deterministic track forecasts remain the main output of RSMC La Réunion, they say nothing about the inherent uncertainty in forecasts. Since December 2011 the RSMC La Réunion website displays dynamical probabilistic cones of uncertainty around the official track forecasts of the RSMC. Instead of including a cone of uncertainty based on the average error climatology, a more sophisticated probabilistic method is used which more realistically takes into account the real degree of uncertainty of each individual TC track forecast situation. The spread information included in the ensemble forecasts (EPS from the ECMWF) is used to better assess the uncertainty and construct an EPS-based probabilistic adaptive cone to convey this uncertainty. Dupont et al. (2011) shows that this methodology has skill over just using climatology.

The TC track forecast performance of the RSMC La Réunion is shown in Figure 5e.1. While short range forecasts have demonstrated very little or no improvement, forecasts at 48 hours lead time and beyond continue to show improvement. In the past few seasons the forecast errors for 60 hours and beyond have shown the most spectacular reduction, which means that the natural trend of increasing error with time becomes drastically flatter. So much so that the gap between 36-hour forecast errors and 72-hour forecast errors has been divided by more than three since IWTC-8. Also, 72-hour forecasts are now better than the 48-hour forecasts were just one or two years ago.

Figure 5e.1. RSMC La Reunion Direct Positional Errors of track forecasts (in km)
f) **RSMC Nadi (Fiji Meteorological Service)**

RSMC Nadi area of responsibility (AOR) is from the Equator to 25°S and 160°E to 120°W covering over 20 million square miles of ocean. Apart from a few ship reports there are no drifting buoys for open waters observations. Land based observations are also very few in most of the island countries which fall in the AOR. In brief this is a data sparse region. RSMC, Nadi issues a 3-day Tropical Cyclone Outlook every day at 0400 UTC from 1 November to 30 April.

TC intensity forecasting especially beyond 24 hours remains a challenge at RSMC Nadi. Each TC is different and behaves somewhat differently to similar environmental condition. For most of the systems, normal development of Dvorak $T = 1$ per day is applied. Midget systems which intensify rapidly are the most difficult ones to forecast where the Dvorak constraint is usually broken.

For analysing a system, we receive Himawari satellite images every 30 minutes from HimawariCloud which is of high resolution and HimawariCast every 10 minutes at lower resolution. The Dvorak technique is applied for analysing the intensity. For low-level circulation centre location, satellite loops, ASCAT passes, land-based observations (if close to land) are used.

The intensity analysis can only be verified if there is an ASCAT pass (useful when the TC intensity is below 50 knots) or land-based observation stations near to the TC centre. The Australian TC Module is used for TC official forecasts, tracks maps and issuance of most products.

For forecast intensity and track, RSMC Nadi is dependent on global model guidance which is imported from the JTWC website to TC Module. RSMC Nadi does not run any locally developed numerical models. Guidance from GFS, UKMO, JTWC, GFDL and JMA are available from the JTWC collaboration site. ECMWF is entered manually from Tropical Tidbits. A consensus forecast track is prepared from all the above models using TC Module. Sometimes the forecast track is shifted when the TC is approaching a land area. The track is moved a little closer to land area mainly for warning purpose. This is after the experience with TC Evan.

For the intensity forecasts, model guidance is used together with the Dvorak rules for intensification and weakening.

Examples of TC track forecast errors for TCs in the RSMC Nadi AOR in the 2016-17 and 2017-18 seasons are shown in Figures 5f.1 and 5f.2.
Figure 5f.1. RSMC Nadi track forecast errors for cases in the 2016-17 season

Figure 5f.2. RSMC Nadi track forecast errors for cases in the 2017-18 season
**g) RSMC New Delhi (India Meteorological Department)**

**Forecasting Tools**

For short range forecasting (up to 24 hours) IMD uses synoptic, statistical, satellite and radar guidance. NWP guidance is mainly used for 24-120 hour forecasts. Consensus forecasts that gather all or part of the numerical forecast tracks and use synoptic and statistical guidance are utilised to issue official forecast (IMD, 2013).

The NWP models used by IMD include individual deterministic models, a multi-model ensemble (MME) and single model ensemble prediction system (EPS). The deterministic models include GFS, the regional WRFDA-WRF-ARW model with 9 km and 3 km horizontal resolutions, HWRF, Unified Model (12 km resolution) and Unified regional model (4.5 km resolution) adapted from UKMO. IMD also makes use of NWP products prepared by some other operational NWP centres such as ECMWF, NCMRWF, JMA, UKMO and Météo-France.

The MME technique (Kotal and Roy Bhowmik, 2011) includes five member models; WRF (ARW), GFS (IMD), GFS (NCEP), ECMWF and JMA. The MME product is available about 9 hours late, so, for example, the 36-hour MME forecast is used for 24-hour official forecasts.

The Ensemble forecast products from ECMWF, NCEP, UKMO, CMC and JMA are available near real-time. A super-ensemble is also developed based on above ensembles. In India, NCMRWF and IMD run the Unified Model Ensemble Prediction System (UM-EPS) and Global Ensemble Forecasting System (GEFS) respectively to provide 7-day forecasts based on 0000 UTC initial condition with a resolution of 12 km each (RSMC, New Delhi, 2018).

**Forecast Performance**

There has been a significant improvement in TC track forecasting over the north Indian Ocean by IMD in recent years. The average track forecast errors of IMD during 2014-18 were 81, 128, 180, 260 and 285 km respectively for 24-, 48-, 72-, 96- and 120-hour forecasts (RSMC, New Delhi, 2018). The forecast performance of individual NWP models, the MME and IMD’s official forecast is shown in Figure 5g.1. It is found that the MME outperforms the individual models. The official forecast accuracy is similar to MME forecast accuracy. In this figure, the operational forecast error has been compared with model errors with a 12 hour lag (i.e. 24-hour model error is compared with 12-hour official error), as the model products used for official forecasts are available with almost 12 hours delay. Considering individual NWP models, it is observed that the HWRF model has the lowest error up to 36 hours. This is followed by the ECMWF model for these lead times. The UKMO model shows the lowest errors for the longer lead times.

The track forecast errors based on 2014-2018 as compared to previous five years are shown in Figure 5g.2. There is an improvement of 25-35% for 12- to 24-hour lead times and of 35-45% for 36- to 72-hour lead times. There has been continuous improvement in track forecasts by IMD (Mohapatra et al., 2013a) due to modernization of IMD (Mohapatra et al., 2013b).
Figure 5g.1. The average track forecast errors of various NWP models used by IMD and IMD’s official forecasts during 2014-18

Figure 5g.2. Comparative track forecast errors of IMD and NWP models for TCs over the north Indian Ocean during 2009-13 and 2014-18
Cone of Uncertainty

Considering the improvement in track forecasting, the radii of the cone of uncertainty based on past five years average track forecast error have been reduced by about 20-25% since 2014 (Mohapatra et al., 2012, 2017; Figure 5g.3). It is being revised every five years and revision is due in 2019. It has its own limitation due to its static nature, especially in the case of recurving tracks. A dynamical cone of uncertainty, which has not been introduced to date, needs to be implemented.

Figure 5g.3. Observed and forecast tracks along with old and new cones of uncertainty in case of TC Hudhud. Initial time 1200 UTC 9 October 2014

Sudden change in track

Situations that are difficult to forecast TC track include recurving TCs, rapid movement of TCs during landfall, slow movement or stationarity of TCs near the coast (Mohapatra and Bandyopadhyay, 2012) and sudden change in direction a few hours before landfall. It is found that the error is higher by about 5-20% for 12- to 72-hour lead times in case of TCs with rapid track changes as compared to the mean track forecast errors based on the data of 2014-18.

Pre-genesis Forecasting

RSMC New Delhi issues TC track forecasts valid up to 120 hours from the stage of deep depression (28-33 knots), in anticipation of intensification into a TC (34 knots or more). This practice has been operative since 2009. It has been further revised in 2018 with track forecasts from the stage of depression (17-27 knots) with a validity period of 72 hours. These forecasts are issued five times a day. However, the track forecast error in the pre-genesis stage is relatively high. This may be due to relatively high initial errors in the estimation of the centre of the depression unlike that of TCs and most of the models do not use vortex initialization or relocation at this stage due to lack of TC vital information from the forecasters.
End-of-life Track Forecasting

RSMC New Delhi issues track forecasts objectively indicating forecast latitude and longitude, whilst the former TC is expected to remain as a depression, even after landfall. No location in terms of latitude and longitude is given in the forecast of a low pressure area (< 17 knots). When the depression weakens into a low pressure area, forecast responsibility is handed over to the local state meteorological centre. Forecasts of the movement of low pressure areas are not provided by IMD.

h) Canadian Hurricane Centre

Regardless of the activity in the Atlantic Basin throughout any season, CHC tend to respond to 4 or 5 TCs or transitioning systems in our Response Zone on any given year. We almost always inherit tracks from the NHC as TCs approach from the south, so by default we have a good initial guidance from their tracks. Historically, we have become accustomed to utilizing other models other than the Canadian Global Deterministic Prediction System as its performance was substandard. However, significant progress has been made with the global model since the introduction of the coupled atmospheric-ocean physics.

Climatologically, tropical systems at our latitudes tend to have a ‘well-behaved’ track as the upper flow is usually well defined. The along-track error component usually dominates the cross-track component for this reason. The error components we use to define our error ellipses (upon which our cone of uncertainty is based) are in Table 5h.1.

<table>
<thead>
<tr>
<th>Hour</th>
<th>Cross-track (nm)</th>
<th>Along-track (nm)</th>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>12</td>
<td>21</td>
<td>30</td>
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<td>145</td>
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<tr>
<td>96</td>
<td>156</td>
<td>189</td>
</tr>
<tr>
<td>120</td>
<td>200</td>
<td>235</td>
</tr>
</tbody>
</table>

These numbers have been in use for a few years and are likely in need of updating in the next few years. The biggest challenge in track forecasting for our latitudes remains the speed of systems as they begin to interact with the mid-latitude upper flow.

CHC find it difficult to find forecast utility of the ensemble information. We do expose some of our clients to ‘track spaghetti plots’ (i.e. ensemble member tracks) at times to give an indication of NWP possibilities. We are also considering having a look at these member tracks superimposed over the climatological error cone to see how dispersed any specific ensemble run is compared to the error cone values to see if information is revealed. It might be a simple assessment: the longer the member tracks remain within the error cone the better behaved
the system might be. It’s more complicated to consider the cross and along track components as well. We may discover that some TCs are suited to longer track forecasts than others.

6. Summary

This report has summarised the latest configurations of many NWP models used for operational TC track forecasting and included performance statistics and future developments. It has also summarised forecasting techniques and recent performance statistics of many operational TC warning centres. The results presented show the continued reduction in TC track forecast errors by both NWP models and TC warning centres. There has been significant development of ensemble prediction systems and their usage by operational warning centres, although challenges remain as to how to communicate the inherent uncertainty in TC forecasts to the wider public.

7. Acknowledgements

The working group rapporteurs would like to thank all the working group members named at the top of the report for providing valuable information used in the compilation of this report.

8. Acronyms of Forecasting Centres and Numerical Models

CHC - Canadian Hurricane Centre
CMC: Canadian Meteorological Centre
COAMPS - Coupled Ocean/Atmosphere Mesoscale Prediction System (USA)
CPHC: Central Pacific Hurricane Center
ECMWF - European Centre for Medium-Range Weather Forecasts
ENS: ECMWF Ensemble System
GEPS - Global Ensemble Prediction System (JMA)
GFS: Global Forecasting System (USA)
GSM - Global Spectral Model (JMA)
HRES: ECMWF High Resolution Model
IMD: India Meteorological Department
JMA: Japan Meteorological Agency
JTWC - Joint Typhoon Warning Center (USA)
KMA: Korea Meteorological Administration
LFM: Local Forecast Model (JMA)
MetUM - Met Office Unified Model (UK)
MOGREPS - Met Office Global and Regional Ensemble Forecasting System (UK)
MSM: Meso-Scale Model (JMA)
NCEP - National Centers for Environmental Prediction (USA)
NCMRWF - National Centre for Medium Range Weather Forecasts (India)
NHC: National Hurricane Center (USA)
NRL - Naval Research Laboratory, Monterey (USA)
PAGASA - The Philippine Atmospheric, Geophysical and Astronomical Services Administration
TEPS - Typhoon Ensemble Prediction System (JMA)
UKMO - United Kingdom Met Office
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TOPIC 2.3 - ADVANCES IN UNDERSTANDING DIFFICULT CASES OF TRACK FORECASTS

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Working Group Members: James D. Doyle and William A. Komaromi (Naval Research Laboratory, Monterey, CA), Fuqing Zhang (Penn State University, PA), Ryan Torn (University of Albany, NY), Chi Kit Tang and Johnny C. L. Chan (School of Energy and Environment, City University of Hong Kong), Munehiko Yamaguchi (Meteorological Research Institute, Japan Meteorological Agency)

1. Background

Figure 1. Two examples of recent difficult cases: ECMWF ensemble track forecasts (grey) for Jebi (left) from 29 August 2018 with symbols indicating the position on 4 September 00UTC and Florence (right) from 4 September 12UTC and with symbols for 14 September 00UTC. The observed track (black) and intensity every 6th hour (circles) are also included. The observed position and intensity for the two times mentioned above in highlighted with hourglass symbol.

Although tropical cyclone track forecast errors of operational warning centres have substantially decreased in recent decades, there are still cases with very large track errors. Ensemble forecasts occasionally also show large uncertainties in the medium-range, and it is not uncommon to have bifurcations in the ensemble distribution, as seen in the examples of super-typhoon Jebi and hurricane Florence from 2018 (Figure 1). In the case of Jebi the ECMWF ensemble issued 6 days before the landfall on Japan still showed the possibility for a landfall on China. In the case of Florence, the majority of ensemble members predicted the storm to move northward over the Atlantic 9 days before the landfall in U.S, but with a few ensemble members predicted the landfall. However, in the case of Florence for this forecast run, most of the ensemble members missed the northerly kink in the track in the short-range predictions leading to relatively large track errors already on 2-3 days range.

In both the case of large ensemble spread and error it is of interest for the community to understand the sources of the errors and propagation of uncertainties in order to be better prepared for future cases. For example, the prediction of the bifurcation in ensemble forecasts for Sandy (2012) draw a lot of attention in the scientific community, and the case was
investigated in e.g Munsell and Zhang (2013), Magnusson et al. (2014) and Torn et. al.(2015). One of the recommendations from the IWTC-8 addressed to both operational centers and research community was to focus on model performance for the most difficult forecast cases and explore the predictability of these events.

Yamaguchi et al. (2017) reviewed an intercomparison study on TC forecasts by operational NWP models, which has been conducted under the Working Group on Numerical Experimentations (WGNE) since 1991. This quarter century-long project clearly shows that TC track forecasts by operational global models have significantly improved over the last quarter century. This improvement can be seen in the verification not only in both hemispheres and the globe, but also in each basin. In the western North Pacific basin, for example, we have succeeded in obtaining approximately a 2.5-day lead time improvement over the last 21 years from 1993 to 2014.

![Figure 2. Box plots of TC position errors of 3-day forecasts of each NWP center. The verification period is 3 years from 2012 to 2014 and the verifying TCs include all TCs over the globe. The red point is the mean value, the box indicates the 25th and 75th percentile of the error distribution. The top and bottom lines connected to the box indicate the largest and smallest values, respectively. (From Yamaguchi et al. 2018)](image)

However, there are still cases of very large errors. It is apparent in Figure 2, taken from Yamaguchi et al. (2017), which shows a boxplot of position errors of 3-day forecasts for TCs over the global from 2012 to 2014 and the mean error of each NWP center. The error distributions reveals that the values of the mean error are larger than the median value for all NWP centers, and the tails (with large errors) extend very far from the mean or the median. Such a distribution implies that while the mean error is decreasing, there still exist many cases in which the errors are extremely large. In other words, there is still a potential to further reduce the annual average TC position errors by reducing the number of such large-error cases.
In mid-latitude forecast evaluation, difficult cases have gained a lot of attention in recent years and are often referred to ‘forecast busts’ or ‘drop-outs’. Rodwell et al. (2013) investigated the linkages between poor forecasts over Europe and upstream flow features. Magnusson (2017) reviewed different techniques for tracking sources of errors such as manual error tracking, ensemble sensitivity (Torn and Hakim, 2008) and nudging (relaxation) experiments toward the analysis. Several of these techniques are useful for both mid-latitude and tropical cyclone investigations. Torn et al. (2015, 2018) used a combination of operational ensemble forecasts taken from the TIGGE database combined with ensemble-based sensitivity analysis to investigate what causes the variability in the ensemble positions. This approach helps to investigate the evolution of the steering flow within a forecast and determine how steering flow uncertainty at earlier lead times impacts the position forecast. It is also possible to decompose the effect of initial perturbation structures in the ensemble by geographical masking the perturbations such as in Nystrom et al. (2018). Another tool to explore the sensitivities for tropical cyclones is adjoint sensitivities, such as in Doyle et al. (2012; 2014) and Magnusson et al. (2014). These techniques are reviewed for hurricane Joaquin in this report.

In this report we will discuss definitions of difficult cases for tropical cyclone track forecasts, diagnostic techniques to understand sources of errors, lessons learnt in recent years and recommendations of work for the coming years. The main focus is for difficult cases in the medium-range (4-10 days ahead), while we acknowledge that also shorter cases sometimes poses difficulties regarding track forecasts.

2. **Definition of forecast busts**

![Figure 3. Ensemble mean error (y-axis) and ensemble spread (x-axis) for 5-day forecasts from ECMWF, for all cases in 2015-2017 cases (left) and cases 0W-100W and south of 35N (right).](image)

The first question to ask is how to define a difficult case. It could be based on (i) large uncertainties in the forecast (ensemble or between models) that challenge the forecasters before the event, it could be (ii) a case of very large errors revealed after the case, and it could be (iii) a case with relatively small uncertainties but where a small change in path changes the potential impact a lot. An example in the last category is the landfall of Hurricane Irma (2017) on Florida, where a small difference in the landfall position made a large difference in which areas to evacuate. To exemplify the two first measures, Figure 3 shows a scatter plot of ensemble spread vs. ensemble mean error in the period 2015-2017, both for all basins and for the Atlantic basin. For the 10 cases with highest error and spread the name of the cyclone is plotted. From both plots it is clear that a few cases are outliers in terms of error and/or spread. For the Atlantic, 3 of the 10 worst cases in terms of 5-day ensemble
mean error are for Hurricane Joaquin and forecasts initialised subsequently from 29 September 2015 12UTC to 30 September 2015 12UTC. For these forecasts also the ensemble spread was very high. As Joaquin at this point was predicted with high probability to make landfall somewhere along the U.S east-coast, this case was qualified as a difficult case for all three aspects (i-iii). Not surprisingly, this case spawned a lot of research and motivates that in this report we will highlight some of the work to understand the low predictability for this case.

The definition of difficult forecast cases is also dependent on the propagation of the cyclone itself. In particular, one can define difficult forecast cases as ones where the position variability relative to the speed of the storm is large. This would effectively remove the large error cases due to the storm moving quickly into the midlatitudes. Another alternative definition is to look at the cross-track position variability within the ensemble. These cases are operationally important because along-track uncertainty just means differences in the timing of impacts, whereas cross-track uncertainty can result in significant differences in TC impacts at a certain geographical location. Furthermore, difficult cases could also be defined in terms of the steering flow in which the TC is located.

Another difficulty is how to decide about a threshold for a bust. For example, Tang et al. (in prep.) defined the cases under one of the following two conditions. The first group (referred to as forecast bias) contains cases in which the track error of the ensemble mean forecast is larger than the 75th percentile of the annual track error distribution of the consensus members. The second group (referred to as forecast spread) consists of cases with a spread among the model predictions larger than the 75th percentile of the annual spread distribution of the consensus members.

3. Diagnostic tools to understand difficult cases: Application to hurricane Joaquin (2015)

In this section we will use Joaquin (2015) to demonstrate different diagnostic techniques for understanding difficult tropical cyclone cases. The results are from independent studies and might not give a coherent picture, and this section should be seen as a toolbox demonstration.

Hurricane Joaquin (2015) was a strong category 4 hurricane (maximum winds of 135 kts) that developed from an upper-level low over the western Atlantic and was noteworthy because of its large impact in the Bahamas. In a forecast issued shortly after genesis (the cyclone formed on 29 September), virtually all of the available dynamical model guidance had been predicting Joaquin to either threaten the U.S. eastern seaboard or recurve out to sea (Figure 4c). As a result, the operational forecast landfall guidance targeted the mid-Atlantic, while in reality the storm moved well offshore (Figure 4b). The models also had severe problems in predicting the rapid intensification before hitting the Bahamas. Ultimately Joaquin moved slowly southwestward towards the Bahamas as a category 4 hurricane (Figure 4a). The consequences of these poor forecasts may have been grave, as the cargo ship El Faro unexpectedly encountered Joaquin while it was a category 3 hurricane (Figure 4d), contributing to sinking of the ship and the loss of all 33 crew members.
Several studies have been conducted with the focus on Hurricane Joaquin. Using TCI-15 dropsonde observations and a high-temporal-resolution CIMSS vertical wind shear (VWS) product, Hendricks et al. (2018) examined the later stages of Joaquin, during which the storm maintained hurricane intensity despite traversing cooler SSTs and straddled a region of larger VWS to its north. The CIMSS VWS product revealed that Joaquin maintained its intensity due in part to the fact that it moved parallel to, but just avoided, a region of stronger shear to the north. From the dropsondes, they found a strong correlation between storm intensity and the vertical alignment of the vortex.
Nystrom et al. (2018) examined the predictability of the track and intensification of Joaquin during the early part of the forecast, when uncertainty was greatest. They used a 3-km regional convection-allowing WRF-EnKF ensemble analysis and prediction system, where they run a number of ensemble sensitivity experiments with initial perturbations withdrawn (i) inside the tropical cyclone, (ii) in the vicinity, and/or (iii) remote from the cyclone. By inspecting the ensemble spread in each ensemble experiment (Figure 5), they could draw conclusions about the origin of uncertainties. For the intensity, perturbing the core of the cyclone created the largest spread. They found the greatest sources of track error to originate 600-900 km from the cyclone, with particularly high sensitivity to differences in the environment to the north. The region within 300 km of the cyclone was the dominant source of initial condition errors contributing to intensity spread. Emanuel and Zhang (2017) further demonstrated that the initial inner-core moisture content can be a significant contributor to the intensity forecast uncertainty besides the initial vortex strength.

Torn et al. (2018) investigated the source of variability in ECMWF ensemble forecasts of Hurricane Joaquin (2015) initialized 0000 UTC 30 September by applying the ensemble sensitivity technique. Their analysis indicates that the ensemble members that correctly forecast the storm to move to the southwest were characterized by ensemble perturbation steering winds that were initially more northerly near the storm during the first 12 h (Figure 6). Over time, these wind perturbations caused the TC to move into locations with significantly different ensemble-mean winds due to the fact that Joaquin is within a steering flow characterized by deformation. In turn, the position variability quickly increases. By contrast, the position forecast appears to be relatively insensitive to the motion of synoptic features initially more than 500 km from the TC position.
The Navy’s COAMPS-TC ensemble was run in real-time during Hurricane Joaquin (2015) using a horizontal resolution of 3 km. While the majority of the COAMPS-TC ensemble members were incorrectly predicting a northward and/or westward track, consistent with the rest of the guidance, two of the eleven members accurately predicted a track towards the Bahamas as a major hurricane in consecutive forecasts at 00 UTC and again at 12 UTC 28 Sep 2015 (Figure 7). Since most of the guidance was too slow in intensifying Joaquin, it was initially hypothesized that the ensemble members with the most accurate track forecast were also the strongest. However, this turned out not to be the case with Joaquin, as the members with a track towards the Bahamas were not, on average, any stronger than the members that brought Joaquin towards the U.S. coastline. Subsequent re-runs of the ensemble using only vortex perturbations (i.e. synoptic and lateral boundary perturbations turned off) confirm this finding, with little sensitivity of the track forecast to modest perturbations to the size, strength or position of the initial vortex (Figure 8a). Alternatively, re-runs using only synoptic and lateral boundary perturbations (vortex perturbations turned off) exhibit comparable spread in both track and intensity to the real-time system (Figure 8b). That said, the intensity forecast from 0-36 h is quite under-dispersive without vortex perturbations, a conclusion that agrees with Nystrom et al. (2018) above.
Figure 7. COAMPS-TC ensemble member forecasts for Hurricane Joaquin initialized 28 September 2015 at 1200 UTC, showing the combined track and intensity information. Circles indicate forecast positions in 24-h increments. The verifying best track is shown in black, with verifying intensity coloured-coded for the best track also shown every 24 h.

Figure 8. As in Figure 7, but for (a) a simulation with vortex strength, location and size perturbations only, and (b) a simulation with environment and lateral boundary conditions perturbations only.
Figure 9. Ensemble-mean 500 hPa height (contoured) and height difference (shaded) between the 3 best ensemble members and the 3 worst ensemble members at (a) t = 0 h, and (b) t = 48 h, for COAMPS-TC ensemble member forecasts initialized 28 September 2015 at 1200 UTC. Positive (negative) values indicate higher (lower) heights in the members with the better track forecast.

Figure 10. Comparison of 300 hPa wind (m s$^{-1}$) for Hurricane Joaquin for two 48-h COAMPS-TC ensemble member forecasts initialized 28 September 2015 at 1200 UTC, with (a) one member that produced a bad forecast, (b) one member with a good forecast, and (d) the verifying COAMPS-TC analysis valid 30 September 2015 at 1200 UTC; and (c) 120-h track forecasts from the aforementioned members (colour coded by intensity), with the verifying best track (black).
Using the COAMPS-TC ensemble and comparing the 3 members that featured the best or worst track error statistics, the track of Joaquin was found to be most sensitive to an anticyclonic wavebreaking event that occurs north of the cyclone, and the interaction between the breaking anticyclone and two troughs located upstream and downstream of the ridge (Figure 9). In particular, the track was sensitive to the zonal position of a trough over the south-central U.S., the strength of the ridge over the northeastern U.S., and the strength and location of an upper-level low southeast of Bermuda. In members that have a more amplified pattern and stronger meridional flow, the upper low amplifies and propagates the furthest southwestward, dominating the subtle steering flow in Joaquin’s environment (Figure 10). This causes the TC to move southwestward. In the incorrect ensemble member forecasts, the upper low de-amplifies and is not a significant factor in the steering currents in Joaquin’s environment. In these members, Joaquin is instead captured by the approaching trough over the continental U.S. and is advected inland.

![Relative Vorticity Sensitivity, Winds, Height (48h)](image)

**Figure 11.** Sensitivity of the kinetic energy surrounding Joaquin to the initial state relative vorticity (colour shading) for (a) 500-hPa and (b) 300 hPa. The geopotential height contours are shown in blue and wind vectors shown in black.

To investigate the sensitivities further, NRL also utilized an adjoint modelling system, the Navy’s COAMPS, to investigate the role of initial condition errors that may have led to the relatively poor track predictions of Hurricane Joaquin. Adjoint models can provide valuable insight into the practical limitations of our ability to predict the path of tropical cyclones and their strength. An adjoint model can be used for the efficient and rigorous computation of numerical weather forecast sensitivity to changes in the initial state. The adjoint sensitivity diagnostics illustrate complex influences on the evolution of Joaquin that occur over a wide range of spatial scales, as shown in Figure 11. The sensitivity results highlight the importance of an upper-level trough to the northeast that provided the steering flow for the poorly-predicted southwesterly movement of the hurricane in its early phase, consistent with the ensemble results. The steering flow and hurricane track are found to be very sensitive to relatively small changes in the initial state associated with: i) the shortwave trough to the northeast of Joaquin, and ii) the upstream trough to the west of Joaquin, as illustrated in Figs. 11a-b.
ECMWF also investigated the sensitivities for the tracks of Joaquin. The ensemble forecast from 30 September 00UTC had an extreme ensemble spread, as seen in Figure 12 (left panel). From this forecast, Figure 12 (right panel) shows the difference in 500 geopotential height, 1.5 days into the forecast was calculated between the group hitting North and South Carolina (red tracks) and the group turning east over the Atlantic (green tracks). The result shows a sensitivity to the position of the cyclone itself but also to the trough to the east and the trough over U.S.

Figure 13. ECMWF experimental ensemble track for TC Joaquin from 30 September 00UTC, and positions on 4 October 0UTC (left panels). Control experiment (top), relaxation over the subtropical ridge (middle) and U.S trough (bottom). The reduction in ensemble spread in z500 in the relaxation experiment relative to the control experiment (right panel).
To test the impact of the sensitivity in the ridge and also to the propagation of the trough from the west, two relaxation experiments were set up, following Magnusson (2017). In each ensemble member, the “truth” was nudged in the forecasts in two boxes, one covering the easterly trough (20N-40N, 50W-60W), and one further to the west (20N-40N, 120W-90W). The reduction in of the ensemble spread in z500 after 48 hours in the two experiments compared to an control experiment without relaxation is shown in Figure 13 (right). As expected the spread reduction is largest inside the two boxes but it was propagated westward from the experiment with the easterly box and eastward in the experiment with the westerly box. Figure 13 (left) shows the cyclone tracks from each experiment, with the control on the top. While applying the relaxation to the west do not change the number of members making a U.S landfall, the relaxation of the easterly trough seems to have a larger impact for this forecast run.

4. Lessons learnt other studies of difficult cases

One important aspect to diagnose in order to understand track errors is the outer circulation structure of a TC (environmental flow), which usually interacts with or is deformed by the peripheral synoptic systems. However, the effect of such asymmetric outer structure of the TC on its track is not well documented. Tang et al. (in prep.) investigated the case of large track errors in TC Hagupit (2008) in different deterministic models. With an ill-defined steering flow near the neutral point, the TC would either recurve or move westward. By removing the azimuthal wavenumber 0 (WN0; i.e. symmetric) component of the TC from the total wind field, a cyclonic gyre is found to the southwest of the TC (Figure 14b). Such cyclonic gyre brings easterly to the TC core and thus the TC moves westward near the northeast of Luzon (not shown). Even though this cyclonic gyre is masked by the circulation of the TC in the total wind field, it makes the circulation of the TC more extensive on the southwest while more constraint on the northeast (see Figure 14a).

The model of UK meteorological office (UKMO) represented well for this case the asymmetry of the TC (Figure 14c) and the cyclonic gyre on the southwest of the TC (Figure 14d) and thus the onward track was well predicted. On the other hand, the NCEP forecast did not represent well the outer circulation of the TC and thus the cyclonic gyre (Figures 14e and f respectively), resulting in large track errors. As the cyclonic gyre would deform the outer circulation of a TC, the outer size of the TC would be altered.

The large track errors during typhoon Fengshen (2008) was investigated Yang et al.(2018) by using PV inversion. With the method they were able to partitioning the contribution to the steering from from different synoptic features. They attributed the large error for this case to the over-predicted subtropical anticyclone.

Torn et al. (2018) investigated three cases (Debby 2012, Joaquin 2015, Lionrock 2016), where the tropical cyclones also were located in a deformation wind field. In such situations, the position variability is sensitive to the near-storm steering flow early in the forecast. The calculations indicate that the position forecast variability increases via a two-stage process. Early on in the forecast, small differences in the near-storm steering flow help advect the storm onto one side or another of the axis of contraction of the deformation steering flow. Following that, the TC experiences different ensemble-mean winds, which in turn advect the TC further away from the ensemble mean position. For subsequent initialization times, the position forecast errors and variability decrease once it becomes clear what side of the axis of contraction the TC will move (i.e. they are no longer difficult cases).
Figure 14. 500 - 850 hPa averaged (left panel) total wind field of TC Hagupit and (right panel) the total wind minus the WN0 component of the TC. Upper, middle and lower panels show the FNL data at 12 UTC 21 September 2008, the +60 h forecast of the models of UKMO and NCEP with initial time at 00 UTC 19 September 2008 and validation time at 12 UTC 21 September 2008, respectively. Shadings show the wind speed in m s-1. The TC symbol in each plot indicates the TC location.

These cases highlight the importance of the outer circulation structure of a TC to its onward track and the need of more attention to the outer circulation structure of a TC during surveillance and along investigations of systematic errors in the global models regarding the prediction of synoptic features.
Dong and Zhang (2016) evaluated ensemble mean errors from ECMWF and NCEP ensembles, with errors from a new ensemble constructed from subset of members based on their 12-hour error. With the method they managed to reduce considerably the ensemble mean forecast error for the extremely large forecast error cases (busts or outliners). One interpretation of this results is when being close to a bifurcation point, the error could sharply decrease when new information is taken into account. This super-ensemble subsetting method has been used operationally at CMA Typhoon and Marine Forecast Center since 2015, and is very successful. Another interesting finding in Dong and Zhang (2016) worth mentioning was that the found almost no correlation between NCEP and ECMWF ensemble mean errors.

5. **Recommended work in the coming 4 years**

In this report we have discussed how to diagnose difficult cases of tropical cyclone track forecasts. For hurricane Joaquin we demonstrated the use of different diagnostic tools such as diagnostics of the environmental flow, ensemble sensitivity, masked ensemble perturbations, adjoint sensitivity and nudging (relaxation) experiments.

For the three latter ones, the user is required to have access to the model to rerun the ensemble with different perturbations, have an adjoint model, or have a nudging code available in the model. This limits the number of users that can apply these otherwise powerful tools, and that they are not easily shared between institute. The ensemble sensitivity is on other hand easier to apply as it does not requires additional forecast simulations. However, this technique requires that the outcome is well captured by the ensemble forecast. It also requires access to global ensemble forecasts, and here the The International Grand Global Ensemble (TIGGE) archive is an invaluable source.

TIGGE is also an essential source to make diagnostics that includes forecasts from different modelling centres, both in terms of meteorological fields and tropical cyclone tracks. Another instrumental initiative here is the collection of global models forecast track to the dataset created by The Working Group on Numerical Experimentation (WGNE) are instrumental to study the TC with large track errors. We strongly recommend that both these initiative shall continue.

Future diagnostic works include to generalize this research (and unify some of the difficult discussion) is to investigate the extent to which large position variability cases are characterized by large horizontal gradients in the ensemble-mean steering flow. This is certainly the case when a TC is located in a deformation steering flow, but this could be generalized to situations where a TC approaches a midlatitude trough, or situations where the steering flow becomes near zero. Ryan Torn plans to investigate the relative contribution of perturbation steering wind and ensemble-mean steering wind gradients on TC position variability over a larger set of cases.

The results from investigations of difficult cases should feed back to observation communities and model and data assimilation development, as a guidance for future work. For the observation part it lies both in targeted observations (Majumdar, 2016), a concept that is currently revised by the use of ensemble sensitivities. The knowledge of where the most important errors on average are can also help to form strategies for dropsonde usage.
The results from difficult cases should also be used to improve the usage of ensemble forecasts and how to communicate the uncertainties (see separate session in IWTC-9). Clearly from cases of a bifurcation, ensemble mean nor a single cone of uncertainty is a good way to communicate the forecast. Finally, the results should also be feed into the training for forecasts to better understand the uncertainties in the forecasts. Here the usage of clustering methods for ensemble tracks might be a useful tool.

To summarize, the research community has developed a number of tools and diagnostics that are relevant for investigating tropical cyclone forecast outlier or “bust” cases, of which some have been described in this section. These tools include ensemble and adjoint sensitivity models and diagnostics, transplant experiments where the entire or part of the initial state is derived from another modelling system, data assimilation diagnostics including analysis of increments, forecast sensitivity observation impact systems (adjoint or ensemble based), model diagnostics such as physics tendencies, and verification tools. These systems are typically applied by individual investigators or single institutions and there is little coordination across institutions. There is a great opportunity to focus the research community on some of these forecasts busts and apply both established and emerging sets of diagnostic and modelling tools in order to apply these in a more systematic manner to better understand the underlying causes of these poor forecasts. Operational centers could recommend the top 1 or 2 poorly forecasted storms from each basin to help focus the effort. We recommend the formation of a working group or team comprised of multiple institutions to better address TC forecast busts in a more systematic manner.

References

Berg, R., 2016: Hurricane Joaquin, National Hurricane Center Tropical Cyclone Report, AL112015


Abstract
This chapter addresses recent advances on forecasting and understanding tropical cyclone (TC) intensity change. Research advances on intensity change have occurred on many fronts, including improved understanding of the role of vertical wind shear and its impact on convection, surface fluxes, ocean eddies, dry/dusty air intrusions, eyewall replacement cycles, spiral rainband dynamics, eyewall instability and inner-core mixing, and the mechanisms by which TCs intensify. On the operational side, advancements in both dynamical and statistical-dynamical models in recent years have led to some improvement in forecasting intensity changes. Despite this progress, the understanding and prediction of rapid intensity change remains a challenging problem. Continued improvements to dynamical models (resolution, data assimilation, and physical parameterizations) are likely to lead to improved intensity guidance in the future. A set of difficult intensity change cases from 2015-2018 is given for the research and operational communities to examine. Better communication and translation of research advances and guidance upgrades into operational centers is needed in the future.

3.0 Introduction

This report summarizes three rapporteur reports on TC intensity change: (3.1) intensity change: internal influences, (3.2) intensity change: external influences, and (3.3) intensity change: operational perspectives. In the first sub-topic, recent advances in understanding how TCs change in intensity as a result of internal influences are reported. In the second sub-topic, progress in understanding how TC change in intensity as a result of external influences is reported. In the final sub-topic, summaries of the current state of forecasting TC intensity change at the operational warning centers across the world are reported, including advances in intensity guidance. All advances are reported from IWTC-8 to the present, or from 2014-2018. Finally, a summary of future recommendations with regard to forecasting and understanding TC intensity change is given in section 3.4

3.1 Intensity Change: Internal Influences

There were a number of recent advances in the understanding of internal influences on TC intensity change, which are summarized below. The main internal influences on TC intensity
change are eyewall instability and inner-core mixing processes, eyewall replacement cycles, spiral rainband dynamics, and interaction of the TC with the ocean through surface fluxes. Special focus topics in this section are internal processes contributing to rapid intensification, fundamental mechanisms by which TCs intensify, and some recent new emerging ideas on internal influences on TC intensity change.

The hurricane eyewall can become dynamically unstable when the radial potential vorticity (PV) gradient changes sign, satisfying the Charney-Stern necessary condition for combined barotropic-baroclinic instability. When the eyewall becomes unstable, it can break down into polygonal structures and mesovortices, and mixing can ensue between the eyewall and eye. Recent research on this topic has extended the previous idealized adiabatic and inviscid studies to more realistic frameworks (three-dimensional and with more complicated diabatic and frictional forcing). One study showed that the secondary circulation can help maintain the annular ring structure and make it less susceptible to instability. Another study emphasized the importance of the vortex Rossby wave-inertia gravity wave instability in destabilizing three-dimensional PV rings.

New research on secondary eyewall formation and eyewall replacement cycles (ERCs) has focused on improved understanding of wind-pressure relationships and intensity changes during ERCs, and improved prediction of ERCs and associated intensity changes. A new intensity change guidance model called the ERC climatology model (E-SHIPS) has been developed and is being used by operational centers. State-of-the-art numerical weather prediction models still have difficulty predicting the onset time of the ERC, the location and contraction speed of the outer eyewall, the dissipation rate of the inner eyewall, and the total duration of the event. With regard to wind-pressure relationships (WPRs), it was found that migration of the WPR is quite different for weak versus strong hurricanes undergoing ERCs. While the classic ERC is associated with weakening, some recent studies have shown that subtle intensity changes can also occur with ERCs where the outer eyewall is maintained for a long time or the inner eyewall does not dissipate.

Spiral rainbands have significant effects on TC structural and intensity change. Recent studies have shown that the outer rainbands are dominated more by ice-phase processes than the inner rainbands (especially over land), and also have high lightning flash densities. Convective heating in inner rainbands have been shown to increase intensity, while stratiform cooling in these bands promotes weakening. Evaporative cooling in the outer rainbands tends to reduce intensity, while this process has a minimal effect for inner rainbands.

The following are the important advances in understanding the role of surface fluxes on TC intensity change. Recent studies have shown that sea spray effects can aid intensification, through enhancing thermodynamic disequilibrium and thus the surface fluxes from the ocean into the boundary layer. New theories were developed to include the effect of TC-induced cooling of the sea surface on TC maximum potential intensity. New studies were performed on understanding the impact of surface fluxes on the TC boundary layer, including boundary layer recovery. With regard to the sea-surface-temperature (SST), it was shown that radial variability of SST across the storm is important, modifying convective available potential energy inside and outside the radius of maximum winds, affecting the intensity change.

Many recent studies focused on improved understanding of the processes responsible for rapid intensification (RI). Studies have shown the RI events usually last longer than 24 h, and that the storm structure (convection, precipitation, and thermodynamic parameters) are often
axisymmetric prior to RI episodes. Although the axisymmetric pathway is common, studies have also shown that RI can occur with asymmetric convective bursts and hot towers in the inner-core. RI events depend on the nature of the precipitation (deep convective versus stratiform) and the shear-relative distribution of the convection. In one study, the onset of RI was marked by a significant increase in stratiform precipitation in all shear-relative quadrants, especially upshear left (Fig. 3.1.1). Further research is needed on whether deep convective bursts are a symptom or cause of RI. Additionally, a consistent definition of RI is needed globally, as different basins have different thresholds based on observed intensity change cumulative distribution functions.

A summary was provided on four main intensification mechanisms for TCs. The first two mechanisms are well known, while the second two mechanisms are newer and have had more active research in recent years. The first mechanism is the well-known balanced symmetric intensification mechanism. Using the quasi-balance equations, diabatic heating drives a secondary circulation in a linear Sawyer-Eliassen sense, which draws isosurfaces of absolute angular momentum (AAM) inward to spin up the vortex. If the heating occurs inside the RMW, the heat energy is more efficiently converted into kinetic energy and thus spins up the vortex faster. The second mechanism is the wind-induced surface heat exchange (WISHE), which is a finite amplitude instability with a positive feedback between the surface winds and speed-dependent surface moist entropy flux. Recent modifications to WISHE include the role of small scale turbulence in the outflow layer and capping of the winds in the surface enthalpy flux. The third mechanism is newer and is a rotating convective framework. This framework explicitly recognizes the importance of localized, rotating deep convection, whose vorticity is amplified several times that of the broad scale vortex circulation via stretching and tilting processes. The

![Figure 3.1.1. Composite shear-relative distribution of the rainfall coverage from (I) all precipitation, (II) stratiform precipitation, and (III) convective precipitation. From left to right: (a) 12–24 h before RI onset, (b) 0–12 h before RI onset, (c) RI onset, (d) RI continuing, and (e) 12–24 h before RI ends. Dotted range rings represent the 25-, 50-, 75-, and 100-km radii. Taken from Tao et al. (2017) – See rapporteur report for Intensity Change: Internal Influences for complete reference.](image-url)
parent vortex is then intensified through upscale growth of these localized vorticity anomalies. Also, more recent, the fourth and final mechanism is the boundary layer spin-up mechanism. This mechanism emphasizes the critical importance on unbalanced processes in the nonlinear boundary layer, where strong radial convergence can lead to spin-up even though AAM is diminished in the boundary layer.

Finally, three new emerging topics on internal influences on TC intensity change have been identified in recent years. In the first topic, the critical role of vortex structure on the subsequent intensification rate (IR) is discussed. In these studies, the IR is shown to depend critically on the radial and vertical structure of the parent vortex. In the second topic, the concept of the maximum potential intensification rate (MPIR) of a tropical cyclone was identified and discussed from observational and energetic perspectives. MPIR is similar to the well-known maximum potential intensity (MPI), except that it is an upper bound on the IR rather than the intensity. Development of a rigorous MPIR theory would eventually lead to better prediction of RI events. Finally, the role of TC outflow on TC intensity change is discussed. Recent field campaigns have had targeted measurements in the outflow region, which may lead to an understanding of outflow’s precise role in intensity variability in the future.

### 3.2 Intensity Change: External Influences

There were a number of recent advances in the understanding of external influences on TC intensity change, which are summarized below. The main external influences on TC intensity change are the interaction of the TC with the underlying ocean, vertical wind shear, trough interactions, and dry or dusty environmental air intrusions. While there exists an understanding of the impact of each of these processes separately on TC intensity change, when multiple external factors act in concert, there is less understanding of dynamical and thermodynamic processes causing intensity changes.

With regard to ocean influences, research in the past four years has focused on the influence of mesoscale warm- and cold-core ocean eddies on TC intensity change. When a TC moves over a warm-core ocean eddy, increased enthalpy fluxes ensue due to moisture disequilibrium, contributing to intensification. When a TC nears a coastal region, TC may interact with fresh water which tends to reduce TC-induced cooling. SST displays a complicated relationship with TC intensity change, varying from basin to basin. During strong El Nino events, ocean heat content (OHC) and SST anomalies can contribute to extreme intensification rates (which occurred in the environment of Hurricane Patricia in 2015). Finally, under global warming conditions, upper ocean thermal stratification may increase leading to stronger TC self-induced cooling, partially offsetting the increased intensification rates expected under warming scenarios.

Vertical wind shear (VWS) is one of the most important external influences on TC intensity change. VWS usually causes a reduction in intensity, however the pathway of this reduction can be quite complicated and is also highly dependent on the VWS magnitude, horizontal variability around the TC, and the vertical profile. With regard to its impact on convection, VWS modulates the azimuthal and radial distribution of the inner-core convection which then affects intensity. While VWS typically produces a wavenumber-one asymmetry in convection with an enhancement downshear, recent work has shown that VWS can also organize deep convection in the upshear left quadrant, favouring intensification. The vertical profile of VWS is important for intensity change, with positive TC-relative environmental helicity favouring
intensification. Due to this interaction with convection, the predictability of TC intensity is lower when the TC exists in moderate VWS (Fig. 3.2.1).

![Fig. 3.2.1. Time evolution of the TC intensity in terms of the 10-m maximum wind speed (m s\(^{-1}\)) for all ensemble members of (a) NOFLOW, (b) SH2.5 (shear of 2.5 m s\(^{-1}\)), (c) SH5, (d) SH6, (e) SH7.5, and (f) combination of SH5, SH6, and SH7.5. All under SST = 27 C. (From Fig. 2 of Tao and Zhang 2015 – see External Influences Rapporteur Report for complete reference).]

Dry environmental air often inhibits TC intensification, especially when it occurs coincident with VWS, since VWS disrupts the inertial stability of the vortex allowing the dry air to be more easily entrained. The location of the dry air and how it interacts with the TC circulation are critical; merely having dry air in the environment near a TC is not a sufficient condition for interaction and weakening. When dry air is ingested in a TC, the TC weakens as the vertical mass flux is reduced due to a reduction of deep convective activity.

Aerosols affect TC intensity change through their indirect effects with the microphysical processes and radiation. Aerosols can act as cloud-condensational nuclei, and if more condensation occurs in the inner-core, column latent heating may be increased, favouring intensification. However, aerosols are often present in dry air masses (e.g. the Saharan Air Layer) which would inhibit intensification.

With regard to TC-trough interactions, recent studies have shown that troughs can both aid and hinder intensification. As an example, one study has shown that the interaction depends on the TC vortex depth, with intensification being more likely for deeper TCs. Another study has shown that the positive eddy-flux-convergence effect is often dominated by the negative VWS effects, causing weakening. The geometry of the TC-trough system was also shown to be important for intensity change. An interesting finding in this section is that upper-level jet streaks can externally force an eyewall replacement cycle.
When multiple external factors act in concert, the predictability of the timing of rapid intensification is low. In particular, the external factors act in complicated ways with the internal processes during RI events. Rapid weakening events were found to occur when TCs cross sharp SST gradients, move into regions of higher VWS, and entrain drier air.

Finally, the storm environment is modulated by the Pacific Decadal Oscillation, El Nino-Southern Oscillation, and the Madden-Julian Oscillation, and therefore these large-scale, low-frequency, modes of variability affect TC intensity change.

### 3.3 Intensity Change: Operational Perspectives

Since IWTC-8 in 2014, considerable work has continued worldwide to improve TC intensity guidance and to understand the influences that sometimes lead to rapid intensity changes. Dynamical models have had improvements in resolution, physics and data assimilation including ocean coupling while statistical-dynamical techniques have advanced further. These enhancements have translated to some improvement in forecast intensity skill, especially at time-scales beyond 24 h and have led to greater confidence in anticipating rapid intensity changes.

It was not long ago that forecasters placed little regard for global model intensity forecasts. However ongoing upgrades have improved their intensity skill. For example, the IFS (ECMWF) 2018 upgrade enabling more sophisticated ocean coupling has improved medium range intensity skill as shown in Fig. 3.3.1. The UK global model upgrades in 2014 and 2015 markedly improved intensity skill and further upgrades in 2019 and 2020 including ocean coupling are likely to improve the results further. The development of a more sophisticated dynamical core [GFDL Finite-Volume Cubed-Sphere (FV3)] is expected to enhance the GFS intensity forecasts in the future.

![TC fcst mean absolute intensity error (hPa)](image)

**Figure 3.3.1.** Intensity verification of the IFS (ECMWF) model showing the improvement in the coupled model (red) especially beyond 72 h.
Regional models have likewise improved, with HWRF in particular being the best intensity performer in the North Atlantic (at all lead times) and eastern North Pacific (lead times < 48 h). Meteo-France has implemented the high resolution AROME model across French territorial waters and is demonstrating promising results including the rapid demise of TC Hellen (2014), the explosive initial development of TC Bansi (2015), the eyewall replacement cycle of TC Fantala (2016) and Hurricanes Irma and Maria (2017).

Further development of statistical-dynamical and consensus techniques occurred in recent years. The ‘ICNW’ approach to combine SHIPS and LGEM with high resolution models HWRF, COAMPS and HMON as well as the (Rapid Intensification Prediction Aid) RIPA index, has led to significant improvements in the quality of objective guidance at JTWC. The global availability of this output has also benefited many other operational centers. A Corrected Consensus Approach (HCCA) for tropical cyclone track and intensity forecasts has been developed at the NHC. The HCCA technique relies on the forecasts of separate input models for both track and intensity and assigns unequal weighting coefficients based on a set of training forecasts. HCCA uses Decay-SHIPS, LGEM, GFS, UKMO, ECMWF IFS, COAMPS-TC, HWRF, GEFS and ECMWF EPS to derive a track and intensity consensus. Such a technique that draws upon the diverse range of models appears to be of great promise but is currently limited to the North Atlantic and Eastern North Pacific.

Following a recommendation from previous IWTC, the sharing of intensity guidance initially designed for the North Atlantic or the East Pacific has benefited other operational centers. Some techniques have been tailored to local basins by some operational centers using available dynamical guidance. JMA have developed TIFS based on SHIPS. KMA have used a version of STIPS that includes HWRF and TRUM (KMA’s Typhoon Regional Unified Model). IMD have adapted their own version of HWRF, and also use an integrated Cyclone Prediction System (CPS) which includes an SCIP (IMD model), RI-index and decay model. Meteo-France have extended their hi-resolution (2.5km) AROME model (initialized by IFS) to all their tropical territories and are using IFS to develop statistical-dynamical tools for 24-h intensity forecasts.

Over the last 4 years, reports of intensity forecast skill from operational agencies are split into two categories: some report a decrease in intensity forecast errors (Fig. 3.3.2) especially at forecast times greater than 24-hours. While a generally stationary trend is noted amongst other agencies (Fig. 3.3.3).

While the trend of intensity skill has started to improve for some operational centers, this trend needs to be confirmed through verification and extended to all operational centers. Some centers were only able to report improvements on an anecdotal basis in the absence of specific verification evidence.

There are strong similarities in how operational centers approach intensity forecasting. This is a testament to collaborations and communication between centers and WMO training. However, it is difficult for forecasters to stay updated with ongoing model upgrades and development of techniques, as well as the underlying scientific research and understanding. Given the operational time constraints facing forecasters (~1-1.5 hours to synthesize forecast track, intensity, and structure guidance before issuing a tropical cyclone forecast), operational centers are challenged to implement robust intensity forecasting processes that take advantage of the range of guidance available. Easy-to-use website displays and software that enable this to occur are essential.
It is apparent that the considerable research efforts into understanding intensity changes as outlined in the companion sub-topics on internal influences (3.1) and external influences (3.2) may not be reaching forecasters. It is important that this research, along with advances in intensity guidance, including verification results, are adequately communicated to operational staff though appropriate notifications, workshops and training material. These efforts will help reduce the lag in seeing the benefits of advances in guidance translate to operations.
Rapid intensity changes remain the primary intensity forecasting challenge and account for the highest forecast errors. In the SWIO the 24-h forecast error for RI events is 19 kt compared to 8 kt for non-RI events. Several agencies reported some success in RI forecasting reflecting a greater confidence in guidance. In particular, the RI-index based on predictors from the environment (from the SHIPS developmental dataset), infrared imagery and the best-track / advisory-based data is proving valuable to JTWC and BoM. Emerging techniques such as DTOPS (being trialed at NHC) are now combining IFS (ECMWF) with US guidance: GFS, HWRF, LGEM, and SHIPS.

Eyewall Replacement Cycles (ERC) continue to be challenging forecasting scenarios. These inner-core mechanisms are associated with intensity fluctuations that sometimes can be quite significant. Until very recently, the skill to anticipate and quantify those intensity variations was rather limited. CIMSS have developed the M-PERC (Microwave-based Probability of Eyewall Replacement Cycle) guidance based on observational studies done previously with aircraft data. M-PERC uses an azimuthal ring score from ARCHER derived with microwave imagery and calculates a probability forecast of the onset of an ERC. The timing and the amplitude of intensity fluctuations through the ERC can be assessed from the observational studies cited previously. The probabilistic guidance is available to all TC forecasters in real-time on the CIMSS web site.

Despite the above improvements, large intensity forecast errors are still occurring. Recommendation No. 2 from IWTC-8 requested operational TC centers identify their most difficult forecast cases as well as extreme events and make them available to the TC community. Table 3.3.1 lists a selection of difficult cases (2015-18) which can be viewed as a starting point for ongoing sharing with the TC community.

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Ocean basin</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAM</td>
<td>6-22 March 2015</td>
<td>South Pacific</td>
<td>RI: 35kt to 135kt when the standard intensification rate was forecast (35-70kt).</td>
</tr>
<tr>
<td>CHOI-WAN</td>
<td>1-7 Oct. 2015</td>
<td>NW Pacific</td>
<td>Monsoon gyre/depression with very slow rate of intensification despite favourable environmental conditions. Forecasts were overestimated. Similar cases: Omais (2016) and Maliksi (2018)</td>
</tr>
<tr>
<td>MEGH</td>
<td>5-10 Nov. 2015</td>
<td>Arabian Sea</td>
<td>RI (7-8 Nov) 40kn/24h cf. forecast 10kt. RW (9-10 Nov) 35kt/24h cf. forecast 20kt.</td>
</tr>
<tr>
<td>ERNIE</td>
<td>5-10 April 2017</td>
<td>Australian region</td>
<td>RI:(6-7 Apr)75kt/24h(40-115kt) cf. forecast 10kt. Initially in moderate shear. DT 2.5 to 7.0 24h.</td>
</tr>
<tr>
<td>Location</td>
<td>Date Range</td>
<td>Forecasted Event</td>
<td>Details</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------</td>
<td>--------------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>NW Pacific</td>
<td>8-17 Sep. 2017</td>
<td>Forecast overestimated due to unexpected strong wind shear, dry air intrusion and/or track over cold SST. Similar case LAN (2017).</td>
<td></td>
</tr>
<tr>
<td>North Atlantic</td>
<td>16 Sep. - 2 Oct. 2017</td>
<td>RI: (18-19 Sep.) 65kt/18h cf. 25kt/24h</td>
<td></td>
</tr>
<tr>
<td>Arabian Sea</td>
<td>29 Nov. - 6 Dec. 2017</td>
<td>RI (1-2 Dec.) 30kt/24h cf. 12kt.</td>
<td></td>
</tr>
<tr>
<td>Australian region (offshore developer)</td>
<td>15-19 Feb. 2018</td>
<td>RI forecast but failed to occur; forecasts eased off but RI eventuated 12h prior to landfall, and then developed an eye as it moved overland.</td>
<td></td>
</tr>
<tr>
<td>South Pacific</td>
<td>8 April - 11 April 2018</td>
<td>RI: RI occurred from depression to 85kt in 48h when forecast was only for initial 24h to 50kt.</td>
<td></td>
</tr>
<tr>
<td>SW Indian Ocean</td>
<td>20 April - 26 April 2018</td>
<td>RI (23-24 Apr) 30kt/24h cf. forecast 10kt. Delay in timing of the expected RI trend, due to unusually high short range along-track error.</td>
<td></td>
</tr>
<tr>
<td>Central North Pacific</td>
<td>27 July - 13 August 2018</td>
<td>Missed post-ERC intensification (06 UTC 9 Aug. to 18 UTC of 10 Aug) 25kt/12h; not forecast.</td>
<td></td>
</tr>
</tbody>
</table>

3.4 Recommendations

Below, the main recommendations from each rapporteur report are given.

3.4.1 Internal Influences

3.1.1 We recommend that future research directions focus on: a) studying RI as an event (rather than a 24-h case-based RI definition), b) improving understanding of the conditions and precursors to RI through symmetrical processes, and c) reconciling seemingly conflicting findings on the conditions and processes in which asymmetric inner-core CBs and HTs may lead to RI precursors.

3.1.2 Continued advancements and diagnostics and testing activities are needed in NWP models to improve the accuracy of SEF and ERC event timing and the associated intensity changes. We recommend that such efforts incorporate non-standard evaluation metrics beyond track, intensity, and wind structure, such as the explicit prediction of eyewall and secondary eyewall structure.

3.1.3 We recommend that specific, targeted observational and modelling investigations be undertaken to better understand interactions between spiral rainbands and their parent TCS and the specific mechanisms by which rainbands influence TC intensity.

3.1.4 Because the PV structure is critical in understanding the vortex state (annular vs. monopole) during instability mixing events, we recommend that future research consider observational strategies to better assess the PV structure of TCS. We also recommend that structure databases include observable markers of mixing processes (eyewall mesovortices as seen in satellite imagery and radar imagery). In general, researchers would benefit from mesoscale analyses of well-observed cases.

3.1.5 Advances in both modelling and observing surface fluxes have improved our understanding of the relationships between TC intensification and the drag and enthalpy coefficients, as well with the SST response, however considerable
uncertainties still remain. We recommend that new observational platforms be devised and routinely deployed to continue advancing understanding of surface fluxes, and that the resulting knowledge be transitioned to operations.

3.1.6 Much recent work has been undertaken on intensification mechanisms, however considerable knowledge gaps remain as to the role of different mechanisms. In particular, the role of the boundary layer dynamics in contributing to eyewall updrafts and convection, as well as in supergradient spin-up, needs to be investigated in future studies based on observations and numerical simulations. To speed up progress in reconciling current debates, we recommend that scientists with competing theories and frameworks to team up together in a larger collaborative effort to resolve some of these long-standing debates. We recommend that funding agencies recognize this potential approach and design funding calls specifically toward this purpose.

3.1.7 We further recommend that the WMO sponsor an international workshop in the near future to bring leading researchers together to review in more detail the issues involved in the controversy on intensification mechanisms and to develop a strategy for future international research collaboration to resolve these issues.

3.1.8 In light of substantial new lines of investigation on the role of vortex structure, outflow, and other environmental influences on the IR of TCs, we recommend that substantial future research further investigate the broad theoretical and numerical basis for ideas such as the MPIR of TCs and the relationship between vortex structure (including the outflow) and IR.

3.1.9 With the finding that the TC IR depends critically on the structure of the vortex, we further recommend that statistical-dynamical intensity prediction schemes consider TC size parameters and that significant efforts continue to be made to ensure that numerical prediction models represent the initial TC structure as accurately as possible.

3.4.2 External influences

3.2.1 The need for improved representation of coastal processes in current TC coupled forecasting models was emphasized since rapid and/or significant intensity change just prior to landfall can have large implications for disaster mitigation.

3.2.2 Improved prediction of ocean pre-storm conditions is recommended as it is thought to be a prerequisite for improved intensity prediction of record-breaking events such as Haiyan (2013) and Patricia (2015).

3.2.3 To improve predictions from coupled models, simultaneous and coincident measurements of oceanic and atmospheric profiles (temperature, salinity, and current in the ocean; temperature, humidity, and winds in the atmosphere) before, during, and after the storm must be made and assimilated into the models. In addition, in-storm oceanic and atmospheric measurements are needed to improve vertical mixing schemes that impact air-sea fluxes and, hence, storm intensity and structure.

3.2.4 Further research is needed to determine the mechanisms for producing upshear convection and determining whether the upshear convection is the cause of rapid intensification or a symptom of other processes such as vertical realignment.

3.2.5 Although dry air is typically viewed as an inhibiting influence, an increased understanding of the pathways by which dry air intrudes into a TC is needed.
3.2.6 Further work is needed to improve the sensitivity of microphysics schemes to droplet concentration and aerosols in order to better determine the response of TC intensity to environmental aerosols, particularly Saharan dust.

3.2.7 Further research is needed on the role of environmental VWS on TC intensity change. In particular, research is needed on the interaction of complex spatially and temporally varying environmental VWS with TC vortices with a wide range of horizontal and vertical structures, and intensities.

3.2.8 Further work is needed on understanding TC-trough interactions and how the geometry of TC-trough system and the TC vortex depth impacts the subsequent TC intensity changes.

3.4.3 **Operational perspectives**

3.3.1 Continue to bring intensity forecast guidance (NWP models, statistical-dynamical models and statistical models) to operations and extend their availability globally to all operational centers. (Research recommendation)

3.3.2 Statistical-dynamical guidance should take advantage of the skill of the range of dynamical models including IFS (ECMWF), UK, GFS etc. and the higher resolution TC models. Websites having intensity guidance should improve visualization to all guidance not just subsets (for example the CIRA multi-model diagnostic comparison is an excellent product but not all the reliable guidance are indicated). An independent assessment of techniques in each TC area should be done. (Research and WMO recommendation)

3.3.3 The results of upgrades to intensity guidance should be regularly communicated to operational centers. Training material (through multiple media) and workshops for forecasters should be available to ensure the appropriate application of the guidance and the underlying science (Research and WMO recommendation)

3.3.4 A continuing effort should be done by the research community to address cases of large errors documented by the operational centers. (Research and Operational recommendation)

3.3.5 All operational centers should regularly verify their intensity forecasts and adopt WMO guidelines on intensity verification. (Operational recommendation)

**Acknowledgments**

The co-chairs are grateful to the rapporteurs and all the members of the intensity change working groups for reviewing and documenting the relevant research and operational advances on TC intensity change from 2014-2018.

**Acronyms used in the report**

AAM – Absolute angular momentum  
ARCHER - Automated Rotational Center Hurricane Eye Retrieval  
AROME - Applications de la Recherche à l’Opérationnel à Méso-Echelle  
BoM – Australian Bureau of Meteorology  
CIMSS – Cooperative Institute for Meteorological Satellite Studies  
COAMPS - Coupled Ocean/Atmosphere Mesoscale Prediction System  
COAMPS-TC – Coupled Ocean/Atmosphere Mesoscale Prediction System – TCs  
CPS - Cyclone Prediction System  
DTOPS - Deterministic to Probabilistic Statistical Model  
ERC – Eyewall replacement cycle
TOPIC 3.1 - INTENSITY CHANGE: INTERNAL INFLUENCES

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Abstract

The past four years have witnessed considerable scientific progress in the area of internal influences on tropical cyclone (TC) intensity change. Observational studies of satellite-sensed cloud and precipitation features, as well as new analyses of lightning data, have improved understanding of the convective morphology before and during RI, particularly with regard to the degree of axisymmetry, the importance of shallow convection around the center, and the radial and azimuthal distribution and evolution of convective bursts and hot towers prior to and during RI. Numerical simulations have increased appreciation of the probabilistic nature of RI processes. The impacts of secondary eyewall formation (SEF) and eyewall replacement cycles (ERCs) on intensity change have become better understood through an expanded climatology of ERCs and the different wind-pressure-relationships that occur in intense and less intense TCs. Improved understanding of the ERC climatology has translated into better operational forecasts of ERC-induced intensity changes. With regard to rainbands and intensity change, recent observational work has shown that outer rainband lightning is positively correlated with subsequent 24-h TC intensity change. Idealized numerical simulations have demonstrated that convective heating in the inner rainband region generally promotes intensification, while evaporative cooling in inner rainbands tends to hinder TC intensification.

Numerical studies on the impacts of inner core instability processes have expanded from 2D barotropic frameworks to more realistic 3D frameworks that include moisture and parameterized mass sinks. Results from simulations in more realistic frameworks show that instability processes may cause intensification under certain assumptions, although considerable uncertainties remain, particularly as to the role of the secondary circulation in either preventing relaxation of the vortex to a monopole (or how quickly it might restore the vortex back to an annular state) and as to the effects of moist convective processes on instability. Advances in modeling and observations of surface fluxes have improved our
understanding of the relationships between TC intensification and the drag and enthalpy coefficients, as well with the sea surface temperature response.

The mechanisms by which TCs intensify has been an area of considerable research, resulting in refinements to existing frameworks for understanding TC intensification (e.g., the rotating-convection framework). Vigorous debate has recently occurred as to the suitability of using balanced frameworks to understand intensification, whether or not WISHE is an essential part of TC intensification, and the exact role of the boundary layer in TC spin-up. This report also includes several new topics that have recently emerged, such as the role of TC outflow, the role of vortex structure on a TC’s IR, and a new theory for what sets the fastest rate at which TCs may intensify.

3.1.1 Introduction

The goal of this Rapporteur Report is to summarize the research progress on internal influences of tropical cyclone (TC) intensity change since IWTC-VIII. Intensity change is a broad topic that does not lend itself to artificial delineation between “internal processes” (this report, Topic 3.1) and “external influences” (Topic 3.2). Indeed, close connections exist between TC intensity change and several other topics in IWTC-IX, such as TC structure analysis and change (Topic 4), secondary eyewall formation and the expansion of the wind field (Topic 4.1), and operational perspectives on intensity change (Topic 3.3). Naturally, there will be some overlap between the Rapporteur reports. At the possible expense of some duplication between reports, we have preferred to avoid letting any studies remain uncovered.

The past four years has witnessed a considerable increase in research activity on internal processes of intensity change. Whereas the previous IWTC-VIII Rapporteur Report for this subtopic (Stern et al. 2014) contained references to 77 new studies since the previous IWTC report, the current report contains 183 references to new studies. To identify the publications on this topic that have been published since 2014, our Working Group (WG) followed a rigorous process to screen a list of papers compiled from Web of Science. The list was compiled by Maggie Lien (see acknowledgments) by searching for all papers that contained one of the following TC-related terms in either the paper’s title or topic: “tropical cyclone”, “hurricane”, and “typhoon” (and their plurals). To further narrow the scope of papers to be screened, a further criterion was added by requiring that papers be from the “Meteorological and Atmospheric Science” discipline. The resulting list of 3417 papers was reviewed by the WG for possible relevance to internal intensity change processes, with approximately 300 papers identified as being possibly relevant. The WG then screened the paper titles/abstracts for relevance to this subtopic and grouped the publications into smaller topical divisions.

The WG was then organized into teams, with each team having the responsibility to write a synthesis of the papers for one section of the subtopic. Although this report focuses mainly on research progress, rather than operational perspectives, we have attempted to make the writing accessible to a broad audience (including forecasters). In order to properly put the recent studies into context, each synthesis includes an introduction with brief discussion of earlier studies, as well as a brief summary with recommendations (if any) for future research directions. Finally, it is also important to note that a reader interested in one particular section below need not read the entire report—each synthesis can be read as a stand-alone document.
These literature syntheses form the following seven sections of this Rapporteur Report:

3.1.2 Rapid Intensification
3.1.3 Eyewall Replacement Cycles
3.1.4 Relation of Rainbands to Intensity Change
3.1.5 Eyewall Instability and Inner-Core Mixing
3.1.6 Relationship between Surface Fluxes and Intensity Change
3.1.7 Mechanisms of Tropical Cyclone Intensification
3.1.8 New and Emerging Research Topics

This report concludes with a summary and conclusions section, overall recommendations for future research directions, acknowledgements, a list of the primary contributors to each section, a list of acronyms used in this report, and references.

3.1.2 Rapid Intensification (RI)

a) Introduction and Definition of RI

Although the prediction of TC track has improved substantially due to more accurate numerical models and more satellite observations over the open ocean, predictions of TC intensity change have proven to be much more challenging. Our understanding of TC intensity changes is very limited, especially during the RI phase because of a lack of understanding of the physical mechanisms that are responsible for these relatively rare events. RI is first defined by Kaplan and DeMaria (2003) using the 95th percentile of the cumulative distribution functions of the 24-h intensity change derived from historical best track data (Landsea and Franklin 2013). In the North Atlantic (NA) basin, the 95th percentile of the 24-h intensity change is 30 kt (Kaplan and DeMaria 2003). Therefore, in this basin RI is defined as a 24-h period with an intensity increase ≥ 30 kt in this basin. Many following studies found that the same 30 kt (or 15.4 m/s) threshold can be used globally (Jiang 2012; Jiang et al., 2013; Zagrodnik and Jiang 2014) or for other basins such as the northwest Pacific (Shu et al., 2012; Wang et al., 2015), northeast Pacific (Kaplan et al., 2010), and the southwest Indian Ocean (Leroux et al. 2018). In contrast, Hendricks et al. (2010) found that the 95th percentile of the 24-h intensity change for TCs during a five-year period (2003–2008) in the northwest Pacific basin was 19 m/s (36.9 kt). The Hendricks et al. (2010) study period is much shorter than other studies, however, so this could be the reason that they found a higher RI threshold.

The topic of RI has seen significant interest from researchers. Since the previous report for this subtopic (Stern et al. 2014), more than 60 refereed papers have been published about RI. This subsection synthesizes results from these publications during the past four years (2014–2018) to summarize the advancements in understanding physical processes associated with RI and how to better forecast these rare events. This synthesis includes subsections on RI climatology (subsection b), observational and idealized and non-idealized numerical perspectives of RI (subsections c, d and e), and new developments in the operational prediction of RI (subsection f), followed by a summary and recommendations for future research.
b) RI Climatology

This subsection reports new insights on TC RI based on recent climatological studies investigating intensification rate (IR) dependence on various internal and external parameters in the North Atlantic (NA) and Western North Pacific (WNP) basins.

Using six decades of NA TC observations from the Hurricane Database (HURDAT2; Landsea and Franklin 2013), Yaukey (2014) found that the onset of intensification (defined as a 15 kt (7.7 m/s) increase over 24 h) was most likely to occur shortly after midnight local time, and least likely to occur shortly before midnight. This statistical analysis also shows that RI is influenced by TC age from genesis, as well as by the wind speed deficit relative to speeds expected for the TC’s central pressure.1 In the NA basin, Qin et al. (2016) used the Extended Best Track (EBT) dataset during the 25-year period of 1990–2014 to perform a statistical analysis of steady state-radius of maximum wind (S-RMWs) associated with rapidly intensifying TCs. In S-RMW cases, the contraction of the RMW during intensification ceases before TCs reach their peak intensities, resulting in nearly steady state RMWs; such features were notably observed in major hurricanes such as Katrina (2005), Megi (2010), and Andrew (1992). An analysis of 55 rapidly intensifying hurricanes that exhibited steady state-RMWs shows that S-RMWs comprise about 53% of the 139 RI events of 24-h duration and 69% of 12-h RI events. Also, S-RMWs tend to occur more frequently in intense storms and when RMWs have already contracted to less than 50 km.

Carrasco et al. (2014) used the NA Hurricane Database (HURDAT2; Landsea and Franklin 2013) to investigate possible connections between TC size and their subsequent propensity to undergo RI. Comparisons between RI and non-RI TCs over a 20-year period of analysis (1990–2010) show that TCs undergoing RI are more likely to be smaller initially than those that do not. For various inner and outer measures of size, such as RMW and average 34-kt radius (AR34), TCs that do not experience RI are approximately 10 n mi (18.5 km) larger than cyclones undergoing RI. They found that RI is unlikely when the initial RMW > 50 n mi (~90 km) and AR34 > 140 n mi (250 km). They also showed that for both size parameters, these thresholds lay near the boundary (RMW = 48 n mi, 89 km) separating medium and large TC, suggesting that RI becomes unlikely once a TC has a large RMW and/or AR34. In contrast, when using the radius of the outermost-closed isobar (ROCI) as the size parameter, the size difference between RI and non-RI cases is negligible (this suggests that intensity forecasts and RI predictions may be improved by the use of the initial size as measured by RMW and AR34). Xu and Wang (2018a) conducted a similar study in the WNP using the Joint Typhoon Warning Center (JTWC) best track database during 1982–2015. RI was found to occur only in a relatively narrow range of the parameter space in storm intensity and both inner-and outer-core sizes, with the highest intensification rate (IR) occurring when Vmax = 70 kt (36 m/s), RMW ≤ 40 km, and AR34 = 150 km. Consistent with the findings for NA TCs, RI was found to occur only for TCs with moderate intensity and small inner-core size, while storms with RMWs > 120 km almost never intensify rapidly (Fig. 3.1.1).

1 Yaukey’s results suggests that taking into account additional storm characteristics such as age, strength, and time of day could help increase the performance of RI forecast schemes such as NHC’s operational Statistical Hurricane Intensity Prediction Scheme (SHIPS) model.
This subsection reports new insights on RI from observational studies. A key aspect of this topic is the relationship between RI and the distribution of inner-core convection and precipitation. Satellite-based statistical studies have often demonstrated that the degree of axisymmetry of convection and precipitation is a vital indicator of RI. Some pioneering studies that were summarized in the previous IWTC-VIII report include Kieper and Jiang (2012) and Zagrodnik and Jiang (2014). Using 15 years of passive microwave satellite data for Atlantic and east Pacific storms, Alvey et al. (2015) found that, compared to TCs with lower IRs, TCs with higher IRs (including RI) possess more symmetric distributions of precipitation prior to the onset of intensification, as well as a greater overall areal coverage of precipitation. Using 14 years of Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) data, Tao and Jiang (2015) compared the contributions to RI by shallow to moderate precipitation versus the contributions by moderately deep to very deep convection. They found that increased and widespread shallow convection around the storm center is a first indication of RI and can be used as a predictor for the onset of RI. The contribution to total volumetric rain and latent heating from shallow and moderately shallow precipitation in the inner core is greater in RI storms than in non-RI storms, while the opposite is true for moderately deep and very deep precipitation. Therefore, Tao and Jiang (2015) argued that RI is more likely triggered by the increase of shallow-moderate precipitation, and that the appearance of more moderately to very deep convection in the middle of RI is more likely a response, or positive feedback, to
changes in the vortex (rather than a cause of RI). Harnos and Nesbitt (2016) used 37- and 85-GHz passive microwave data to quantify the relative prevalence of cold clouds (i.e., deep convection and stratiform clouds) versus predominantly warm clouds (i.e., shallow cumulus and cumulus congestus). They found that TCs undergoing subsequent RI or intensification possessed a greater presence of combined liquid and frozen hydrometeors associated with cold clouds. Compared to the full intensity change distribution, TCs undergoing RI episodes exhibited approximately an order of magnitude increase of inner-core cold cloud frequency relative to warm cloud presence.

Figure 3.1.2. Composite shear-relative distribution of the rainfall coverage from (I) all precipitation, (II) stratiform precipitation, and (III) convective precipitation. From left to right: (a) 12–24 h before RI onset, (b) 0–12 h before RI onset, (c) RI onset, (d) RI continuing, and (e) 12–24 h before RI ends. Dotted range rings represent the 25-, 50-, 75-, and 100-km radii. Figure 4 of Tao et al. (2017).

Conventionally, RI is defined as a 24-h period with intensity increase ≥ 30 kt (15.4 m/s), by following Kaplan and DeMaria’s (2003) pioneering work on RI, with each 24-h period treated as a separate case. The main drawback of this approach is that it neglects storm evolution information. In reality, RI usually happens as an event, which can last 48–60 h or longer. In order to place the individual 24-h RI cases within the context of the entire RI event, Tao et al. (2017) first introduced an RI event-based definition. An RI event was defined as multiple, continuous, and overlapping 24-h periods where the maximum sustained winds of each period increased by at least 30 kt (15.4 m/s), as illustrated in Tao et al. (2017)’s Fig. 1 (not shown). They used this definition to examine the relative importance of stratiform and convective precipitation with respect to the evolution of RI events from a 16-y TRMM PR dataset. They found that the onset of RI follows a significant increase in the occurrence and azimuthal coverage of stratiform rainfall in all shear-relative quadrants, especially upshear left (Fig. 3.1.2). They also found that rainfall intensity and total volumetric rain, which are mainly contributed by convective precipitation, do not increase until several hours after RI onset.
Therefore, they argued that the convective precipitation is more likely a response, or positive feedback, rather than the trigger of RI. Jiang et al. (2018) used the same RI event-based definition as in Tao et al. (2017) to examine the evolution of different precipitation types during RI events. By further separating convective precipitation into shallow and deep types, Jiang et al. (2018) found a significant increase in the inner-core coverage of stratiform precipitation and shallow convection 3 to 21 h before the onset of RI.

A normalization technique was used by Fischer et al. (2018) to analyze anomalous TC convective characteristics and their relationship to TC intensity change. They showed that anomalously cold infrared and 85-GHz brightness temperatures, as well as anomalously warm 37-GHz brightness temperatures, in the upshear quadrants of the TC are associated with increased rates of TC intensification, including RI. For RI episodes in the NA basin, they found that an increase in anomalous liquid hydrometeor content precedes anomalous ice hydrometeor content by approximately 12 h, suggesting that convection deep enough to produce robust ice scattering is a symptom of, rather than a precursor to, RI. In the eastern North Pacific basin, they found that the amount of anomalous liquid and ice hydrometeors increases in tandem near the onset of RI. Fischer et al.’s (2018) study suggests that normalized infrared and passive microwave brightness temperatures could be utilized to skillfully predict episodes of RI.

Oyama (2017) examined the relationship between TC intensification and cloud-top outflow revealed by upper-tropospheric atmospheric motion vectors (AMVs) derived from geostationary satellite observations of 44 TCs during 2011–2014. He found that the IRs of 66% of the TCs peaked 0–36 h after the maximum outflow was observed. For TCs undergoing RI, the peak IR also occurred after the maximum outflow. He also found that the correlation between outflow and the TC IR was higher for TCs accompanied by convective bursts (CBs) than for those without CBs, implying that a rapid deepening of inner-core convection is important for intensification of a TC’s secondary circulation. Gao et al. (2017) undertook a water budget analysis of TCs to examine four water-budget components (total precipitable water, surface evaporation, precipitation, and column-integrated moisture flux convergence) associated with WNP TCs of different intensity change categories. The water budget parameters were derived from satellite observations and model reanalysis data during 2001–2009. Their results showed that surface evaporation plays an important role in storm RI and the highest evaporation rates are associated with rapidly intensifying TCs over the highest sea surface temperatures (SSTs). They also found that total precipitable water in the outer environment, where moisture is mainly provided by surface evaporation, is also vital to storm RI because RI is favored when there is less dry air intruding into the storm circulation.

Lightning serves as an important proxy of convective intensity. The relationship between the spatial and temporal distribution of lightning activity and RI has been examined statistically across specific basins and globally. Using 16 years of TRMM Lightning Imager Sensor data, Xu et al. (2017) found that rapidly intensifying TCs showed significantly smaller inner-core flash density and volume of 30 dBZ echoes in the mixed phase region than slowly intensifying TCs, indicating the potential use of these parameters in forecasting RI. They also found that inner-core (outer-rainband) flash density decreases (increases) 12–18 h preceding the onset of RI, while inner-core (outer-rainband) flash density increases (decreases) 6–12 h prior to TC weakening (Fig. 3.1.3). Using lightning data from the World Wide Lightning Location Network (WWLLN), Zhang et al. (2015) investigated the relationship between inner-core lightning and
TC intensity changes over the WNP basin. They found that the differences in lightning density between RI and rapidly weakening (RW) storms are largest in the inner core, and that the lightning density for RI cases is larger than for RW cases in the inner core (0–100km). Using WWLLN data for TCs in the Southwest Indian Ocean (SWIO), Bovalo et al. (2014) found that the proportion of periods with lightning activity is higher during rapid intensity changes of TCs. They also found that during tropical storm stage, lightning activity in the outer rainbands begins increasing 18 h before a RI period. The WWLLN data were also used to examine the characteristics of lightning activity in TCs over North Indian Ocean (NIO) by Ranalkar et al. (2017). They discovered that during RI, TCs exhibit high lightning flash rates.

Figure 3.1.3. (a, c) Flash density (FLD) and (b, d) 30-dBZ echo volume (VOL30) between -5 and -40°C in the inner-core region (a and b) and outer-rainband region (c and d), as a function of time period relative to the onset of TC weakening (green bars) and RI (red bars). Figure 9 of Xu et al. (2017).

During the IWTC-IX reporting period, two field experiments were dedicated to collecting data for TC intensity and intensity change, including RI: 1) the National Aeronautics and Space Administration’s (NASA) Hurricane and Severe Storm Sentinel (HS3) during 2012–2014 (Braun et al. 2016), and 2) the Office of Naval Research Tropical Cyclone Intensity (TCI) field program during 2015 (Doyle et al. 2017). These two field campaigns, along with many previous ones, have provided crucial flight-level, dropsonde, and remote sensing data for RI case studies. Using NASA HS3 data, the relationship between thermodynamic and dynamic structures, and convection and precipitation during the symmetrization process of Hurricane Edouard (2014) and its association with RI was investigated by Zawislak et al. (2016) and Rogers et al. (2016). Zawislak et al. (2016) found that the precipitation distribution is intimately linked to the thermodynamic symmetry, which becomes greater as the frequency, areal coverage, and, in particular, rainfall rate increases upshear. Their results suggest that the upshear moisture content could be a predictor for RI. Rogers et al. (2016) demonstrated that deep convection was located farther inside the RMW during the intensifying period than the weakening period.
Their results highlighted the importance of the azimuthal coverage of precipitation and the radial location of deep convection for RI. Using ONR TCI data, Duran and Molinari (2018) studied the dramatic inner-core tropopause variability during the RI of Hurricane Patricia (2015). Based on the observations of eyewall penetrations into the stratosphere during RI, the existence of a narrow inflow layer near the tropopause and the role of subsidence from the stratosphere in developing an upper-level warm core, they hypothesized three mechanisms of inner-core tropopause variability: destabilization of the tropopause inversion layer (TIL) through turbulent mixing, weakening of the TIL over the eye through upper-tropospheric subsidence warming, and increasing tropopause height forced by overshooting updrafts in the eyewall. They further argued that none of these processes are seen as the direct cause of RI, but rather are a part of the RI process that features strong increases in boundary layer moist entropy.

The RI of Hurricane Earl (2010) was extensively examined by Stevenson et al. (2014), Susca–Lopata et al. (2015), and Rogers et al. (2015) using a variety of available data sources. Stevenson et al. (2014) found that the inner-core lightning activity in the inner core of Earl precessed from left-of-shear to upshear beginning just prior to the onset of RI, which was considered to be an extremely rare event since it differed markedly from previous studies. They hypothesized that Earl’s RI may have occurred, in part, because the vertical wind shear acted to reduce the upshear tilt, and the occurrence of convection inside the RMW helped to enhance the warm core. The role of deep convection in Earl’s RI was further investigated by Susca–Lopata et al. (2015), and Rogers et al. (2015). Both studies found that asymmetric deep convection in the initially vertically misaligned vortex, initially left-of-shear but not distinctly up- or down-shear, subsequently rotated into upshear regions. By the end of this stage, the vortex was aligned and extended over a deep layer, the precipitation symmetry increased, and RI commenced.

Guimond et al. (2016) documented a similar rotation of deep CBs from the downshear quadrants into the upshear quadrants during the RI Hurricane Karl (2010). Guimond et al. (2016) argued that the bursts form and are maintained through a combination of two main processes: 1) convergence generated from counter-rotating mesovortex circulations and the larger vortex-scale flow, and 2) the turbulent transport of anomalously warm, buoyant air from the eye out into the eyewall at low levels. They also documented the development of a pronounced axisymmetric vortex following the pulsing CBs; this vortex included a sloped eyewall structure and the formation of a clear, wide eye.

Sanger et al. (2014) found that vortical updrafts were common before and during RI of Super Typhoon Jangmi (2008). They further claimed that rotating convective clouds are important elements in the TC spin-up process. Similarly, Shimada et al. (2018) found enhanced eyewall convection inside the RMW during the RI of Typhoon Goni (2015).

d) Idealized Numerical Perspectives on RI

Most recent studies are based on idealized, or real-case, ensemble TC simulations using convection-permitting models. For instance, a large ensemble of 270 idealized TC simulations was used by Miyamoto and Nolan (2018) to study the structural changes of TCs preceding RI. The ensemble average of RI cases had two distinct intensification phases. In the first phase, both the RMW and the vortex tilt decrease with time. In the second phase, the equivalent
potential temperature in the lowest 1 km and the radius of maximum convergence (RMC) increase prior to the onset of RI. The Rossby number was also larger in the simulations (119) that experienced RI in the subsequent 24 h compared with the samples without RI. These findings are consistent with the study of Miyamoto and Takemi (2015), which showed that TC vortices with larger Rossby numbers were more likely to experience RI and, hence, to evolve into strong hurricanes (Fig. 3.1.4).

Figure 3.1.4. Relationship between Rossby radius (Ro) and the time (t) of the onset of RI. Figure 20 of Miyamoto and Takemi (2015).

Using Weather Research and Forecasting (WRF) model ensemble simulations with different environmental vertical wind shear, SST, and ambient moisture conditions, Tao and Zhang (2014) found that the environmental shear could significantly affect the timing of TC intensification by influencing the spatial distribution of convection and subsequently changing the positive feedback between diabatic heating and the TC vortex primary circulation. In particular, the changes in the distribution and intensity of the diabatic heating were found to subsequently affect the secondary circulation strength and the vortex mean circulation. From idealized numerical experiments, Wang and Heng (2016) also evaluated the contribution of the near-surface high energy air in the eye region to TC intensification rate. Their results showed that when the surface entropy flux was turned off in the eye region, the equivalent potential temperature and convective available potential energy in the eye were largely suppressed while the IR of the simulated storm was reduced by about 30% during the RI phase. These results suggest that the near-surface high entropy air in the eye region can be crucial for initiating convection near the inner edge of the eyewall and facilitating eyewall contraction. This process leads to higher inner-core inertial stability, and thus, higher dynamical efficiency as the eyewall heating spins up the tangential winds near the RMW. All of this leads to a larger IR in the simulated TC.

Using five high-resolution ensembles based on the Advanced Research version of the WRF (ARW) model, Judt and Chen (2016) investigated the predictability of RI during Hurricane Earl (2010), which is considered as one of the best-observed hurricane RI cases to date. While environmental conditions control the maximum TC intensity and the likelihood of RI during the TC lifetime, both environmental and internal factors are found to contribute to uncertainty in RI timing. Complex interactions among environmental vertical wind shear, the mean vortex, and internal convective processes govern the TC intensification process and lead to diverse pathways to maturity. Although the likelihood of Earl undergoing RI seems to be predictable, the exact timing of RI has a stochastic component and low predictability. Despite uncertainty
in the timing of RI, two dominant modes of RI emerged: members which undergo RI early in the storm lifecycle, and members which undergo RI later in the life cycle. In the early RI cases, a rapidly contracting RMW accompanies the development of the eyewall during RI. The late RI cases possess a well-developed eyewall prior to RI and form an upper-level warm core during the RI process. These differences indicate that RI is associated with distinct physical processes during particular stages of the TC life cycle.

Kowch and Emanuel (2015) analyzed frequency distributions of intensification and dissipation developed from synthetic open-ocean tropical cyclone data, and found that RI is part of a continuum of intensity change that shows no propensity toward a fat tail. This result suggests that TC intensification and dissipation are controlled by randomly distributed environmental and internal processes.

e) Numerical Perspectives on RI

This subsection reports new insights on RI from modeling studies. The relationship between deep convection including CBs and RI is a key aspect of this topic. Tang et al. (2018a) simulated Typhoon Mujigae (2015) using the ARW model and showed that the CBs play an important role in the formation of the warm cores in the middle and upper troposphere, respectively, which trigger and maintain RI. To focus on the roles of latent heating, Miller et al. (2015) used a WRF simulations of Hurricane Wilma (2005) to examine the impacts of changing latent heating rates on the RI. They found that simulated TCs experience substantially reduced IRs in experiments in which the latent heating is reduced. Simulations with greater latent heating rates generate more inner-core CBs during RI, with peak vertical motion in the eyewall occurring at higher altitudes. Li et al. (2016) simulated Typhoon Megi (2010) using the WRF model, which experienced both RI and gradual intensification processes during its lifetime. They showed that in small- or moderate-shear environments, the enhanced CBs release large amounts of latent heat in the upper troposphere, which enhances the upper-level warm core and leads to the intensification phase. During RI onset, strong convective cells concentrated in the eyewall downshear or left-of-shear. As Megi intensified rapidly, symmetric structures became well developed.

In WRF simulations of Typhoon Megi (2010), Lee and Wu (2018) found polygonal eyewall structure during the RI period, with high winds concentrated at each vertex of the polygonal eyewall. Furthermore, when conditions are conducive to TC intensification, the winds often amplify near each vertex of the polygonal eyewall, resulting in high inertial stability, more energy gain from enhanced local surface heat fluxes, higher tangential winds due to radial absolute angular momentum advection, greater supergradient winds, and a higher frequency of CBs located inside the RMW. Therefore, they suggested that the polygonal structure of the eyewall likely facilitates RI by amplifying the aforementioned features at each vertex, and enhancing their impact on the vortex-scale intensification.

Stern and Zhang (2016) examined the vertical aspects of the warm-core structure of Hurricane Earl (2010) on four different days, spanning periods of both RI and weakening. This study used a convection-permitting forecast, as well as high-altitude dropsondes. Results showed that during RI, strong warming occurs at all heights. Further, Chang and Wu (2017) explored the processes leading to the RI of Typhoon Megi (2010) in a sensitivity experiment that used a convection-permitting, full-physics ARW model and a different microphysical scheme. Their
study revealed that the intermittent, active convection gradually strengthens the primary circulation, and that the development of a mid-level warm core tends to serve as a precursor to RI.

Another series of studies examined the relationship between RI and factors such as low-level convergence, surface fluxes, and vertical mixing. Through a WRF simulation of Typhoon Haikui (2012), Zhang et al. (2017e) showed that three factors play a key role in the RI process: 1) a remarkable increase in low-level moisture transport toward the inner core, 2) a favourable large-scale background field with low-level convergence, and 3) upper-level divergence. They also indicated that upper-level divergence could be used as an indicator for RI approximately six hours in advance. Zhang et al. (2017f) investigated Super Typhoon Rammasun (2014) in an ARW simulation and indicated that the storm's intensification was closely related to the net energy gain rate, defined as the difference between the energy production due to surface entropy flux and the energy dissipation due to surface friction near the RMW. Liu et al. (2017) used the ARW model to study the RI of Hurricane Katrina (2005) before its subsequent weakening and landfall in the southern U.S. with the ARW model. During the RI period, modest differences (e.g. over 10 hPa) were seen in the simulated minimum sea-level pressure between two simulations with different boundary layer schemes. This suggests that improved representation of surface fluxes and vertical mixing in the boundary layer are essential for the accurate prediction of hurricane intensity changes. To explain why a hurricane experiences RI after the RMW contraction ceases, Qin et al. (2018) used the WRF model to examine a simulation of Hurricane Wilma (2005). When simulated RI is occurring but the RMW is nearly steady-state (no contraction), the local absolute angular momentum (AAM) tendencies in the eyewall are smaller in magnitude and narrower in width than those during the contracting RI stage. In addition, during the non-contracting stage, the AAM tendencies in the planetary boundary layer (PBL) increase with time following the time-dependent RMW, but during the contracting stage these tendencies decrease with time. These results suggest that intensification can be maintained during the non-contracting stage if the radial flux convergence of AAM overcompensates for the losses due to the vertical flux divergence of AAM at the RMW.

New insights regarding cloud microphysics have also been reported. Harnos and Nesbitt (2016a,b) investigated the initiation and maintenance of RI using two 1-km WRF simulations of the RI periods of hurricanes Ike (2008) and Earl (2010), under low and high wind shears, respectively. Although the intensification time series of each simulated storm is similar, the hydrometeor characteristics differ between the two cases, with Ike possessing less asymmetry and less vigorous convection than Earl. At least some of the diabatic heating remains within the RMW following eye development in each storm. The majority of the diabatic heating within the RMW of both cases occurs at subfreezing temperatures. This result indicates the importance of clouds associated with ice processes in these RI simulations. Further, they evaluated differences in the vertical velocity characteristics associated with various cloud populations for two simulated cases of RI under varying wind shears prior to the RI phase. In the simulated low-shear TC (Hurricane Ike), the top 1% of updraft magnitudes within the RMW occur at a height of 7 km, while in the simulated high-shear case (Hurricane Earl), the top 1% of updraft magnitudes occurred at 12 km.
Regarding the relationship between the TC atmospheric environment and RI, Chen and Gopalakrishnan (2015) investigated Hurricane Earl (2010) using the results of a forecast from the operational Hurricane WRF (HWRF) system and showed that the tilt was large at RI onset and decreased quickly once RI commenced. This result suggests that vertical alignment is the result, rather than the trigger, for RI. RI onset is associated with the development of upper-level warming in the eye, which results from upper-level storm-relative flow advecting the warm air caused by subsidence warming in the upshear-left region toward the low-level storm center. This scenario does not occur until persistent CBs are concentrated in the downshear-left quadrant. The temperature budget indicates that horizontal advection plays an important role in the development of upper-level warming in the early RI stage. Chen et al. (2018b) used ARW model simulations of Typhoon Vicente (2012) to investigate the key inner-core processes that effectively resist environmental vertical wind shear during RI onset. The convective precipitation shield (CPS) embedded in the downshear convergence zone plays a vital role in preconditioning the vortex before RI. The CPS induces a mesoscale positive vorticity band (PVB) characterized by vortical hot tower (HT) structures upstream and shallower structures (~4 km) downstream. Multiple mesovortices form successively along the PVB and are detached from the PVB at its downstream end, rotating cyclonically around the TC center (Fig. 3.1.5). The sufficient magnitude of the vorticity anomalies in the PVB facilitates the upscale growth of a mesovortex into a reformed inner vortex, which eventually replaces the parent TC vortex (i.e., downshear reformation), leading to RI onset. Tao and Zhang (2015) used WRF simulations to explore the effects of environmental shear on the dynamics and predictability of TCs. They showed that larger shear magnitudes resulted in less predictable TCs, especially at time of RI onset. This effect continues until the shear becomes too large for TC formation.

![Figure 3.1.5.](image)

**Figure 3.1.5.** Hourly evolution of 900-hPa relative vorticity (shading; 10–3 s−1) and geopotential height (contoured every 2 x 102 gpm) from (a) 1400 to (f) 1900 UTC 22 Jul 2012 for Typhoon Vicente (2012). The black hurricane symbol (dot) in each panel denotes the surface (500 hPa) TC center. Labels A–D denote different mesovortices. Note that mesovortex D is weak, loosely organized, and never dominates the vorticity asymmetries in 900 hPa, and thus its label D is an exception of chronological labeling. Figure 7 of Chen et al. (2018b).
Regarding the effects of ocean coupling on RI, Kanada et al. (2017) investigated Typhoon Megi (2010) using the three-dimensional atmosphere–ocean coupled regional model, the Cloud Resolving Storm Simulator – Non-Hydrostatic Ocean model for the Earth Simulator (CReSS–NHOES). Because the warm sea increased near-surface water vapor and, hence, the convective available potential energy, the high SST in the eye region facilitated tall and intense updrafts inside the RMW and led to the start of RI. In contrast, high SST outside this radius induced local secondary updrafts that inhibited RI, even when the mean SST in the core region exceeded 29.0 degrees C. These secondary updrafts moved inward and eventually merged with the primary eyewall updrafts; the storm then intensified rapidly when the high SST appeared in the eye region. Thus, changes in the local SST pattern around the storm center strongly affect the RI process by modulating the radial structure of core convection. Wang and Wang (2014) also investigated Typhoon Megi (2010) in a simulation using the ARW model with both dynamical initialization and large-scale spectral nudging. They showed that the onset of RI was triggered by CBs that penetrate into the upper troposphere, leading to upper-tropospheric warming and the formation of the upper-level warm core. In turn, CBs with their roots inside of the eyewall in the boundary layer, were buoyantly triggered/supported by slantwise convective available potential energy (SCAPE) accumulated in the eye region. During RI, the convective areal coverage in the inner-core region increases, while decreases were seen in the updraft velocities in the upper troposphere and in the number of CBs. Ma et al. (2017) studied the impact of including a sea-spray scheme and a modified algorithm for momentum exchange on RI using the Australian Bureau of Meteorology’s current operational TC model for TC Yasi (2011). The study showed that the revised model simulates a cooler and more moist region near the surface in the eyewall/eye region, and that this leads to an earlier RI evolution with stronger subsidence in the eye. The modified model simulation also features a stronger radial pulsating of the eye and eyewall convection on relatively short time scales. The enhancement of RI by the new scheme is characterized by eyewall ascent, radial convergence, and inertial stability inside the radius of azimuthal-mean maximum wind over low-to mid-levels, and by a ring-like radial distribution of relative vorticity above the boundary layer.

Regarding the reproducibility of TCs that rapidly intensified, Kanada and Wada (2015) tried to reproduce Typhoon Ida’s (1958) extreme deepening (defined as a central pressure drop exceeding 90 hPa/24 h) using the JMA 2-km mesh nonhydrostatic mesoscale model (JMA-NHM). The combination of shallow-to-moderate convection and tall, upright CBs was found to be crucial to simulating the extreme RI. In a follow-up study, Kanada and Wada (2017) investigated 34 intense TCs with best-track minimum central pressures ≤ 900 hPa in the WNP. This study used a 20-km-mesh atmospheric general circulation model (AGCM20), which was subsequently downscaled via a 5-km-mesh regional atmospheric nonhydrostatic model (ANHMS). While most of the intense best-track TCs underwent RI and attained maximum intensities south of 25N, the AGCM20-simulated TCs tended to intensify longer and more gradually; only half of them underwent RI. Qin and Zhang (2018) conducted ultra-high resolution (finest horizontal mesh size of 333 m) WRF simulations of Hurricane Patricia (2015), the hurricane which broke intensification records both for peak intensity and 24-h change in intensity over the eastern Pacific basin. They revealed that Patricia’s extraordinary development and its inner-core structures could be reasonably well simulated if ultra-high horizontal resolution, appropriate model physics, and realistic initial vortex intensity are incorporated. They concluded that the large-scale conditions (e.g., warm SST, weak vertical wind shear, and the moist intertropical convergence zone) and convective organization all
played important roles in determining the predictability of Patricia’s extraordinary RI and peak intensity.

A number of studies in this period examined the effectiveness of ensemble forecasts to elucidate key features of RI. Munsell et al. (2017) explored the dynamics and predictability of the intensification of Hurricane Edouard (2014) through a 60-member convection-permitting ensemble initialized with an ensemble Kalman filter for a WRF model that assimilated dropsondes collected during NASA’s HS3 field program. Utilizing composite groups created according to the near-RI-onset times of the members, for increasing magnitudes of deep-layer shear, RI onset is increasingly delayed; intensification does not occur once a critical shear threshold is exceeded. Although the timing of intensification varies by as much as 48 h in the simulations, a decrease in shear is observed across the intensifying composite groups similar to that seen 6–12 h prior to RI. This decrease in shear is accompanied by a reduction in vortex tilt, as the precession and subsequent alignment process begin similar to that seen in the 24–48 h prior to RI. Leighton et al. (2018) also investigated Hurricane Edouard (2014) on the differences in both the TC inner-core structure and large-scale environment using ensemble forecasts from HWRF. They revealed that, for RI cases, as deep convection wrapped around from the downshear side of the storm to the upshear-left quadrant for RI members, vortex tilt and asymmetry reduce rapidly, and RI occurs. In contrast, for non-intensifying (NI) members, deep convection remains in the downshear/downshear-right quadrant, and storms do not intensify. The budget of tangential wind tendency reveals that in the RI members, the positive radial eddy vorticity flux significantly contributes to the spin-up of tangential wind in the middle and upper levels and also acts to reduce the tilt of the vortex (Fig. 3.1.6). In the NI members, the negative eddy vorticity flux spins down the tangential wind in the middle and upper levels and does not help the vortex become vertically aligned.

Figure 3.1.6. Horizontal cross sections of (a) eddy radial vorticity flux \( (\text{m s}^{-1} \text{ h}^{-1}) \), (b) eddy radial component of storm-relative flow (vectors) and eddy vorticity (shading; \( 10^{-4} \text{ s}^{-1} \)), (c) storm-relative flow (vectors) and vorticity (shading; \( 10^{-4} \text{ s}^{-1} \)) averaged for RI members between 6 and 10 km and \(-3\) and \(0\) h. (d)–(f) As in (a)–(c), respectively, but for the Non-intensifying (NI) members averaged between \(-7\) and \(-4\) h. Dark blue circles indicate the RMW and red arrows denotes the shear vector. Figure 10 of Leighton et al. (2018).
New Developments in the Operational Prediction of RI

This subsection reports new insights on the development or improvement of RI forecast schemes since IWTC-8. Zhang et al. (2017d) evaluated the impact of modifying the vertical eddy diffusivity (K-m) in HWRF’s boundary layer parameterization on forecasts of TC RI. Results show that improvement in the vertical eddy diffusivity led to improved RI forecasts. HWRF forecasts with reduced K-m at RI onset possess a shallower boundary layer with stronger inflow, more unstable near-surface air outside the eyewall, stronger and deeper updrafts in regions farther inward from the RMW, and stronger boundary layer convergence closer to the storm center. Despite these structural differences, the mean storm intensity (as measured by the 10-m winds) is similar for the two groups (Fig. 3.1.7).

![Figure 3.1.7. RI verification using the categorical performance diagram for the low-Km and high-Km groups. Note that a perfect forecast lies in the top right of the diagram when the probability of detection (POD) and success ratio (SR) approach unity.
Figure 2 of Zhang et al. (2017d).](image)

Shimada et al. (2017) investigated the relationship between both current intensity and degree of axisymmetry on a TC’s future intensity change during the development and decay stages. These results, based on analysis of hourly Global Satellite Mapping of Precipitation (GSMaP) data (0.1° resolution) for 380 WNP TCs that occurred during 2000–2015, showed that the IR at the current time, and 6- and 12-h after the current time, are strongly related to both the current intensity and degree of axisymmetry during the development stage. When TCs start with a current central pressure (maximum sustained wind) between 945 and 995 hPa (85 and 40 kt, or 43.7 and 20.6 m/s, respectively), TCs with higher degree of axisymmetry experience a larger intensity change in the next 24 h, on average. For TCs starting with a current central
pressure of 960–990 hPa, the mean value of the degree of axisymmetry is much higher for TCs experiencing RI than those for non-RI TCs. These results suggest that once a TC becomes axisymmetric, it tends to keep its axisymmetric structure and continue to intensify, so long as the environment remains favorable for intensification.

Zhuge et al. (2015) used TRMM data and the SHIPS development dataset to evaluate the potential for using inner-core HTs in operational RI forecasts for each of the TC-prone basins. The efficacy of using inner-core HTs to predict RI differed depending on the basin. For instance, the stand-alone HT-based RI prediction scheme showed little skill in the NA and eastern and central Pacific (ECP) basins, but yielded skill scores of >0.3 in the southern Indian Ocean (SI) and WNP basins. When HTs were used in conjunction with several storm and environmental parameters [previous 12-h intensity change, potential intensity (PI), percentage area from 50 to 200 km of cloud-top brightness temperatures lower than -10°C, and 850–200-hPa vertical shear magnitude with the vortex removed], the predictive skill score in the SI was 0.56. This is comparable to that of the SHIPS RII scheme, which is considered to be the most advanced RI prediction method. Rozoff et al. (2015) examined the probabilistic prediction of TC RI in the NA and eastern Pacific basins using a series of logistic regression models trained on environmental and infrared satellite-derived features. Results show that the inclusion of Microwave Imagery (MI)-based predictors yield more skillful RI models for a variety of RI and intensity thresholds. Compared with the baseline forecast skill of the non-MI-based RI models, the relative skill improvements from including MI-based predictors range from 10.6% to 44.9%. Grimes and Mercer (2015) also investigated the possibility to use large-scale processes as RI indicators within TC environments in the Atlantic basin. In the first phase of their study, the synoptic-scale variables that yielded the largest statistically significant differences between RI and non-RI TCs were identified through spatial analysis of NASA’s Modern Era Retrospective-analysis for Research and Applications (MERRA) data from 1979 to 2009. A logistic regression and a support vector machine (SVM) classification algorithm were then used to diagnose the onset of RI at the 24-h lead time. The SVM model’s skill, using synoptic-scale variables as predictors, was found to outperform the logistic regression model. The approach identified mid-level vorticity, pressure vertical velocity, 200–850-hPa vertical shear, low-level potential temperature, and specific humidity as the most significant predictors for diagnosing RI.

g) Summary of Recent Findings on RI

Despite extensive research on the RI topic over the past four years, many uncertainties remain regarding how to better simulate and predict the onset and continuation of RI. First, a better definition of RI is needed and should be applied to future studies. Most of the previous statistical studies used the 24-h case-based RI definition as defined by Kaplan and DeMaria (2003). As pointed out by Kieper and Jiang (2012) and Tao et al. (2017), RI usually happens as an event, which can last up to 78 h or even longer. About 76% of RI events lasted more than 24 h (Tao et al. 2017). The approach of treating any 24-h RI case as a single and independent event does not distinguish between the stages of an RI event, including at RI onset, during the middle of an RI event, and the ending period of an RI event. Failing to distinguish these different stages will cause challenges when studying the evolution of an RI event/storm. Second, it has been well recognized based on satellite observations that a high degree of axisymmetry of precipitation, convective, and thermodynamic parameters is associated with the subsequent RI (Kieper and Jiang 2012; Zagrodnik and Jiang 2014; Alvey
et al., 2015; Tao and Jiang 2015; Zawislak et al., 2016; Tao et al., 2017; Xu et al., 2017; Shimada et al., 2017; Fischer et al., 2018; Jiang et al., 2018). On the other hand, case studies using aircraft observations and numerical simulations (Sanger et al., 2014; Stevenson et al., 2014, Susca–Lopata et al., 2015; Miller et al., 2015; Rogers et al., 2015; Rogers et al., 2016; Guimond et al., 2016; Li et al., 2016; Tang et al., 2018a) have recognized asymmetric CBs and HTs in the inner core as important factors contributing to the subsequent RI. In light of these findings, we recommend that future research directions focus on: a) studying RI as an event, improving understanding of the conditions and precursors to RI through symmetrical processes, and c) improving understanding of the conditions in which asymmetric CBs and HTs in the inner core may lead to RI precursors.

3.1.3 Eyewall Replacement Cycles (ERC)

a) Introduction

Satellite and in-situ observations demonstrate that concentric eyewall structures are common in intense tropical cyclones (TCs). These observations have shown that such structures are associated with pronounced changes in TC intensity and structure (Willoughby et al., 1982 and many studies afterwards). Observations also reveal that there are typically three distinct phases of intensity change associated with the secondary eyewall formation (SEF) and the subsequent ERC (Fig.3.1.8). In phase I, intensification tends to slow near the onset of SEF. In Phase II, substantial weakening often occurs as the ERC progresses. In phase III, there is a likelihood of reintensification after the ERC completes, concurrent with a persistent contraction of the new primary eyewall (e.g. Sitkowski et al., 2011; Yang et al., 2013; Zhou and Wang 2013; Kossin and DeMaria 2016). At the time of the previous report for this subtopic (Stern et al. 2014), numerical models had started to be able to develop concentric eyewall structures, although ERCs were relatively rare in numerical simulations of TCs compared with the observed frequency. More recently, numerical models have demonstrated increased capabilities for generating concentric eyewalls and for predicting the associated intensity change.

Figure 3.1.8. Schematic of the mean evolution of TC intensity during an ERC. The three inset figures illustrate typical radial profiles of flight-level tangential wind. From Sitkowski et al. (2011), Kossin and Sitkowski (2012), and Kossin (2015). Fig. 9 of Kossin (2015).
This subsection synthesizes the peer-reviewed published literature of the past four years (2014–2018) to summarize the advancements in understanding that have been made of the TC intensity changes closely connected with the SEF and ERC. This synthesis includes an updated understanding of the climatology of intensity changes and the wind-pressure relationship during an ERC, observed ERCS with subtle intensity change, as well as the performance of (and uncertainty in) predicting ERC-associated intensity changes in state-of-the-art numerical models.

b) **Climatological ERC Model and Wind–Pressure Relationship during ERCS**

Noticing the disparity in intensity changes between the recon-anchored best-track data and the SHIPS model (DeMaria et al. 2005) (Fig. 3.1.9), Kossin and DeMaria (2016) developed a climatological model to reduce TC intensity change forecast errors in SHIPS during the weakening phase of ERCS (Phase II in Fig. 3.1.8). The weakening phase of an ERC event in observations is generally concurrent with either slow intensification, slow weakening, or a steady state intensity in SHIPS forecasts, suggesting that the weakening during an ERC is driven mostly by processes internal to the TC. Such weakening is distinct from the remainder of the weakening phase in the life cycle of TCs that occurs primarily due to the hostile external atmospheric conditions, less conducive oceanic conditions, or landfall.

![Figure 3.1.9. Comparison of 12-h intensity change in the recon-anchored best-track (HURDAT) versus SHIPS predictions following the onset of ERC weakening. Fig. 2 of Kossin and DeMaria (2016).](image)

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2 The recon-anchored data herein are the NA best-track data (HURDAT2) during periods in which the hurricanes were actively sampled by aircraft reconnaissance.

3 SHIPS is one of the primary guidance models that NOAA/NHC (National Oceanic and Atmospheric Administration/National Hurricane Center) uses for operational intensity forecasts.
This ERC climatology model, developed as a complement to SHIPS, is named E-SHIPS. The model was constructed based on 19 ERC events, in which aircraft reconnaissance data were intensively collected. Figure 3.1.10 demonstrates that E-SHIPS manifests its best skill when applied at the onset of ERC weakening. Such an application is only feasible, however, when a forecaster has a high level of confidence, not only in the occurrence of an impending ERC, but also in the onset time of the associated weakening, since E-SHIPS substantially underestimates hurricane intensity when applied too early (e.g. 6-h prior to the onset of ERC weakening). A compromise approach, which is also a more realistic scenario, is to apply E-SHIPS at times when an ERC has begun and the TC is showing clear signs of weakening. When applied at 6 h after the onset of ERC weakening, E-SHIPS shows a significant reduction in errors of intensity predictions. For instance, the mean absolute errors were reduced more than 50% at 18-h lead-time. Due to this demonstrated success, E-SHIPS is being utilized by NOAA’s NHC operations as a sub-algorithm of SHIPS.

Figure 3.1.10. Error distributions for the ERC climatology model and SHIPS when the model is applied (a) at the onset of ERC weakening to 24 h after, (b) 6 h prior to the onset of weakening (too early), and (c) 6 h after the onset of weakening. Errors are relative to recon- anchored best-track values. Positive (negative) values denote where the model-predicted intensities are higher (lower) than the best-track data. Sample size, N, is shown for each forecast lead-time. The operational SHIPS data are available with 12-h resolution for pre-2005 storms, and with 6-h resolution out to 24-h lead-time and 12 h at longer lead times for 2005 and after. Mean absolute and root-mean-square errors are shown as numerical pairs above or below each boxplot (kt). Fig. 4 of Kossin and DeMaria (2016).

Kossin (2015) showed that, during an ERC, the wind–pressure relationship (WPR) migrates away from the climatology used by the Dvorak technique, and toward a weaker maximum wind for a given minimum central pressure. The migration of the WPR during an ERC is quite different between hurricanes with intensities weaker and stronger than 100 kt (51.4 m/s). The weaker hurricanes usually get stronger when going through the three typical stages of ERC-associated intensity change (Fig. 3.1.8), while the stronger hurricanes tend to become weaker.4

4 Please note the intensity change herein is calculated by subtracting the mean intensity in Phase I from the mean intensity in Phase III (Figs. 1 and 4). The average of intensities at points 1 (3) and 2 (4) is used as a proxy for the mean intensity in Phase I (III) in Kossin (2015). In other words, this intensity change presents the total change through the periods of intensification, weakening, and reintensification.
Compared with the Dvorak climatology during the three phases of ERC intensity change, weaker hurricanes experience a large drop in minimum central pressure for a given increase in maximum wind speed. Meanwhile, stronger hurricanes tend to experience a slight increase in minimum central pressure given an equivalent magnitude of wind speed reduction (Fig. 3.1.11). On average, the weaker (stronger) hurricanes intensify (weaken) by 8 (10) kt [4.1 (5.1) m/s], while their minimum central pressure decreases (increases) by 15 (2) hPa. The modified WPR can be applied to operational intensity forecast for hurricanes undergoing an ERC.

Figure 3.1.11. Mean WPR changes for TCs that begin an ERC as a weaker hurricane (Vmax < 100 kt (51.4 m/s) and as a stronger hurricane (Vmax > 100 kt (51.4 m/s)). The averages for the start and end are based, respectively, on values at points 1 and 2, and points 3 and 4 in Fig. 3.1.8. From Kossin (2015).

c) **ERCs with Subtle Intensity Change**

Satellite-based observational studies reveal that, statistically, typhoons with long duration concentric eyewalls (Yang et al., 2013), or with a wider moat (Zhou and Wang 2013), appear to maintain their intensity during the early ERC period, deviating from the mean behavior of all ERC cases. Supporting this finding, Tsujino et al. (2017) and Zhang and Perrie (2018) used radar observations of Typhoon Bolaven (2012) and Hurricane Ike (2008), respectively, and reported a lack of the typical intensity changes that might be expected during an ERC. Both studies identified the maintenance of the inner eyewall intensity and the nearly stationary radius of the outer eyewall as common factors. Using the CReSS model, Tsujino et al. (2017) reproduced the outer two eyewalls of the triple eyewalls and the associated intensity and structure evolution of Bolaven. They also carried out dynamical analyses to understand the responsible dynamical processes. Dougherty et al. (2018) reported on and studied the lack of intensity change associated with Hurricane Bonnie’s (1998) ERC (Fig. 3.1.12), which did not have a long-lived concentric eyewall structure. In this case, Bonnie’s intensity was largely maintained during the ERC (apart from a brief decrease), as the maximum wind speeds in the new concentric eyewall matched those in the old eyewall. After the ERC, the storm did not reintensify and the new eyewall underwent only limited contraction.
Performance of and Uncertainty in Numerical Models

Hazelton et al. (2018) evaluated TC forecasts in the 2-km resolution nested NOAA/Geophysical Fluid Dynamics Laboratory (GFDL) fvGFS (recently named as hfvGFS; finite-volume cubed-sphere dynamical core using the Global Forecast System (GFS) physical parameterizations) model covering most of the NA basin (hereafter, fvGFS-2km). They reported that an over-forecast of intensity during the ERC of Hurricane Earl (2010) was likely tied to an incorrect depiction of the secondary eyewall. In contrast, fvGFS-2km decently reproduced the weakening during the ERC in the forecast of Hurricane Matthew (2016) (Fig. 3.1.13). This weakening was attributed to the correct depiction of the SEF onset time and a satisfactory forecast of the ERC duration. The simulated ERC completed somewhat earlier than in the observed storm, resulting in a short-term (and unobserved) reintensification of the simulated storm after the ERC completed and before the environmental vertical wind shear became detrimental to intensification. The ability to generate a secondary eyewall and the subsequent ERC in the Matthew forecast demonstrates that the fvGFS model is capable of predicting at least some of the internal structural changes of ERCs, along with the associated intensity changes.

Using the WRF-ARW model, Zhang et al. (2017a) carried out a set of 20 idealized, ensemble simulations in an environment of moderate vertical wind shear on two different computer clusters. Thirty-eight out of the 40 simulations produced at least one ERC, or an ERC-like [termed as “partial ERC” in Zhang et al. (2017a)] event, during the integration. This suggests that mild uncertainty exists concerning whether or not an SEF will occur in this given shear environment. These results show that the onset time of SEF, intensity and structure of the concentric eyewalls, and the ERC evolution are highly sensitive to small, unobservable, and random perturbations of the initial conditions. In most of these cases, the first ERC or ERC-like event takes place right after the end of the period of RI. The uncertainty in the onset time and duration of the RI period adds uncertainty to the ERC and, therefore, to the timing and amplitude of the associated intensity change (Fig. 3.1.14).
Figure 3.1.13. Maximum wind speed (kt) of Hurricane Matthew starting at 0000 UTC 5 Oct 2016 and ending at 0000 UTC 10 Oct 2016 from the NHC best-track (black) and the fvGFS forecast (red). The 2-km RMW from fvGFS forecasts and radar observations are shown by the red and gray triangles, respectively. Figure 13b of Hazelton et al. (2018).

Figure 3.1.14. Evolution of maximum 10-m wind (m s⁻¹, running smoothed) on the (a) Stampede computer cluster and (b) Jet computer cluster. Lines with the same colors are the simulations with same initial conditions. (c) Comparison of the ensemble mean (solid line) and standard deviation (dash line) of 10-m wind for each ensemble. Figure 1 of Zhang et al. (2017a).
Summary of Recent Findings on ERCs and TC Intensity Change

The E-SHIP model and the migration of the wind-pressure relationship during ERCs both provide helpful guidance for intensity forecasts of hurricanes undergoing an ERC. It is unclear how well, or whether, the ERC climatology represents TCs in the WNP or other ocean basins where low-level inner-core aircraft data are rarely collected. Furthermore, uncertainty about the onset time of the SEF and ERC, variance in observed intensity changes, and variations in the documented durations for each phase (e.g. Sitkowski et al. 2011; Kossin and DeMaria 2016) are major sources of forecast errors in the simple ERC climatology model. The Microwave-based Probability of Eyewall Replacement Cycle (M-PERC) model\(^5\), developed by the Cooperative Institute for Meteorological Satellite Studies (CIMSS), provides the probability of the onset of an ERC based on microwave-based predictors [CIMSS/Automated Rotational Center Hurricane Eye Retrieval (ARCHER); Wimmers and Velden 2016]. Details about this model are given in the Rapporteur Report for Topic 3.3: “Intensity guidance in operational perspectives”.

While outer eyewall formation is no longer a rare event in state-of-the-art numerical models, it remains challenging to make accurate predictions of the occurrence and the details of an ERC event [e.g. the onset time of SEF and ERC; the location and contraction speed of the outer eyewall; the dissipation (intensification) rate of the inner (outer) eyewall; the duration, etc.]. SEF and ERC events have been suggested to be regulated by different factors and mechanisms, such as outer rainband heating (e.g. Rozoff et al., 2012; Zhu and Zhu 2014), which may be closely tied to environmental vertical wind shear (Fang and Zhang 2012; Didlake et al., 2018) and relative humidity (Hill and Lackmann 2009; Ge 2015); the storm intensity and structure (e.g. Kuo et al., 2008; Zhu and Zhu 2015; Ge et al. 2016; Guan and Ge 2018); boundary layer dynamics (e.g. Huang et al., 2012; Kepert 2013; Slocum et al., 2014; Abarca and Montgomery 2015; Kepert 2017); diurnal radiation cycles (Tang et al., 2017); and, the Wind-Induced Surface Heat Exchange (WISHE) mechanism (Cheng and Wu 2018). Uncertain representation of model physical processes (Zhu and Zhu 2015), uncertainty about the initial model conditions, and the chaotic nature of fluid dynamics (Zhang et al., 2017a) all add uncertainty to predictions of SEF and ERCs, and therefore, to intensity predictions during an ERC. Dynamical processes and factors affecting SEF and ERC are discussed in the Rapporteur Report for Topic 4.1: “The structure analysis and change: Secondary eyewall formation and expansion of the wind field”.

3.1.4 Relation of Rainbands to Intensity Change

a) Introduction

Immediately outside the TC eyewall exists a region with a filamentation time less than the typical overturning time scale of individual convective clouds (Rozoff et al., 2006; Wang 2008; Li and Wang 2012a,b); this region is known as the rapid filamentation zone (RFZ). Inner

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rainbands are prominent in this zone because of straining deformation (Li and Wang 2012a,b; Moon and Nolan 2015a,b; Li et al., 2017). The TC outer core lies radially outside of the RFZ (approximately three times the RMW; Wang 2008; 2009), where outer spiral rainbands predominantly develop. Outer rainbands can be classified into two types: principal rainbands and distant rainbands (Houze 2010). Principal rainbands are stationary relative to the TC center and extend outward with a striking azimuthal wavenumber-1 signature. Distant rainbands are located farther from the center and contain more vigorous convective elements. Many studies confirm that the activity of spiral rainbands can significantly influence TC structure and intensity (Wang 2012; and cited references therein). This subsection discusses recent advancements in understanding on the role of rainbands in TC structure and intensity change.

b) Relationships Between Spiral Rainbands and TC Intensity Change

While the potential vorticity (PV) structure of TCs suggests that rainbands play a major role in size changes (Hill and Lackmann 2009), rainbands can also interact with the inner core of the TC to impact intensity. Kossin et al. (2000) show that eyewall–rainband interaction can arise from vortex Rossby wave interaction—a process that can result in the weakening of the primary eyewall. In attempts to unravel the relationship between spiral rainbands and intensification in observations, lightning activity has been used as a measure of convective activity/latent heat release in the outer-rainband region. Lightning activity—especially in the rainband regions—has been documented to be a potential indicator of TC intensity change. Xu et al. (2017) used global TRMM data to investigate TC lightning characteristics and their relationships with intensity change. The results demonstrated that TC total lightning flash density is maximized in the outer-rainband region and minimized in the inner-rainband region. Inner-core (outer rainbow) lightning is generally negatively (positively) correlated to TC intensity change in the next 24 h (+24 h), with intensifying TCs having lower flash density than weakening and neutral TCs. This finding is consistent with the relationship found by DeMaria et al. (2012) and Stevenson et al. (2016) for Atlantic basin TCs, and a Hurricane Maria (2017) case study by Fierro et al. (2018) that leveraged preliminary Global Lightning Mapper data. However, DeMaria et al. (2012) did not find this relationship to hold true in the Eastern North Pacific basin [although Stevenson et al. (2016) did], and the discrepancies between various lightning studies still need to be addressed. Griffin (2017) examined tropical overshooting tops in longwave infrared imagery from geostationary satellites for rapidly intensifying and weakening TCs and confirmed the results of Xu et al. (2017). Griffin's study also showed that TRMM parameters of the convective depth and vertically integrated ice content in both the inner core and outer rainbands are both greater in intensifying TCs compared with TCs with a neutral intensity trend. Yang et al. (2018) examined the stratiform and convective characteristics of TCs in the WNP and found that the highest fraction of stratiform raining areas was located in the inner-band region; this promotes TC intensification. Didlake et al. (2018) found that increased rainband activity and organization occurred during the RI of Hurricane Earl (2010), consistent with Stevenson et al. (2014) and Yang et al. (2018). While a link has been found between rainband lightning activity and intensity change, the physical mechanisms behind this relationship need to be explored further.
Diabatic heating and cooling within the TC circulation have long been known to play a critical role in TC structure and intensity change (e.g. Malkus and Riehl 1960; Riehl and Malkus 1961; Yanai 1961; Möller and Shapiro 2002; Bui et al., 2009). Furthermore, diabatic heating and cooling in the various regions of a TC may play different roles in TC structure and intensity, and their associated changes (Eliassen 1951; Vigh and Schubert 2009; Pendergrass and Willoughby 2009; Wang 2009; Fudeyasu and Wang 2011; Rogers et al., 2013). Since the convection in TC rainbands is heterogeneous, the manner in which the rainband-associated diabatic heating and cooling affects TC structure and intensity change remains an unresolved issue in TC dynamics (Moon and Nolan 2010; Li et al., 2014a). Li et al. (2014a) revealed that the removal of heating (cooling) in the inner rainband region reduces (increases) storm intensity. This result is in a sharp contrast to the roles of diabatic heating and cooling in outer spiral rainbands, where an increase in heating (cooling) leads to a less intense (more intense) TC (Wang 2009).

Chen et al. (2018a) conducted a series of numerical sensitivity experiments to extend Li et al. (2014)'s study by evaluating the respective effects of convective and stratiform heating and cooling in the inner-rainband region on TC structure and intensity. They found that removing the convective heating within the inner-rainband region can effectively eliminate the inner-rainband activity and produce a moat-like zone outside the eyewall. Eyewall updrafts are significantly suppressed, the inner-core size is reduced, and the TC decays. When the convective heating in the inner-rainband region is increased by 50%, the storm first intensifies at a relatively slow rate, and then the TC inner-core size quickly expands outward. Hence, the conversion ratio of diabatic heating to kinetic energy can be effectively increased, which is responsible for RI. Removal of stratiform heating in the inner-rainband region leads to a slower intensification with a moderate final intensity. The decreased stratiform cooling elevates the equivalent potential temperature ($\theta_e$) in the mid- to lower-troposphere and favors the formation of a thick, high-entropy boundary layer. As a result, the inward transport of high-entropy air in the boundary layer triggers RI. As the simulated storm intensifies further, the low-level $\theta_e$ outside the eyewall begins to decrease as a result of compensating subsidence, such that the simulated TC eventually terminates RI and then maintains a roughly steady state. The doubled stratiform cooling in the inner-rainband region is effective in eliminating TC RI because of the low-entropy air that prevails from the surface to the mid-troposphere during the early stage. If both the stratiform heating and cooling are removed, the structure and intensity changes bear close resemblance to the results in which the stratiform cooling was halved. Doubling both the stratiform heating and cooling generates the weakest storm.

Chan and Chan (2016) examined the sensitivity of the simulated TC intensity to microphysical schemes. They pointed out that, although the simulated TC track is not sensitive to the microphysical schemes, its intensity is significantly influenced by the choice of microphysical scheme. The simulated TC intensity is similar in the simulations using the WRF Single-Moment 5-class and WRF Single-Moment 6-class schemes, and is higher than those using the Ferrier scheme. The WRF Single-Moment 5-class and Single-Moment 6-class schemes generate more diabatic heating in rainbands than the Ferrier scheme. More diabatic heating could lead to larger upward motion, and hence result in higher upper-tropospheric divergence, lower-tropospheric convergence, and precipitation rates. This, consequently, leads to stronger inflow.
in the lower troposphere, enhances an inward transport of absolute angular momentum, and, 
thus, higher TC intensity.

Although the potential effects of diabatic processes associated with spiral rainbands on TC 
intensity changes have been examined with idealized numerical experiments, further 
observational evidence from real cases is needed to confirm the insights offered by these 
simulations.

d) **Role of Rainband Rainwater Evaporation in TC Intensity Change**

Li et al. (2015) revisited the effects of the evaporation of raindrops in different regions on TC 
structure and intensity by performing several sensitivity numerical experiments. Evaporation of 
raindrops in the outer-rainband region is shown to suppress the final intensity of a TC, 
whereas the effects of evaporation in the inner rainbands on TC intensity are very limited. The 
low-$\theta_e$ air in the boundary layer that results from evaporative cooling is transported radially 
inward and mixed into the eyewall region, reducing $\theta_e$ under the eyewall, and thus, reduces TC 
intensity. Evaporation in the inner rainbands hardly affects the activity of outer rainbands. 
Outer rainbands can still form when evaporation is switched off in the outer-core region. This 
result seems to suggest that the cold-pool dynamics associated with evaporation lead to the 
growth and/or sustenance of outer rainbands, rather than to their initiation. Li et al. (2015) 
also showed that excluding evaporation in inner rainbands has a very weak effect on the inner-
core size of a storm. Evaporation in outer rainbands, however, generally limits the inner-core 
size.

e) **Radar Observations of TC Spiral Rainbands**

Yu et al. (2018) used long-term radar observations (2003–2015) to investigate a considerable 
number of outer rainbands from different TCs as they approached Taiwan island. Their study 
revealed that outer rainbands and squall lines frequently share similar structures. Outer 
rainbands with squall-line-like airflow patterns are common (~58%) and are generally 
characterized by convective precipitation and an obvious convergence zone between the band-
relative rear-to-front flow and front-to-rear flow at low levels, with updrafts that tilt either 
frontward or rearward. The majority of non-squall-line airflow patterns are characterized by 
less convective precipitation and a deep layer of either front-to-rear flow (14%) or rear-to-
front flow (16%) within the rainband.

Tang et al. (2018b) also showed that the mesoscale structure of the principal rainband shares 
some similarities with squall lines. They used airborne radar reflectivity fields and visible 
satellite images of Typhoon Hagupit (2008) to identify multiple quasi-linear subbands within 
the principal rainband. These subbands possessed upright and elevated updrafts and 
reflectivity cores. The flow pattern could be characterized as a hybrid structure, with some 
similarities to both inner and outer rainbands. The subbands contained a midlevel jet on the 
inner side of the reflectivity core that is likely accelerated by the heating of stratiform 
precipitation. They also contained a low-level jet that is attributed to the heating of convective 
precipitation (Fig. 3.1.15).
Tang et al. (2018b) also found that the subbands in Hagupit’s principal rainband accumulate PV at lower levels. At midlevels, the significant horizontal advection of absolute angular momentum associated with the PV anomalies may act to intensify the TC. Compared to a previous analysis of a single subband (Tang et al., 2014), multiple passes from the aircraft document substantial variability in the strength of convection and estimated PV generation. This variability is attributed to variations in low-level shear and cold-pool interactions. In the ‘optimal state’ with the strongest upright convection, the low-level shear is approximately balanced by the cold pool, similar to the dynamics of a squall line. However, variations in the convective life-cycle and local environment of the principal rainband modulate the strength of the dynamical impacts pertaining to PV generation and absolute angular momentum advection. Low-level outflow associated with the secondary circulation of the subband may also hinder intensification by posing a barrier to the inflow.

The microphysical characteristics of TC rainbands may also affect intensity change. Brown et al. (2016) compared multiple microphysics parameterizations in WRF with polarimetric radar observations and found substantial differences in the probability distributions of simulated rain drop sizes and amounts. In aggregate, the schemes that produced the greatest rainfall accumulations resulted in the most intense simulated TCs. This suggests a link between total convective heating in the eyewall and rainbands, and intensity. That study did not partition the heating and microphysics contributed by the eyewall, inner rainbands, and outer rainbands, but another study (Wu et al., 2018) found that ice-phased microphysical processes above the melting level (including aggregation and riming) constitute the major pathway of rainfall production over land in the outer rainband. However, Wu et al. (2018) found that the microphysical processes were different from that of the inner rainband analyzed in Wang et al. (2016). The latter study documented a predominance of warm-rain processes in the inner rainband, which tends to concentrate heating at lower levels. In the intermediate region near the principal rainband, ice processes associated with stratiform rain may play a critical role in initiating a secondary eyewall; as discussed earlier in this report, this can have a profound influence on TC intensity (Didlake et al., 2018).

Radar observations suggest that microphysics, heating, and the dynamics of inner, principal, and outer rainbands have a complicated relationship, with no single factor dominating the influence on TC intensity. As viewed from either the PV generation or angular momentum advection frameworks, the overall effect of convective heating appears to be a spin-up the
local low- and mid-level circulation. Mid-level jets associated with stratiform heating can also spin-up the local circulation through angular momentum advection above the frictional boundary layer. This local spin-up may have a positive influence on the overall outer core strength of the TC by increasing the total circulation. However, the local spin-up through rainband convective or stratiform heating may come at the expense of the eyewall intensity due to the interception and reduction of the low-level inflow at an outer radius. The past four years have seen extensive observational analysis on the dynamic and microphysical structure of rainbands. Such studies have shown that significant variability exists in ‘snapshots’ of rainband structure at different radii and at different stages of the convective life-cycle. This variability in the observed structures renders the determination of causal relationships between rainbands and intensity very difficult.

f) Summary of the Role of Rainbands in TC Intensity Change

Spiral rainbands comprise one of the major components of a TC, and their structural characteristics play significant roles in TC structure and intensity change. As such, rainbands have been examined by a number of observational and modeling studies over the past four years. Radar observations show that the finescale structures of outer rainbands frequently resemble squall lines. Additionally, these studies have concluded that ice-phased microphysical processes above the melting level dominate the major pathway of rainfall production in the overland outer rainband, in contrast to the predominance of warm-rain processes that occur in the inner rainband. Observations also indicate that the lightning flash density is maximized in the outer-rainband region and minimized in the inner-rainband region. Additionally, outer rainband lightning is found to be positively correlated to TC intensity change in the next 24 h. Idealized numerical simulations have demonstrated that convective heating in the inner rainband region generally promotes an increase to TC intensity; meanwhile, stratiform cooling in inner rainbands tends to hinder TC intensification. Evaporation of raindrops in the outer rainband region tends to suppress the final TC intensity, but the effects of evaporation in the inner rainbands are not significant. Although the physical link between spiral rainbands and TC intensity change has been established mainly through idealized numerical experiments, definitive observational evidence will be required to confirm these findings. The interactions between spiral rainband behavior (particularly microphysical processes within rainbands) and other TC components, and how these interactions affect TC intensity change, remain open issues (especially since rainbands are also strongly affected by the environment). Therefore, we recommend that specific, targeted observational and modeling investigations be undertaken to better understand interactions between spiral rainbands and their parent TCs and the specific mechanisms by which rainbands influence TC intensity.

3.1.5 Eyewall Instability and Inner-Core Mixing

a) Introduction

Mature tropical cyclones (TCs) tend to develop nonmonotonic PV profiles in the vicinity of the eyewall and, thereby, are susceptible to instabilities. For instance, the pronounced peak in the radial PV distribution may accommodate counter-propagating vortex Rossby (VR) waves with the ability to phase lock and induce mutual growth. This classic barotropic instability mechanism has been thoroughly investigated in the adiabatic two-dimensional (2D) nondivergent framework (where absolute vertical vorticity and PV are equivalent; e.g.
Schubert et al., 1999) and is often assumed to be responsible for the generation of asymmetric features observed in real TCs (e.g. Reasor et al., 2000; Hendricks et al., 2012) as well as mixing induced within the inner core. Although this is one plausible explanation (for the origin of asymmetries), real TCs are essentially moist, three-dimensional (3D) continuously stratified vortices that possess distinct mean secondary circulations. As such, the applicability of simplified 2D arguments awaits rigorous comparison to more realistic theories and numerical simulations. This subsection summarizes advances in understanding eyewall instability and inner-core mixing processes over the last four years.

b) Effect of Instability on TC Intensity Change in a Shallow Water (SW) System with Forced Mass Sink (2D case)

As a first step towards understanding the effects of diabatic heating on inner-core instabilities, Hendricks et al. (2014) applied a mass sink (intended to parameterize moist convection) to a one-layer shallow water system. Depending on specifics of the parameterization, the impact of eyewall instability on TC intensity can exhibit either distinct similarities or differences when compared to the outcome of barotropic instability in the adiabatic 2D system. In particular, it was shown that when instabilities were triggered by a prescribed mass sink that has an annular shape the onset of instability was marked by a decrease of the maximum velocity, while simultaneously deepening the central pressure deficit. This finding is consistent with the outcome from the unforced 2D case. On the other hand, when the forcing was designed to be proportional to the relative vorticity, the instability resulted in an overall intensification of the vortex (contrary to the unforced 2D case).

c) Effect of Instability on TC Intensity Change in a SW System with Precipitation and Evaporation (2D case)

The results of Hendricks et al. (2014) are interesting and potentially relevant. However, the fact that they largely rely on the characteristics of an ad hoc mass sink (the forcing) introduced in the SW system is a significant shortcoming. Lahaye and Zeitlin (2016) appear to have recognized this limitation and have presented results with a one-layer shallow water model augmented by adding a prognostic humidity equation, as well as self-consistent (but crude) parameterizations for precipitation and evaporation. In agreement with Hendricks et al. (2014), they found that the instability released within a moist precipitating simulation (that includes evaporation) results in intensification of the vortex. Perhaps one notable difference resides in the long-term impact of the instability on the vortex structure. In the case of Lahaye and Zeitlin (2016), the initial annular vortex relaxes into a monopolar structure, whereas in Hendricks et al. (2014) the annular vortex reforms after its initial breakdown.

d) Effect of Instability on TC Intensity Change in 3D Cloud-Resolving Models

The one-layer SW model is arguably a simple and useful tool that retains significant dynamical features of the primitive equations. Despite this, it can only describe an oversimplified version

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6 It should be noted that not all cases with annular forcing presented in the paper resulted in an instability. For example, a broad and weak annular forcing may lead to a thick vortex ring that can remain stable.
of the real atmosphere. A more complete evaluation of the impact of moist convection on inner-core instabilities requires the usage of 3D cloud-resolving models. Naylor and Schecter (2014) and Wu et al. (2016) applied this option in order to provide further insight. To elaborate, Naylor and Schecter (2014) quantitatively compared the instabilities in full-physics simulations to those in dry simulations where the vortices have the same azimuthal wind structure. Of interest, they found that moist convection has little impact on the initial exponential growth of inner-core asymmetries (similar growth rates of the asymmetries between moist and dry cases; Fig. 3.1.16). A detailed analysis of eddy kinetic energy reveals that the radial shear of mean angular velocity is a primary source in the budgets, whereas the production terms associated with the mean secondary circulation are relatively small. The secondary circulation only becomes important at later times in that it restores the vorticity annulus (in contrast with the dry simulations where the vortices relaxed into monopoles) and arrests the intensity change associated with horizontal PV mixing.\(^7\) On the other hand, Wu et al. (2016) compared the vortex evolution in a number of simulations with variable convective heating.\(^8\)

![Figure 3.1.16. Time series of the squared amplitude of select components from the Fourier expansion of tangential velocity. Moist simulations are in the left plots, and dry simulations in the right. Here, it can be seen that before nonlinear saturation is apparent, the fastest growing modes have wave numbers ranging from 4 to 6 and e-folding times ranging from 15 to 20 min. The growth rates of the dominant modes are very similar between the moist simulations and their dry counterparts. Adapted from figure 4 of Naylor and Schecter (2014).](image)

\(^7\) Note that, in their study the simulations were initialized with quasi steady state vortices. By the end of the moist simulations, the maximum winds are approximately the same as in the initial conditions. On the other hand, the maximum winds in the dry simulations steadily decreased.

\(^8\) In particular, the convective heating within a selected microphysics scheme was adjusted by a constant factor at each grid point in the domain.
In contrast to Naylor and Schecter (2014), their experiments appear to emphasize the significant role of the mean secondary circulation in maintaining the initial annular vortex structure. Note that both the results of Naylor and Schecter (2014) and Wu et al. (2016) are based on a relatively small sample of experiments and, thus, there is no firm reason to believe that they are general. For a more general picture, a 3D perturbation theory that incorporates both moisture and the vortex mean secondary circulation is needed. Fortunately, such a tool has been recently developed successfully by Schecter (2018) and awaits a thorough investigation.

e) Effect of Instability on TC Intensity Change due to Waves

While the previous discussion focused on barotropic instability and subtler variants, this mechanism is not the only one supported within an annular vortex. Another instability mechanism involves a VR wave in the vortex core that spontaneously emits a frequency-matched spiral inertia gravity (IG) wave into the environment (e.g. Schecter and Montgomery 2004). The IG wave radiation is destabilizing because its wave activity is negative. To conserve total wave activity, the positive component associated with the VR wave must grow. It is not always clear whether barotropic instability or radiation-driven instability should prevail (in the context of annular vortices). Menelaou et al. (2016) attempted to address this question with a comprehensive 3D linear stability analysis (applied to annular barotropic vortices whose basic state is in gradient and hydrostatic balance), and a suitably designed wave-activity diagnostic. The picture that emerges from their study suggests that increasing the Froude number \((Fr)\) beyond unity tends to cause a transition (which can be abrupt or gradual depending on specifics) from nonradiative instabilities to radiation-driven instabilities\(^9\) (Fig. 3.1.17). The essence of this figure can be captured following the relative importance of the term RAD (circle symbol), which represents the contribution to the growth rate from inertia-gravity wave radiation. From the left panel, it can be seen that the dominant eigenmode of this cyclone exhibits an abrupt transition at a critical Froude number. For \(Fr < 1.5\), the magnitude of RAD is very small compared to that of other partial growth rates. As \(Fr\) increases beyond its critical value, \(n\) (which denotes the azimuthal wavenumber) changes from 4 to 2 and the status of RAD immediately elevates from negligible to dominant. On the other hand, from the right panel it can be seen that the prevailing instability of this cyclone gradually transitions from a nonradiative process to a radiation-driven affair as the Froude number becomes greater than 2. The transition is relatively smooth despite a sequence of abrupt drops in the azimuthal wavenumber from 5 to 4 to 3 to 2 followed by a jump to 3 and return to 2. Nevertheless, for certain case studies, it was further shown that the dominant modes of instability can also involve multiple mechanisms operating simultaneously\(^10\) (e.g. radiative and barotropic instability).

\(^9\) Here, the analysis excludes moisture and is applied to annular vortices without a peripheral vorticity skirt. Adding parameterized eyewall moisture or an outer vorticity skirt can switch the order of dominance between nonradiative and radiation-driven modes of instability.

\(^10\) Note that for a multi-mechanistic mode, assessing the role of each mechanism in destabilizing the vortex requires special care and can lead to inconsistencies without the right diagnostic (Schecter and Menelaou 2017).
While it is important to understand the time scale and spatial structure of the dominant inner-core instability, it may be more important to understand its consequences on TC structure and intensity. Although the linear stability analysis of Menelaou et al. (2016) revealed that the VR-IG wave instability may become relevant in the parameter regime of a major TC, it says nothing about its long-term (and nonlinear) effects. Menelaou and Yau (2018) attempted to further elucidate this using a conventional 3D primitive equation nonlinear model initialized with dry non-convective annular TC-like vortices. At first, their study verified that spontaneous radiative imbalance can indeed be the dominant destabilizing mechanism even within a nonlinear model. After destabilization, they demonstrated that its long-term nonlinear effects can lead to the formation of mesovortices, vortex merger, and mixing processes that can relax the initial annular vortex into one with a monotonic distribution (similar to the long-term outcome of classical barotropic instability; Fig. 3.1.18).

Figure 3.1.17. Froude number, $Fr$, dependence of the generic instability of an annular cyclone with (left) thin annulus and a shallow central vorticity hole, or (right) thin annulus and a deep central vorticity hole. Growth rate (GR; star symbol) and partial growth rates (remaining symbols) scaled to the basic state angular velocity. The partial growth rates are calculated from suitable angular pseudo-momentum budgets. See text for more details. Adapted from figure 8 of Menelaou et al. (2016).

Figure 3.1.18. Long-term nonlinear evolution of spontaneous radiative imbalance excited in an annular cyclone perturbed by an initial $n = 3$ thermal pulse. (top left) Horizontal cross section of normalized relative vorticity $\zeta = \zeta / [\zeta \text{max}; t=0 \text{ h}]$ at initial time $t = 0 \text{ h}$. (center and right column) Normalized relative vorticity vs time. The cross sections are taken at a selected vertical level. The normalization factor $[\zeta \text{max}; t=0 \text{ h}]$ is the initial maximum value of the relative vorticity. Figure 11 of Menelaou and Yau (2018).
e) **Summary of the Role of Instability and Mixing Processes on TC Intensity Change**

Recent work has extended numerical analyses of inner core instability processes from 2D barotropic frameworks to more realistic 3D frameworks that include moisture and parameterized mass sinks. Whereas, barotropic instability in a 2D framework leads to deepening of the pressure deficit but a decrease in intensity, results from simulations in more realistic frameworks show that instability processes may cause intensification under certain assumptions [cf Lee and Wu (2018), as discussed in subsection 3.1.2e]. Considerable uncertainty remains as to whether the secondary circulation prevents relaxation of the vortex to a monopole (or how quickly it might restore the vortex back to an annular state) and as to the effects of moist convective processes on instability. Additional studies examined other types of instabilities caused by spontaneous IG radiation from VR waves. More work is needed to understand the long-term and nonlinear effects of VR-IG instability. Because the PV structure is critical in understanding the vortex state (annular vs. monopole) during instability mixing events, future research should consider observational strategies to better assess the PV structure of TCs.

3.1.6 **Relationship between Surface Fluxes and Intensity Change**

a) **Introduction**

Latent heat energy is critical to drive TCs. Many studies have shown that sea-surface fluxes play an essential role in providing latent heat to the TC core where the energy is converted into kinetic energy (e.g. Raymond and Herman 2012). It is also well understood that the surface friction dissipates the kinetic energy of TC (e.g. Ekman 1905; Haurwitz 1935, 1936). Consequently, TCs are largely controlled by surface enthalpy and momentum fluxes as can be shown through potential intensity theory (e.g. Kleinschmidt 1951). While the community has long recognized the importance of surface fluxes in TC intensity changes, recent literature from the past four years (2014–2018) continues to provide new understandings of this topic.

b) **The Role of Surface Fluxes in TC Intensity Change**

Since surface fluxes are parameterized through bulk aerodynamic formulae in most numerical and theoretical models, the effects of air–sea exchange coefficients on TC intensity and structure have remained a vital area of investigation. Despite knowing the critical importance of the surface drag coefficient, obtaining accurate measurements of this quantity at the higher wind speeds found in intense TCs remains problematic (e.g. Vickery et al., 2000; Powell et al., 2003; Bell and Montgomery 2008; Powell et al., 2009; Bell et al., 2012; Rastigejev and Suslov 2014). Soloviev et al. (2017) studied the impact of wind-speed dependence of the surface drag coefficient on TC intensification. They found that the drag coefficient has a local minimum at approximately 60 m s⁻¹, and that the resulting negative slope of the drag coefficient between 35 and 60 m s⁻¹ contributes positively to TC intensification; meanwhile, the positive slope above 60 m s⁻¹ favours weakening (Fig. 3.1.19).

Kwon and Kim (2017) demonstrated that a change in the momentum coefficient with wind speed affects the radial distribution of angular momentum (i.e. the size of TC), which changes the TC intensity. Using dropsondes from aircraft flights, in situ observations, and satellite data
for Hurricane Earl, Jaimes et al. (2015) showed that the bulk enthalpy fluxes are controlled by the thermodynamic disequilibrium between the sea surface and the near-surface air, not by the wind speed. Ma et al. (2017) examined the impacts of revised parameterization of sea-surface fluxes including processes associated with sea spray on TCs, and showed that sea spray processes result in cooling and moistening of the near-surface air in the eyewall and eye regions; this increases the thermodynamic disequilibrium and enhances the surfaces fluxes, favoring RI. When the exchange coefficients are treated stochastically in an ensemble modeling framework, the standard deviation of TC intensity forecasts decreases (Torn 2016). Meanwhile, when the ocean conditions are treated stochastically, the standard deviation of the intensity forecasts is greater. An increase in the drag coefficient results in a narrower radius and a lower height of maximum tangential wind (Coronel et al. 2016).

Figure 3.1.19. (Top) Wind-speed dependence of surface drag coefficient. (Bottom) Observed rate of change in wind speed 10-m level at as a function of wind speed. Figure 7 of Soloviev et al. (2017).

Green and Zhang (2014) investigated the impacts of four parameters proposed to control the wind-speed dependence of exchange coefficients: two are multiplicative factors, while the other two control the coefficient at high wind speeds. They found that the impact of the multiplicative parameter for the drag coefficient on the WPR is larger than that for the enthalpy coefficient. The coefficients also affect the simulated warm-core structure and precipitation (Ming and Zhang 2016). Li et al. (2014b) showed that including the nonbreaking wave-induced mixing in the parameterization, which is caused by surface wave stirring, results in better forecasts of TC intensity. Zhang et al. (2017b) showed that incorporation of effects of sea spray increases the maximum cooling of SST in the right-hand side of Typhoon Rammasun (2002).
c) Measuring and Parameterizing Surface Fluxes

Measuring the surface fluxes under strong wind conditions is a challenging topic. Potter et al. (2015) succeeded in making the first-ever direct measurements of sea-surface momentum fluxes during the Impact of Typhoons on the Ocean in the Pacific (ITOP) campaign. Their analysis shows evidence of a rolloff at wind speeds faster than 22 m s\(^{-1}\). Mueller and Veron (2014) formulated a simple model developed from Lagrangian stochastic simulations. Their results show that the spray-mediated fluxes may be sensitive to the size distribution of the drops. Parameterizations of the surface exchange coefficients have been developed by several studies. Zweers et al. (2015) developed a parameterization incorporating effects of sea spray, which has a wind-speed dependence consistent with observations; they showed that a model using this parameterization can reasonably simulate TC intensity. Andreas et al. (2015) developed a physics-based bulk algorithm for the air–sea surface flux with spray-mediated transfer as well as the interfacial process by molecular motion. As their algorithm is physics-based, it can be extended to hurricane winds. Liu et al. (2017) investigated the sensitivity of simulated Hurricane Katrina (2005) to boundary layer schemes. They showed that the Mellor–Yamada–Janjic scheme results in stronger surface fluxes and vertical mixing, which enhances air-sea interaction. The measurement of surface fluxes under fast-wind conditions is still difficult and needs to be conducted in the future.

The effects of surface fluxes on intensity and structure of TCs have been investigated by several studies. Wada (2015a) showed that the RI of Typhoon Man-yi is associated with a mesovortex inside the RMW, which is attributed to barotropic-convective instability induced by relatively high SST and steep gradients of sea-level pressure and tangential wind. Wada (2015b) showed that the minimum value of tropical cyclone heat potential (TCHP) for intensification in the WNP is low (40–60 kJ cm\(^{-2}\)) around 5–10\(^\circ\)N, west of 120\(^\circ\)E and east of 140\(^\circ\)E, whereas it is high (80–100 kJ cm\(^{-2}\)) around 15–20\(^\circ\)N. Ma et al. (2015) examined the relative roles of thermal and moisture effects by considering the sea-spray effects and showed that TC intensity is sensitive to latent heat flux, not total enthalpy flux. Xu (2015) showed that overland latent heat fluxes intensified Typhoon Haitang when it was near Taiwan island, while the sensible heat fluxes from the land weakened it. Chen et al. (2017) revealed that—compared to a case with fixed cold-wake SST—the decrease in TC intensity due to a cold wake is delayed when air-sea interaction is allowed in the simulation. This delayed weakening of the TC is attributed to a “wake jet” that transports moist air inward (Fig. 3.1.20).

d) Potential Intensity and Surface Fluxes

As surface fluxes play a dominant role in the PI theory (e.g. Kleinschmidt 1951), some researchers have studied PI theory by focusing on the fluxes. Based on observational data, Kowaleski and Evans (2015) showed remarkable differences in observed surface fluxes compared with fluxes calculated from PI theory, especially around the RMW. Strazzzo et al. (2015) analyzed TCs generated by two global climate models and showed that the sensitivity of PI to SST is not statistically different from that of observed maximum intensity or limiting intensity. Chavas (2017) developed a simple theory of TC ventilation and showed that capping the surface flux reduces the PI and amplifies the detrimental effect of ventilation. Miyamoto et al. (2017) developed an analytical model of PI that incorporates the TC-induced sea-surface cooling (Fig. 3.1.21). They derived a nondimensional parameter that represents the degree of ocean cooling, which depends on TC intensity, size, translation speed, and ocean stratification.
Figure 3.1.20. Conceptual model of the physical processes associated with the atmospheric response in a translating TC from right to left with a trailing ocean cold wake (green) with an atmospheric cold pool (light blue). Figure 13 of Chen et al. (2017).

Figure 3.1.21. (a) TC intensity, (b) SST, and (c) mixed-layer depth as a function of translation speed of TC. The red and blue lines represents Emanuel’s PI and PI incorporating ocean cooling. The circles show numerical simulations using an ocean model. Figure 2 of Miyamoto et al. (2017).
Many studies have examined the impacts of surface fluxes on the TC boundary layer since this region is directly affected by such fluxes. Lee and Chen (2014a,b) showed that the boundary layer is stable above the TC-induced cold wake in the right-rear quadrant, which suppresses rainbands and enhances inflow in the boundary layer (Fig. 3.1.22). Analysing an integrated energy equation that encloses all of the TC Carnot legs, Kieu (2015) found that the dissipative heating in the boundary layer is inherently included in the energy budget in PI theory. Based on observations by the Global Positioning System dropsonde, Zhang et al. (2017c) showed the importance of the surface-flux induced boundary layer recovery in regulating the low-level thermodynamic field of TC. Zhu et al. (2016) showed that including TC-induced SST cooling decreases the stability in the boundary layer; this reduced stability is below the criterion for the generation of roll vortices so such roll vortices do not form in this scenario. In contrast, when TC-induced cooling is not considered, the criterion is satisfied and roll vortices can form. The effects of roll vortices on TC intensity and structure have not been completed and hence further studies are desired.

Figure 3.1.22. Schematic of boundary-layer flow in (a) a coupled model and (b) an uncoupled model. Figure 15 of Lee and Chen (2014a).

e) Sea-Surface Temperature Response

A number of studies have shown that the radial distributions of surface fluxes play an important role in determining the intensity and size of TCs. To the degree that these surface fluxes depend on SST, which is a function of the ocean’s response to the TC-induced mixing and upwelling, the TC intensity depends on the time-evolving radial distributions of SSTs in a complicated fashion that depends on the disequilibrium of the air-sea interface. Sun et al. (2014) showed that the enhancing SSTs within the range of 1.5–2.0 times the RMW contributes to an increase in TC intensity and a decrease in inner-core size, while enhancing the SSTs outside works in an opposite manner. Kanada et al. (2017) showed that high SST inside the RMW increases CAPE and is more likely to produce strong convective updrafts, which can lead to RI. In contrast, high SSTs outside the RMW induces secondary updrafts that inhibit RI. Zhang et al. (2017b) investigated the energetics at the ocean surface and showed that the surface flux is approximately balanced with energy dissipation inside 2.3 times the RMW. Ma et al. (2015) examined the sensitivity of TC size to surface sensible heat flux and found that TC size shrinks by over 20% when the heat flux is removed. The adiabatic cooling
associated with radial inflow is largely balanced with the heat flux. Zhao and Chan (2017) examined the relationship between SST cooling and the subsequent change in TC size. In their coupled simulations, an initially small TC retains its small size throughout its life cycle, whereas the initially large TCs (Fig. 3.1.23) become more intense due to higher enthalpy fluxes in the inner core region.

Several other studies have examined the TC-induced cooling. Potter et al. (2017) analyzed observational data in the Philippine Sea in 2010 and showed that the decrease in mixed layer temperature is well predicted by the TC’s translation speed and wind speed. They attributed 12–47% of the mixed layer heat loss to enthalpy fluxes, which is much greater than previous reports. Wei et al. (2017) used a machine learning technique to propose a parameterization of TC-induced SST cooling. This machine-learning-based parameterization performs better at predicting the SST cooling than a method based on linear regression. Jullien et al. (2014) conducted a multidecadal, coupled regional simulation in the South Pacific. They showed that anticyclonic ocean eddies have the effect of insulating against storm-induced upwelling and mixing. This tends to reduce the SST cooling. In contrast, cyclonic eddies promote stronger SST cooling. Lai et al. (2015) showed that the TC-induced SST cooling differs between coastal areas and the open sea. Seroka et al. (2016, 2017) illustrated the importance of representing the coastal regions by examining the effect of the Mid-Atlantic Bight on the intensity of Hurricane Irene (2011) and Tropical Storm Barry (2007).

Figure 3.1.23. Time series of RMW in (a) uncoupled simulations, (b) simulations with 20-m mixed-layer depth, (c) with 50-m depth, and (d) with 100-m depth. The initial RMW is denoted as the digit with R. Figure 5 of Zhao and Chan (2017).
Summary of the Role of Surface Fluxes and TC Intensity Change

The role of surface fluxes in TC intensity change continues to be a critical research topic. Advances in both modeling and observing surface fluxes have improved our understanding of the relationships between TC intensification and the drag and enthalpy coefficients. New physics-based parameterization have been developed which incorporate the effects of sea spray and interfacial effects (Andreas et al., 2015; Soloviev et al., 2017). In particular, the wind-speed dependence on the drag coefficient that results from sea spray effects appears to produce a local minimum near 60 m s⁻¹; this may explain, in part, why TCs rapidly intensify from 35–60 m s⁻¹, but weaken soon after reaching high intensity (Soloviev et al., 2017). Also, recent work has shown that bulk enthalpy fluxes are controlled by the thermodynamic disequilibrium between the sea surface and the near-surface air, not by the wind speed (Jaimes et al., 2015), and that sea spray processes can increase the thermodynamic disequilibrium favoring enhanced fluxes and RI (Ma et al., 2017). Additionally, TC intensity has been found to be sensitive to latent heat fluxes, but not total enthalpy fluxes (Ma et al., 2015). Models which incorporate the effects of sea spray can reasonably simulate TC intensity (Zweers et al., 2015), and models which include the mixing produced by nonbreaking waves can improve TC intensity forecasts (Li et al., 2014b).

Progress has also been made with regard to understanding of the role of surface fluxes on potential intensity and the impact of the SST response of the ocean. Dissipative heating in the boundary layer is found to be inherently included in the energy budget of PI theory (Kieu 2015). A number of studies have shown that the radial distributions of surface fluxes play an important role in determining the intensity and size of TCs (Sun et al. 2014; Lee and Chen 2014a,b; Kanada et al., 2017; Zhao and Chan 2017). Analysis of the energetics at the ocean surface shows that the surface flux is approximately balanced with energy dissipation inside 2.3 times the RMW (Zhang et al., 2017b). TC-induced cooling may also decrease the instability in the boundary layer to the point where roll vortices do not form (Zhu et al. 2016), however the overall effect of roll vortices on TC intensity change is not yet known.

Despite considerable progress over the last four years, considerable uncertainties still remain as to the wind-speed dependence of the surface drag and enthalpy coefficients. Observations of surface fluxes in high wind conditions remains a pressing need. Additional efforts are also needed to transition recent research advancements into operations.

3.1.7 Mechanisms of Tropical Cyclone Intensification

a) Introduction

The challenge of understanding the mechanisms by which TCs intensify has captivated the research community for much of the past half century. Scores of papers have been written proposing (or discussing) the various intensification mechanisms. Because of the difficulty in applying observational evidence to definitively answering the deep questions on intensification mechanisms, much of the research to date has utilized theories and numerical simulations. The incompleteness of theoretical approaches, limited observational sampling, and the imperfections of models have resulted in considerable epistemic uncertainty, leaving much room for debate. With this in mind, we enter this section realizing that terminology can be vital. For instance, referring to a description of one or more intensification mechanisms as a
paradigm may have the implicit connotation (whether intended or not), that the theoretical or conceptual description being put forward is the dominant paradigm (that is, that the view is already widely accepted or broadly held by the community) and that competing ideas are ‘wrong’. In reality, it is likely that a number of different intensification mechanisms are operating in concert with each other. A better word to describe the theoretical or conceptual description of a collection of intensification mechanisms would be framework. A more holistic view, then, is to realize that while previous frameworks may have been incomplete, recent frameworks largely expand on and refine previous frameworks. Understanding the relative contributions of each mechanism to the overall intensification of the TC should be a key goal, although this aspect has often been given lesser attention in studies. In this introduction, we do not attempt to review all variants of the intensification frameworks that have been proposed, but to provide context for the following discussion, we briefly review several of the key historical frameworks. For more thorough reviews of historical intensification frameworks, we refer the reader to the cogent discussions of Montgomery and Smith (2014) and Montgomery (2016).

The first main intensification framework was proposed separately, but nearly simultaneously, by Charney and Eliassen (1964) and Ooyama (1964), who posited that TC development and subsequent intensification involved a collaborative interaction between convection and the larger vortex scale. In this view, the combined effects of convective updrafts lead to the development of a secondary circulation that results in the import of angular momentum and moisture into the vortex. The associated influx moisture has the effect of invigorating the convection, while the import of angular momentum results in a spin-up of the vortex circulation. It was further hypothesized that these two effects result in an instability feedback loop, with stronger convection leading to more spin-up and vice versa. This collaborative effect was termed Convective Instability of the Second Kind (CISK), and was studied in a quasi-geostrophic balance model. CISK was criticized, in part, because it was a linear model (it used geostrophic balance).

Ooyama (1982) proposed a refinement to the CISK idea by adding gradient wind balance to the theory. As Montgomery (2016) points out, this theory, termed the “cooperative intensification theory for tropical cyclones”, had its roots in Ooyama’s (1969) paper, which studied TC intensification in an axisymmetric, balanced vortex in a stably-stratified atmosphere. The addition of gradient wind balance and recognition of the role of differential latent heating from the organized convection made this a nonlinear theory, but the basic idea is similar to CISK. For the purposes of this review, recent advancements to this intensification mechanism are covered below in subsection b) “Balanced Symmetrical Intensification Mechanism”.

The next major development occurred with Emanuel (1986), who recognized the critical role of air-sea latent and sensible heat fluxes in both the development and maintenance of TCs. In this view, the intensification of a TC can be viewed as a finite amplitude air-sea interaction instability. Later, Emanuel (1991) coined the term wind-induced surface heat exchange (WISHE), with Yano and Emanuel (1991) providing further explanation: ‘The acronym WISHE is intended to replace and unify the terms “air-sea interaction” used by E87 [Emanuel 1987] and “evaporation-wind feedback” used by Neelin et al. (1987).’ Subsequently, this framework has gone on to receive widespread recognition as a plausible explanation for the growth of hurricanes. The major limitations of the original WISHE theory are the assumption of
axisymmetry and quasi-balance. The original WISHE theory has undergone revisions in recent years. Emanuel (2012) modified the theory to account for small-scale turbulence in the outflow layer, which sets the thermal stratification there, affecting both the maximum intensity and intensification rate. Zhang and Emanuel (2016) capped the wind speed used in the surface enthalpy flux calculation, and derived a new maximum potential intensity (MPI) formula. Recent discussion on this intensification mechanism is covered below in subsection c).

This synthesis summarizes 40 papers that have been written since 2014 either on, or are related to, intensification mechanisms. In addition to advanced ideas on the historical intensification mechanisms, we also cover papers from a recently-proposed boundary-layer spin-up mechanism (subsection d) and the attempt to combine several key intensification mechanisms into a unified framework called the “rotating-convection” framework (subsection e). A summary follows, along with a recommendation on a possible path to resolve some of the long-standing debates.

b) Balanced Symmetrical Intensification Mechanism

The Eliassen (1951) vortex model has provided numerous insights into the response of balanced, rotating dynamics to forcing, especially in the context of TCs. The balanced response to diabatic heating in a vortex with radially and vertically varying static stability, inertial stability, and baroclinicity reminiscent of observed tropical cyclones has assisted in providing a mechanism for intensification, RI, warm-core structures, and eyewall replacement (e.g. Shapiro and Willoughby 1982; Schubert and Hack 1982; Vigh and Schubert 2009; Sitkowski et al. 2012; Musgrave et al., 2012). With respect to intensification and maintenance of observed TCs, recent in situ aircraft and tail Doppler radar and ground-based lightning network TC studies (e.g. Rogers et al., 2013, 2015, 2016; Martinez et al., 2017, Stevenson et al., 2018; Dougherty et al., 2018) have found ties between observations and the theoretical results that link TC intensification to the location of diabatic heating in relation to the high inertial stability region.

However, criticisms of the balanced, symmetric dynamics lie in the extent to which the conceptual ideas that arise from the balanced vortex model can be applied quantitatively to real TCs or in comparisons against numerical simulations (e.g. Smith et al., 2018). In addition to asymmetric arguments, the criticisms primarily focus on the inability of the balanced, symmetric model’s diabatic forcing to dynamically evolve in time with the vortex from one balanced state to the next as well as the framework’s inability to adequately link the unbalanced dynamics of the boundary layer to the overlying fluid. Solutions of the inviscid, balanced vortex model miss the coupling between the boundary layer Ekman pumping and eyewall convection (e.g. Raymond and Herman 2012).

While time-dependent, analytic solutions of the Eliassen (1951) balanced vortex model that allow diabatic heating to evolve have not been found, Schubert et al. (2016) offer a new perspective on balanced, symmetric intensification through using wave-vortex theory (Salmon 2014). By developing a forced, balanced axisymmetric model from the theory, Schubert et al. (2016) illustrate the dry, dynamical processes involved with the incubation time (Ooyama 1969) of a TC prior to spin up. The authors also show that there is not a one-to-one relationship between absolute angular momentum surfaces and the RMW during intensification in that the contraction of the RMW can cease prior to reaching peak intensity (Stern et al.,
and absolute angular momentum surfaces can continue to shift inward (Smith and Montgomery 2015). Even though this framework offers new insight into balanced, symmetric intensification, it is important to know that the small Froude number ($Fr$) restriction imposed by a wave-vortex theory may limit the model’s applicability to a stratified fluid.

Despite advances in balanced, symmetric dynamics with respect to TC intensification, the development of analytical solutions that connect the unbalanced boundary layer dynamics to the diabatic forcing in the free atmosphere of a TC continues to remain elusive.

c) **WISHE Intensification Mechanism**

Under the WISHE intensification mechanism, an axisymmetric TC intensifies through a self-induced positive feedback between the tangential wind field and the wind-speed dependent surface moist entropy flux (Fig. 3.1.24; Emanuel 1997, 2004, 2012; Montgomery et al., 2009; Montgomery and Smith 2014). In recent studies, the viewpoint of WISHE as the dominant intensification mechanism has been reviewed and investigated.

![Figure 3.1.24. Schematic of the evaporation-wind intensification mechanism. See the paper for a detailed discussion of this figure. Figure 6 in Montgomery and Smith (2014).](image)

Montgomery et al. (2015) found “contradictory definitions of WISHE as well as ambiguous and generally incomplete descriptions of the putative intensification mechanism” in the literatures, and examined “shortcomings in the linkages proposed by others between these fluxes and other elements of the intensification process”. For instance, The COMET Program (Chapter 8, 2013) failed to mention the wind speed-dependent heat flux in the WISHE feedback mechanism. The study also reiterates the important role of surface moisture fluxes in intensification but showed that the wind-speed dependence of surface fluxes is not necessary for intensity change (figure 1 in Montgomery et al., 2015) and that TC intensification can proceed even without evaporative downdrafts (also shown in Montgomery et al. 2009), as
opposed to that in Emanuel (1997). This is also the case for tropical depression intensification in which spin up follows even with wind-independent heat fluxes (Murthy and Boos 2018). Lee and Frisius (2018), using simple and complex TC models, found a “positive relationship between the radial CAPE gradient and the intensification rate which disagrees with the basic assumption of WISHE model.”

Zhang and Emanuel (2016), on the other hand, redefined WISHE by proposing a tendency equation for the peak wind speed in an idealized, balanced, axisymmetric TC model (Eqns. 5 and 8 in the paper, Eqn. 17 in Emanuel 2012) to quantify the feedback of cyclone winds at the RMW on the surface fluxes. Their analytical solution (Eqn. 10 and fig. 1a in the paper) and numerical simulations with capped surface enthalpy fluxes (figs 4 and 5 in the paper) show that wind-induced surface enthalpy flux affects the rate of intensification, even though it is not a necessary condition for intensification of TCs in general. They also reiterated that “some other process or processes must work to bring the system to such a state that WISHE could conceivably lead to further amplification” that is, “once a mesoscale column of nearly saturated air is established, WISHE can begin to amplify the disturbance” (Emanuel 1989, 2012). The results in Chavas (2017) further verify the importance of WISHE on the intensity dynamics of real-world TCs but also noted the non-necessity of the WISHE mechanism to intensification. However, and as pointed out by Montgomery et al. (2014), the revised tendency equation in the new WISHE mechanism introduces an additional term that describes a control of “ring-like eddy structures encircling the vortex axis” on TC intensification. “In reality, real turbulent mixing occurs locally in azimuth and the axisymmetric assumption is highly questionable” as shown in Persing et al. (2013). With the inclusion of non-gradient wind effects above the boundary layer in Emanuel’s WISHE formulation, the IR found in a nonhydrostatic numerical model was reproduced (Peng et al., 2018).

d) Boundary Layer Spin-Up Mechanism

The boundary layer spin-up mechanism is a component of the rotating-convection framework (described below in subsection e) which provides an explanation for the occurrence of the maximum tangential wind speed in the boundary layer. It is important to note that the boundary layer spin-up mechanism requires the classical mechanism to operate (in contrast to what was purported in Smith et al. 2009, statements which have since been corrected in subsequent papers). Also, this mechanism does not propose a separate explanation for a positive tendency of the maximum wind speed above the boundary layer.

Observations (e.g. Kepert 2006a,b; Bell and Montgomery 2008; Zhang et al., 2011; Sanger et al. 2014; Montgomery et al. 2014) as well as numerical model simulations (e.g. Zhang et al., 2001; Smith et al., 2009; Persing et al., 2013) show that the maximum tangential wind in a mature TC occurs in the frictional boundary layer, typically a few hundred meters above the surface. An explanation for this finding was proposed by Smith and Vogl (2008) and Smith et al. (2009). This so-called boundary-layer spin-up mechanism, may be understood as follows. In the boundary layer, air parcels converge comparatively rapidly because, unlike the flow above the layer, which is in approximate gradient wind balance, the flow is subgradient (i.e. the sum of the centrifugal force and Coriolis force acting on an air parcel is less than the inward-directed pressure gradient. As the air parcels spiral cyclonically inward in the boundary layer, they lose some of their absolute angular momentum $M$ to the surface because of the opposing frictional torque. The tangential wind component $v$ is
related to $M$ by the formula $v = \frac{M}{r} + \frac{1}{2} fr$ where $r$ is the radius and $f$ is the Coriolis parameter. Thus, $v$ may increase significantly as $r$ decreases if the fractional rate of loss of $M$ is appreciably less than the relative rate of decrease of the air parcel’s radius. In such circumstances, the increase in $v$ may be large enough for $v$ to exceed its local (gradient) value (say $v_g$) at the top of the boundary layer.

Since the rate of loss of $M$ per unit radial distance decreases with the number of spirals the air parcel makes for a given radial displacement, the rate is a monotonically decreasing function of the inflow speed. However, the loss rate increases monotonically as the surface drag and, thus, the frictional torque increase. If $v$ does exceed $v_g$ at some radius, the agradient force (the sum of the centrifugal, Coriolis, and pressure gradient forces) acting on an air parcel is positive and we say that the flow there is supergradient. If this happens, the agradient force combines with the radial frictional force to produce a rapid deceleration of inward-moving air parcels, whereupon the flow turns upward. As air parcels are expelled vertically from the boundary layer, they carry their tangential momentum with them and the positive agradient force drives them outward while approximately conserving their $M$. As a result, $v$ decreases as the air parcels adjust toward a new state of gradient balance above the boundary layer.

Whether or not $v$ does actually exceed $v_g$ at some inner radii can be ascertained only by doing a nonlinear boundary layer calculation or a full vortex simulation, although the foregoing considerations show this to be a plausible possibility. In fact, both simulations and observations of intensifying and mature TCs show regions of supergradient flow as the air decelerates radially in the boundary layer and turns upward into the eyewall (Bao et al., 2012; Smith et al., 2009; Montgomery et al., 2014). Recent papers emphasizing the role of the boundary layer spin-up mechanism are Montgomery and Smith (2014), Smith and Montgomery (2016a,b), Smith et al. (2017), and Kilroy et al. (2017b).

There has been recent debate on the importance of the boundary layer spin-up mechanism in the overall intensification of a TC (Heng and Wang 2016a; Heng et al., 2017; Smith and Montgomery 2016a; Montgomery and Smith 2018; Heng and Wang 2016b; Heng et al., 2018). The essence of the debate is twofold: 1) whether the boundary layer spin-up mechanism contributes significantly to the intensification of a TC or if it is just a fast adjustment processes to surface friction (Heng and Wang 2016a,b; Smith and Montgomery 2016a); and 2) whether the secondary circulation in a TC simulated in a full-physics model can be captured by the quasi-balanced symmetrical vortex dynamics (the linear Sawyer-Eliassen equation). Heng and Wang (2016a,b) considered that the boundary layer spin-up mechanism proposed by Smith et al. (2009) explains the formation of supergradient wind, a process that has been well-studied previously in the literature (e.g, Kepert 2001; Kepert and Wang 2001), and that the formation of supergradient wind (namely the boundary layer spin-up mechanism of Smith et al. 2009) is a fast adjustment process that could not be a major mechanism of TC intensification. Nevertheless, if the boundary layer spin-up mechanism articulated above is only attempted to explain the formation mechanism of supergradient wind in the TC boundary layer, the debate would be irrelevant and should not be a major issue at all.

Although the second issue is partly related to the first issue, the crux of the matter lies in the treatment of the numerical solution of the Sawyer-Eliassen equation. In order to obtain a converging solution, it is necessary to assure the ellipticity of the equation. The solution is also
sensitive to vertical resolution, and in particular, in the frictional boundary layer where the vertical gradient of flow is extremely large. Heng et al. (2017, 2018) showed that the solution based on the linear Sawyer-Eliassen equation could largely capture the secondary circulation in a TC simulated in a full-physics model, even in the boundary layer where the flow is largely unbalanced. This is in sharp contrast to the earlier results in Bui et al. (2009). Heng et al. (2018) clarified that although the balanced symmetrical vortex dynamics still underestimate the inflow in the frictional boundary layer to some extent, the underestimation does not affect the overall azimuthal mean tangential wind budget. That means that the quasi-balanced symmetrical vortex dynamics can largely explain the intensification of a TC. They also emphasized that the unbalanced boundary layer dynamics is key to TC intensification, mainly through modifying the strength and radial location of eyewall updraft and thus diabatic heating (see also Kepert 2017), but not in the way of the boundary layer spin-up mechanism articulated by Smith et al. (2009).

Thus, the key point of contention of recent debates is not on whether the unbalanced boundary layer dynamics are important to TC intensification, but on how the unbalanced boundary layer dynamics do so—whether this occurs through the spin-up of supergradient wind—or through its modification of the strength and radial location of eyewall updraft and thus diabatic heating. Therefore, future observational and numerical studies need to investigate the manner in which boundary layer dynamics contributes to eyewall updraft/convection.

e) Rotating-Convection Intensiveon Framework

Recent theoretical work has led to the development of a new framework for understanding both tropical cyclogenesis and TC intensification, the so-called rotating-convection framework. Reviews of this framework and its relationship to previous theories of TC behaviour are provided by Montgomery and Smith (2014, 2017), Smith and Montgomery (2016c), and Smith et al. (2017). In essence, the new description constitutes an overarching framework for interpreting the complex vortex-convective phenomenology in simulated and observed TCs. It is important to point out that this framework includes and generalizes the classical mechanism of Ooyama (1964, 1969, 1982) and the boundary layer spin-up mechanism (Smith and Vogl 2008; Smith et al., 2009; Montgomery and Smith 2014; Smith and Montgomery 2016a,b; Smith et al., 2017; and Kilroy et al., 2017b). The rotating-convection framework explicitly recognizes the presence of localized, rotating deep convection whose vorticity is amplified greatly over that of the broad-scale vortex circulation by vortex-tube stretching and tilting processes. The framework includes an azimuthally averaged description of storm behaviour that takes into account the effect of locally asymmetric (or eddy) processes. The framework can be framed in terms of absolute angular momentum or absolute vorticity.

From a vorticity perspective, an important mechanism for the intensification of an existing vortical circulation is the inward flux of absolute vorticity into the vortex in the lower troposphere brought about by inflow produced there by the collective effects of deep convection. This is, in essence, the classical mechanism for intensification articulated by Ooyama (1969), and is reviewed in detail in section 4 of Montgomery and Smith (2017). In an angular momentum framework, this mechanism is equivalent to the radial convergence of absolute angular momentum, which, in axisymmetric flow and in the absence of friction, is approximately materially conserved.
The rotating-convection framework has been used to interpret the dynamics in tropical cyclogenesis idealized numerical model calculations (Kilroy et al., 2016, 2017a,b, 2018; Kilroy and Smith 2017). Kilroy et al. (2017a) showed that there is no intrinsic difference between the dynamics of tropical genesis and intensification. The mechanism has been used also to interpret the development of tropical lows over land (Smith et al., 2015; Kilroy et al., 2016, 2017c; Tang et al., 2016) from a vorticity perspective using data provided by ECMWF analyses.

f) Summary of TC Intensification Mechanisms

Publications in the time period (2014–2018) covered in this synthesis focused largely on developments in three major intensification mechanisms: (i) balanced symmetrical intensification mechanism, (ii) wind-induced surface heat exchange (WISHE), and (iii) boundary layer spin-up mechanism. Additionally, a new rotating-convection framework has emerged, which combines several of these intensification mechanisms, along with previous historical ideas, into the new framework that recognizes that several intensification mechanisms act together in concert. The recent review papers (Montgomery and Smith 2014; Montgomery 2016; Smith and Montgomery 2016c; Montgomery and Smith 2017) have been quite beneficial in discussing some of the overarching similarities and distinctions between these mechanisms and their roles in various historical and recently-posited intensification frameworks. We recommend that future research continue this more holistic approach, especially focusing on methods to determine the relative contributions of these mechanisms to overall TC intensification, as well as to investigate whether there are complementary or competing interactions between the mechanisms. In particular, the role of the boundary layer dynamics in contributing to eyewall updrafts and convection needs to be investigated in future observational and numerical studies. To make more rapid progress, it is possible that more organized and coordinated efforts are needed. One path forward would be for scientists of competing theories and frameworks to team up together in a larger collaborative effort to resolve some of these long-standing debates. We recommend that funding agencies recognize this potential approach and design funding calls specifically toward this purpose. We further recommend that the WMO sponsor an international workshop in the near future to bring leading researchers together to review in more detail the issues involved in the controversy on intensification mechanisms and to develop a strategy for future international research collaboration to resolve these issues.

3.1.8 New and Emerging Research Topics

a) Introduction

Several new topics on internal influences on TC intensity change have emerged in recent years. In this section, we discuss some of the more prominent recent ideas, including: (i) the role of vortex structure on TC intensification rate, (ii) the maximum potential intensification rate (MPIR) of TCs, and (iii) the role of upper level outflow on TC intensity change.

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11 Smith and Montgomery (2016) is a review published in Weather that was written for the educated lay person, including forecasters.
b) Role of Vortex Structure on TC Intensification Rate

Carrasco et al. (2014) compared the RMW and AR34 of TCs that underwent RI versus those that slowly intensified or were steady state over a 24-h period for NA TCs during 1990–2010. They found that the intensity change was negatively correlated with both RMW and AR34. Xu and Wang (2015) examined the dependence of TC IR on SST, storm initial intensity (maximum sustained surface wind speed $V_{\text{max}}$), and storm size, in terms of the RMW parameter from the Automated Tropical Cyclone Forecast (ATCF) system b-decks\(^{12}\) for NA TCs. They found that, for NA TCs during 1988–2014, the TC IR depends strongly on storm intensity, the RMW, the average radius of gale-force wind, and the outer-core wind skirt parameter DR34 (= AR34 - RMW). Xu and Wang (2015) showed that TC IR increases with increasing storm intensity when TC $V_{\text{max}}$ was below about 70 to 80 kt (or 36.1 to 41.2 m/s), but decreases with increasing intensity afterwards (Fig. 3.1.25a), and that TC IR is negatively correlated with the RMW, AR34, and DR34 (Figs. 3.1.25b,c,d).

Figure 3.1.25. Scatter plots of subsequent 24-h IR vs. (a) storm intensity, (b) RMW, (c) AR34, and (d) DR34 in the NA from 1988 to 2012. Red and black curves are the 95th and 50th %-iles of IR for given storm intensity in (a) and size parameters in (b)-(d), respectively.

Figure 1 of Xu and Wang (2015).

\(^{12}\) It is important to note that the RMW parameter is not a “best-tracked” quantity in HURDAT2 or the ATCF b-decks. That is, it does not undergo the post-season analysis that other best-tracked parameters like track and intensity undergo. For more discussion on this issue, see Vigh et al. (2012) and the accompanying supplement.
Xu and Wang (2015) also found that RI can only happen in a relatively narrow range of the parameter space that includes the storm intensity, and both the RMW and AR34 (or DR34). More recently, Xu and Wang (2018a) extended the statistical analysis of NA TCs to WNP TCs during 1982–2015. Overall, similar to that in the NA, TC IR is positively (negatively) correlated with storm intensity when $V_{\text{max}}$ is below (above) 70 kt (36 m/s), and the TC IR is negatively correlated with the RMW. RI occurs only in a relatively narrow range of parameter space in storm intensity and both inner- and outer-core sizes, with the highest IR appearing for $V_{\text{max}} = 80$ kt (41.2 m/s) [compared with 70 kt (36 m/s) for the NA], RMW $\leq 40$ km, AR34 = 150 km, and DR34 = 100 km. The highest frequency of occurrence of intensifying TCs occurs for $V_{\text{max}} \sim 40–60$ kt (20.6–30.9 m/s), RMW $\sim 20–60$ km, AR34 = 200 km, and DR34 = 120 km.

To improve the representation of TC structure and its relationship to TC intensity and intensification, Guo and Tan (2017) proposed a new concept of TC ‘fullness’ to quantitatively measure the storm wind structure. The TC fullness is defined as the ratio of the extent of the outer-core wind skirt to the outer-core size of the TC. They found that TC intensity is more strongly correlated with fullness than with other measures comprising just a single size parameter, and rapidly increasing fullness favors the intensification of a TC. However, how the new parameter is connected to the dynamical characteristics of the TC vortex still needs to be more thoroughly understood.

The dependence the TC’s IR on its initial structure has been numerically studied based on ensemble simulations using an axisymmetric model (CM1) by Xu and Wang (2018b). The results show that a TC with an initially larger RMW, or with a slower radial decay of tangential wind outside the RMW, possesses lower inertial stability inside the RMW (or relatively higher inertial stability outside the RMW), and develops more active convection in the outer core region and weaker boundary-layer inflow. Such TCs experience a lower IR during the primary intensification stage, suggesting one possible explanation for the observed dependence of TC IR on TC size and structure.

Wang and Heng (2016) used idealized ensemble numerical simulations to evaluate the contributions of the near-surface high energy air in the TC eye to IR. They found that the near-surface high energy air in the eye contributes about 42% to the IR of a simulated TC, which is in sharp contrast to the 3-4% that such air contributes to the MPI. This was found to occur not through the enhancement of CBs in the eyewall, as had been previously hypothesized, but through initiation of convection near the inner edge of the eyewall. This new convection facilitates eyewall contraction and leads to higher inner-core inertial stability, and thus higher dynamical efficiency of eyewall heating in spinning up the tangential winds near the RMW. Since the near-surface high energy air in the TC eye is also determined by the surface wind distribution inside the RMW, the finding also strongly suggests that the inner core wind structure of the initial TC vortex is a key determinant of the future IR, in particular for those storms with relatively large eye size.

Although both SST and the initial storm intensity have been included in some operational statistical intensity prediction schemes (e.g. SHIPS; DeMaria et al., 2005; Kaplan et al., 2015), storm size parameters have not been considered in RI schemes (e.g. Rozoff et al., 2015). This might be partly due to the lack of a systematic analysis of the dependency of TC IR on storm structure and size based on observations, and partly due to the lack of accurate
measurements of storm size and structure parameters from observations. Note that although the RMW is currently estimated routinely in various ocean basins, the shape parameter for the radial tangential wind profile is not routinely provided in real time in any ocean basin. Nevertheless, results from Xu and Wang (2018b), together with those of Carrasco et al. (2014), Xu and Wang (2015), and Xu and Wang (2018a), strongly suggest that it is important to consider TC size parameters in statistical intensity prediction schemes, and to accurately represent the initial TC structure in numerical prediction models in order to achieve improved TC intensity forecasts (e.g. Kaplan et al., 2015; Bender et al., 2017).

c) Maximum Potential Intensification Rate (MPIR)

Since TC intensification and maintenance are controlled by similar physical processes, a natural extension of the MPI concept is the maximum potential intensification rate (MPIR), introduced by Xu et al. (2016). Based on the best track data of NA TCs (Landsea and Franklin 2013), they showed that SST exerts a strong control, not only the MPI, but also on the MPIR, with the latter reflecting the upper bound of IR that a TC can reach given favorable environmental conditions. They constructed an empirical relationship between the MPIR and SST for TCs over the NA based on the best track TC data and observed SSTs during 1988–2014. Similar to the empirical relationship between MPI and SST, the empirically fitted MPIR increases with increasing SST, with a more rapidly increasing trend when SST is higher than 27°C in the NA (Fig. 3.1.26).

Figure 3.1.26. (a) IR frequency (kt day$^{-1}$) and (b) lifetime maximum IR (IR$\text{max}$, kt day$^{-1}$) versus SST (°C) for NA TCs (1988-2014). Also plotted in (b) is the scatter diagram of IR$\text{max}$ (dots). Both panels include the empirically fitted MPIR (dashed blue, kt day$^{-1}$). Figure 3 of Xu et al. (2016).

More recently, Xu and Wang (2018a) also constructed an empirical relationship between the MPIR and SST for WNP TCs. The SST-determined MPIR shows a linear increasing trend of MPIR with increasing SST (for SSTs larger than 26°C). This is roughly consistent with the trend in the same SST range in the NA, although the MPIR–SST relationship in the NA is expressed as an
exponential function of SST with a sharp increase when SST is greater than 27°C (Xu et al. 2016). The empirically fitted MPIR is higher (lower) over SSTs above (below) 28°C over the WNP than over the NA, which is shown to be related to the weaker (stronger) environmental vertical wind shear (VWS) in regions with higher (lower) SSTs over the WNP than over the NA. Such differences are consistent with the different spatial distributions in the climatological SST and VWS. Results also show that only 10% (5.5%) of intensifying TC cases reached 40% (50%) of their MPIR and about 24% (15%) of TCs’ lifetime maximum IR (IR_{\text{max}}) reached 50% (60%) of their MPIR, and only 6% reached 80% of their MPIR. Almost all TCs reached their lifetime IR_{\text{max}} while experiencing moderate VWS of around 6–10 m s^{-1}. This was especially true for TCs with large IR_{\text{max}}, consistent with the well-understood fact that large VWS is generally unfavorable for TC intensification.

The preference of the lifetime IR_{\text{max}} to occur in moderate VWS is interesting and as yet, remains unanswered. It could be due to the fact that most TCs reached their lifetime IR_{\text{max}} after they reached relatively strong intensity [e.g. over 70 kt (36 m/s)], and thus are able to effectively resist the detrimental effect of moderate VWS. Another possible explanation could be due to the fact that moderate deep-layer VWS is common in the tropics where SST is high (Wang et al. 2015; Finocchio and Majumdar 2017). As a result, SST could dominate VWS in controlling the TC IR under the condition of moderate VWS. Nevertheless, the results provide observational evidence for the existence of the MPIR for TCs, and this suggests that it should be possible to develop a theoretical MPIR. On the other hand, although SST is one of the most important parameters for TC intensification, the relationship between SST and TC IR varies considerably from basin to basin, with SST explaining less than 4% of the variance in TC IRs in the NA, 12% in the WNP, and 23% in the eastern Pacific. Several factors are shown to be responsible for these inter-basin differences. This variation can be explained as smaller horizontal SST gradients in the NA, and SST tends to vary out of phase with VWS and outflow temperature in the WNP (Balaguru et al., 2015; Foltz et al., 2018).

![Figure 3.1.27. Frequency of TC IRs (kt day^{-1}) against TC intensity (V_{\text{max}}, knot) for the WNP TCs (1982-2015). The fitted 95th percentiles as a function of SST for three 1.5°C intervals of SST starting at 27, 28, and 29°C are shown as black, red, and green curves, respectively. Note that for the SST ranges given in the legend, “(“ means “greater than”, “]” means “less than or equal to”. Figure 6 of Xu nd Wang (2018a).](image-url)
Note that the intensity dependence of IR in observations (Fig. 3.1.26a) could be partially contributed by the dependence of IR on SST. Therefore, in a more recent study, Xu and Wang (2018a) discussed the frequency distribution of all intensifying TC cases and also TC cases in specified SST ranges for the intensity dependence of IR for WNP (Fig. 3.1.27, a similar result can be obtained for NA TCs, not shown). It confirms that the intensity dependence of IR does not result from the dependence of IR on SST. Furthermore, higher SST corresponds to higher IR and also higher MPIR, which also shifts toward the higher TC intensity side. For the SST above 27°C, the MPIR is the largest for TCs with $V_{\text{max}}$ around 60 to 70 knots, which is similar to that observed for NA TCs (Figure 1a). Note that in these previous studies, emphases have been on the top 95th percentiles because the studies have attempted to reveal the intrinsic IR with minimum negative effects from strong external influences as discussed below. The recent results thus strongly suggest that the intensity dependence of TC IR and the dependence of MPIR on SST are both determined primarily by internal dynamics. However, neither of them can be inferred from the current IR theory.

The empirical MPIR was shown to increase with the SST under the TC, or equivalently, to increase with the MPI of the TC itself, because the MPI is largely determined by SST. Xu et al. (2016) also found that the empirical MPIR depends roughly linearly on the MPI computed from observations. However, the existing IR theory predicts the MPIR as a function of the square of MPI at $V_{\text{max}} = 0$ (Emanuel 2012; Ozawa and Shimokawa 2015). This means that current IR (and MPIR) theory does not adequately reproduce the dependence of the MPIR on TC MPI and TC intensity in observations. The discrepancy in the MPIR dependence on storm intensity between the current theory and observations suggests that some dynamical processes key to TC intensification could be missing in the current theory, or that some assumptions are too restrictive and not suitable for the early intensification stage for which the theory was developed. Motivated by the observed dependence of TC MPIR on storm intensity and MPI, Wang et al. (2016) introduced an energetically-based MPIR theory (unpublished conference presentation). They used the MPI model of Emanuel (2012), and as in Ozawa and Shimokawa (2015), but instead of focusing on the steady-state maximum intensity for which power generation and power dissipation are equal, they examined the unsteady period of

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**Figure 3.1.28.** Schematic showing power dissipation (blue curve) and power generation (red curve) as functions of 10-m sustained wind speed in a typical TC. The pink shaded area indicates the power available for the TC to intensify up to its MPI (modified from Wang 2012, 2015).
intensification when power generation exceeds dissipation (Fig. 3.1.28). From this approach, an energy gain rate is obtained, from which the MPIR is found. The new ingredient of their MPIR theory is the introduction of a dynamical efficiency of the Carnot heat engine, which is parameterized as a function of the inner-core inertial stability of the TC based on the best track TC data instead of the constant 70% value used in Ozawa and Shimokawa (2015). Since the energetically-based MPIR theory does not include any detailed dynamics, it is likely that an alternative MPIR theory could be further developed, which could provide useful for the upper bound of TC intensity forecasts. Considerable further research is needed in this area.

d) Role of TC Outflow on Intensity Change

In recent years, there has been a renewed interest in the role of outflow on TC intensity change. The TC’s deep convective mass flux, which is processed through the inner-core region, is then exhausted to the environment at upper tropospheric levels through asymmetric outflow jets. Such jets exist because the TC outflow follows the path of least resistance, which tends to be regions of weak inertial stability (Rappin et al. 2011). Often, either (or both) an equatorward and a poleward jet may exist at some point in the TC life cycle. The linkage of the internally-forced TC outflow with the environment through these jets, and their role in intensity change, has been a subject of recent interest, building on earlier work (e.g., Merrill 1988a,b). Field campaigns have occurred in recent years, obtaining new unique measurements of the upper levels over the TC. The 2012–2014 HS3 (Braun et al. 2016) used an unmanned Global Hawk (GH) aircraft to take long-duration measurements of the outflow and below using both in-situ and remote measurements. The TCI (Doyle et al. 2017) used a manned WB-57 aircraft with a new dropwindsonde system to measure the critical outflow region at high horizontal and vertical resolution. Building on HS3, the National Oceanic and Atmospheric Administration (NOAA) Sensing hazards with operational unmanned technology (SHOUT) field campaign was conducted in 2015–2016 using the GH to obtain measurements through the troposphere from the outflow layer to the surface.

The mechanism by which TCs undergo internal intensity change through outflow dynamics is currently not well understood. As evidence of the potential importance of outflow in intensity change, Emanuel (2012)’s modification of WISHE hypothesized that small-scale turbulence in the outflow region can set the outflow temperature and thermal stratification, and thus affect maximum potential intensity and intensity change. Recently, there has been renewed debate on the active versus passive outflow scenarios (Komaromi and Doyle 2018). In the passive scenario, the outflow is a slave to the underlying vortex, and does not feed back to the vortex to affect the intensity change. In the active scenario, upper level forcing can enhance TC outflow, and through secondary circulation changes, affect the intensity change of the low-level vortex. Recent results from idealized modeling suggest that radiative forcing in the outflow may play an important role in TC intensity change (Navarro and Hakim 2016; Navarro et al. 2017). It is expected that as a result of the recent field campaigns described above, new research on understanding the role of outflow on TC intensity change will be obtained in the future.
Summary of Emerging Research Topics

Three new emerging topics on internal influences on TC intensity change were discussed. The first topic emphasizes the critical role of vortex structure on the subsequent IR. In particular, the highest IRs are observed to occur in a relatively narrow subrange of the parameter space [i.e., $V_{\text{max}} \sim 40$–60 kt (20.6–30.9 m/s), $R_{\text{MW}} \sim 20$–60 km, $AR_{34} = 200$ km, and $DR_{34} = 120$ km]. Results strongly suggest that it is important to consider TC size parameters in statistical intensity prediction schemes, and to accurately represent the initial TC structure in numerical prediction models in order to achieve improved TC intensity forecasts. The second topic seeks to understand the factors setting the upper bound on the IR (the MPIR) using observational and theoretical approaches based on energetics. The TC intensity, SST, and MPI all appear to be important, but the current theory is inadequate to fully explain the MPIRs of observed TCs. The final topic emphasizes the possible role of TC outflow on the IR, and whether active or passive outflow is a dominant factor. In closing this subsection, we recommend that substantial future research further investigate the broad theoretical and numerical basis for ideas such as the MPIR of TCs and the relationship between vortex structure (including the outflow) and IR.

3.1.9 Overall Summary and Conclusions

This report summarizes approximately 177 peer-reviewed publications during the 2014–2018 period to assess progress in understanding of internal influences on TC intensity change. The subject of internal influences on intensity change covers a wide range of dynamical and physical aspects, ranging from the role of rainbands, shallow convection, CBs, ERCs to aspects of inner core instability and mixing, and surface fluxes. This report also includes special sections on RI and intensification mechanisms, as well as several new topics that have recently emerged, such as the role of TC outflow, the role of vortex structure on a TC’s IR, and a new theory for what sets the fastest rate at which TCs may intensify. A brief overview of the developments in each of these areas is now given.

The issue of RI has been a considerable focus of researchers in the past few years, with 60 publications touching on this topic. One aspect that has recently received more appreciation is on how the definition of RI impacts the framing of the study. While many statistical studies have used a case-based definition [e.g., a 30 kt (15.4 m/s) increase in intensity in 24 h], it has recently been recognized that RI is an event which can last up to 78 h or longer. Thus, it is important to study the various stages of an RI event to learn more about what types of structures and dynamical processes are involved in initiating, sustaining, and terminating RI in TCs. Recent work has bolstered earlier findings that increased and widespread shallow convection around the storm center is a first indication of RI and can be used as a predictor for the onset of RI. A common theme among many observational satellite-based studies is that a high degree of axisymmetry is associated with the subsequent RI, however other case studies using aircraft observations and numerical simulations have recognized asymmetric pathways to RI, with inner core CBs and HTs recognized as important factors. Recent studies using lightning data have resulted in new understanding through detailed analysis of the radial and azimuthal distribution and movement of CBs before and during RI. Despite extensive research on the RI topic, many uncertainties remain regarding how to better simulate and predict the onset and continuation of RI.
SEFs and ERCs have long been recognized as important modulators of TC intensity change. By 2014, observational studies had established the basic climatological understanding of ERC influences on intensity change. Since 2014, the climatological understanding of ERCs has been updated to provide additional details on the wind-pressure-relationship, recognizing distinctly different behaviors between less intense and more intense TCs. This improved climatological knowledge has recently been applied to operational forecasting via the E-SHIPS statistical model. New studies have also increased understanding of non-canonical ERC events, such as those in which there are only subtle intensity changes. The increasing capability of numerical models to simulate ERCs, both in idealized and operational settings, has lead to new appreciation of the dynamical processes and associated uncertainties with respect to: the onset time of SEF and ERC, the location and contraction speed of the outer eyewall, the dissipation (intensification) rate of the inner (outer) eyewall, and the duration of ERC events. While accurate deterministic predictions of the impact of ERCs remain elusive, the improved understanding that has resulted from these various lines of investigation is leading to more accurate intensity forecasts through techniques such as E-SHIPS.

Spiral rainbands comprise a major portion of the TC and their structural characteristics play significant roles in TC structure and intensity change. Recent observational work has found that outer rainband lightning is positively correlated with subsequent 24-h TC intensity change. Idealized numerical simulations have demonstrated that convective heating in the inner rainband region generally promotes intensification, while stratiform cooling in inner rainbands tends to hinder TC intensification. Evaporation of raindrops in the outer rainband region tends to suppress the final TC intensity, but these effects are not significant in inner rainbands. Despite these advances, considerable uncertainties still remain in the understanding of the interactions between spiral rainband behavior (particularly microphysical processes within rainbands) and other TC components, and how these interactions affect TC intensity change.

Recent work has extended numerical analyses of inner core instability processes from 2D barotropic frameworks to more realistic 3D frameworks that include moisture and parameterized mass sinks. Whereas, barotropic instability in a 2D framework leads to deepening of the pressure deficit but a decrease in intensity, results from simulations in more realistic frameworks show that instability processes may cause intensification under certain assumptions. Considerable uncertainty remains as to whether the secondary circulation prevents relaxation of the vortex to a monopole (or how quickly it might restore the vortex back to an annular state) and as to the effects of moist convective processes on instability. Additional studies examined other types of instabilities caused by spontaneous IG radiation from VR waves. More work is needed to understand the longer-term and nonlinear effects of VR-IG instability on the vortex evolution. Because the PV structure is critical in understanding the vortex state (annular vs. monopole) during instability mixing events, future research should consider observational strategies to better assess the PV structure of TCs.

Surface fluxes play an essential role in providing latent heat to the TC core where energy is converted into kinetic energy, as well as in dissipating kinetic energy through friction. As a result, TCs are largely controlled by surface enthalpy and momentum fluxes. Advances in both modeling and observing surface fluxes have improved our understanding of the relationships between TC intensification and the drag and enthalpy coefficients, as well with the SST response. In particular, recent work suggests that the wind-speed dependence of the drag
coefficient, with a minimum near 60 m s⁻¹, may partially explain why many TCs intensify rapidly between 35 and 60 m s⁻¹, but tend to weaken soon after reaching Category 5 intensity. Despite progress over the last four years, considerable uncertainties still remain and the research advancements still need to be transitioned to operations.

The mechanisms by which TCs intensify has been a hotly debated area of research. From the first descriptions of TC intensification frameworks more than 60 years ago, the community has seen various major frameworks arise, such as the CISK framework (involving cooperation between convection and the vortex scale), the WISHE mechanism (wind-induced surface heat exchange), the balanced, symmetric mechanism, and most recently, the rotating convection framework (rotating small-scale convection in conjunction with boundary layer spin-up). Many of these frameworks have built upon previous frameworks, adding refinements or descriptions of new intensification mechanisms that operate in conjunction with previously-described mechanisms. Nevertheless, vigorous debate is still occurring as to the suitability of using balanced frameworks to understand intensification, whether or not WISHE is an essential part of TC intensification, and the exact role of the boundary layer in TC spin-up. Despite more than 40 additional studies on intensification mechanisms in this period, very considerably uncertainty remains.

This report also covered three new emerging topics on internal influences on TC intensity change. The first topic emphasizes the critical role of vortex structure on the subsequent IR. Through analyzing past observed TCs, as well as numerical simulations, the phase space of IR dependence on initial intensity, SST, RMW, and size was explored. These results showed that the fastest IRs occurred in a relatively narrow subrange of the parameter phase space at relatively low initial intensities and small to modest vortex scales [i.e., Vmax ~ 40–60 kt (20.6–30.9 m/s), RMW ~ 20–60 km, AR34 = 200 km, and DR34 = 120 km]. This finding has motivated development of new ideas on the factors that set the upper bound on the IR (the MPIR) from an energetics perspective. The third topic emphasizes the possible role of TC outflow on the IR, and whether active or passive outflow is a dominant factor.

In conclusion, significant advances in understanding of internal influences on TC intensity change have been made over the past four years. With several notable exceptions, these advances have been largely incremental, and have been spurred by new observations, more sophisticated numerical simulation approaches, and through new lines of theoretical development. Below, we offer recommendations for new research directions and strategies that might be undertaken to make even more rapid progress in the coming years.

### 3.1.10 Recommendations

A number of recommendations have been made by the WG, as follows:

1. We recommend that future research directions focus on: a) studying RI as an event (rather than a 24-h case-based RI definition), b) improving understanding of the conditions and precursors to RI through symmetrical processes, and c) reconciling seemingly conflicting findings on the conditions and processes in which asymmetric inner-core CBs and HTs may lead to RI precursors.

2. Continued advancements and diagnostics and testing activities are needed in NWP models to improve the accuracy of SEF and ERC event timing and the associated
intensity changes. We recommend that such efforts incorporate non-standard evaluation metrics beyond track, intensity, and wind structure, such as the explicit prediction of eyewall and secondary eyewall structure.

3. We recommend that specific, targeted observational and modeling investigations be undertaken to better understand interactions between spiral rainbands and their parent TCs and the specific mechanisms by which rainbands influence TC intensity.

4. Because the PV structure is critical in understanding the vortex state (annular vs. monopole) during instability mixing events, we recommend that future research consider observational strategies to better assess the PV structure of TCs. We also recommend that structure databases include observable markers of mixing processes (eyewall mesovortices as seen in satellite imagery and radar imagery). In general, researchers would benefit from mesoscale analyses of well-observed cases.

5. Advances in both modeling and observing surface fluxes have improved our understanding of the relationships between TC intensification and the drag and enthalpy coefficients, as well as the SST response, however considerable uncertainties still remain. We recommend that new observational platforms be devised and routinely deployed to continue advancing understanding of surface fluxes, and that the resulting knowledge be transitioned to operations.

6. Much recent work has been undertaken on intensification mechanisms, however considerable knowledge gaps remain as to the role of different mechanisms. In particular, the role of the boundary layer dynamics in contributing to eyewall updrafts and convection, as well as in supergradient spin-up, needs to be investigated in future studies based on observations and numerical simulations. To speed up progress in reconciling current debates, we recommend that scientists with competing theories and frameworks team up together in a larger collaborative effort to resolve long-standing debates. We recommend that funding agencies recognize this potential approach and design funding calls specifically toward this purpose.

7. We further recommend that WMO sponsor an international workshop in the near future to bring leading researchers together to review in more detail the issues involved in the controversy on intensification mechanisms and to develop a strategy for future international research collaboration to resolve these issues.

8. In light of substantial new lines of investigation on the role of vortex structure, outflow, and other environmental influences on the IR of TCs, we recommend that substantial future research further investigate the broad theoretical and numerical basis for ideas such as the MPIR of TCs and the relationship between vortex structure (including the outflow) and IR.

9. With the finding that the TC IR depends critically on the structure of the vortex, we further recommend that statistical-dynamical intensity prediction schemes consider TC size parameters and that significant efforts continue to be made to ensure that numerical prediction models represent the initial TC structure as accurately as possible.
Primary contributors to each section

This report would not have been possible without the diligent work and substantial contributions of the WG members. Following is a list of the primary contributors to each main section of the report. For each section, WG members are listed in author-order by the degree to which they contributed to writing and editing.

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3.1.4 Relation of Rainbands to Intensity Change
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3.1.5 Eyewall Instability and Inner-Core Mixing
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3.1.6 Relationship between Surface Fluxes and Intensity Change
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3.1.7 Mechanisms of Tropical Cyclone Intensification
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3.1.8 New and Emerging Research Topics
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Acknowledgments

We are grateful to Chun-Chi (Maggie) Lien (National Taiwan University) for creating the list of 3417 papers that have published on tropical cyclones since 2014. We also thank her for sharing a detailed explanation of the technique that was used to create this list.

Acronyms used in the report

AAM – Absolute angular momentum
AGM – Atmospheric general circulation model AMV – Atmospheric Motion Vector
ANHM – Atmospheric Nonhydrostatic Model
ARCHER – Automated Rotational Center Hurricane Eye Retrieval AR34 – Average 34-kt wind radius
ARW – Advanced Research WRF
ATCF – Automated Tropical Cyclone Forecast (ATCF) system CAPE – Convective available potential energy
CB – Convective burst
CIMSS – Cooperative Institute for Meteorological Satellite Studies
CISK – Conditional instability of the second kind
CM1 – Cloud-resolving Model 1
CPS – Convective precipitation shield
CReSS-NHOES – Cloud Resolving Storm Simulator-Non-Hydrostatic Ocean model for the Earth Simulator
DR34 – outer-core wind skirt parameter (DR34 = AR34 - RMW)
ECP – Eastern and Central Pacific
ERC – Eyewall replacement cycle
GFS – Global Forecast System
GH – Global Hawk
GSMaP – Global Satellite Mapping of Precipitation
HURDAT2 – Hurricane database
HS3 – Hurricanes and Severe Storms Sentinel
HT – Hot tower
HWRF – Hurricane Weather Research and Forecasting
IG – Inertia-gravity
IR – Intensification rate
ITOP – Impact of Typhoons on the Ocean
IWTC – International Workshop on Tropical Cyclones
JMA – Japan Meteorological Agency
JTWC – Joint Typhoon Warning Center
MAE – Mean absolute error
MERRA – Modern Era Retrospective-analysis for Research and Applications
MI – Microwave imagery
M-PERC – Microwave-Based Probability of Eyewall Replacement Cycle
MPI – Maximum potential intensity
MPIR – Maximum potential intensification rate
NHC – National Hurricane Center
NHM – Nonhydrostatic model
NA – North Atlantic
NASA – National Aeronautics and Space Administration
NOAA – National Oceanic and Atmospheric Administration
OHC – Ocean heat content
ONR – Office of Naval Research
PBL – Planetary boundary layer
PI – Potential intensity
POD – Probability of detection
PR – Precipitation radar
PV – Potential vorticity
PVB – Positive vorticity band
RI – Rapid intensification
RMC – Radius of maximum convergence
RMW – Radius of maximum winds
RSME – Root mean squared error
RW – Rapid weakening
ROCI – Radius of outermost closed isobar
SCAPE – Slantwise convective available potential energy
SEF – Secondary eyewall formation
SHIPS – Statistical Hurricane Intensity Prediction System
S-RMW – Steady-state radius of maximum winds
SHOUT – Sensing Hazards with Operational Unmanned Technology
SST – Sea surface temperature
SVM – Support vector machine
SW – Shallow water
SWIO – Southwest Indian Ocean
TC – Tropical cyclone
TCHP – Tropical cyclone heat potential
TCI – Tropical Cyclone Intensity
TIL – Tropopause inversion layer
TRMM – Tropical Rainfall Measurement Mission
VMAX – Maximum sustained wind near surface
VR – Vortex Rossby
VRW – Vortex Rossby wave
VWS – Vertical wind shear
WG – Working Group
WISHE – Wind Induced Surface Heat Exchange
WMO – World Meteorological Organization
WNP – Western North Pacific
WPR – Wind pressure relationship
WRF – Weather Research and Forecasting
WWLLN – World Wide Lightning Location Network
References


TOPIC 3.2 - INTENSITY CHANGE: EXTERNAL INFLUENCES

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Abstract
This report focuses on recent (2014-2018) advances regarding external influences on tropical cyclone (TC) intensity change. Special attention is given to the influences of sea-surface temperature (SST) and ocean heat content, vertical wind shear, trough interactions, dry and/or dusty environmental air, and situations in which multiple factors may act in concert to impact TC intensity change. Studies on ocean interactions highlight the important roles of warm- and cold- core eddies, as well as freshwater plumes and coastal barrier waters, in the modification of surface fluxes and their impacts on intensity. Studies of the impact of vertical wind shear highlight the role that shear plays in modulating the structure and intensity of inner-core convection and its feedback to intensity. Vertical wind shear also significantly impacts the predictability of TC intensity, likely because of its interaction with the convection and TC vortex. While dry environmental air is often an inhibiting influence, the response of a TC can be varied, with dry air in some situations actually favouring intensification and in other cases preventing secondary eyewall formation and the associated impacts on intensity. The effects on storm intensity of aerosols, especially in the Saharan Air Layer, remains a source of significant uncertainty. Complex interactions between the various environmental influences on intensity can affect the timing of rapid intensification (RI), with vertical wind shear often decreasing the likelihood of RI, but SSTs, dry air, convection, and the TC vortex contributing to significant uncertainty in the timing of RI. Rapid weakening typically occurs when a TC crosses over a sharp SST gradient, experiences increasing wind shear, and drier environmental air. Finally, multiple modes of variability, including the Pacific Decadal Oscillation, El Niño Southern Oscillation, and the Madden-Julian Oscillation are found to influence TC intensification.

3.2.1 Introduction

Much like tropical cyclogenesis, TC intensity is greatly impacted by the storm environment, aspects of the ocean or atmosphere that exist independent of the storm, typically on meso- to synoptic spatial scales. Critical processes related to the environment include ocean interactions [related to sea-surface temperature (SST) and ocean heat content (OHC)], vertical wind shear, humidity, and potentially aerosols-cloud-precipitation interactions. These basic processes are often tied to specific oceanic features (e.g. warm/cold-core eddies, seasonal or interannual SST anomalies) and weather systems (upper-level troughs/lows, or modes of large-scale tropical variability, Saharan air layer outbreaks). This section focuses on these environmental, or external, influences on TC intensity change and is organized as follows. The first several
sections (3.2.2-3.2.5) highlight individual topics such as the impacts of ocean processes, vertical wind shear (VWS), trough interactions, dry air, and aerosol interactions. Since most storms are not impacted just by a single process, but by a combination of these processes, Section 3.2.6 summarizes findings related to multi-factor influences such as joint ocean-VWS or VWS-dry air impacts and the influences of large-scale modes of variability such as El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and Madden-Julian Oscillation (MJO).

### 3.2.2 Ocean influences

The findings of this group of papers with respect to oceanic impacts on TCs focused on SSTs, warm- and cold-core eddies (WCE, CCE), climate variability such as El Niño, and climate change. The impact of mesoscale ocean eddies on tropical cyclone intensities was assessed by Ma et al. (2017) using a combination of observations and coupled models. The SST data showed that CCEs tend to promote cooling given that the thermocline lies closer to the surface whereas TC interaction with WCEs points to small SST decreases as the depth of the thermocline is much deeper. Moisture disequilibrium induced by the WCE is track dependent and vanishes after departure of the TC due to the dependence of surface fluxes on wind stress. Jaimes et al. (2016) found that North Atlantic Hurricane Isaac (2012) strengthened as it moved over a WCE, with sea-surface warming (positive feedback mechanism) of 0.5 K measured over a 12-h interval and with enhanced enthalpy fluxes during this intensification stage (Fig. 1). Enthalpy fluxes were enhanced during Issac’s intensification stage due to an increase in moisture disequilibrium between the ocean and atmosphere over the WCE. This enhanced buoyant forcing from the ocean is an important intensification mechanism in TCs over WCEs.

![Figure 1. Best track of Isaac (black: Tropical storm; green: Cat 1 Hurricane) relative to the complex ocean circulation and ocean heat content in the Gulf of Mexico from Meyers et al. (2014) for 25 August 2012 (WCE: Warm core eddy; CCE Cold core eddy; LC: Loop Current). (From Fig. 1 of Jaimes et al. 2016)](image-url)
As shown in Fig. 2, Walker et al. (2014) found that slow translation over a CCE caused the rapid collapse of Northeast Pacific Hurricane Kenneth (2005) as sea surface cooling caused enthalpy fluxes to become negative, cutting off fuel to Kenneth (e.g. the time available for mixing/upwelling is longer for slower speeds). This study challenged the notion that Kenneth’s weakening was due only to VWS (Pasch 2006).

Figure 2. SST on 15 Sept 2005 and hurricane Kenneth track (14-30 Sept) where intensity are shown with coloured circles. The 26°C isotherms reveal limits to Kenneth’s development and triangles depict CCE locations from 21 Sept to 1 Oct. The white box depicts the area shown in panels for SSTs (panels a,b,c) and sea-surface height anomaly (SSHA) (panels e,f,g) on 16, 21 and 27 Sept respectively relative to 6-hr positions and intensity of Kenneth. Panels d,h depict the along-track time evolution of SST and SSHA where the stars are the position on 16 and 21 Sept. respectively. Notice the extreme cooling on 21 Sept in panel b.

(From Fig. 1 of Walker et al. 2014)

Several papers (Newinger and Toumi 2015; Androulidakis et al., 2016; Yang and Wang 2017) examined TC interaction with fresh water river plumes and barrier layers that include the effects of both salinity and temperature. In general, fresh water can increase stability and may reduce TC-induced cooling; hence, they may be more favourable for TC intensification. However, Newinger and Toumi (2015) found that an additional factor, ocean colour, also needs to be considered. In the river plume region, the turbid-coloured plume can block sunlight from the deeper ocean, thus cooling the upper subsurface ocean (typically ~0.3 K in the upper 100-m temperature). They found that this negative impact from ocean colour can offset the positive impact from fresh water on TC intensification.
TC interaction with coastal waters is of high interest because most existing studies focus on interactions over the open ocean. Seroka et al. (2016) reported that due to coastal baroclinic processes, there can be significant ahead-of-the-eye cooling of >6 K in the Mid-Atlantic Bight, which explained Hurricane Irene’s (2011) rapid decay prior to landfall. They emphasized the need for improved representation of coastal processes in current TC coupled forecasting models since rapid and significant intensity change just prior to landfall can have large implications for disaster mitigation.

As noted by Foltz et al. (2018), SST and TC intensification relationships vary considerably from basin to basin as suggested in previous studies. For example, SST explained less than 4% of the variance in TC intensification rates in the Atlantic, 12% in the Western North Pacific, and 23% in the Eastern Pacific. While along-track SST variability is lower in the Atlantic due to smaller horizontal gradients compared to the Pacific, along-track gradients in OHC are quite large in the Atlantic basin, which can lead to strong air-sea interactions as recently observed in Hurricane Isaac (see Fig. 1). The more important rationale in the Western Pacific is that SST tends to vary out of phase with VWS and TC outflow temperatures (higher SST with lower VWS and lower outflow temperatures, all leading to greater intensification). Presumably, this strengthens the relationship between SST and TC intensification more in the Western Pacific than in the Eastern Pacific or Atlantic.

Foltz and Balaguru (2016) studied the El Niño conditions of 2014–2015 and the rapid intensification (RI) of Hurricane Patricia in the Eastern Pacific. Warm SSTs with a deeper than normal thermocline contributed to Patricia's RI, leading to an increase in its maximum potential intensity by 14 m s⁻¹. In this oceanic regime where Patricia intensified, SST was 1.5 K higher and sea-surface height was 10–14 cm higher compared to conditions during the last extreme El Niño in 1997, emphasizing the extraordinary nature of the 2015 anomalies. As shown in Fig. 3, the OHC was almost double that during normal El Niño conditions (Rogers et al., 2017). Within this climate context, Fraza and Elsner (2015) found a longer-time-scale influence of SST on intensification in North Atlantic hurricanes from 1986–2013. After removal of cooler SSTs and slower translation speeds, on average, mean intensification of TCs increases by about 16% for every 1-K increase in mean SST. A clustered region where the model underpredicts intensification is noted over the southeastern Caribbean Sea, perhaps related to the fresh-water plume that sets up a strong salinity gradient across the oceanic barrier layer from the Orinoco River (Rudzin et al., 2017, 2018).

![Figure 3. Depth of the 26°C isotherm (m: upper panel) and OHC (kJ cm⁻²: lower panel) from and average of El Niño years (02,04, 06, 09: black curve) and a one standard deviation average (gray) relative to the 2015 El Niño at 104.5W, 17.5N along Patricia’s track. Notice OHC is double that of previous El Niño years. (From Fig. 7 of Rogers et al. 2017)](image-url)
Hegde et al. (2016) studied the role of remote-ocean SST in regulating Typhoon Man-Yi (July 2007) using an uncoupled regional-scale model by adding and subtracting 3 K from the “real” SST over the Indian Ocean and the South China Sea. In the Indian Ocean, warm oceans can substantially reduce the intensification of Western North Pacific cyclones, whereas cool oceans can enhance their strength. This effect is intimately associated with the enhancement/weakening of the moisture supply through the moisture conveyor belt (MCB) in the lower troposphere (Fig. 4) from the Indian Ocean and South China Sea into the vicinity of the cyclone center. In the warmer ocean experiments, the MCB is not as well developed compared to that of the cold SST experiments in the Indian Ocean. It would be interesting to revisit these results using a coupled model.

Figure 4. Spatial patterns of sea-level pressure (SLP, contours) and vertically integrated moisture flux (colour) for warm (left) and cold (right) experiments ranging from ±3°C (top), ±2°C (middle) and ±1°C (bottom) and their impact on the typhoon in the Western Pacific from sensitivity experiments at 1200 UTC 12 Sept 2007. Note the moisture flux of less than 7000 kg m⁻¹ s⁻¹ are suppressed. (From Fig. 7 of Hegde et al. 2016)

A number of record-breaking TCs have been observed in the past few years, including Supertyphoon Haiyan (2013) in the Western Pacific and Hurricane Patricia (2015) in the Eastern Pacific. Haiyan reached a peak intensity of 87 m s⁻¹ (170 kt) and Patricia 95 m s⁻¹ (185 kt), both 10–15 m s⁻¹ (20–30 kt) higher than most category-5 TCs. Lin et al. (2014), describing Haiyan as a “Category 6” storm, suggested that Haiyan’s extraordinary intensification was associated with a multi-decadal La Niña-like condition. They argued that the upper ocean heat content increased by ~20% (Fig. 5) because of the strengthening of the easterly wind, which piled up warm water to the east of the Philippines, thereby creating conditions to support Haiyan’s intensification. Huang et al. (2017) also quantified the important role that natural climate variability plays in setting up unique ocean preconditions to fuel these record-breaking events. They argued that improved prediction of ocean pre-storm conditions is a prerequisite for improved intensity prediction of these record-breaking events.

Contrary to La Niña or La Niña-like conditions, which increase OHC over the western Pacific, Zheng et al. (2015) reported that ENSO can greatly reduce OHC by ~20–30%. This reduction
in OHC can offset the favourable conditions due to longer-traveling distances over ocean for
western Pacific typhoons during ENSO, and help reduce intensification of typhoons.

Huang et al. (2015) pointed out that the ocean subsurface environment can be much different
under global warming conditions. Specifically, the gradient of the upper-ocean (top 200 m)
thermal profile sharpens, leading to increased stratification. As a result, TC self-induced ocean
cooling may increase ~10–20% from current conditions associated with global warming.
Because this cooling effect is a negative influence on TC intensification, it may partially
counteract the upward trend in TC intensity associated with warming SSTs. A follow-up study
by Emanuel (2015) confirms this negative impact. Emanuel found that if this new factor is
considered, then under global warming the frequency of category 5 TCs will be 15% less than
under existing projections that do not consider this new effect. Emanuel also reported a 13%
decrease in TC Power Dissipation Index (PDI) if this new factor is included (Fig. 6).

Figure 5. Time series (1993–2013) of the typhoon-season averaged depth of the 26°C
isotherm (D26) and Tropical Cyclone Heat Potential over the western Pacific TC Main
Development Region (122-180°E, 4-19°N) to the east of the Philippines. Both parameters
have increased significantly over the 21-year period. (From Fig. S7 of Lin et al. 2014)

Figure 6. Power dissipation (m³ s⁻¹) time series for upper-ocean thermal structure
that is fixed (blue) and variable (red). Results are obtained for the western North Pacific by
downscaling seven global climate models assuming RCP8.5 emissions. The solid curves and
dashed lines represent the multi-model means and linear trends, respectively, while the
shading indicates the standard deviations among the seven models.
(From Fig. 2 of Emanuel 2015)
Vertical wind shear and TCs

Vertical wind shear is one of the most influential factors on TCs. The processes associated with shear are fundamentally three dimensional, i.e. asymmetric processes are critical, and the remaining uncertainties about VWS processes make them a frequent topic of research. Two main themes arose within research over the past four years: 1) the influence of VWS on convection and precipitation within TCs and the feedback to intensification, and 2) other influences of VWS on TC vortices, including sensitivity to the vertical profile of VWS, the effects of asymmetries in wind and notion was questioned by several studies examining airborne data sampled during Hurricane Earl (2010), all of which showed deep convection in the upshear-left quadrant associated with a mid-tropospheric vortex before the onset of intensification (Stevenson et al., 2014; Rogers et al., 2015; Susca-Lopata et al., 2015).

Following the onset of deep upshear-left convective activity, a more symmetric convective structure was evident during Earl’s rapid intensification (RI; Rogers et al., 2015; Susca-Lopata et al., 2015). Other observed TCs that intensified in the presence of moderate VWS also exhibited deep updrafts leading to a more symmetric convective structure, including Typhoon Ida (1958; Kanada and Wada, 2015), Typhoon Megi (2010; Li et al., 2016), and Hurricane Edouard (2014; Rogers et al., 2016; Zawislak et al., 2016; Leighton et al., 2018). A detailed analysis of airborne data from multiple TCs confirmed that intensifying TCs are associated with more frequent, deeper, and thermodynamic fields, and the influence of VWS on predictability. These topics are described below.

Vertical wind shear influences on convection and feedback to intensity

A common theme amongst many studies was the relationship between the spatial distribution of precipitation and TC intensity changes, especially in environments with moderate and strong VWS (5 m s$^{-1}$ or greater). It is well established that VWS organizes precipitation in a wavenumber-one pattern, with frequent deep convection in the downshear half and less frequent convection in the upshear half of the storm. However, this stronger updrafts in the upshear-left quadrant than steady-state TCs (Wadler et al., 2018). Altogether, these studies suggest that the shift from asymmetric to symmetric convection, signaled by the presence of deep updrafts in the upshear-left portion of the storm, is conducive to RI. Tao and Jiang (2015), in a study using 14 years of Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar data, showed that deep convection was more frequent and more symmetric during, rather than before, RI (Fig. 7). Nguyen and Molinari (2015) suggested that deep vortex stretching within the intense shear-organized convection can lead to the re-development of a single, vertically-aligned vortex that is able to intensify in the presence of VWS.

Vertical wind shear influences on intensity

A key theme in recent years was how the impact of VWS depends on the vertical profile of the shear. TC-relative environmental helicity (TCREH) has been suggested as one useful metric of the vertical shear profile (Onderlinde and Nolan, 2014, 2016). In idealized experiments, with identical values of deep-layer shear, development occurs earlier with positive TCREH (Fig. 8). In reanalysis data, only a weak, but statistically significant, correlation between environmental helicity and TC intensity change is suggested, with positive helicity being more favourable for intensification (Onderlinde and Nolan, 2014). The reason for these differences is most likely tied to the distribution of convection. The overlap of positive TCREH and convection potentially leads to longer lasting and more vigorous thunderstorms that can more efficiently generate latent heating. In addition, when TCREH is
positive, convection is more readily advected upshear and air parcels that experience larger fluxes are more frequently ingested into the TC core (Onderlinde and Nolan 2016). Furthermore, Onderlinde and Nolan (2017) showed that the simulated TCs do not recover their intensity when the shear is smoothly increasing, which is inconsistent with some previous studies. When the shear is transitioning to low values, the TC response is opposite.

![Figure 7. Composite shear-relative distribution of the percent occurrence of moderate precipitation for (a) weakening, (b) neutral, (c) slowly intensifying, (d) RI, (e) RI initial, and (f) RI continuing. The black arrow represents the orientation of the vertical wind shear vector. The 25-, 50-, 75-, and 100-km radii are shown as dotted rings. (From Fig. 3 of Tao and Jiang 2015)](image)

Fowler and Galarneau (2017) examined TCs generated from four consecutive easterly waves over the North Atlantic in late August and early September 2010. Two of them quickly developed into major hurricanes, while the other two achieved weak intensities. One TC influenced large-scale motion, which subsequently provided dry air to another TC and delayed the intensification. Chen et al. (2017) investigated processes for two intensification periods in Typhoon Vincente (2012) simulated by the Weather Research and Forecasting (WRF) model. They showed that the TC intensified through radial transport of eddy angular momentum before the onset of RI. Eddy radial transport occurred through an interaction between large-scale monsoonal flow and a vortex-scale vorticity perturbation.

![Figure 8. Evolution of minimum surface pressure for (left) the eleven 120-h simulations with varying TC-relative environmental helicity and (right) their corresponding 850–200-hPa hodographs. (From Fig. 4 of Onderlinde and Nolan 2014)](image)
Further understanding of the different pathways by which VWS can modify the inner-core thermodynamics and storm intensity has been achieved in recent years. Using budget calculations of moist entropy in idealized experiments, asymmetric convection outside of the eyewall has been demonstrated to reduce boundary layer moist entropy by upward transport of high moist entropy (Gu et al., 2015). By depositing this high moist entropy outside of the eyewall above the boundary layer, the inner-core gradient of moist entropy was reduced, which was hypothesized to weaken the TC. A quantification of this effect on intensity change, however, was not provided. Gu et al. (2016) investigated the azimuthal dependence of changes in wind speed, and thereby intensity, under VWS. In essence, the tangential wind may evolve differently in different quadrants due to asymmetries in the radial advection of absolute angular momentum and the subsequent azimuthal redistribution by the tangential wind. The asymmetries in the radial advection are mainly due to asymmetries in the radial wind. It is suggested that, in addition to the vortex-scale storm-relative flow, it is the clustering effect of the shear-induced convective asymmetries in the eyewall and the outer rainbands that contributes to the quadrant-dependent evolution of the low-level inflow and thus, by extension, the structure and strength of the tangential winds.

Two studies have focused on the predictability of TC intensity in the presence of VWS. Zhang et al. (2015) indicated that the impact of shear on TC intensity may exhibit some sensitivity to the vertical grid resolution and distribution of vertical grid levels in the operational Hurricane WRF. A physical reasoning for this apparent sensitivity was not provided and this sensitivity may well be model dependent. Tao and Zhang (2015) investigated the predictability of TC intensity under moderate VWS. Simulated TCs generally became less predictable as VWS increased (Fig. 9). The initial random perturbations in moisture quickly affected the location and timing of convection, with subsequent changes in convection influencing the precession of the vortex and the onset time of RI as the convection interacts with the vortex and the environmental flow.

Figure 9. Time evolution of the tropical cyclone intensity in terms of the 10-m maximum wind speed for all ensemble members of (a) NOFLOW, (b) SH2.5 (shear of 2.5 m s⁻¹), (c) SH5, (d) SH6, (e) SH7.5, and (f) combination of SH5, SH6, and SH7.5. All under SST = 27 C. (From Fig. 2 of Tao and Zhang 2015)
Finocchio and Majumdar (2017) statistically analysed global reanalysis data, particularly in terms of the height and depth of the VWS. Vertical wind shear in both TC and non-TC environments occurred most frequently in shallow layers and in the upper troposphere. Linear correlations between each shear parameter (height, depth) and TC intensity change showed that shallow, upper-level shear is slightly more favourable for TC intensification, although neither parameter independently explained more than 5% of the variance in TC intensity change. Due to this weak relationship, the two parameters appear to inadequately describe the influence of VWS on intensity. Finocchio et al. (2016) conducted idealized TC simulations with varying height and depth of the VWS, but with the same deep-layer shear. The different intensity and structure evolutions suggest that deep-layer shear by itself may be insufficient for explaining or predicting the impact of VWS on TC intensification. However, in general, they found that VWS that is shallower and lower in the troposphere tends to be more destructive to intensification because it more strongly tilts the vortex into the downshear-left quadrant, prevents vortex precession and realignment, and more effectively flushes the boundary layer with lower entropy air from convective downdrafts. Hendricks et al. (2018), analyzing high-altitude dropsonde data from four flights over Hurricane Joaquin (2015), found that deeper layers of weak vortex tilt in the lower troposphere were associated with stronger storm intensities while larger vortex tilt in the upper troposphere was associated with weaker intensities.

Finally, the following studies examined the impacts of shear on TC intensity change by analyzing best-track and reanalysis data. A statistical analysis by Wang et al. (2015b) for the western North Pacific during 1981–2013 revealed that a deep-layer-shear metric calculated between 1000–300 hPa was more representative of the attenuating deep-layer shear effect than that between 850–200 hPa. More than any deep-layer shear metric, low-level shear, calculated between 1000 and 700 or 850 hPa, correlated negatively with TC intensity during the active typhoon season. This low-level shear, however, was calculated within a radius of 5°, so it is unclear to what extent this metric represents environmental conditions or a projection of storm structure onto the shear metric. Na et al. (2018) assessed the effects of VWS on the intensity change of TCs over the western North Pacific from 1982–2005, finding that westerly shear was more strongly negatively correlated with intensity change than easterly shear. They find that zonal shear is negatively correlated with SST, suggesting that warmer SSTs may offset the weakening effect of westerly shear. Under the hypothesis that storm characteristics or other environmental factors may offset the negative influence of VWS, Rios-Berrios and Torn (2017) examined the climatology of TC intensity changes under moderate VWS by comparing intensifying storms with steady state storms. The intensifying events happened closer to the equator, had greater westward motion, were stronger and larger, and moved in environments with warmer SSTs, greater mid-tropospheric water vapour, and more easterly VWS. No systematic differences were found in the vertical profiles of environmental flow.

3.2.4 Trough interactions and extratropical transition

Anticipating how a trough will influence changes in TC intensity remains a challenging prediction problem, as demonstrated by the unexpected rapid intensification of TC Michael (October 2018) just before landfall on the Florida Panhandle in the presence of an approaching trough and attendant moderate VWS. Since the IWTC-8 report, studies have sought to clarify the importance of TC-trough interactions on TC intensity with observational and numerical modeling-based methods. Overall, a complex, rather muddy picture of how troughs influence TC intensity emerges, with some studies indicating that troughs aid TC intensification, and others that they hinder it.
New findings suggest that how a trough influences TC intensity may depend on the maturity of the storm. A test of how a vortex responds based on its initial intensity in numerical simulations of a realistic TC-trough interaction scenario (Leroux et al., 2016) reveals that vortices initially at tropical depression strength intensify much less than vortices at tropical storm strength or greater, suggesting that vortex depth modulates how a trough influences TC intensity. In fact, when a TC is at least at tropical storm intensity, the presence of a trough can aid a TC in reaching its maximum potential intensity (Leroux et al., 2016). Consistent with this study, observational analyses of TCs once they are at tropical storm strength indicate that, overall, upper-level troughs promote TC intensification, both for North Atlantic (Fischer et al., 2017) and western North Pacific systems (Wei et al., 2016).

The geometry of the TC-trough system has been revealed as important in determining how TC intensity will be influenced by a trough (Wei et al., 2016; Leroux et al., 2016; Fischer et al., 2017). Consistent with observational evidence pointing to the importance of upshear convection on TC intensification after genesis (e.g. Galarneau et al. 2015), North Atlantic TCs experiencing RI just after genesis feature TC-trough configurations that promote stronger quasi-geostrophic ascent to the left of, and upshear of, the TC center and more symmetric convection compared to TC-trough configurations where TCs remain at essentially the same intensity (see Fig. 10; Fischer et al., 2017). Rapid intensification cases tend to occur with relatively sharp troughs compared to steady state TCs (Fischer et al., 2017). For the RI cases, the potential vorticity (PV) anomalies associated with the troughs are stronger and deeper compared to neutral intensification or slow intensification cases. The geometry of the TC-trough set up is also found to influence TC intensification for western North Pacific cases, with strengthening TCs typically located in the equatorward sectors of the troughs and weakening TCs distributed in the poleward sectors (Wei et al., 2016). Overall, these recent studies suggest that intensification is sensitive to the location of the TC relative to the exact position and shape of a nearby trough. In particular, Komaromi and Doyle (2018) found that TC-trough interactions are most favourable for intensification when the relative distance between the TC and the trough is 0.2–0.3 times the wavelength of the trough in the zonal direction and 0.8–1.2 times the amplitude of the trough in the meridional direction. In terms of improving TC intensity forecasts in TC-trough interaction cases, it is proposed that correctly initializing TC intensity and position, not just the large-scale environment, is critical (Leroux et al., 2016).

Recently the role of eddy flux convergence (EFC) in differentiating between whether a trough can be expected to positively or negatively affect TC intensity — the so-called “good trough/bad trough” problem investigated by DeMaria et al. (1993) and Hanley et al. (2001) — has been reexamined. Revisiting Hanley et al. (2001) with a methodology that factors in TC potential intensity and a more comprehensive dataset, Peirano et al. (2016) find that in contrast to Hanley et al. as well as most of the studies mentioned above, trough interaction overall has a negative influence on TC intensity for the North Atlantic (Fig. 11). This is generally consistent with DeMaria et al. (1993), although trough interaction is found to be not quite as unfavourable for intensification as indicated by DeMaria et al. The negative impact overall is explained by the fact that although EFC positively influences intensity in general, the positive influence is frequently counteracted by the detrimental effects of VWS. Consistent with this result, EFC is found to be a poor predictor of intensity change compared to VWS (Peirano et al., 2016). The influence of EFC on TC intensification for the North Atlantic is consistent with that seen for the western North Pacific: the mean EFC for an intensifying western North Pacific TC is less than for a weakening TC (Qian et al., 2016b). Consistent with Peirano et al. (2016), this is because high values of EFC tend to be accompanied by large VWS and low SSTs, as well as high upper-level inertial stability, suppressing upper-level outflow (Qian et al., 2016b).
Figure 10. Schematic of the flow pattern at the time of genesis for (top) rapid TC genesis (RTCG) and (bottom) neutral TC genesis (NTCG) events based on an observational study of North Atlantic TC genesis. The “L” denotes the TC position. Blue lines depict upper-level streamlines. Black, scalloped regions depict the location of deep convection. The green, filled ovals show the location of quasi-geostrophic ascent. Red, curved arrows are scaled to represent the magnitude of the upper-level potential vorticity anomaly, whereas black outlined arrows are scaled to represent the deep-layer vertical wind shear magnitude and direction. (From Fig. 14 of Fischer et al. 2017)

Figure 11. The frequency of 6 h periods with TCs that strengthen, remain steady, or weaken in the subsequent 24 h for the following categories: superposition trough interaction (1047 periods, blue), distant trough interaction (1133 periods, red), no trough interaction (790 periods, green), and all eligible times (6146 periods, black). Circles indicate observed frequency, and bars indicate the 95th confidence interval. Stars indicate values of Hanley et al. (2001) for the corresponding categories. Note that the latter study did not provide an all-eligible category equivalent. (From Fig. 3 of Peirano et al. 2017)
Another aspect of the environmental influence on TC intensity is how such interactions influence storm intensity through their influence on storm structure. The role of an upper-level jet streak in an idealized modeling study (Dai et al., 2017) reveals that a jet streak can cause an eyewall replacement cycle, thereby affecting TC intensity. With a moderately strong upper-level jet streak poleward of a TC, a robust secondary eyewall formation/eyewall replacement cycle, with attendant intensity fluctuations, occurs (Fig. 12, left four panels), whereas such structure change is not present in simulations with no jet (Fig. 12, right four panels). Furthermore, by inducing an eyewall replacement cycle, the jet streak interaction tends to delay a TC’s attainment of steady state intensity, and results in a slightly lower final intensity (Dai et al., 2017).

The destructive nature and complex structural evolution of Hurricane Sandy (2012) motivated studies of key factors dictating re-intensification of the storm near landfall (e.g. Qian et al., 2016a; Shin and Zhang 2017; Fu and Fu 2015). A key finding was that the TC-trough interaction associated with Sandy resulted in intensification just prior to landfall primarily by triggering frontogenesis that produced deep convection and diabatic heating (Shin and Zhang 2017). While Sandy was near steady state, an approaching trough triggered three successive rainbands associated with spiraling frontogenetic zones. The resulting wind streaks preconditioned the outer region of the system and eventually contributed to vortex re-intensification through cyclonic inward advection of absolute angular momentum. While not the primary factor in Sandy’s re-intensification, the trough also aided intensification by wrapping in relatively warm stratospheric air and reducing sea-level pressure (Shin and Zhang 2017).

![Figure 12. Hovmöller diagrams of the azimuthal-mean tangential wind at approximately 2-km altitude for idealized simulations, each initialized with a different set of random perturbations, with a jet (left four panels) and without a jet (right four panels). In each panel, the black curve is the radius of maximum azimuthal-mean tangential wind. (From Dai et al. 2017, their Figs. 8 and 9, left and right four panels, respectively)](image)

### 3.2.5 Dry air and aerosol influences

Environmental dry air in midlevels of the troposphere can inhibit TC intensification, especially when coinciding with VWS. Dry air arises from sources in the midlatitudes/subtropics (Fowler and Galarneau 2017), shear-induced subsidence (Zawislak et al., 2016), and the Saharan Air Layer (SAL; Braun et al., 2016). The inward flux of dry air is a component of ventilation (e.g.
Riemer et al., 2010; Tang and Emanuel 2010). Ventilation strongly controls intensification, but its effects on intensification are heterogeneous and nonlinear (Lin et al., 2017). For example, ventilation can be counteracted by sufficiently strong surface fluxes, as shown by analytical theory in which surface fluxes are capped (Chavas 2017) and as inferred from surface-flux observations (Juračić and Raymond 2016; Gao et al., 2017). The location of dry air in the environment and how it interacts with the TC circulation are important factors for intensification. Simply having dry air in the environment around a TC might not be a factor in intensity changes if it cannot get entrained into the TC inner core (Bukunt and Barnes 2015). In fact, dry air located ahead of TCs is associated with intensification (Wu et al., 2015; Ditchek et al., 2017). Increased understanding of the pathways by which dry air intrudes into a TC is needed.

If dry air intrudes into a TC, it can have profound effects on the convective structure, inhibiting intensification. Analyses of data from recent field campaigns have shown evidence of dry air intruding into TCs, either weakening them, such as Tropical Storm Gaston (2010) (Davis and Ahijevych 2012; Fowler and Galarneau 2017) or hindering intensification, such as Hurricane Edouard (2014) (Zawislak et al., 2016). In Tropical Storm Florence (2012), dry air and shear, associated with the SAL, caused the convectively driven energy production cycle to weaken (Ross et al., 2016). Dry air increases the relative frequency of cumulus congestus versus deep cumulonimbus, narrows the region in which deep convection occurs, and increases the frequency of weak convective downdrafts (Fig. 13; Tang et al., 2016). The result is a decrease in the vertical mass flux, which reduces the intensification rate and results in a smaller TC, as dry air subsides into the inflow layer closer to the center (Alland et al., 2017). Further effects of dry-air intrusion are a decrease in the column moist entropy, or $\theta_e$ (Juračić and Raymond 2016) and a decrease in the vertical extent of the high potential vorticity column (Bhattacharya et al., 2015).

![Figure 13. Contoured frequency by altitude diagrams (CFADs) of the convective mass flux for intensifying TCs in a (a) moist environment and (b) dry environment. Note the scale is logarithmic (base 10) in order to resolve the tails of the CFADs. (c) Sign of the difference between (a) and (b), where the red shading represents points where the CFAD is larger for (a), and the blue shading represents points where the CFAD is larger for (b). (From Fig. 6 of Tang et al. 2016)
On the other hand, TCs with more moisture in the inner core have a greater chance of intensifying (Ditchek et al., 2017; Gao et al., 2017), but the intensity-change effects due to increased moisture in the environment are mixed. In particular, positive moisture anomalies in the rear of a TC may lead to greater intensification rates, but those ahead of a TC may cause convection that deforms the flow topology, enhancing a dry- air intrusion pathway (Wu et al., 2015). Once a TC is mature, greater environmental moisture may modulate rainbands and increase the size of secondary eyewalls, leading to greater intensity fluctuations (Ge 2015).

Aerosols, and their indirect effects on microphysics, may affect TC intensity. A greater concentration of aerosols, such as associated with continental air masses or SAL outbreaks, can lead to greater concentrations of cloud condensation nuclei and cloud droplets, and alter microphysical processes within clouds, invigorating convection and increasing column latent heating (Fig. 14) (Herbener et al., 2014; Khain et al., 2016; Qu et al., 2017). If this invigoration occurs in the eyewall, intensification can result. If this invigoration occurs in rainbands, leading to more active rainbands and/or the formation of larger secondary eyewalls, weakening can result (Lynn et al., 2016; Qu et al., 2017). Further work is needed to improve the sensitivity of microphysics schemes to droplet concentration and aerosols (Khain et al., 2016).

Figure 14. The conceptual model of the distribution of the cloud hydrometeors and airflows in the inner and outer rainbands of Typhoon Saomai (2006) for (top) maritime and (bottom) continental environments. The smaller cloud droplets have lower collision-coalescence efficiency, leading to fewer raindrops in the inner rainbands. Larger graupel or hail particles in the outer rainbands melt into larger raindrops in the outer rainbands. The convection of the outer rainbands in the continental environment was stronger, so the boundary layer inflow air in the inner rainbands was weaker.

(From Fig. 14 of Qu et al. 2017)
Higher inner-core moisture and convective available potential energy (CAPE) were factors in developing high intensification rates in idealized TCs in Stovern and Ritchie (2016). Higher CAPE values lead to more active and intense convection within the inner core of the TC, leading to high latent heat release, precipitation rates, and PV production compared with TCs with lower initial inner-core CAPE. Furthermore, a positive relationship between the radial CAPE gradient and the intensification rate of model TCs was found in Lee and Frisius (2018).

High moisture and low VWS resulting in strong convection, diabatic heating, and development of PV were also factors in the inter-comparison between strongly developing and non-developing cyclones in the Bay of Bengal (Kotal et al., 2014). Furthermore, high moisture transported from large distances within a MCB in the western North Pacific was found to be related to higher TC intensities in Fujiwara et al. (2017). They theorized that low-level air can obtain considerable moisture from the underlying ocean during the transport within MCBs. There also appears to be a mutual relationship between the existence of the TC and the development of the MCB, i.e. the existence of the TC triggers the development of the MCB.

### 3.2.6 Multi-factor process interactions

#### 3.2.6.1 Rapid intensification and weakening

Kowch and Emanuel (2015) suggest that, statistically speaking, RI is not a result of special processes in the atmosphere, but that rather, RI is part of a continuum of processes globally associated with intensification. Regardless of this, there does appear to be seasonality associated with RI occurrence in particular basins. In the western North Pacific, RI is favoured in the peak summer season (Ge et al., 2018). However, the likelihood of RI relative to the total number of TCs is higher during the late fall season. Ge et al. (2018) find that during the late Fall, a lower latitudinal location, pronounced ambient cyclonic vorticity, a lower outflow layer temperature (e.g. greater thermal efficiency), a deeper ocean mixed layer, and stronger ocean subsurface thermal stratification all contribute to the higher relative rate of RI. In the South China Sea, RI is not favoured during the monsoon season because of high VWS in the region and most cases of RI occur post-monsoon. Typical flow patterns and environmental factors that favour RI when compared to non-RI cases include weak VWS and relatively strong forcing from midlatitude troughs (Chen et al., 2015). Upper-level flow patterns that favour the development of one or two outflow channels is also preferred. In the north Atlantic, RI is also maximized during the peak of the TC season in September (Wang et al., 2017) with three regions of maximum RI occurrence: the western tropical North Atlantic, the Gulf of Mexico and Caribbean Sea, and the open ocean just east and southeast of Florida. Rapid intensification also exhibits interannual and decadal variability over the period 1950–2014, but no long-term trend due to climate change in the North Atlantic basin.

Complex interactions among environmental VWS, the mean vortex, and internal convective processes govern the TC intensification process and lead to diverse pathways to maturity. As such, although many TCs undergo RI and intensify into major hurricanes, the timing of RI is highly uncertain. While environmental conditions, including SST, control the maximum TC intensity and the likelihood of RI during the TC lifetime, both environmental and internal factors contribute to uncertainty in RI timing. To address the question of environmental versus internal control of RI, five high-resolution ensembles of Hurricane Earl (2010) were generated with scale-dependent stochastic perturbations from synoptic to convective scales (Judt and Chen 2016). They find that the predictability of RI is higher when the environment is favourable for an extended period of time. The timing of RI, however, has more limited
predictability. Vertical wind shear plays an important role in the timing of RI (Fig. 15a). First, stronger shear leads to a reduction of the likelihood or RI while interactions between VWS, convection, and the TC vortex (in terms of vortex tilt and inertial stability, Figs. 15b and 15c) contribute to RI-timing uncertainty.

Rapid weakening (RW) of TCs is defined in Wood and Ritchie (2015) as 15 m s\(^{-1}\) (30 kt) in 24 hours, which represents the 94th (80th) percentile in the North Atlantic (eastern North Pacific) of over-ocean weakening TCs. Rapid weakening events are associated with greater 24-hr official forecast errors, with a bias toward overestimation of intensity in both basins. Most RW events occur as a TC crosses a sharp SST gradient, moves into higher VWS, and entrains drier environmental air (Fig. 16). In the South China Sea, rapid weakening occurs most often in October to November (Zheng et al., 2017). South China Sea RW also exhibits decadal variation with a maximum in the 1970s, rapidly decreasing in the 1980s and 1990s, then quickly increasing from 2000. No relationship with longer-term climate trends was noted.

Figure 15. Histograms of (a) deep-layer (850-200 hPa) VWS averaged over radii of 200-800 km and over the intensity bifurcation period (24-48 h). (b) Vortex tilt between 2 and 6 km altitude and (c) inertial stability averaged over the first 9 hours of the bifurcation period (24-33 h). Early RI cases are in blue, late RI cases in red.
(Adapted from Figs. 3, 6, and 7 of Judt and Chen 2016)

Figure 16. Composite Climate Forecast System Reanalysis (CFSR) relative humidity at 500–700 hPa (%; shaded) and Reynolds SST (°C; contours) for 55 North Atlantic RW events at (a) 24 h before RW, (b) at the onset of RW, and (c) 24 h after RW.
(Adapted from Fig. 4 of Wood and Ritchie 2015).
3.2.6.2 **Intensity change and tropical variability**

The interannual relationship between ENSO and annual RI number in warm Pacific Decadal Oscillation (PDO) phases is strong and statistically significant for the western North Pacific basin. El Niño events are accompanied by a stronger Walker circulation in the equatorial Pacific in the warm PDO phase than in the cold PDO phase. The results indicate that the stratification of ENSO-based statistical RI forecasts by the PDO can greatly improve the accuracy of statistical RI predictions (Wang and Liu 2016). Over the eastern South Indian Ocean, the large-scale MJO (and ENSO) perturbation pattern reinforces unstable cyclonic meridional shear of the low-level zonal wind giving a larger modulation of the number of tropical depression (TD) initiations (Duvel 2015). TC frequency and RI of TCs is higher in La Niña versus El Niño regimes during the primary TC season in the Bay of Bengal (BoB). Further, when the MJO is active over the BoB (phases 3–4; characterized by enhanced convective activity in the BoB) under La Niña conditions, environmental conditions were more conducive for enhancement of TC activity and RI of TCs compared to corresponding MJO phases under an El Niño regime. An increase in mid-tropospheric humidity and reduction in VWS have been identified as the primary and secondary factors enhancing the likelihood of RI of TCs in the BoB during phases 3-4 of the MJO under a La Niña regime (Girishkumar et al., 2015).

During the warm (cold) phase of the PDO, the annual RI number is generally lower (higher) and the average location of RI occurrence tends to shift southeastward (northwestward) over the western North Pacific. The easterly trade winds are strengthened during the cold PDO phase at low levels, which tends to make equatorial warm water spread northward into the main RI region, resulting from meridional ocean advection associated with Ekman transport. Simultaneously, an anticyclonic wind anomaly is formed in the subtropical gyre of the western North Pacific. This anomaly, therefore, may deepen the depth of the 26ºC isotherm and directly increase TC heat potential over the main RI region (Wang et al., 2015a).

There is a high positive correlation between TC frequency over the East Asian midlatitude region and the Western North Pacific Monsoon Index (Choi et al., 2016). Interaction of TCs with monsoon gyres lead to rapid weakening of the TCs over tropical western North Pacific (Liang et al., 2016, 2018b). Numerical simulations confirm the important effects of the interaction between TCs and monsoon gyres on TC intensity (Liang et al., 2018a).

3.2.6.3 **Other factors**

A lower tropopause level is found to cause higher TC intensity and a more distinct double warm-core structure (Moon and Kieu 2017; Ferrara et al., 2017). Likewise, a weaker lower-stratosphere layer stratification also corresponds to a warmer upper-level core and higher intensity. The formation of a double warm-core structure is more sensitive to tropopause variations in the western North Pacific basin than in the North Atlantic basin, given the same SST. An idealized modelling study showed that the potential intensity of an atmosphere in radiative-convective equilibrium and constant invariant SST increases by 0.4-1 m s⁻¹ for each 1 K of tropopause temperature reduction (Wang et al., 2014). The actual modelled TCs, when superposed on this environment exceeded the potential intensity substantially, but a dependence of ≈0.4 m s⁻¹ per 1 K of tropopause cooling was still found, a result that was insensitive to grid resolution (up to 8 km).
Using an idealized version of the 2014 GFDL model, Tuleya et al. (2016) examined TC sensitivity across a wide range of three environmental factors (Fig. 17) that are often identified as key factors in TC evolution: SST, atmospheric stability (upper-air thermal anomalies), and VWS (westerly through easterly). The results confirm that a scenario (e.g., global warming) in which the upper troposphere warms relative to the surface will have less TC intensification than one with a uniform warming with height. The idealized model simulations showed weak disturbances dissipating under strong easterly and westerly shear of 10 ms$^{-1}$. The impact of VWS on intensity was different when a strong vortex was used in the simulations. In this case, none of the initial disturbances weakened, and most intensified to some extent.

**Figure 17.** (a) Distribution of minimum sea-level pressure (MSLP) for a set of 5-day simulations using 11 different upper-tropospheric temperature anomalies and 11 different SST anomalies. Values are colour shaded for strong vortex cases and contoured (solid lines) for weak vortex cases. Dashed lines show domain-averaged upper-level temperature anomalies at 60 hours relative to the control experiment. (b) Same as (a), but for area-mean rainfall (cm). MSLP and rainfall intensify for higher SST anomaly and lower 300-hPa temperatures. Bottom panels show MSLP as a function of vertical wind shear and SST anomaly for (c) weak and (d) strong vortex cases. For weak vortices, stronger VWS of either sign is detrimental to intensification, while for strong vortices, intensification is greater under easterly VWS. (Adapted from Figs. 5, 9, and 12 of Tuleya et al. 2016)
3.2.6 Summary and conclusions

This report focuses on recent (2014-2018) advances regarding external influences on tropical cyclone (TC) intensity change. While numerous topics were found in relation to this broad subject, papers generally focused on the influences of SST and OHC, VWS, trough interactions, dry and/or dusty environmental air, and situations in which multiple factors acted in concert to impact TC intensity change. Studies on ocean interactions highlighted the important roles of warm- and cold-core eddies and their associated impacts on surface fluxes and storm intensity. Enhanced buoyant forcing from the ocean is an important intensification mechanism in TCs over WCEs. Freshwater plumes and coastal barrier waters were found to increase stability in the ocean and reduce TC-induced cooling, thereby creating more favourable conditions for intensification. In contrast, turbid waters detected by ocean colour can block sunlight and cool the upper subsurface ocean, thereby countering the effects of fresh water. Changes in subsurface ocean conditions associated with global warming may lead to greater TC-induced ocean cooling, which may offset some of the effect of warming oceans on TC intensification. Remote influences of SSTs were also described, including in relation to ENSO. El Niño’s role in the extreme intensification of Patricia (2015) is noted. In addition, enhancements or weakening of the moisture supply to storms in moisture conveyor belts covering long distances can ultimately play a role in the intensification of storms.

Studies of the impact of vertical wind shear highlight the role that shear plays in modulating the structure and intensity of inner-core convection and its feedback to intensity. Recent studies have noted the development of convection near the radius of maximum wind in the upshear-left quadrant of storms near the onset of RI. Vertical wind shear also significantly impacts the predictability of TC intensity, likely because of its interaction with the convection and TC vortex. While VWS is often viewed in the context of deep-layer shear, the shear profile is likely important, with shallower and lower-tropospheric shear being less favourable for intensification. Westerly shear tends to be more unfavourable for intensification than easterly shear, although for weak vortices both tend to be destructive. Trough interactions with TCs remains complicated, with the impact on intensification often related to the relative position of the TC to the trough and on the maturity of the storm. The role of eddy flux convergence of momentum can act both negatively or positively, but trough interaction is often negative because of the detrimental effects of VWS.

While dry environmental air is often an inhibiting influence, the response of a TC can be varied. If dry air intrudes into a TC, it can affect the convective structure and flush the boundary layer with lower-entropy air. In some situations, dry air actually favours intensification, although these situations require further study. While high humidity in the inner core favours intensification, high humidity in the environment can favour rainband formation and the development of secondary eyewalls, which can then inhibit further intensification. The effects on storm intensity of aerosols, especially in the Saharan Air Layer, remains a source of significant uncertainty since intensity change may depend on whether convection is invigorated within the eyewall or in outer rainbands.

Complex interactions between the various environmental influences on intensity can affect the timing of rapid intensification (RI), with vertical wind shear often decreasing the likelihood of RI, but SSTs, dry air, convection, and the TC vortex contributing to significant uncertainty in the timing of RI. Rapid weakening typically occurs when a TC crosses over a sharp SST gradient, experiences increasing wind shear, and drier environmental air.
Finally, multiple modes of variability, including the Pacific Decadal Oscillation, El Niño Southern Oscillation, and the Madden-Julian Oscillation are found to influence TC intensification. During the warm (cold) phase of the PDO, the annual RI number is generally lower (higher) and the average location of RI occurrence tends to shift southeastward (northwestward) over the western North Pacific. The stratification of ENSO-based statistical RI forecasts by the PDO can improve the accuracy of statistical RI predictions in the western North Pacific. TC frequency and RI of TCs is higher in La Niña versus El Niño regimes during the primary TC season in the Bay of Bengal (BoB).

3.2.7 Recommendations

A few recommendations were identified during the review and are summarized below.

• The need for improved representation of coastal processes in current TC coupled forecasting models was emphasized since rapid and significant intensity change just prior to landfall can have large implications for disaster mitigation.
• Improved prediction of ocean pre-storm conditions is recommended as it is thought to be a prerequisite for improved intensity prediction of record-breaking events such as Haiyan (2013), Patricia (2015), and Michael (2018).
• To improve predictions from coupled models, simultaneous and coincident measurements of oceanic and atmospheric profiles (temperature, salinity, and current in the ocean; temperature, humidity, and winds in the atmosphere) before, during, and after the storm must be made and assimilated into the models. In addition, in-storm oceanic and atmospheric measurements are needed to improve vertical mixing schemes that impact air-sea fluxes and, hence, storm intensity and structure.
• Further research is needed to determine the mechanisms for producing upshear convection and determining whether the upshear convection is the cause of RI or a symptom of other processes such as vertical realignment.
• Although dry air is typically viewed as an inhibiting influence, an increased understanding of the pathways by which dry air intrudes into a TC is needed.
• Further work is needed to improve the sensitivity of microphysics schemes to droplet concentration and aerosols in order to better determine the response of TC intensity to environmental aerosols, particularly Saharan dust.

Acronyms used in the report

BoB - Bay of Bengal
CAPE - Convective Available Potential Energy
CCE - Cold Core Eddy
CFAD - Contoured Frequency by Altitude Diagram
CFSR - Climate Forecast System Reanalysis
EFC - Eddy Flux Convergence
ENSO - El Niño Southern Oscillation
GFDL - Geophysical Fluid Dynamics Laboratory
IWTC - International Workshop on Tropical Cyclones
MCB - Moist Conveyor Belt
MJO - Madden-Julian Oscillation
MSLP - Minimum Sea-Level Pressure
NCAR - National Center for Atmospheric Research
NOAA - National Oceanic and Atmospheric Administration
NTCG - Neutral Tropical Cyclone Genesis
OHC - Ocean Heat Content
PDI - Power Dissipation Index
PDO - Pacific Decadal Oscillation
PV - Potential Vorticity
RCP - Representative Concentration Pathway
RI - Rapid Intensification
RTCG - Rapid Tropical Cyclone Genesis
RW - Rapid Weakening
SAL - Saharan Air Layer
SLP - Sea-Level Pressure
SSHA - Sea-Surface Height Anomaly
SST - Sea-Surface Temperature
TC - Tropical Cyclone
TCREH - Tropical Cyclone Relative Environmental Helicity
TD - Tropical Depression
TRMM - Tropical Rainfall Measuring Mission
VWS - Vertical Wind Shear
UNSW - University New South Wales
WCE - Warm Core Eddy
WRF - Weather Research and Forecasting (model)

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Abstract
This review summarizes techniques used by operational centers to forecast tropical cyclone intensity change. Recent advances and major changes over the past four years are presented, with a special focus on forecasting rapid intensity changes. Although intensity change remains one of the most difficult aspects of tropical cyclone forecasting, objective guidance has shown some improvement, and operational forecast centers have been able to leverage these advances to increase forecast skill, albeit incrementally. The greatest improvements are realized when consensus methods are utilized, especially those that blend statistical-dynamical based guidance with dynamical ocean-coupled regional models. These models become even more skillful when initialized with inner core observational data. It is noteworthy that the realization of a recommendation from IWTC-8, to adapt guidance initially developed for the North Atlantic and Eastern North Pacific to other basins, has led to improved forecast skill of some agencies. Recent worldwide difficult cases are presented so that the research community can further investigate, potentially leading to improved intensity forecasts when similar cases are observed in the future.

3.3.1 Introduction
The IWTC-8 session on intensity guidance (Sampson and Knaff, 2014) provided this assessment of intensity forecasting: "Over the last 15 years, intensity forecasting at the operational centers have shown little improvement (...) the mean errors in the intensity guidance available to forecasters is gradually decreasing at the rate of 1-2 % per year at 24-72h and if this trend continues, the official forecasts could also start to improve along with the guidance."

This report presents an updated picture of operational intensity forecasting. Rapid intensification (RI) is a particular focus given the potentially catastrophic consequences when RI occurs just prior to landfall. Section 2 provides an update on selected intensity guidance available, or planned to be soon available to the operational agencies. Section 3 provides the recent progress of intensity forecasting by selected operational agencies along with current practices and guidance employed. Section 4 summarizes and provides recommendations for the research and operational communities for the next 4 years.

3.3.2 Recent advances in intensity guidance
The following section is aimed to highlight recent advances in intensity guidance, stratified into five model categories as described below.
3.3.2.1 Statistical models

As stated in the previous report, statistical models are primarily used as skill baselines for both operational and model forecasts. Several operational centers used an equivalent of SHIFOR (Jarvinen and Neumann, 1979) to benchmark their forecast skill.

Since the IWTC-8 in 2014, some TC intensity forecast improvements have been achieved with an analog approach for the North-West Pacific, which has been developed from historical best tracks by selecting a number of closest analogs to the target cyclone track and initial intensity (Tsai and Elsberry, 2014, 2015 and 2018). A recent result from the ONR Tropical Cyclone Intensity (TCI) Directed Research Initiative has been development of a 7-day combined, three-stage Weighted Analog Intensity Pacific (WAIP) intensity prediction and intensity spread guidance product (Tsai and Elsberry 2018). This new combined WAIP has special treatments (including intensity bias correction) for the pre-formation stage, the intensification stage, and the ending storm stage (hence the three-stage). In addition, WAIP also provides a quantitative value of the intensity forecast uncertainty (calibrated to include 68% of the verifying intensities), which was one of the recommendations from IWTC-8.

This 3-stage WAIP will be operationally tested at JTWC during the 2019 season, and the 3-stage WAIA for the North Atlantic is in final development and will be tested at the National Hurricane Center later in the 2018 season. Another good point with WAIP/WAIA is that it can be produced on a desktop computer in a few minutes given only the official track forecast and the initial intensity, and thus similar techniques could in principle be developed in other TC basins.

Also available at JTWC is a seven-day North-West Pacific track and intensity forecasts that is created using a combination of persistence and climatological trajectories to estimate track and a LGEM (Logistic Growth Equation Model, DeMaria 2009) approach integrated over climatological SST fields along the forecast track. This model, “Trajectory CLIPER” (TCLP) is operationally available at JTWC (Sampson and Knaff, Personal Communication).

3.3.2.2 Statistical-Dynamical models and probabilistic guidance

Statistical-dynamical guidance such as Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al., 2005) have proven to be reliable objective intensity guidance and later on the Logistic Growth Equation Model (LGEM; DeMaria 2009) are the most known models.

A recent advance is the installation of Rapid Intensification Prediction Aid (RIPA) at JTWC (Knaff et al., 2018), based on predictors from the environment (from the SHIPS developmental dataset), IR imagery and the best-track / advisory-based data. Two statistical methods are used to create probabilistic forecasts for seven intensity thresholds including 25-, 30-, 35-, and 40-kt changes in 24 h; 45- and 55-kt in 36 h; and 70-kt in 48 h. These forecast probabilities are further used to create an equally weighted probability consensus that is then used to trigger deterministic forecasts equal to the intensification thresholds once the probability in the consensus reaches 40 %. The deterministic forecasts are incorporated into an operational intensity consensus forecast as additional members, resulting in an improved intensity consensus during rapid intensification period (independant verification during the 2016 and 2017 typhoon season). Experimental running of these aids in the Indian Ocean and Southern Hemisphere have been rather succesful capturing the attention of forecasters at JTWC and at the Australian Bureau of Meteorology. These aids have proven skillful enough to be incorporated into the JTWC intensity consensus (ICNW). Feedback thus far has concerned
overprediction in cases when the TC is relatively weak and the creation of deterministic forecasts when the TC is making or is expected to make landfall.

Recently DTOPS has been developed for National Hurricane Center to forecast the likelihood of RI (Onderlinde and DeMaria, 2018). This uses IFS, GFS, HWRF, LGEM, and SHIPS. The intensity change forecasted by these models along with several other geographic (e.g. storm latitude) or multi-model parameters were compiled for numerous cases from 2011 – 2017 in the Atlantic and East-Pacific basins. These forecasts were compared to Best Track intensity change, and binomial logistic regression was used to derive coefficients for each model or parameter. These coefficients then were used for the multi-model logistic prediction scheme. The largest improvements (when compared to SHIPS-RII) occurred in the Atlantic basin where substantial Brier Skill Scores improvements were obtained. DTOPS has been run experimentally at the National Hurricane Center during the 2017 and 2018 hurricane seasons and has been referenced in operational products during this time.

A challenging case for intensity forecasting also comes when an Eyewall Replacement Cycle (ERC) is taking place. This inner core mechanisms are associated with intensity fluctuations that sometimes can be quite significant. Until very recently, the skill to anticipate and quantify those intensity variations was rather limited. CIMSS have developed the M-PERC guidance.
(Microwave-based Probability of Eyewall Replacement Cycle) based on observational studies with aircraft data done previously (Sitkowski et al., 2011 and 2012; Kossin et al., 2012), M-PERC uses an azimuthal ring score from ARCHER derived with microwave imagery and calculates a probability forecast of the onset of an ERC. The timing and the amplitude of intensity fluctuations through the ERC can be assessed from the observational studies cited previously (Figure 3.3.2.2).

This new probabilistic guidance appears very promising as it is available to all TC forecasters in real-time on the CIMSS web site. Further improvements of this guidance are also likely within the next few years.

Figure 3.3.2.2. The M-PERC guidance
Following recommendations from IWTC-7 and IWTC-8, guidance available in the North Atlantic and Eastern North Pacific have continued to be implemented in others centers. In 2015, a version of STIPS has been developed at the Korea Meteorological Administration (KMA) using ocean-coupled potential predictors (Kim et al. 2018) associated with Land-STIPS to improve TC landfalling intensity prediction. For lead times up to 48h, the KMA version of STIPS shows the smallest MAEs relative to operational dynamical models (JMA-GSM, GFS and HWRF) in 2016 and 2017. Further improvement towards RI prediction is underway with the inclusion of a new predictor that has TC-induced vertical mixing and parametrization of the air-sea exchange process.

From 2015 to mid-2016, the Meteorological Research Institute (MRI) at Japan Meteorological Agency (JMA), developed the RSMC Tokyo version of SHIPS (Statistical Hurricane Intensity Prediction Scheme, DeMaria and Kaplan 1994; DeMaria and Kaplan 1999; DeMaria et al., 2005) with great support from SHIPS developers in the US (Yamaguchi et al., 2018). This version, named as TIFS (Typhoon Intensity Forecast scheme based on SHIPS) at RSMC Tokyo, predicts central pressure (Pmin) as well as maximum 10-min sustained wind speed (Vmax) for the North-West Pacific basin. Figure 3.3.2.3 shows root mean square errors (RMSEs) and biases of TIFS forecasts for both Pmin and Vmax. TIFS has considerable forecast skill relative to the GSM and a climatological statistical model (Statistical Hurricane Intensity FOREcast, SHIFOR, Jarvinen and Neumann 1979; Knaff et al., 2003). Accordingly, the trial use of TIFS has greatly improved accuracy of RSMC Tokyo official intensity forecast as discussed in section 3.

Shimada et al. (2018) incorporated TC rainfall and structural predictors into TIFS to examine the impact of the predictors on the accuracy of TIFS. Results show some substantial improvement of the TIFS forecast but the latency of the rainfall product prevents operational implementation of TIFS with the rainfall predictors. Microwave satellite-based data with a high-temporal resolution and little latency are desirable to further improve the accuracy of statistical-dynamical models.

Figure 3.3.2.3. Root mean square errors (RMSEs) of (a) Pmin (hPa) and (b) Vmax (kt) forecasts. TIFS, JMA/GSM, and SHIFOR (Pmin only) are black, blue, and green lines, respectively. Black open circles show the number of samples corresponding to y-axis on the right. RMSEs are based on RSMC Tokyo’s best track data. Forecast samples are from 2013 to 2015 for the North-West Pacific basin. This Figure is from Yamaguchi et al. (2018).
Some statistical-dynamical tools were also developed and evaluated recently at RSMC La Réunion, in order to meet the needs of the forecasters for specific guidance on that matter (pending publication from Leroux), using atmospheric and oceanic synoptic parameters (mostly from ERA-Interim data during the learning phase but with data from IFS in operation). The first one uses the Multivariate Adaptive Regression Splines (MARS) method, which allows simple non-linear behaviours. Its goal is to forecast the intensity changes (for 10-min maximum winds) within the next 24h. The second one is a decision tree developed to predict the occurrence of a RI during the next 24h. These tools are complementary because the first statistical model is not suited for extreme variations. They should become available for the forecasters in the near future.

The Indian Meteorological Department (IMD) uses an integrated Cyclone Prediction System (CPS) based on statistical-dynamical guidance as described at IWTC-8. The three intensity components are: (i) Intensity prediction by SCIP model, (ii) prediction of probability of rapid intensification by RI-Index, and (iii) decay of TCs after landfall by decay model.

### 3.3.2.3 Dynamical models

NWP models are still an area of great effort and great improvement in tropical cyclone intensity forecast. Hereafter we highlight some recent or planned improvements for some selected global and regional models.

**a) Recent or planned improvement with some selected global models**

Although the skill of global models is less than that of the high-resolution regional models for intensity prediction, and especially so for RI, global models have improved considerably in recent years. It was not long ago that global model intensity forecasts were considered unskilful and were essentially ignored by forecasters. It is now admitted that these models nonetheless provide very useful guidance to operational forecasters since they often provide clues as to TC development and intensity trends.

In July 2017, an improvement in the ensemble data assimilation system along with adaptative quality control and observations errors for dropsondes, lead to a better handling of tropical cyclones at initial time for the global model IFS (Integrated Forecast System) at the European Centre for Medium-Range Weather Forecast (Vitard et al., 2018). A major upgrade was implemented in the operational version in June 2018 (CY45r1) with ocean and sea-ice models coupled in the high-resolution forecast. The change of SST from the Ocean near real time analysis (OCEAN5) is added to the initial OSTIA SST 1/20 degree for 4 days and then relaxed to 0 gradually from day 4 to day 8 for a full coupling thereafter. Verification of this implementation shows a small statistically-significant improvement in the intensity error at medium-range (Figure 3.3.2.4).
In 2014 and 2015, two changes were made to the Met Office Global Model (MOGM – sometimes referenced as UKMO or UK in the followings sections of the report) which had a significant impact on tropical cyclone predictions (Hemming and Vellinga, 2018). Global Atmosphere 6 (GA6) implemented in July 2014 included changes to the MOGM dynamical core, physics and horizontal resolution and improved satellite data usage. In February 2015, a new technique for initialization of TCs was introduced using TC warning centre estimates of central pressure. In 2017, the MOGM horizontal resolution was increased again. Longer lead time forecasts of TCs are now often too strong (as measured by central pressure). However, 10m winds are still too weak, which is evidence of a bias in the wind-pressure relationship. Near real-time trials of an atmosphere-ocean coupled version have shown some promising results. Over-deepening which occurs in some cases of slow moving TCs, those which move over their previous track or those in the subtropics is markedly reduced in the coupled model. Operational implementation is planned for 2020. Experiments to cap the drag coefficient in the model at higher wind speeds have shown positive results by increasing forecast 10m winds for strong TCs without reducing the central pressure further. If trials results continue to be positive, operational implementation could take place in 2019.

The GFDL Finite-Volume Cubed-Sphere (FV3), dynamical core was selected for the US National Weather Service’s Next-Generation Global Prediction System (NGGPS), has been transferred to the National Weather Service’s (NWS) National Center for Environmental Prediction (NCEP), and is scheduled to become operational at NCEP in January 2019 as the replacements for the NWS’s Global Forecast System (GFS). An improved version of the model was recently developed at GFDL (referred to as fvGFS) and has been run daily in real time since 2 July 2018. The intensity performance of fvGFS is significantly improved with the new 2018 version of the GFDL fvGFS model compared to the 2017 version (degraded scores compared to
The new model had the lowest intensity errors of all available operational guidance at 3 to 5 days (Fig. 3.3.2.5), even beating the high-resolution regional hurricane models HWRF and COAMPS-TC.

![Figure 3.3.2.5. Average intensity errors (knots) for a portion of the 2018 tropical cyclone season (July 2nd through September 18th), for the North Atlantic, Eastern Pacific, Western Pacific, and the combined 3 ocean basins, comparing the operational GFS (black) with other operational models including the EMC version of fvGFS (FV3-GFS, red) and the new 2018 experimental version of fvGFS (purple), developed at GFDL and run in near real time. Results are for the interpolated models and compared with the official forecast (black dot-dashed line).](image)

Taking advantage of the nesting and grid stretching capability developed in the FV3 core, a high-resolution version of the model (hfvGFS) was adapted for the entire Atlantic hurricane basin (Fig. 3.3.2.6). The hfvGFS model uses the 13-km global domain with a 3-km, two-way interactive nest covering the tropical North Atlantic, and is run to 126 hours. Real time tests during the very active 2017 hurricane season over the North Atlantic, showed a reduction in mean absolute errors at almost all lead times, mostly due to a smaller negative bias at all forecast hours. It is anticipated that the development of this high-resolution version of fvGFS could eventually find a path to transition into NOAA’s next generation hurricane model which will take advantage of the unified modelling approach that the FV3 modeling system was uniquely designed for.

b) Recent or planned improvement with some selected regional models

Regional Hurricane modeling systems implemented at NOAA’s National Weather Services /National Center for Environmental Predictions operations are now used for forecasting guidance in all ocean basins of the world (Mehra et al., 2018). HWRF has made significant improvements to the state of the art in numerical forecast guidance. Verification shows that
early guidance of this model was the best performer over the North Atlantic in 2017 at all lead times and for short lead times (< 48h) over the Eastern Pacific. Further improvements of HWRF in 2018 include increasing horizontal resolution (1.5km at the inner core), improvement of the data assimilation system (including the admission of new data sets like GOES16 AMW’s, NOAA 20, SFMR, Dropsondes drift and Tail Doppler Radar from the G-IV) and the physics. Improvements are also planned for the non-NHC basins with an increase in the vertical resolution and ocean coupling (HYCOM) for the southern hemisphere basins. Early verification over the North Atlantic suggests similar or slightly better performances than the 2017 version.

The Environmental Modelling Center hurricane team has also developed another non-hydrostatic hurricane model in NOAA Environmental Modeling System (NEMS) framework known as HMON (Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic) model which was implemented at NCEP operations this past year over the North Atlantic and Eastern Pacific. HMON came in to implement a long-term strategy at NCEP/EMC for multiple static and moving nests globally with one- and two-way interaction and coupled to other models (ocean, wave, land, surge, inundation, etc). Validation of the skill of the model during the 2017 hurricane season shows the skill lags behind HWRF, mainly due to a better modeling configuration for HWRF than HMON (Figure 3.3.2.7). Development of HMON is consistent with, and a step closer to developing NGGPS chosen FV3 dynamic core based global to local scale coupled models in a unified modeling framework.

Since February 2016, Meteo France has significantly improved its numerical modelling capabilities for the overseas French territories (La Réunion, Mayotte, Martinique, Guadeloupe, French Guiana, New-Caledonia and French Polynesia). AROME, a non-hydrostatic fine scale spectral model (2.5 km of horizontal resolution) initialised by the IFS analysis runs now 4
times per day up to 42h in each french territories domains (Figure 3.3.2.6). In 2017 (Faure et al., 2018), a 1D ocean coupling and reduction of the spin-up time has been implemented. 1D ocean-coupling allows the model to represent cooling in TC wake even with no observations.

![Figure 3.3.2.6. In red, Meteo-France non-hydrostatic AROME regional model domains associated with french overseas territories.](image)

The results in terms of short-range forecasts are already supportive for both intensity and structure, along with excellent track forecast scores that remains near IFS valuable guidance. At RSMC La Réunion, AROME has successfully forecast a number of TC events including the rapid demise of TC Hellen in March 2014 (further information below), the explosive initial development of TC Bansi in January 2015 (AROME trial period), and the Eyewall Replacement Cycle of TC Fantala in April 2016. In the North Atlantic, Arome forecast has been verified against available observations (radar, recon, RSMC analyses, ...) during IRMA and MARIA in September 2017 as those systems were crossing the lesser Antilles (Dupont et al., 2018). The model demonstrated its excellent ability to forecast realistic structures, tracks and intensities. Many additional improvements are possible within the next few years including; better initial state through an own 3D-Var scheme and assimilation of cloudy microwave radiances and radar data, 3D ocean coupling, improved wind-pressure relationship and increased horizontal resolution or a high-resolution ensemble system.

Indian Meteorological Department (IMD) have adapted Hurricane-WRF model HWRFV 3.7+ from NCEP for the North Indian Ocean. The model runs with nested domain of 18 km, 6 km and 2 km horizontal resolution and 61 vertical levels. The model provides 6 hourly track and intensity forecasts along with surface wind and rain swaths valid up to 120 hours. The model uses IMD GFS-T1534L64 analysis/forecast for initialisation.

### 3.3.2.4 Consensus and ensemble-based guidance

Consensus methods are extensively used for track forecasting but the systematic use of a consensus for intensity matters are less widespread, potentially due to a lack of specific tools in some agencies to properly visualize full-resolution intensity forecast provided by the guidance.

The ‘ICNW’ approach to combine SHIPS and LGEM with high resolution models HWRF, COAMPS and HMON as well as the RIPA index, has led to significant improvements in the quality of
objective guidance at JTWC. For example, at mid-typhoon season 2018, the ICNW outperformed JTWC from day 1 to day 4.

In the framework of the Hurricane Forecast Improvement Program (HFIP), a Corrected Consensus Approach (HCCA) for tropical cyclone track and intensity forecasts has been developed at the National Hurricane Center (Simon et al., 2018). The HCCA technique relies on the forecasts of separate input models for both track and intensity and assigns unequal weighting coefficients based on a set of training forecasts. HCCA uses Decay-SHIPS, LGEM, GFS, UKMO, IFS, COAMPS TC, HWRF, GEFS and EPS to derive a track and intensity consensus. The HCCA track and intensity forecasts for 2015 were competitive with some of the best-performing operational guidance at the National Hurricane Center. The relative magnitudes of the intensity coefficients were more varied but the most important input models for HCCA intensity forecasts are HWRF and COAMPS-TC model initialized from the GFS. Several updates were incorporated into the HCCA formulation prior to the 2016 season. Verification results indicate HCCA continued to be a skillful model in both basins (North Atlantic and East Pacific).

Recent work at RSMC La Réunion has designed a technique to generate weighted ensemble predictions around the official track and intensity forecast (Quetelard et al., 2018) by combining 5-years statistical errors of RSMC forecasts and ECMWF ensemble forecast spread, allowing a situation-dependent quantification of official intensity forecast as recommended during IWTC-8.

3.3.3 Intensity forecast by operational agencies

Although it was not manageable to include all operational agencies that issue tropical cyclone forecasts, a significant number of them contributed to this report, including notably all RSMCs. Thus, the pictures described in the following section regarding intensity forecast performances and current operational procedure, is expected to be well representative of the state of the art.

3.3.3.1 Inter-annual intensity forecast error trend

Over the last 4 years and for the first time, reports of intensity forecast skill from operational agencies are split into two categories: a small number of agencies (3) report a decrease in intensity forecast errors along with a concurrent increase in skill, while a continuous generally stationary trend is noted amongst other agencies. Figure 3.3.3.1 show the scores of operational agencies reporting those improvements. Although the progress has not been steady over recent years, improvements are remarkable at the NHC, especially for forecasts beyond 48 hours for both the North Atlantic (NA) basin and to a lesser extend the Eastern North Pacific (ENP). For the NA, the 2011-2013 official intensity forecast skill that was around 10-15% for the 12-36 hours leadtimes and near 0% for longer leadtimes (previous IWTC report), have increased on average between 25-45% at all leadtimes for the period 2014-2017. The NHC reports that until recently, the statistical/dynamical models DSHIPS and LGEM were generally the most reliable guidance for intensity prediction. In recent years, however, consensus models such as the equally weighted variable-member consensus (IVCN) and the HCCA, along with the dynamical HWRF model, have become the best intensity guidance for the Atlantic basin. In fact, the HWRF has been the best-performing individual model for intensity in the Atlantic for the past 3 years. Another promising aspect of the HWRF model is its ability to assimilate data such as aircraft-observed Doppler radar velocities in the TC inner core.
Over the North-West Pacific, the JMA has upgraded intensity guidance as seen in the previous section, with mainly the development of the RSMC Tokyo version of SHIPS, TIFS. RSMC Tokyo started using TIFS on a trial basis as one of the tropical cyclone (TC) intensity forecast models since the middle of 2016. RSMC Tokyo is planning to operationalize TIFS from the 2019 typhoon season along with the extension of intensity forecasts from 3 days to 5 days. Accordingly, the trial use of TIFS has greatly improved the accuracy of RSMC Tokyo intensity forecasts. RMSE of the RSMC Tokyo official intensity forecast (Pmin forecast) decreased greatly in 2017 (Figure 3.3.3.2) and skill has increased since 2016 passing from below 10% to 15-20% for leadtimes 24, 48 and 72 hours.

Over the past 17 years (2000-2017) and still for the North-Western Pacific, there has been a gradual decrease in the JTWC average forecast intensity errors at 48 and 72 hours with no significant change at 24 hours. However, a more pronounced improvement is evident in the very recent years at the 96-hour and 120-hour verification points. The JTWC has recently implemented significant enhancements to the forecast intensity guidance suite to include:

- Rapid Intensification Forecast Aids (Knaff 2018) – deterministic forecasts (RI25, RI30, RI35, RI40, RI45, RI55 and RI70) incorporated into the intensity consensus (ICNW)
- M-PERC
- CIRA / RAMMB Eye Probability
- Weighted Analog Intensity (WANI) Guidance (Tsai and Elsberry 2015)
In all the other selected agencies that contributed to this report, intensity forecast scores show no or little recent significant improvement as illustrated in Figure 3.3.3.2 with the example of the Indian Meteorological Department (IMD or RSMC New-Delhi) and Meteo France La Réunion (MFR or RSMC La Réunion).

![Figure 3.3.3.2. Intensity verification at IMD Arabian Sea and Bay of Benguale, and Meteo France South-West Indian Ocean](image)

### 3.3.3.2 Operational intensity procedures

All selected operational agencies have shared an update of their intensity forecast process. A common feature is that the intensity forecast process follows the determination of the analysis fix and forecast track and its inherent uncertainty. As steering levels change with intensity, the intensity forecast is tightly connected with the track forecast, both being interdependent. All selected agencies based their intensity forecast process on an understanding of the current large-scale environment (upper level flow, vertical wind shear, low to mid-level moisture, ocean heat content, low level inflow and proximity to land factors) and the analysed intensity and trend over the past 24 hours or so along with inner core structural changes seen on microwave imagery. The intensity process then requires examination of the expected changes to the large-scale environment as indicated by NWP as well as the examination of key differences between NWP. Consideration is also given to continuity to avoid large changes from one forecast cycle to the next. A summary of specific procedure in each agency is provided below in no particular order.

#### a) RSMC Tokyo

TIFS, SHIFOR, JMA/GSM (JMA global model), JMA/MSM (JMA mesoscale regional model), HWRF, and cyclone phase space (CPS) based on JMA/GSM are used for intensity forecasts. JMA/MSM is used when TCs approach Japan. In general, mesoscale regional models are good at forecasting intensity changes associated with topography. JMA/GSM forecast is reliable when TCs are in the incipient stage or the extratropical transition stage. HWRF forecast is monitored to consider a possibility of RI. An intensity change scenario, including intensity change rate, peak intensity and its timing, and extratropical transition, is constructed based mainly on TIFS forecast with some modifications. For the incipient stage, TIFS intensity change rate is revised downward in most cases accounting for the bias of TIFS to overforecast intensity (e.g. Shimada et al. 2018). For the subsequent intensification stage, TIFS intensity change rate may
be adjusted upward or downward to reach forecast peak intensity, depending on the discrepancy between the past TIFS forecasts and the latest Dvorak analysis. For the weakening or landing stage, forecast intensity is modified so as to gradually approach JMA/GSM forecast intensity.

b) The Korea Meteorological Agency (KMA)

For 120 h intensity forecast, KMA used the STIPS based on statistical-dynamic model and dynamical model results of HWRF and TRUM (KMA Typhoon Regional Unified Model). The decision whether a decaying TC transforms into an extratropical cyclone or not is mainly based on Cyclone Phase Space diagram and KMA operational extratropical cyclone transition manual (KMA, 2007). KMA intensity forecast is relied on the results from the STIPS.

c) The Bureau of Meteorology (BoM)

An initial intensity forecast estimate is typically considered in a Dvorak T-no. framework. For example, D for 0-24h, D+ 24-48h, D-/S 48-72h, W+ 72-96h etc. where D represents an increase of 1.0 T-no. per day.

This is followed by a review of the objective NWP intensity forecasts and statistical-dynamic models. The Bureau follows research by NRL to improve objective statistical-dynamic intensity guidance. The latest version of the SHIPS approach, 'ICNW' is used routinely by BoM along with the Rapid Intensification Index RII. It is limited by not including some models such as IFS and UK.

Figure 3.3.3.3. Example of BoM's tool for the operational intensity forecast. To assimilate the range of NWP intensity estimates including ensemble outputs with the analysis and previous forecasts, BoM developed the intensity tool with the operational software package TCMODULE. This also allows the forecast to be automatically generated and edited onscreen and includes the standard inland decay rate.
Consistency between dynamical models is an important consideration with bias given to the better performing and higher resolution models. The highest-resolution model, HWRF, is the most likely model to indicate rapid intensification. BoM also consider trends in the ECMWF ensemble intensity output. The trends in model intensity are given greater consideration rather than the absolute values as NWP have historically underestimated the intensity. However, this is changing as model resolution increases.

Guidance from these forecast aids are combined with a subjective assessment of potential environmental influences and recent intensity changes to determine forecast intensity. A combination of synoptic assessment and persistence is usually weighted most heavily for the short term (to +24 h), after which increasing weight is given to objective guidance and consistent trends in dynamical models. Consistency over a series of model runs is also considered to avoid fluctuating from one forecast to the next.

Finally, the forecast intensity is compared to the previously issued forecast for policy consistency and adjusted accordingly. This is especially the case when there is high uncertainty. For example, if there is a significant change from what was issued previously the official forecast may be adjusted closer to the previous issue estimates until the evidence for the change becomes stronger. Rapid intensity changes especially at longer lead times are typically avoided as it is so difficult to pick the timing of such changes.

d) RSMC New-Delhi (IMD)

The intensity forecast has been issued by RSMC, New Delhi from deep depression stage (MSW: 28-33 kts) onwards since 2009 for 12, 24, 36, 48, 60 and 72 h forecast periods (Mohapatra et al., 2013). The TC intensity forecast is issued 4 times a day at the interval of six hours, i.e. based on 00, 06, 12 and 18 UTC observations with every three hourly updates and validity period extended up to 120 hrs since 2013. The forecasts are issued about three hours after the above-mentioned observation time. The tools and methods used by IMD for intensity forecasting of TCs over the North Indian Ocean includes satellite, radar and synoptic guidances, as well as guidances from various global and regional deterministic models like IMD-GFS, NCMRWF(India)-GFS, IFS, UKMO, JMA, ARP (MeteoFrance), IMD-WRF, WRF run at Indian Institute of Technology - Delhi, NCMRWF-WRF, HWRF, NCEP-HWRF and probabilistic predictions from ensemble prediction systems like NCMRWF-GEFS, ECMWF-EPS etc. (Mohapatra et al., 2013b). In addition, outputs from the Dynamical-statistical Cyclone Prediction System (CPS) are used routinely at IMD.

e) RSMC La Réunion (Meteo-France)

The short-range intensity forecast process is mainly influenced by the identification of ongoing internal / external influences detected at initial time. For the longer ranges, forecasters make environmental conditions assessments that are generally derived from analyses of environmental fields and chiefly from the main numerical guidance: IFS and GFS deterministic models constituting the main reference. With the progressive increase in resolution of numerical models, some raw parameters like maximum winds, central MSLP ... are also looked at more closely by the forecasters. They appear very valuable for the post-tropical phase and to a lesser extent during cyclogenesis. Among the usual models, IFS and GFS deterministic data are the most popular but ECMWF EPS, GEFS, UKMO, ARP (Meteo France global model) and aids received from JTWC (NVGM, HWRF, GFDN, CONW) are also frequently considered.
In the recent years, one main evolution was the implementation of the Meteo-France Arome-IO model in 2016. The tendency in this fine scale model to over-intensify was less apparent during last season (2017/2018) – probably owing to the inclusion of the ocean coupling – whereas some rapid intensification events were correctly forecast. These promising results along with expected valuable improvement of the model in the coming years should lead to increase use of this model for the short-term forecast.

f) The Joint Typhoon Warning Center

The JTWC forecaster only has about 1-1.5 h to synthesize forecast track, intensity, and wind distribution guidance before issuing a tropical cyclone forecast. The following forecast intensity practices and strategies are applied:

- Since HWRF is considered a reliable model for predicting intensity change rates, forecasters generally hedge close to or above HWRF guidance.
- Forecasters may also hedge above COTC / ICNW when output is consistent.
- Leverage Dvorak’s (Velden 2006) climatological intensification model
  - In a very favourable environment, the intensification rate may exceed 1.5 T-numbers per day
  - In an unfavourable environment, it may be well below one T-number per day
- Identify annular structure using EIR imagery.
- Identify eyewall replacement cycles, primarily through analysis of microwave satellite data and M-PERC data.
- Identify a cyan ring structure in 37 GHz colour composite microwave imagery (Kieper 2012), which may signal an imminent RI phase.
- Identify observed, sharp increase in objective intensity estimates, which may signal an imminent RI / ERI event.
- Identify areas of increasing vertical wind shear and cooler sea surface temperatures that tend to weaken a tropical cyclone.
- Identify synoptic-scale influences on outflow patterns around the tropical cyclone.
- If the outflow channel is directed poleward, the average maximum rate of intensification is 15-20 knots every six hours. If the outflow channel is directed equatorward, then the average maximum rate of intensification is 25-28 knots every six hours.
- Tropical cyclones with dual channel outflow intensify at a maximum rate of 35 knots every six hours. Dual channel outflow is a key factor in many cases of rapid intensification. The TUTT must also be considered as a major contributor to tropical cyclone intensity change in the western North Pacific. Both the placement and proximity of the TUTT to the tropical cyclone will determine the effect - positive or negative - that the TUTT will have on the intensity change of the tropical cyclone.
- Identify favourable sea surface temperature areas (between 26 and 29°C). Rapid intensification is more likely if sea surface temperature is 28.5°C or greater.
- Identify favourable areas of high ocean heat content, which is especially important for slow moving TCs.
- Identify and track the subtropical ridge access since rapid intensification often occurs as the tropical cyclone approaches the subtropical ridge axis, where the translation speed of the tropical cyclone decreases, vertical shear is usually very low, outflow is exceptionally favourable, and the underlying sea surface temperatures are sufficiently warm and ocean heat content is sufficiently high.
• Rapid intensification may occur wherever and whenever conditions are conducive. However, a few areas are noted for having such conducive conditions on a regular basis, including the Philippine Sea, Mozambique Channel, and Gulf of Carpentaria.

g) The Central Pacific Hurricane Center (CPHC)

A large percentage of Central Pacific TCs enter the basin from the east after reaching their peak intensity in the eastern Pacific, and are typically “spinning down” on their way to becoming a remnant low or dissipating. This is largely due to strong environmental vertical wind shear typically found in the basin, with this shear effectively entraining dry mid- and upper-level air into the cyclone’s circulation, leading to the demise of most TCs. The warmest ocean temperatures in the basin are typically south of the main TC storm track, and limited ocean heat content usually plays a role in limiting the intensity of central Pacific TCs. With a minimal amount of land mass in the basin, interaction with land and topography rarely plays a role in forecasting intensity change. A pair of recent TCs (Iselle 2014 and Darby 2016) have made landfall on the Big Island of Hawaii, and in these limited cases, forecasters had to consider interaction with the extreme topography of the Big Island when developing the intensity forecast.

Statistical-dynamical model guidance is referenced during every forecast cycle. Known as SHIPS/LGEM, this guidance is based on climatology, persistence, and statistical relationships to current and forecast environmental conditions. Presented in tabular form, these data give the forecaster guidance on what factors may be most critical in the intensity change of a TC. The SHIPS guidance also includes statistical information on the probability of rapid intensification over the first 48 hours of the forecast.

Regional (HWRF/HMON) and global (GFS, IFS, COAMPS-TC, UKMET) dynamical model guidance is operationally referenced for anticipating intensity change. Although advances in global model capabilities have led to increased accuracy in TC track forecasts, they remain of limited utility in intensity forecasts due to several reasons. These limitations include insufficient model resolution to capture inner-core dynamics critical to intensity change, poorly understood inner-core dynamics, and challenges related to the model’s representation of environmental shear. Consensus and ensemble guidance is utilized as well, with ICON/IVCN guidance representing a blend of the SHIPS/LGEM/HWRF/COAMPS-TC guidance. Ensemble guidance in the form of the Florida State Super Ensemble (FSSE) is available to CPHC forecasters, with this corrected-consensus utilizing dynamical models and the previous official forecast. These forecast techniques have been some of the best performers in anticipating intensity change. In the operational setting, persistence is used quite a bit, especially when anticipating short-term changes in intensity. Forecasters also look for obvious environmental signals, i.e. cooler waters/increasing upper-level winds/decreased environmental moisture, and evaluate model guidance to determine if these are properly analysed. Intensity forecasts at RSMC Honolulu tend to be conservative; as extreme intensity changes are rarely observed in the basin, they are almost never forecast.

h) The Fiji Meteorological Service

For forecast intensity and track, global model guidances are imported from the JTWC website to TC Module. Guidance like GFS, UKMO, JTWC, GFDL, JMA are available from the JTWC collaboration site. IFS is entered manually from Tropical Tidbits. For the intensity forecast,
model guidance is used together with the DVORAK rules for intensification and weakening. Midget systems which intensify rapidly is most difficult to forecast.

1) The National Hurricane Center

No major change in the operational procedure for intensity forecast compared to the last IWTC report. Data from the initial state analysis are used as input into statistical-dynamical models, such as SHIPS and Logistic Growth model (LGEM; DeMaria 2009), and dynamical models such as the GFDL and HWRF hurricane models. Combination of various statistical-dynamical guidance and dynamical guidance are then performed to derive simple consensus, like the IVCN (an equally weighted variable-member consensus) or more sophisticated consensus like the HCCA (see above). Recently, those guidances along with HWRF, have become the most reliable for the North Atlantic as shown in Figure 3.3.3.4 below.

![Figure 3.3.3.4](image.png)

**Figure 3.3.3.4.** Intensity error (kt) for all (a) Atlantic and (b) eastern North Pacific forecasts from 2015 to 2017 for AVNI (NCEP GFS deterministic model), DSHP (Decay Statistical Hurricane Intensity Prediction Scheme), HCCA (HFIP Corrected Consensus Approach), HWFI (Hurricane Weather Research and Forecasting Model), IVCN (equally weighted variable-member consensus), LGEM (Statistical Hurricane Intensity Prediction Scheme Logistical Growth Equation Model), and OFCL (NHC official forecasts).

The NHC forecasters also consider RII and DTOPS for RI, and are proving to be quite useful in operations.
3.3.3.3. Dealing with rapid intensity changes

The main challenge in terms of intensity forecasting remains the prediction of rapid intensity changes (i.e. Rapid Intensification (RI) and Rapid Weakening (RW)). According to the recent IWTC-LP IV report on recent advances in research and forecasting of tropical cyclone track, intensity and structure at landfall (Leroux et al., 2018), recent climatological studies of intensity changes have quantified the possible range of TC intensification and decay in different tropical regions outside of the NATL, that was documented since 2003 (Kaplan and DeMaria). Leroux et al. (2018) established thresholds of RI and RW appropriate for the SWIO using a 17-year climatology based on best-track data. Similar to the 30kt threshold commonly used in the NATL for 1-min sustained wind speeds, RI in the SWIO is defined as a minimum 24-h increase of 15.4 m/s (29 kt) in the maximum 10-min sustained windspeed. RW in the SWIO can be defined as a minimum 24-h weakening of 13.9 m/s (25 kt), although this threshold may not be appropriate for all systems (tropical depressions or storms or cyclones). According to Shimada et al. (2017), RI can be defined as at least -30 hPa over a 24h period for North-West Pacific TCs from RSMC Tokyo best track data.

The JTWC report that in the North-West Pacific for the period 1970-2016, there were a total of 1387 TCs, of which 37.6% underwent RI and 11.7% underwent Extreme Rapid Intensification (ERI ie increase of Vmax greater or equal to 50 kts). Leroux et al. (2018), report that over the SWIO, and for the 1999-2016 period, 43% of all tropical systems and all very intense tropical cyclones (10-min wind greater or equal to 116 kt) underwent RI at least once during their lifetimes. Statistics indicate that operational intensity forecast errors are significantly greater at 24-h lead times for RI cases (19 kt versus 8 kt for non-RI events). Consequently, forecasters are generally not inclined to reflect a RI in their official forecast. However, some recent success has been reported in predicting RI (Harvey (2017) over the NA and Marcus (2018) over the Australian region). In both cases, an agreement between various skillful RI guidance, lead to provide forecasters with confidence to predict RI.

Some agencies are using specific guidance that target the likelihood of RI (please refer to section 2 for further details), including statistical, dynamical-statistical and dynamical guidance. Selected operational agencies of the working group have reported insights they have gained in order to deal with similar cases in the future. Here is a synthesis of their feedbacks:

For Atlantic forecasts where RI occurred (Figure 3.3.3.4a), the NHC official forecasts have the lowest error out to 24 h, while HWRF has the lowest error from 36 h – 120 h. While the statistical models, DSHP and LGEM, would have typically performed better than the dynamical models several years ago, the high-resolution forecasts of HWRF (HWFI) have become the best intensity guidance for systems that rapidly intensify. HCCA and IVCN perform slightly better than the purely statistical models, but lag behind the performance of HWRF. The least skillful model for RI prediction included in this sample is GFS (AVNI). Although the skill of global models is less than that of the high-resolution regional models for intensity prediction, and especially so for RI, global models have improved considerably in recent years.

The intensity error of RI forecasts for the eastern North Pacific (Figure 3.3.3.4b) exhibit slightly different characteristics than those for the Atlantic. The best performing model from 24 h to 120 h is HCCA, which outperforms the NHC official forecasts by quite a wide margin at medium- and long-range forecast hours. The two worst performing models are AVNI and HWFI. Relative to the purely dynamical models, the statistical/dynamical models, DSHP and LGEM, perform better for RI forecasts in the eastern North Pacific compared to the Atlantic.
This suggests that statistical/dynamical models (and corrected consensus techniques) still have an advantage in the eastern North Pacific over dynamical models.

Figure 3.3.3.5. Intensity error (kt) for (a) Atlantic and (b) eastern North Pacific forecasts from 2015 to 2017 that experienced at least a 30 kt increase in intensity over 24 h for AVNI (interpolated GFS), DSHP (Decay Statistical Hurricane Intensity Prediction Scheme), HCCA (HFIP Corrected Consensus Approach), HWFI (interpolated HWRF), IVCN (equally weighted variable-member consensus), LGEM (Statistical Hurricane Intensity Prediction Scheme Logistical Growth Equation Model), and OFCL (NHC official forecasts). Only the 24 h periods from each forecast that encompass the RI events are included in the verification.

The JTWC reports the following insights:

1) Early presence of RI intensity aids may signal an RI event in the near future
2) Sharp increasing trend / high values of RI probabilities above the 40% threshold may indicate greater potential for RI / ERI
3) If used in conjunction with mesoscale models / other evidence, RI intensity aids may bolster confidence in imminent RI / ERI event
4) Consistent presence of RI intensity aids may indicate greater likelihood of RI event occurring. However, inconsistent behaviour may indicate reduced likelihood of RI event.
At RSMC Tokyo (JMA), TIFS is not good at predicting RI. To capture precursors to RI in real time, the formation of an eyewall ring is monitored from microwave satellite imagery and upper-level outflow is monitored from infrared satellite imagery. When eyewall formation and strong outflow are confirmed, forecast intensification rate is subjectively increased. For rapidly weakening TCs, TIFS forecast is used in combination with JMA/GSM forecast and the timing of extratropical transition.

Kotal et al. (2017) from RSMC New-Delhi, studied the evolution of thermodynamic structure during RI and RW periods of extremely severe cyclonic storm *Chapala* in November 2015. The inception of RI was associated with substantial increase of convective heating and its vertical extent in the inner core. Latent heat release produced a diabatically generated potential vorticity (PV) in vertical column. The amplification of PV in the vertical column over the inner-core region during RI reflects the amplification of the vortex as a whole. The RW coincided with the significant weakening in updraft of moisture flux consequently decrease of diabatic heating in the middle and upper troposphere and dissipation of upper and lower PV. From the operational point of view for forecasting RI in real time, it is a challenge to identify the threshold value of the inertial stability for the efficient conversion of diabatic heating and for convective bursts within the inner core. Further study is needed to identify the key characteristics of the inertial stability and the conditions that lead to the development of convective bursts necessary for RI.

**Figure 3.3.3.6.** Vertical cross section plots of diabatic heating (shaded in °C) for TC *Chapala* (November 2015) (a) non-RI phase: 0000 UTC 28 October 2015 to 0000 UTC 29 November 2015, (b) RI phase-I: 0000 UTC 29 October 2015 to 0000 UTC 30 November 2015, (c) RI phase-II: 1200 UTC 29 October 2015 to 1200 UTC 30 October 2015, (d) RW phase: 0000 UTC 2 November 2015 to 3 November 2015.
At RSMC La Réunion, the most extreme events like the Very Intense Tropical Cyclone *Hellen* in March 2014 (around 150 hPa absolute variation in 48h, pending publication from Colomb & Kriat) are studied intensively, with the support of researchers from CNRM (National Centre for Meteorological Research) and LACY (Laboratory of Atmosphere and Tropical Cyclones at Réunion Island University). Those cases are also extensively used to improve the quality of the non-hydrostatic Arome-IO model. During experimental tests, this model has been able to closely predict those extreme intensity variations of *TC Hellen*. Based on these simulations and on a few radiosondes, dry air and vertical windshear at mid levels (400 hPa) were found to be the main cause of *Hellen*’s rapid weakening by 90 kt in 24 h. Downdrafts originating at mid levels flushed the inflow layer with low-entropy air. This process contributed to depress near core $\theta_e$ values, which upset the updrafts in the eyewall. The upper half of the warm core was consistently ventilated by the vertical wind shear, which also contributed to the storm rapid weakening (from hydrostatic considerations).

While forecasters are increasingly conscious of identifying cases suitable for rapid intensification, there have been cases of RI that fall outside the standard scenario of developing in 'favourable environments' especially cases in moderate rather than low wind shear. *Ernie* (2017) and *Marcia* (2015) are two recent cases over the BoM area of responsibility, of development in moderate shear which may align with research from Ryglicki in which the convectively induced upper level outflow effectively reduces the shear. In both cases the wind shear decreased during the process of RI. An as yet unrealised opportunity is to harness the collective research on intensification under moderate shear (e.g. 2018 AMS Hurricane conference session: Doyle et al., and others) to present as training for operational forecasters.

![Figure 3.3.3.7. Vis images of Ernie, 24h apart at 06UTC, 6 April (left) and 7 April (right) 2017. The DT change was from 2.5 to 7.0.](image)
Some challenges in intensity forecasting at RSMC Honolulu include the recent Hurricane Hector (EP10 - August 2018), despite a fairly accurate track forecast. Hector remained an intense cyclone over the basin for an extended time period, and displayed concentric eyewalls and eyewall replacement cycles (ERCs) not typically observed in the central Pacific. One such ERC preceded a period of strengthening, and was well analysed and anticipated by the recently developed objectively-based M-PERC. One of the lessons from Hector is that forecasters may be better than model guidance in anticipating short-term intensity changes, especially under certain conditions. Environmental factors appeared conducive for Hector to continue as a strong hurricane as it moved west to the south of the main Hawaiian Islands, with low environmental wind shear and SSTs between 27°C and 28°C expected. Despite what appeared to be an environment conducive for the maintenance of a strong TC, the majority of the intensity guidance indicated that Hector would gradually weaken from a peak intensity near 135 kt. The re-strengthening observed as the ERC ended was not well anticipated by the official forecast, nor the bulk of the guidance. Had the forecasters had more confidence in the timing and completion of the ERC, the official forecast more than likely would’ve better anticipated Hector’s second peak in intensity.

3.3.4 List of recent difficult cases

Recommendation number 2 from IWTC-VIII that was addressed to both Operational centers and Research Community stated that operational TC centers identify their most difficult forecast cases as well as extreme events and make them available to the TC community. The TC research community is encouraged to use this list to focus on model performance and explore the predictability of these events. A selection of difficult cases (2015-2018) are presented in Table 3.3.4.1. This should be viewed as a starting point for ongoing sharing by agencies to the TC community.

Table 3.3.4.1 Difficult intensity cases (2015-2018) For further information, please refer to the official agencies represented in this working group

<table>
<thead>
<tr>
<th>Tropical Cyclones</th>
<th>Period</th>
<th>Ocean basin</th>
<th>Characteristics (RI, RW, ERC ...)</th>
<th>Observed intensity change (kt)</th>
<th>Official intensity change forecast (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAM</td>
<td>6-22 March 2015</td>
<td>South Pacific</td>
<td>RI: Several 3-days forecast during the development stage of Pam strongly underestimated the rate of intensification. As a climatological development was expected from CAT 1 (AUS) / 35 kt to CAT 3 (AUS) / 70 kt, PAM actually intensified from a CAT 1 (AUS) to a Cat 5 TC (AUS) / 135 kt</td>
<td>+55</td>
<td>+22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RI (00 UTC of 29 Oct to 00 UTC of 30 Oct)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RI (12 UTC of 29 Oct to 12 UTC of 30 Oct)</td>
<td>+60</td>
<td>+21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RW (00 UTC of 2 Nov to 00 UTC of 3 Nov)</td>
<td>-35</td>
<td>-22</td>
</tr>
<tr>
<td>CHAPALA</td>
<td>28 October – 04 November 2015</td>
<td>Arabian Sea</td>
<td>RI (00 UTC of 29 Oct to 00 UTC of 30 Oct)</td>
<td>+55</td>
<td>+22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RI (12 UTC of 29 Oct to 12 UTC of 30 Oct)</td>
<td>+60</td>
<td>+21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RW (00 UTC of 2 Nov to 00 UTC of 3 Nov)</td>
<td>-35</td>
<td>-22</td>
</tr>
<tr>
<td>TC Name</td>
<td>Dates</td>
<td>Region</td>
<td>Description</td>
<td>Intensification Details</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
<td>--------</td>
<td>-------------</td>
<td>------------------------</td>
<td></td>
</tr>
<tr>
<td>CHOI-WAN</td>
<td>1–7 October 2015</td>
<td>North-West Pacific</td>
<td>Monsoon gyres and/or monsoon depressions with very slow rate of intensification despite favourable environmental conditions. The forecasts overestimated the actual intensity. Similar cases with Omais (2016) and Maliksi (2018).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEGH</td>
<td>05-10 November 2015</td>
<td>Arabian Sea</td>
<td>RI (00 UTC of 7 Nov to 00 UTC of 8 Nov) +40 +10 RI (12 UTC of 7 Nov to 12 UTC of 8 Nov) +30 +8 RW (00 UTC of 9 Nov to 00 UTC of 10 Nov) -35 -20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PALI</td>
<td>08–15 January 2016</td>
<td>Central North Pacific (unusual location and low lat TC)</td>
<td>Missed intensification: between 12 UTC of 10 Jan and 18 UTC of 12 Jan, little or no intensification anticipated but PALI’s strength increased from 35 kt to 85 kt. RW (00 UTC of 13 Jan to 00 UTC of 14 Jan) -35 -5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ERNIE</td>
<td>5–10 April 2017</td>
<td>Australian region</td>
<td>RI (12 UTC of 6 Apr to 12 UTC of 7 Apr) +75(!) +10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TALIM</td>
<td>8–17 September 2017</td>
<td>North-West Pacific</td>
<td>Suspended intensification due to unexpected strong vertical wind shear, dry air intrusion and/or the passage over cold waters. Forecast can overestimate quite significantly. Similar cases with typhoon LAN (2017).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MARIA</td>
<td>16 September – 2 October 2017</td>
<td>North Atlantic</td>
<td>RI (06 UTC of 18 Sept to 06 UTC of 19 Sept) +55 (+65/18hrs) +25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCKHI</td>
<td>29 November - 06 December 2017</td>
<td>Arabian Sea</td>
<td>RI (00 UTC of 1 Dec to 00 UTC of 2 Dec) +30 +12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KELVIN</td>
<td>15–19 February 2018</td>
<td>Australian region (offshore developer)</td>
<td>Kelvin was expected to develop quickly in a favourable environment off the coast. When that failed to occur, forecasts eased off but the TC eventually developed rapidly in the 12h prior to landfall, and continued to show an improved satellite signature as it moves overland developing an eye.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KENI</td>
<td>8 April – 11 April 2018</td>
<td>South Pacific</td>
<td>RI: At the initial stage (8th of April), the system was expected to rapidly intensified from a tropical depression to CAT 2 (AUS) / 50 kt in 24 hr. The intensification rate was expected to level-off after that. Actually, KENI almost did the first 24hr expected intensification (CAT 1 (AUS) / 45 kt) but continue on that trend to reach CAT 3 (AUS) / 85 kt during the next 24 hours.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typhoon</td>
<td>Date &amp; Duration</td>
<td>Region</td>
<td>Event</td>
<td>Short Range Along Track Error</td>
<td></td>
</tr>
<tr>
<td>---------</td>
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<td>--------</td>
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<td>------------------------------</td>
<td></td>
</tr>
<tr>
<td>Fakir</td>
<td>20 April – 26 April 2018</td>
<td>South-West Indian Ocean</td>
<td>RI (06 UTC of 23 Apr to 06 UTC of 24 Apr) – Strong delay in timing and localization of the expected rapid weakening trend, due to unusually high short range along track error.</td>
<td>+30</td>
<td></td>
</tr>
<tr>
<td>Hector</td>
<td>27 July – 13 August 2018</td>
<td>Central North Pacific</td>
<td>Missed post-ERC intensification (06 UTC of 9 Aug to 18 UTC of 10 Aug)</td>
<td>+25</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.3.4.2. Fakir’s case in April 2018 in the South-Western Indian Ocean. The poor intensity forecast is associated with a remarkable short-range along track error due to a rarely seen forward motion at this latitude. The weakening trend was delayed and the system passed close to La Réunion just below its peak intensity.
3.3.5 Summary and conclusions

Since IWTC-8 in 2014, considerable work has continued worldwide to improve tropical cyclone intensity guidance and understanding internal and external influences that sometimes lead to rapid intensity changes. Recent improvements are reported with statistical, statistical-dynamical and dynamical guidance. Especially, sophisticated statistical-dynamical new techniques, weighted consensus along with improvement in the physics and data assimilation of some regional models has led to improve skill for intensity forecasting and even in anticipating rapid intensity change, that remains a forecast issue. Following a recommendation from previous IWTC, the sharing of intensity guidance initially designed for the North Atlantic or the East Pacific has allowed some upgrade in intensity forecast of some operational centres. Recently, the intensity score has started to improve for some agencies but this trend needs to be confirmed and also extended to all operational centers. For this purpose, a continuing support should be maintained to operational agencies that provide useful and globally available intensity guidance like NRL, CIMSS and CIRA.

Although all this ongoing efforts, large intensity forecast errors are (and will) still occurring in operation. A list (likely non-exhaustive) of these cases over the past 4 years, is presented in the report (as a recommendation of the previous IWTC) at the attention of the research community to explore the predictability of this events.

3.3.6 Recommendations

1) Continue to bring forecasting intensity algorithms (NWP models, statistical-dynamical models and statistical models) to operations. (Research recommendation)

2) This guidances should extend globally (pursuit of the ongoing effort) with real-time availability and visualisation of all guidance not just subsets (for example the CIRA multi-models diagnostic comparison is an excellent product but not all the reliable guidance are indicated). An independent assessment of this techniques in each TC area should be done. (Research and WMO recommendation)

3) Training materials (through multiple media) and/or training sessions for forecasters should be planned in order to ensure a good handle of this new intensity forecast techniques (WMO recommendation)

4) A continuing effort should be done by the research community to address cases of large errors documented by the operational centres. (Research and Operational recommendation)

Acknowledgements

Thanks go to all the contributors from the working group and to Joe Courtney, who has put his trust in me to prepare this report.

Acronyms used in the report

AMV - Atmospheric Motion Vectors
AROME - Meteo France non-hydrostatic fine scale spectral model
ARCHER – Automated Rotational Center Hurricane Retrieval
SHIFOR - Statistical Hurricane Intensity FORecast (statistical baseline)
TC – Tropical cyclone
TCLP - Trajectory CLIPER
TCWC – Tropical Cyclone Warning Center
TIFS - Typhoon Intensity Forecast scheme based on SHIPS used at JMA
TRUM - KMA Typhoon Regional Unified Model
TUTT – Tropical Upper Tropospheric Trough
WAIA - Weighted Analog Intensity Atlantic
WAIP - Weighted Analog Intensity Pacific
WANI - Weighted ANalog Intensity

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Vitard, F., and colleagues, 2018: *ECMWF: Research developments and plans*. Presentation for ECMWF member states.

Abstract
This chapter summarizes ongoing advances in our understanding of the size, shape, and temporal evolution of the wind fields of tropical cyclones. Much like the period of time between the previous two IWTC meetings, there have been significant improvements in analyses and forecasts of the TC wind field, due both to increasing and improving satellite technologies, and also increasing understanding of the physical processes that cause significant changes to the wind field, most notably secondary eyewall formation and the eyewall replacement cycle, and extratropical transition.

4.0 Overview

As forecasts of TC position and intensity continue to improve, there is also increasing attention to the structure, size, and asymmetries of the wind fields of these storms, because this information is equally important in determining warning areas and levels of preparation, especially at long lead times, when errors of both position and wind field size can be large. This topic chapter describes the state of operational analysis and forecasting of TC wind fields, along with the two physical processes that cause the most significant structure changes: secondary eyewall formation and extratropical transition. Note that in this summary, most references have been removed, but they can be found in the original text of the subsequent chapters.

4.1 Analysis and prediction of wind structure

Analysing the surface wind field of TCs is of great importance to monitor the current area of influence of storm winds. The accurate analysis of the surface wind field is also sought from the NWP community as it is used for evaluation of model outputs and as it can be used in data assimilation to create better initial conditions for both global and regional models. In addition, the surface wind field is used for post-processed guidance such as storm surge and wave forecasts. Therefore, forecasting the surface wind field of TCs is crucially important for disaster risk reduction operations and for achieving impact-based forecasting.
4.1.1 Current Status

Wind structure analyses and forecasts are generally provided by forecast centers as “wind radii”. These wind radii vary from one center to another, but are generally defined as the maximum extent of some threshold wind speed in terms of circles, semi-circles, or compass quadrants (northeast, southeast, southwest and northwest) surrounding the TC. The critical thresholds used are generally for gales (17 m/s or 34 kt), storm force (25 m/s or 50 kt), and hurricane force (33 m/s or 64 kt) radii. With the expectation to forecast two or more wind radii in each of the 4 quadrants, for each of the required forecast intervals (12, 24, ....120 hours), this part of the TC forecast cycle is often the most time consuming.

4.1.2 Gale Wind Radii Estimates

Aircraft observations including flight-level winds, dropsondes, and SFMR are the most useful and reliable data for estimating the surface wind structure. These observations are limited mainly to the North Atlantic basin where aircraft reconnaissance is available about 30% of the time, more often when landfall is a threat. The second most accurate, source of wind field information is from scatterometers, which can provide broad areas of useful data when the instrument (e.g. ASCAT) footprints pass near or over TCs. However, their coverage is not continuous and they do not provide reliable values when the wind speeds exceed 25 m/s and/or there is significant precipitation. IR proxies, other satellites, and even the forecast models themselves also provide skillful information about the TC wind field at the analysis time. A consensus algorithm known as OBTK combines all available data to provide the most accurate estimate. Still, mean errors can be larger than 10%.

4.1.3 Gale Wind Radii Forecasts

A starting point for forecasts is the gale wind radii climatology and persistence model known as DRCL, which can be used as a baseline and also as a first-guess for other schemes. A statistical-dynamical gale radii forecast model (DSHA) is also available, which uses current TC information, IR imagery, and global model forecasts. Finally, the model output from global models themselves can be harvested for wind radii around each TC. Much like OBTK, the radii consensus forecast RVCN, computed using all of these models, has lower mean forecast errors and biases than any other individual model or scheme.

4.1.4 Inner Core Structure

A critical first step in assessing both outer-core and inner-core sizes is an accurate estimate of the TC center. A new method that has come to increasing use is the Automated Rotational Center Hurricane Retrieval (ARCHER). This algorithm combines IR images with microwave and scatterometer data (when each is available) to locate the TC center. It also provides an estimate of eye diameter. An extension of the ARCHER framework is the Microwave Probability of Eyewall Replacement Cycle (M-PERC) model, which uses primarily microwave satellite data to assess the likelihood of an ERC to begin within the next 36 h.

4.1.5 Recent Practices at the Operational Centers

At the Japanese Meteorological Agency (JMA), a new technique has been developed that uses low-level atmospheric motion vectors (AMVs) for estimating the surface wind structure. The low-level wind speeds are converted to surface winds using 76% of the low-level wind speed
and wind directions are adjusted toward the TC center by 9°. Although low-level AMVs can be obstructed by high clouds, the frequent refresh rate of the Himawari satellite makes it possible to estimate surface winds over the larger areas around TCs, especially in the daytime when more channels are available.

The Joint Typhoon Warning Center (JTWC) has established a goal of predicting gale force and 25 m/s wind radii within of 20% of their verified values. The new consensus guidance models such as OBTK and RVCN have improved forecast wind radii errors to generally less than 30%, close to the desired goal. Still, challenges remain, such as with predicting wind fields around incipient or weak TCs, and also in distinguishing the distances at which strong winds can be attributed to TCs; this is especially problematic for large TCs.

In the North Atlantic, estimated errors for verified (best track) wind radii remain large, as much as 40, 30, and 25 nmi for 34, 50, and 64 knot winds. These uncertainties range from 1/3 to 1/2 the forecasted wind radii. A recent verification study, made by comparing to reconnaissance data, found that forecasts were indeed skillful when compared to climatology and persistence. Much like JTWC, in recent years NHC has come to rely more on RVCN, which should lead to more accurate wind radii forecasts.

### 4.1.6 Conclusions

From an operational perspective, great strides are being made in both analysis and forecasting of surface wind structure. The last four years have seen new and improved algorithms for estimating surface winds in the vicinity of TCs. Improvements in NWP data assimilation and forecasting have yielded guidance for analysis, forecast and forecast error estimates of gale wind radii and possibly inner core radii. Validation of inner core radii estimates and forecasts remains difficult due to the paucity of observations, but there is hope that new sensors and algorithms to address inner core radii will help alleviate this problem.

### 4.1.7 Recommendations

The recommendations for guidance on wind structure and wind structure asymmetry are:

1) Develop high quality inner core wind radii observational datasets both for real-time guidance and to construct high quality post-season analyses.
2) Continue to bring analysis algorithms to operations, especially those which address inner core wind structure analyses and forecasts.
3) Continue to develop NWP both for analyses and forecasts of wind structure so that they can be effectively used to disseminate long-range, accurate warnings of the onset of winds, waves, swell and surge.
4) Continue to launch satellites with potential to discern wind fields.

### 4.2 Secondary Eyewall Formation and Expansion of the Wind Field

#### 4.2.1 Introduction

Secondary eyewall formation (SEF) and the eyewall replacement cycle (ERC) are one of the most striking phenomena associated with tropical cyclones. SEF occurs when rainbands outside of the primary eyewall become organized into an increasingly symmetric pattern, ultimately forming a new, “secondary” eyewall. This occurs at least once in a significant majority of
strong tropical cyclones, and sometimes it occurs multiple times. SEF is usually, but not always, followed by ERC, where the secondary eyewall strengthens, contracts, and replaces the original inner eyewall. SEF and ERC are important because they are associated with major changes in intensity and size: usually the storm weakens while the wind field expands; then, the storm often re-intensifies in its core as the ERC completes. Although SEF/ERC occurs quite reliably in strengthening, major TCs, more specific prediction of these events remains difficult, although statistical methods show some skill beyond climatology. As discussed further below, there is no consensus on the exact cause and physical processes of SEF, or even a formal definition that is widely used. These shortcomings probably contribute to the low predictability of SEF/ERC at this time.

4.2.2 Observations of SEFs and ERCs

Satellite observations, flight-level data, and airborne radar data accumulated over many years now contribute to a large collection of observational data sets of TC rainbands, SEF, and ERC. Rainbands are often organized into a “rainband complex” with narrower, convective bands in the upshear quadrants merging into a larger, stratiform region as they spiral toward the downshear-right and downshear-left quadrants. In recent years, an increasing importance has been discerned for this stratiform region in SEF. Its more persistent, positive diabatic heating above the melting level projects more strongly onto the symmetric flow, more efficiently increasing the tangential wind, contributing to the expansion of the wind field. Secondly, cooling below the melting level generates a mid-level, descending inflow (MDI) that accelerates the tangential flow, and also descends into the boundary layer, perhaps triggering a deep updraft that is well organized, reinforces the overturning circulation in that region, and ultimately “wraps up” into the secondary eyewall. These observational findings are in agreement with recent modelling studies that have also identified “top-down” processes such as stratiform heating and strong downdrafts penetrating into the boundary layer as critical for SEF.

As noted above, SEF/ERC causes important structural changes with operational implications. Before SEF, TCs tend to be smaller, and have minimum pressures that are higher than the expected value for their peak winds. After ERC, the reverse is true, with lower pressures for their current wind speeds. Numerous observational and modelling studies reproduce this expansion of the wind field during and after ERC. However, a complete ERC does not occur in all cases; sometimes the outer eyewall decays, and sometimes the two eyewalls both persist for extended periods.

4.2.3 Numerical Simulations

While the realism of physical processes in numerical simulations must always be carefully considered, they offer the benefit of providing a continuous record of the physical processes they simulate. Thus, numerical simulations have been used extensively in efforts to improve our understanding of SEF and ERCs. Nonetheless, in many cases these efforts have led to contradictory findings.

For example, some simulations clearly point to the influence of asymmetric processes – either asymmetric forcing from the environment, or internal asymmetries associated with asymmetric waves and rainbands, as important to the process of developing a secondary wind maximum. In other cases, SEF and ERC can appear in simulations with no asymmetric forcing at all (e.g. no mean flow and no shear), or analyses of the output of such simulations come to different
conclusions about the relative roles of asymmetric processes. These differences in outcomes and conclusions from fairly similar methodologies highlight the mysterious nature of SEF.

Similarly, numerical simulations have been used to try to determine if the physical processes leading up to SEF can be described accurately by “balanced” dynamics, where the symmetric overturning evolves only in response to the evolution of the primary, tangential circulation, or whether the time evolution and nonlinear dynamics (e.g. advection) of the boundary layer flow itself play a role. Much like the aforementioned findings with asymmetric dynamics, recent studies have come to conflicting conclusions, ranging from no role in the nonlinearity of the boundary layer response, to a minor role, to a dominant role. This topic remains under fierce debate.

The robustness of SEF and ERC in numerical simulations is, not surprisingly, also dependent on both boundary layer and microphysical parameterization schemes. In particular, recent studies have found that overly fast fall speeds for frozen hydrometeors in some schemes was unfavourable for SEF, leading to more convection in the moat region (directly outside the eyewall), and less rainfall activity. Reducing these fall speeds led to more frequent SEF and ERC. A similar finding was reported for shortwave radiation and the diurnal cycle, with its absence leading to excessive convection in the moat region and suppression of SEF.

4.2.4 Theories for SEF

As noted above, some observational and numerical studies have suggested that “top-down” processes associated with rainbands are responsible for initiating SEF. However, in recent years more theoretical studies – using simplified models or approximated equations – have focused primarily on the boundary layer. Reduced and analytical models of swirling boundary layers show that vertical motion out of the boundary layer is extremely sensitive to both the presence of a local wind maximum, and the radial profiles of wind and vorticity around that local maximum. If enhanced boundary layer convergence (regardless of whether it is due to mostly balanced or unbalanced processes) leads to increased vertical motion and increased convection, SEF may easily ensue. But this still leaves the question of how the local tangential wind maximum, even a small one, first develops. It may be initiated from the top-down processes noted above, or conceivably, it could be due to an inherent instability of the boundary layer when coupled to the free atmosphere, as found by one highly theoretical study. All the theoretical studies, however, find that the expansion of the wind field that almost always precedes SEF significantly increases the potential for such instabilities or feedbacks.

4.2.5 Summary

There is broad agreement about the following aspects of SEF: (1) In real TCs, SEF generally occurs in association with initially asymmetric outer rainbands, which (at least partly) through diabatic heating enhance the vertical vorticity in a radially confined region and thereby increase the tangential winds; (2) there is a broad radial expansion of the tangential wind field that is associated with SEF (which implies a net import of vorticity), and many studies find that this expansion precedes SEF; (3) boundary layer dynamics focus convergence in the region where SEF occurs; and (4) SEF is associated with a region of supergradient flow in the upper boundary layer.

At the time of the previous IWTC, there was no single widely-accepted theory for SEF, and this remains true today. There is continued disagreement regarding the specific mechanisms that
cause SEF and/or are responsible for amplifying existing wind maxima. The most prominent of these disagreements is whether enhanced boundary layer convergence is essentially a response of the otherwise-balanced vortex to friction (and the supergradient flow is itself also a consequence of the frictional response), or if instead the convergence is caused by the supergradient flow. The roles and significance of other physical processes – microphysics, radiation, turbulent diffusion – also remain active topics of research.

4.2.6 Recommendations

Recommendations for research on SEF and wind field expansion are:

1) Continue to use both idealized and real-case numerical experiments to attempt to distinguish between those mechanisms that can potentially affect SEF and those mechanisms that are actually essential to SEF.

2) There is a lack of systematic investigations into the ability of operational numerical models to skillfully forecast SEF and ERCs, although it is generally believed that such skill is currently absent. Given that idealized simulations are capable of producing secondary eyewalls, operational forecasts should in principle be able to do so as well. Focused studies are recommended to help answer these questions.

3) All studies should make clear how they define SEF, and consider how this choice affects their analyses and conclusions in comparison to other studies. Ideally, a common definition can be developed, although given the intrinsic differences between what is simulated and what can be readily observed, this may not be possible.

4.3 Extratropical transition

4.3.1 Introduction

The process by which TCs transition into baroclinic cyclones as they recurve into the mid-latitudes is known as extratropical transition (ET). As TCs travel poleward, they interact with extratropical westerlies, which can cause the rapid structural and track changes of the ET system itself. The distinguishing characteristic of ET is the structural change of the remnant TC from a symmetric, warm-core vortex to an asymmetric, cold-core circulation with well-defined frontal features. Associated with this structural change is the transition of the primary energy source for the system from surface enthalpy fluxes to the large-scale baroclinic conversions germane to midlatitude cyclones. Depending on the state of the midlatitude jet, the impact of ET on this waveguide varies from a slight intensification of the jet core to the development of a high-amplitude Rossby wave train that can lead to multiple high-impact weather events downstream. The prediction of specific basin-scale outcomes from ET in both weather and climate models is at once challenging and essential, not the least because of the economic and societal costs that these events can incur.

4.3.2 Structural Evolution

A TC that travels poleward into a baroclinic environment with its attendant temperature and moisture gradients typically undergoes a structural change from a deep warm-core cyclone into either a shallow warm-core or a deep cold-core cyclone, with an asymmetric, frontal structure. Specifically, as a TC moves poleward and the transformation stage of ET begins, its outer circulation encounters a midlatitude baroclinic zone, and the deep, moist convection of the inner-core becomes increasingly asymmetric. Subsequently, as the TC becomes collocated
with and embedded into the baroclinic zone, the TC acquires substantial vertical tilt, develops features such as the conveyor belts characteristic of extratropical cyclones, and thunderstorm activity becomes isolated some distance poleward of the center. Likewise, during the transformation stage, the cyclone's near-surface wind field becomes asymmetric and grows, resulting in an increase of the cyclone's integrated kinetic energy. Concurrently, precipitation fields become asymmetric and expand radially with increased areal coverage.

Since 2014, observations from several field campaigns – particularly the THORPEX Pacific Asian Regional Campaign (T-PARC) – have helped confirm the validity of previously developed conceptual models of the transformation stage of ET previously. During step 1 of the transformation stage, the TC translates poleward, its outer circulation encounters a midlatitude baroclinic zone, and the deep, moist convection of the inner core becomes more asymmetric, with an associated wavenumber-one asymmetry in the vertical motion and radar reflectivity fields with maximum ascent and reflectivity downshear-left, and maximum descent and minimum reflectivity in the upshear semicircle. During step 2 of the transformation stage, the TC becomes superposed on the midlatitude baroclinic zone. Observational studies indicate that processes associated with this superposition, rather than a response to vertical wind shear, are the cause of asymmetries in the cyclone structure during this stage. Warm frontal development east of the transitioning cyclone leads to forced ascent, in turn triggering deep, moist convection and the formation of a broad stratiform precipitation region that causes heavy precipitation to the northeast of the transitioning TC. On the western flank of the cyclone, cold frontal development is weak, and deep, moist convection is suppressed due to warm and dry air aloft and cold air near the surface.

Advances in understanding of wind-field structural evolution during ET since the last IWTC have been limited to risk-modelling applications, including quantification of variability in ET-related near-surface wind field structures and the development of improved parametric and statistical models for wind field structure during ET. The classic framework used to understand the TC wind field, which is a symmetric vortex combined with the TC forward motion, has been found to be inadequate for TCs with significant wind shear, and even less valid for storms undergoing ET. As shear increases, maximum surface winds tend to occur in the downshear left quadrant, rather than the right-front quadrant relative to storm motion, because of the enhanced inflow associated with the convective asymmetries. This asymmetry tends to shift downwind during ET as baroclinicity and shear increase. As a result, attempts have recently been made to model and forecast the asymmetric wind field of transitioning TCs with a modified parametric model, a statistical-dynamical model, and even through machine learning. All of these show some promise, but more work remains.

Rainfall with ET events may be directly – e.g. resulting from the direct interaction of the TC with the midlatitude baroclinic zone – or indirectly – e.g. such as in the case of a predecessor rain event (PRE) – related to the transitioning TC. Studies during the past four years have shown that the amount of rainfall directly associated with ET events is related to environmental factors including the amount of environmental moisture, the strength of the midlatitude baroclinic zone and its proximity to the TC during ET, the strength of moisture and temperature advection during ET (and associated frontogenesis and forcing for ascent on sloped isentropic surfaces), and the alignment of the motion and vertical wind shear vectors. The pattern (coverage and asymmetry) of rainfall directly associated with ET events is also related to interaction with topography, the strength of the midlatitude baroclinic zone and its proximity to the transitioning TC, moisture and temperature advection strength, the ascent of
moist air along sloping isentropes poleward and downstream of the TC, and the alignment of the motion and vertical wind shear vectors.

### 4.3.3 Trough Interaction and Downstream Development

Prior to 2014, idealized model simulations and real-data case studies revealed that the phasing and interaction of a transitioning TC with an upstream trough is crucial for the development of the transitioning TC and its downstream impact. Specifically, upper-tropospheric potential vorticity advection by the divergent component of the wind typically strengthens the local extratropical potential vorticity gradient (or waveguide), intensifying the jet streak between the upstream trough and downstream ridge, and amplifies the downstream ridge by deforming potential vorticity contours poleward. This process may impede the upstream trough’s eastward propagation, contributing to the favourable phasing of the TC with the upstream trough. This non-linear interaction results in a more poleward track of the TCs and a stronger amplification of the downstream flow. The ascent resulting from the non-linear interaction between the TC, upstream trough, and the midlatitude baroclinic zone manifests itself in an upper-tropospheric divergent flow. Though it has not yet been rigorously tested, it is assumed that the divergent outflow during ET is mostly driven by latent heat release. Initial estimates using the quasigeostrophic omega equation corroborate this assumption, and poleward moisture transport (which can be thought of as a proxy for latent heat release upon ascent) is crucial to downstream ridge amplification and Rossby wave packet initiation.

Further downstream, Rossby wave dispersion and the equatorward advection of anomalous cyclonic PV (induced by the anticyclonic wind field associated with the downstream ridge and the outflow anticyclone associated with the TC) result in the development of a trough downstream of the transitioning cyclone and downstream ridge. This downstream trough triggers downstream lower-tropospheric cyclogenesis, with the resulting cyclone itself associated with the poleward transport of warm and moist air (i.e. manifest as a warm conveyor belt). This contributes to ridge amplification further downstream with impacts to hemispheric weather on the synoptic to sub-seasonal scales.

To date, most investigations of high-impact weather resulting from downstream development associated with ET have been case studies of individual events, with most focusing on transitioning western North Pacific and North Atlantic TCs. In the western North Pacific, a systematic relationship between ET events and downstream high-impact weather has not yet been established; however, in the Atlantic, the magnitude of – and the area affected by – heavy precipitation in downstream regions is significantly enhanced 2-3 days after the interaction of North Atlantic TCs with the midlatitude flow. However, there is some indication that downstream impact of ET in the North Atlantic may shift the location of high-impact weather events rather than causing them to occur when they otherwise would not have occurred.

### 4.3.4 Predictability of Extratropical Transition

High-impact meso- to synoptic-scale weather events downstream of ET events are generally associated with degraded forecast skill as compared to that of the background midlatitude flow. It is not yet clear, however, whether this is an intrinsic property of the system or instead is a shortcoming of our existing observational, data assimilation, and numerical weather prediction systems. Recent research has expanded our understanding of the environmental
sensitivities contributing to degraded forecast skill during ET and thus of the practical predictability of ET and associated downstream high-impact weather. Numerous earlier studies have shown that the phasing between the upstream trough and the recurving TC has a dramatic impact on ET and the downstream impacts thereof. However, more recent work has highlighted the fact that other midlatitude features can also have an important impact on the predictability of downstream flow evolution. The uncertainty in the strength and orientation of the upstream jet, and the strength and location of other wave packets, and other mid-latitude features, all contribute to the growth of downstream forecast errors. Two recent field programs (and resulting papers), NAWDEX and HyMEX, used numerous aircraft to sample the features that influence downstream evolution, on large scales in the North Atlantic, and on small scales in the Mediterranean, respectively. Complementary work has used large ensembles of forecasts to try to distinguish forecast spread during events of TC recurvature and ET and climatological spread. Despite numerous insights and papers from these projects, universally applicable statements about the intrinsic predictability of ET remain elusive.

Additional studies on individual TC/ET events, such as Sandy (2012) and Nadine (2012) have identified “bifurcation points” that occur when a small change in one interaction parameter (e.g. midlatitude trough or TC vortex structure) leads to a large change in the storm’s track during transition. Adjoint methods provide objective and automated algorithms to the locations or identify features responsible for bifurcations. Such sensitivities lead to “clustering” of ensemble forecasts into two (or more) track patterns, with little hope of knowing in real-time which will be correct.

The most direct measure of the current limits of practical predictability during ET is the quality of forecasts issued by operational centers before and during the event. Recent improvements in deterministic and ensemble numerical guidance as well as observational capabilities, have benefited operational centers. An operational center’s ET forecasts should be assessed within the context of expected numerical model forecast skill, including insight as to when skill is likely to be either anomalously high or low. An example of this is given by Sandy (2012), wherein members of the United States’ global ensemble system with inaccurate track forecasts simultaneously had inaccurate cyclone classification forecasts.

4.3.5 Extratropical Transition and Climate

As long-period historical reanalyses become more available and the effects of climate change become increasingly felt by the general population, studies of ET in long-term contexts and under different climate-change scenarios have become more prevalent. One of the fundamental questions surrounding ET, and indeed TCs more generally, is whether there are any detectable trends in frequency-of-occurrence in the observational record. However, the relatively short length of the satellite era and the large interannual variability of ET frequency have made teasing out long-term trends in the historical record difficult.

ET climatologies vary substantially across the TC-active basins. The western North Pacific and the North Atlantic have the highest frequency of ET events (around 50% of all TCs). TCs in these basins are more likely to undergo ET later in the season, when the greatest overlap between conditions favourable for TC maintenance and extratropical cyclone development occurs. Conversely, the eastern North Pacific and the North Indian Oceans have the lowest frequencies of ET events. In the future, these climatologies may change because of, for
example, an ongoing global poleward shift in TC genesis locations and/or regionally varying trends on midlatitude baroclinicity.

Despite the increasing volume of published literature regarding potential changes of TCs in an evolving climate, ET has received relatively little attention. Recent efforts have been undertaken to apply traditional ET metrics [including the Hart (2003) CPS] to climate model output. One study found systematic differences between the model results and diagnostics from the Climate Forecast System and ERA-Interim reanalyses for North Atlantic storms over the 1980-2002 period. The largest number of ET events occurs in September in both the model simulations and reanalyses; however, the month with the 2nd largest number of ET occurrences in the simulations is October, as opposed to July in the reanalyses and IBTrACS. They also found that the ET process extends for a longer time period in the model simulations than in the reanalyses. Another study using a GFDL climate model found that that despite a decrease in TC frequency in the North Atlantic basin under RCP4.5, the number of storms undergoing ET increased slightly. With a more favourable storm formation environment over the eastern North Atlantic, the preferred recurvature track lies in the western North Atlantic at the expense of storms forming and tracking into the Caribbean Sea and Gulf of Mexico.

4.3.6 Summary and Recommendations

Since the last IWTC four years ago, notable advances have been made in our understanding of ET, particularly as it relates to the collection of in situ observations of structural change, and indirect and downstream impacts from ET events. Nonetheless, many fundamental aspects of the ET process are not yet well-understood, and forecasts can still be significantly improved. Our primary recommendations are:

1) As reported in the last IWTC, a universally applicable definition for ET did not exist. This remains true today. Although the Hart (2003) CPS has become the de facto classification standard, a community-wide discussion is needed as to whether a universally applicable alternative definition is necessary and achievable.

2) There have been few advances in operational/applied research as it relates to ET in recent years. Recent high-impact ET events such as North Atlantic TC Sandy (2012) highlight forecast communication issues during ET events, as discussed in the IWTC-8 report, and suggest that further work is needed to improve our ability to effectively communicate evolving cyclone threats during ET to the public. Further, recent advances in geostationary and polar-orbiting satellite technology enable us to observe transitioning cyclones better than ever before, and suggest that further research on how to best leverage these technologies in the advisory and forecast (both operational and numerical) process is warranted.

3) Although recent years have seen the collection of the first in situ observations of structural change and downstream development during ET, the sample size of cyclones for which such observations exist is very small, and more observations are necessary to document and understand case-to-case variability. Detailed analyses of data from the recent NAWDEX, HyMeX, and NOAA sampling campaigns may prove fruitful in these regards.
The first studies with the goal of documenting or predicting the influence of climate change on ET climatologies have appeared. Given the apparent presence of persistent differences between reanalysis datasets and systematic model errors during ET, more studies in this vein are required to allow the community to make clear and compelling statements about the presence or absence of secular trends in ET in both the historical record and in climate projections.

**Acronyms used in this section**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AMV</td>
<td>Atmospheric Motion Vector</td>
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<tr>
<td>ARCHER</td>
<td>Automated Rotational Center Hurricane Retrieval</td>
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<td>ASCAT</td>
<td>Advanced Scatterometer</td>
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<td>CPS</td>
<td>Cyclone Phase Space</td>
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<td>DAV</td>
<td>Deviation Angle Variance</td>
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<tr>
<td>DRCL</td>
<td>Wind Radii CLIPER</td>
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<tr>
<td>DSHA</td>
<td>Statistical-dynamical wind radii forecasts based on GFS model data</td>
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<tr>
<td>ECCC</td>
<td>Environment and Climate Change Canada</td>
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<tr>
<td>ERC</td>
<td>Eyewall Replacement Cycle</td>
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<tr>
<td>ET</td>
<td>Extratropical Transition</td>
</tr>
<tr>
<td>JMA</td>
<td>Japan Meteorological Agency</td>
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<tr>
<td>JTWC</td>
<td>Joint Typhoon Warning Center</td>
</tr>
<tr>
<td>HyMeX</td>
<td>Hydrological Cycles in the Mediterranean Experiment</td>
</tr>
<tr>
<td>IBTraCs</td>
<td>International Best Track Archive for Climate Stewardship</td>
</tr>
<tr>
<td>MDI</td>
<td>Mesoscale Descending Inflow</td>
</tr>
<tr>
<td>M-PERC</td>
<td>Microwave Probability of Eyewall Replacement Cycle</td>
</tr>
<tr>
<td>MRI</td>
<td>Meteorological Research Institute</td>
</tr>
<tr>
<td>NAWDEX</td>
<td>North Atlantic Waveguide and Downstream impact Experiment</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanographic and Atmospheric Administration</td>
</tr>
<tr>
<td>NRL</td>
<td>Naval Research Laboratory</td>
</tr>
<tr>
<td>NWP</td>
<td>Numerical Weather Prediction</td>
</tr>
<tr>
<td>OBTK</td>
<td>Objective R34, an equally-weighted average of R34 estimates</td>
</tr>
<tr>
<td>PRE</td>
<td>Predecessor Rain Event</td>
</tr>
<tr>
<td>RVCN</td>
<td>R34 Forecast Consensus=AHNI+HHNI+EMXI+CHTI+DSHA</td>
</tr>
<tr>
<td>SFMR</td>
<td>Stepped Frequency Microwave Radiometer</td>
</tr>
<tr>
<td>SEF</td>
<td>Secondary Eyewall Formation</td>
</tr>
<tr>
<td>SMAP</td>
<td>Soil Moisture Active Passive</td>
</tr>
<tr>
<td>TC</td>
<td>Tropical Cyclone</td>
</tr>
<tr>
<td>UCAR</td>
<td>University Corporation for Atmospheric Research</td>
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Abstract

Great strides have been made in real-time analysis and forecasting of the surface wind field asymmetries in the last four years, mostly leading to improvements in forecasts of gale wind radii. New observation platforms, new algorithms, advances in NWP, and the capability to bring information to operations have all contributed to these improvements. This chapter summarizes many of the recent changes and improvements to guidance available at a few operational centers.

4.1.2 Gale Wind Radii Estimates

The best observed TC wind fields are in the North Atlantic basin where aircraft reconnaissance is available about 30% of the time (Rappaport et al., 2009), more often when landfall is a threat. These observations include flight-adjusted winds, dropsondes, and the Stepped Frequency Microwave Radiometer (SFMR). Scatterometry is used extensively for verification as it is one of the best methods to construct wind radii analyses around TCs, especially when
aircraft-based data isn't available. The footprints of the scatterometers cover large areas of the ocean, provide useful estimates of wind speeds less than 25 m/s and can be used for gale wind analysis (e.g. Bentamy et al., 2008; Brennan et al., 2009; Chou et al., 2013). However, scatterometer data is less useful for monitoring TC wind field evolution because of its coarse temporal resolution and frequent partial swaths. It is also not useful for wind speeds greater than 25 m/s or in rain areas as the signal attenuates in heavy rain.

Gale wind radii estimation is among the more tractable structure problems. In addition to scatterometer passes, there are infrared (IR) proxies (Knaff et al., 2016), microwave sounder algorithms, multi-satellite platform analyses (Knaff et al., 2011) and NWP models that show skill in analysing the outer structure of TCs. A consensus value can be calculated using all available estimates, which is useful both for ground truth and real-time forecasts (OBTK in Figure 1 and Sampson et al. 2018). Additional sources of winds have recently become available to operational commands (e.g. those from algorithms using L-band radiometers discussed in detail in Sub-topic 5.1). These are particularly valuable in the absence of scatterometer or aircraft data. Efforts are also underway to improve NWP analyses of TC winds, which should further improve and stabilize estimates of gale wind radii.

Errors in the best track wind radii have been estimated to be as high as 40% (Landsea and Franklin 2013, Knaff and Sampson 2015), depending on the quality and quantity of the available observational data. Even in instances when scatterometer passes and/or aircraft are present, the estimates can have significant errors. For example, the average difference between the consensus (OBTK) and the JTWC subjective estimates of gale wind radii in Figure 1 is 21 n mi, with a standard deviation of 18 n mi. As suggested by Torn and Snyder (2012), the standard deviation can be used as a measure of the uncertainty, and 18 n mi is about 14% of climatological mean (125 n mi) of the gale wind radii for this data set.

Figure 1. 34-kt wind radii fix mean errors (brown) and biases (blue) relative to JTWC 2014-2016 best tracks coincident with scatterometer fixes (ASCT). OBTK is a mean of the individual estimates. Errors and biases are in n mi and standard error is shown as black bars on means.
Reasonably accurate and continuous estimates of gale wind radii make the wind radii analysis more tenable. Table 1 shows timelines of wind radii estimates at selected operational centers (the timelines start at the initial text and are only approximations). Most of these are real-time estimates, although the National Hurricane Center, Australian Bureau of Meteorology, and Central Pacific Hurricane Center have been consistently including wind radii in their post-season analyses (the so-called “best tracks”) since 2004. Others have recently started that effort as well. These best tracks can in turn be used to develop and verify wind radii forecasts as well as downstream applications that rely on wind radii. A note of caution: Each agency will have its own procedures to vet wind radii and those procedures could change in time as new sensors and estimates become available and others are deprecated. Researchers developing algorithms, evaluating performance or constructing trend analysis should contact the individual operational centers regarding potential uses and issues with their data. For example, the JTWC best tracks have subjective post-analysis for the gale wind radii only at present. The NHC post-season analysis currently applies to gale, storm force, and hurricane force wind radii, but not eye diameter or radius of maximum winds. The Australian Bureau of Meteorology wind radii were analysed post-season through some of the past three decades, but only consistently over the last 15 years.

Table 1. Wind Radii Record Timelines for Selected Operational Centers

<table>
<thead>
<tr>
<th>Year</th>
<th>North Atlantic</th>
<th>Eastern North Pacific</th>
<th>Western North Pacific</th>
<th>Southern Hemisphere</th>
<th>North Indian Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>Wind Radii Worksheets (NHC)</td>
<td>In the Model Bogus (NHC)</td>
<td>Best Tracked</td>
<td>Real-time Estimates (various)</td>
<td>Real-time Estimates (various)</td>
</tr>
<tr>
<td>1985</td>
<td>In the Model Bogus (NHC)</td>
<td>Best Tracked</td>
<td></td>
<td>In Best Tracks (JMA)</td>
<td>In Best Tracks (JTWC)</td>
</tr>
<tr>
<td>1990</td>
<td>Real-time Estimates (various)</td>
<td>Best Tracked</td>
<td>In the Model Bogus (various)</td>
<td>Real-time Estimates (various)</td>
<td>Intermittently Best Tracked (BoM)</td>
</tr>
<tr>
<td>1995</td>
<td>In Best Tracks (JMA)</td>
<td>Best Tracked</td>
<td>In Best Tracks (JTWC)</td>
<td></td>
<td>Best Tracked (BoM)</td>
</tr>
<tr>
<td>2000</td>
<td>In Best Tracks (JMA)</td>
<td>Best Tracked</td>
<td>Best Tracked</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>In Best Tracks (JTWC)</td>
<td>Best Tracked</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Best Tracked</td>
<td></td>
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<td></td>
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<tr>
<td>2015</td>
<td></td>
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4.1.3 Gale Wind Radii Forecasts

The Wind Radii CLIPER (DRCL; Knaff et al., 2007) is based on a parametric vortex and has been used both as a skill baseline and a first guess for wind radii forecasts. The DRCL inner core wind radii (i.e. 25 m/s and 33 m/s) are prescribed and so do not suffer from the model resolution issues seen in NWP models. The western North Pacific DRCL has recently been redeveloped with the quality controlled best track data from JTWC (Knaff et al., 2018) and is now more competitive with the NWP model radii in terms of biases. The new DRCL also retains more of the initial wind asymmetry through the forecast.

A statistical-dynamical model has also been developed for most basins (Knaff et al., 2017) that is competitive with NWP model guidance (DSHA in Fig. 2). This model uses the SHIPS (DeMaria et al., 2005) large scale diagnostics files along with IR imagery and current TC information to predict the TC size change. It is currently run operationally at the Joint Typhoon Warning Center for the western North Pacific, the Southern Hemisphere and the northern Indian Ocean. As with DRCL, this guidance is not directly affected by NWP model resolution. Figure 2 shows an evaluation of gale wind radii of six operationally available forecast aids and an equally weighted average or “consensus” of the forecasts (RVCN). The consensus has the lowest mean forecast errors and smallest mean biases for the sample. This is in line with findings for other parameters such as track and intensity.

![Figure 2. Consensus (RVCN) gale wind radii forecast performance using reanalysed JTWC best tracks as ground truth for 2014-2016 western North Pacific seasons. Acronyms are as defined at the end of this sub-topic.](image)

The errors associated with the forecasts can be estimated similar to track consensus forecasts. In Fig. 3 a case is shown where RVCN model forecasted the gale wind radius to double in size in the northwest quadrant and then shrink as the TC decayed. The dashed lines (Sampson et al., 2018) indicate the 67th percentile of the predicted error, which in this case contained the post-season best track through the 48-h forecast. The consensus and spread can be used in tandem. The consensus is difficult to beat and can serve as a baseline, with the spread indicating reasonable deviations from the baseline.
4.1.4 Inner Core Estimates and Forecasts

Accurate location of the TC center position is critical in estimating TC structure parameters. The center location uncertainty can exceed 100 km at times and operational centers generally only report center locations every six hours. Errors of this magnitude are on the scale of the inner core radii so this can be a major issue for automated inner core radii estimates. The Automated Rotational Center Hurricane Retrieval (ARCHER) algorithm developed by Wimmers and Velden (2010, 2015) is one possible way to address TC locations. ARCHER uses a spiral and ring scoring algorithm to objectively locate the TC center using geostationary (IR, visible and near-IR), passive microwave imager, and scatterometer data. ARCHER includes information concerning the fix confidence based on the imagery source, scanning geometry and magnitude of the spiral and ring scores.

Ring scores from ARCHER can be used to estimate the TC eye diameter and probability of an eye from geostationary IR and passive microwave imagery. Eye diameter represents the diameter at sensor height which is 10 km for 89 GHz imagery and 16 km for IR. Using an eyewall slope of 45 degree allows the estimation of surface radius of maximum winds, one of the analysed parameters from the operational centers.

An important structure change that can modify the TC wind field is secondary eyewall formation (SEF) and the eyewall replacement cycle (ERC). As discussed more thoroughly in chapter 4.2, ERC development often leads to expansion of the TC wind field (Maclay et al., 2008, Sitkowski et al., 2011) affecting all critical wind radii. A step change of the radius of maximum winds also occurs as the outer ring in the TC becomes the primary eyewall and the radius shifts from the inner ring to the outer. The Microwave Probability of ERC (M-PERC) model, which is under development through the Joint Hurricane Testbed program produces probabilities of ERC onset using features derived from ~89 GHz imagery in a logistic regression.
model. The principle components are derived from brightness temperature ring scores evaluated at each pixel radius of 89 GHz imagery along with the time evolving changes in these candidate rings and the TC wind intensity determined from the real-time Vmax estimates provided by the warning agency. A standalone TC wind intensity model is also provided to show the contribution made by the microwave imagery. The resulting forecast is a probability of an ERC within 36 h. Figure 4 shows an example of an M-PERC plot for Hurricane Irma in 2017.

A technique that has not yet made it into operations is the DAV (deviation angle variance) technique (Piñeros et al., 2008) for pre-genesis tracking (Rodriguez-Herrera et al., 2015), genesis determination (Wood et al. 2015), intensity estimation (Ritchie et al., 2014), and wind radii estimation (Dolling et al., 2016) for the symmetric or quadrant R34, R50, and R64 radii. The DAV is a parameter that objectively measures the departure of cloud systems in IR imagery from axisymmetry. In particular, the wind radii technique uses the “map of variances” calculated for the entire tropical cyclone to estimate the wind radii in each cardinal quadrant. The model for wind radii is a multiple linear regression model that uses the radius of the highest correlated DAV value along with SST, TC intensity, and the age of the TC since reaching 17 m/s maximum sustained surface winds. The model was developed using the North Atlantic best track dataset and is being developed and tested for the Australian region. Figure 5 shows cross-validation by quadrant and radii for the North Atlantic basin along with simple reconstructed wind fields for Hurricane Ike (2008) with the best track wind radii overlaid in thick contours.
4.1.5 Operational Centers Analysis and Forecasting

Japan Meteorological Agency (JMA)

Although scatterometer-derived winds are extremely valuable for TC wind analysis, the relatively small spatial scatterometer footprint, limited temporal coverage (a maximum of twice daily), sensor saturation in heavy precipitation, and potential biases resulting from the first guess present some limitations. To augment TC surface wind analyses, JMA’s Meteorological Satellite Center (MSC) converts low-level Atmospheric Motion Vector (AMV) data from Himawari-8 to surface winds (Nonaka et al. 2016 and Figure 6). Low-level wind speeds are converted to surface winds using 76% of the low-level wind speed and wind directions are adjusted toward the TC center by 9°.
Sea surface AMVs are overlapped with ASCAT winds in daily operations and best-track analysis (Fig. 7). Although these near-surface AMVs are not available under dense clouds, Himawari’s 10-minute full-disk refresh rate and high spatial resolution make it possible to estimate strong winds (>15 m/s) in areas surrounding TCs. Forecasters take into consideration the uncertainty in accuracy under deep convection near TC centers, as well as data availability which may differ during day and night depending on the band to use for AMVs. For example, band 03 for visible imagery (B03, 0.64μm) is available only during daytime.

**Figure 7.** Sea surface AMVs and ASCAT wind composite for Typhoon Lan October 21, 2017 (left: sea surface winds from ASCAT, middle: sea-surface AMVs, right: overlapped for both winds ≥30 kts).

**JTWC**

The current JTWC forecast accuracy goals for wind radii specifies that gales and 25 m/s wind radii should be predicted within 20% of the verified values. The addition of new and/or improved analysis and forecast guidance such as OBTK and RVCN described above, as well as improved software, enabled JTWC to extend operational wind radii forecasts from 72 hours to 120 hours in November 2016. Sampson et al. (2018) found average R34 error for all forecast times to be 15-30%, which is within 10% of the stated JTWC goal for accuracy. Additionally, 120-hour mean forecast R34 errors are now on par with those at 72 hours prior to 2016. Besides the obvious benefit of providing decision makers with additional lead time for gale (R34) and 25 m/s (R50) wind radii that drive U.S. Department of Defense resource protection measures, the consensus of skillful guidance has significantly improved JTWC handling of TC growth throughout a system’s lifecycle, particularly during extra-tropical transition. The explicit forecast of 96-h and 120-h wind radii also improves how an algorithm that predicts uncertainty of gale wind radii (the JTWC error swath) conveys these long range uncertainties to DoD users. Prior to 2016 the error swath algorithm was forced to use 72-h wind radii at 96 and 120 h while the current algorithm employs the new JTWC long-range wind radii forecasts. This can be particularly important if the wind radii expand or contract dramatically.

Despite these improvements, operational challenges associated with TC wind structure remain. Because of differences in the timing at which the various analyses or forecasts reach the specified wind thresholds, there may be limited guidance available. This is particularly problematic during the very weak incipient stages of TC development. Another key difficulty is assessing the maximum radius at which winds are no longer attributable to the TC but instead to the large-scale gradient flow. This is a routine consideration for large TCs, such as those that develop out of monsoon depressions or those approaching areas known to have geographically-enhanced channeling of flow such as the Taiwan and Luzon Straits.
In the North Atlantic, over the open ocean, the wind radii best tracks are believed to have an uncertainty of around 40, 30, and 25 n mi for 34-, 50-, and 64-kt winds (Landsea and Franklin 2013). Given that these large uncertainties are on the order of about one third to one half of the values they are depicting (Figure 8), routine verification of NHC size forecasts with limited verification data is not currently justified.

Figure 8. Relative uncertainty in the best tracks for intensity, central pressure, position, 34-, 50-, and 64-kt wind radii for tropical storms and hurricanes. (From Landsea and Franklin 2013).

Cangialosi and Landsea (2016) produced a formal verification of a subset of the NHC wind radii forecasts and selected guidance. The verification of the reconnaissance-only dataset, which was used to get the most accurate “ground truth” information, showed that the NHC wind radii average errors increased with forecast time and were skillful when compared against climatology and persistence. The dynamical models, however, were generally not skillful and had errors that were much larger than the NHC forecasts and mainly had negative biases. It is worth noting, however, that the magnitude of these NHC wind radii errors - especially for the short-term (12, 24, and 36 hour forecasts) for this reconnaissance-only verification was about the same size as the uncertainty in the best track values themselves (Landsea and Franklin 2013). Thus continued development of observational techniques is desired, as these will better assist efforts for both operational and best track assessments of the tropical-storm-force and hurricane-force wind radii. In addition, NHC forecasts of wind radii can be improved by better guidance being made available to the forecasters. This would include improved explicit representation of the tropical cyclone wind field in both global and mesoscale hurricane models, statistical-dynamical approaches, as well consensus techniques (Sampson and Knaff 2015). This last approach – the wind radii variable consensus method (RVCN) – has been available to NHC forecasters during 2017 and 2018 and is quickly becoming the most relied-upon guidance for wind radii predictions.

4.1.6 Conclusions

From an operational perspective, great strides are being made in both analysis and forecasting of surface wind structure. The last four years have seen new and improved algorithms for estimating surface winds in the vicinity of TCs. Improvements in NWP data assimilation and
forecasting have yielded guidance for analysis, forecast and forecast error estimates of gale wind radii and possibly inner core radii. The expectation is that we should see further improvement in wind radii and wind radii asymmetry estimates as algorithms from new observing platforms (e.g. L-band radiometers discussed in Sub-topic 5.1 and shown below in Figure 9) gain acceptance in the operational community, and we should see further improvements in wind radii forecasting as NWP models improve and new guidance on inner core radii (e.g. M-PERC and DAV) are used more effectively. Validation of inner core radii estimates and forecasts remains difficult due to the paucity of observations, but there is hope that new sensors and algorithms to address inner core radii will help alleviate this problem.

Figure 9. JTWC 34-, 50-, 64-kt wind radii (concentric radii) at 20180926 12 UTC overlaid on Soil Moisture Active Passive (SMAP) winds at 20180926 09 UTC (Meissner et al., 2017) available on operational forecast system for 28th TC of 2018 western North Pacific season.

4.1.7 Recommendations

The recommendations for guidance on wind structure and wind structure asymmetry are:

1) Develop high quality inner core wind radii observational datasets both for real-time guidance and to construct high quality post-season analyses. Not only does this include aircraft and satellite observations, but also available radars. Weather radar data has traditionally been difficult to obtain/share among forecast agencies yet provides data that could be used to augment traditionally shared data from satellite platforms.

2) Continue to bring analysis algorithms to operations, especially those which address inner core wind structure analyses and forecasts.

3) Continue to develop NWP both for analyses and forecasts of wind structure so that they can be effectively used to disseminate long-range, accurate warnings of the onset of winds, waves, swell and surge.

4) Continue to launch satellites with potential to discern wind fields.
Acronyms used in the report

AMV – Atmospheric Motion Vector
AMSU – Advanced Microwave Sounding Unit, wind radii estimates based on AMSU
ASCAT – Advanced Scatterometer
ASCT – Objective gale wind radii fixes from ASCAT
ARCHER – Automated Rotational Center Hurricane Retrieval
AVNO/AHNI – Global Forecast System model radii analyses/interpolated forecasts
BOM - Australian Bureau of Meteorology
CHTI – COAMPS-TC model radii/interpolated forecast
CIRW – CIRA multi-platform surface wind analysis
COAMPS– Coupled Oceanographic Atmospheric Mesoscale Prediction System
COAMPS-TC – COAMPS Tropical Cyclone model
DAV – Deviation Angle Variance
DoD – U.S. Department of Defense
DRCL – Wind Radii Clipper
DSHA – Statistical-dynamical wind radii forecasts based on GFS model data
DVRK – Dvorak estimate wind radii
EMXI – European Center model R34 interpolated forecast
ERC – Eyewall Replacement Cycle
GFDT – GFDL TC model wind analysis
GPCE – Goerss Predicted Consensus Error
INTF – Official Intensity forecast (kt), 6-h old interpolated or consensus
HWRF/HHNI – Hurricane Weather Research Forecast model radii/interpolated forecast
JMA/MSC – Japanese Meteorological Agency Meteorological Satellite Center
JTWC – Joint Typhoon Warning Center
M-PERC - Microwave Probability of Eyewall Replacement Cycle
NWP – Numerical Weather Prediction
OBTK – Objective R34, an equally-weighted average of R34 estimates
NHC – The National Hurricane Center, Miami, FL
R34 – Gale (17 m/s or 34 kt) wind radii
R50 – Storm force (25 m/s or 48 kt) wind radii
R64 – Hurricane force (33 m/s or 64 kt) wind radii
RVCN – R34 Forecast Consensus=AHNI+HHNI+EMXI+CHTI+DSHA
SFMR – Stepped Frequency Microwave Radiometer
SHIPs – Statistical Hurricane Intensity Prediction System
TC – Tropical cyclone
Vmax – Maximum wind intensity near the center of a TC

References


TOPIC 4.2 - TC STRUCTURE ANALYSIS AND CHANGE: SECONDARY EYEWALL FORMATION AND EXPANSION OF THE WIND FIELD

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Abstract
This report summarizes recent progress in understanding secondary eyewall formation, eyewall replacement cycles, and the expansion of the wind field that occurs in association with these processes. A growing body of observational case studies has led to an improved understanding of the structural relationships between initially asymmetric outer rainbands (particularly the stratiform region), kinematic and thermodynamic features that result from such convection, and the ultimate emergence of a distinct secondary eyewall and wind maximum. Numerous simulation studies agree that secondary eyewall formation takes place through feedbacks between rainband convection and boundary layer frictional convergence. However, notable disagreements remain regarding the importance of a gradient flow as a causal mechanism for secondary eyewall formation, the relative contribution of balanced and unbalanced processes, of symmetric and asymmetric processes, and of internal and external forcing. New theories for SEF continue to be developed, demonstrating that this topic remains an active and evolving area of research.

4.2.1 Introduction

Once a tropical cyclone is sufficiently well organized, deep convection becomes concentrated in a narrow annular region, forming a distinct eyewall, which is also the location of strongest wind speed. Outside of the eyewall, convection tends to be organized in banded regions of variable extent and concentration, which spiral inwards towards the eyewall (Houze 2010). Under certain conditions (particularly for category 3-5 TCs), such rainbands can evolve to form a distinct outer eyewall, which is also associated with a wind speed maximum (e.g. Willoughby et al., 1982, Black and Willoughby 1992, Sitkowski et al., 2011). This process of Secondary Eyewall Formation (SEF) is the main focus of this subtopic. Following SEF, the outer eyewall typically strengthens and contracts while the inner eyewall weakens and eventually disappears, resulting once again in a single eyewall associated with a single wind maximum. These Eyewall Replacement Cycles (ERCs) can occur repeatedly, and in general, the eyewall becomes systematically larger as a result of this process (Sitkowski et al., 2011). On average, an individual ERC lasts for about 36 h, though there is large variability in the length of this period (Sitkowski et al., 2011). Alternatively, a secondary eyewall can decay before replacing the inner eyewall, or it can become long-lived, and concentric eyewalls are sometimes maintained without the completion of an ERC (Yang et al., 2013). Occasionally, three simultaneous eyewalls and wind maxima have been observed (Zhao et al., 2016).
SEF and ERCs are critically important for operational forecasting of TCs, as this phenomenon results in large and systematic modulation of both intensity and wind field structure. As discussed in Sitkowski et al. (2011), unanticipated intensification following an ERC can have catastrophic consequences such as in Hurricane Andrew (1992) (Willoughby and Black 1996), and the wind field expansion associated with SEF can result in both a much larger area affected by damaging winds and an enhancement in the storm surge at landfall, such as in Hurricane Katrina (2005) (Irish et al., 2008). Although there has been recent progress in statistical techniques for predicting the onset of SEF and the associated intensity and structure changes (Kossin and Sitkowski 2012), numerical weather prediction models remain unable to skillfully predict these changes (Zhang et al., 2015). Climatologically, the strongest signal for SEF is TC intensity, and the overall probability of imminent (within 12 h) SEF is 60% for category 5 hurricanes, as compared to less than 5% for category 1 hurricanes (Kossin and Sitkowski 2009). Although a statistical model based on knowledge only of current intensity has skill, this skill is substantially improved through the inclusion of environmental predictors (e.g. shear, relative humidity) from SHIPS and predictors based on infrared satellite imagery. Kossin and Sitkowski (2012) have also developed a statistical model for predicting the duration and amount of weakening, the rate of reintensification, and the net change in RMW during an ERC. As described in section 4.1, a new prediction model that uses both infrared and microwave imagery to predict ERCs, known as M-PERC, is currently undergoing testing through the Joint Hurricane Testbed program.

Although substantial progress has been made in recent years in understanding SEF, some key disagreements remain, and there continues to be no consensus on any single theory of SEF. It is generally agreed that both the tangential and radial wind fields expand outwards prior to SEF (though some studies suggest that this may actually be part of SEF itself), and that a focused region of boundary layer convergence ensues, which may trigger (or enhance pre-existing) deep convection. And it is also generally agreed that once a sufficiently well-organized region of deep convection has formed, feedbacks between enhanced diabatic heating and enhanced boundary layer convergence result in amplification of a secondary eyewall and associated tangential wind maximum. A key disagreement within the research community regarding SEF is whether the localized region of boundary layer convergence is a consequence of the response of an otherwise balanced vortex to surface friction, or is instead caused by the supergradient flow that tends to develop in the upper portion of the boundary layer.

As noted by Kossin and Sitkowski (2009) and Dougherty et al. (2018), there is no formal definition of SEF for which there is general agreement, and different criteria have been used in various studies, including the formation of an azimuthal mean tangential wind speed maximum (e.g. Dougherty et al., 2018), the time at which an outer wind speed maximum becomes stronger than the inner maximum (e.g. Miyamoto et al., 2018), or the formation of an outer ring of convection (e.g. Kossin and Sitkowski 2009). Because of these differing definitions, it can be challenging to determine which processes are part of the mechanism for SEF, and which processes might instead be a manifestation or consequence of SEF.

In the following sections, we summarize recent progress in our understanding of SEF, ERCs, and related structural evolution of TCs. We have divided this into three parts, covering observations, numerical simulations, and theory. Note, however, that there is some overlap between these sections, as some observational and simulation studies have also made contributions to our theoretical understanding of SEF.
4.2.2 Observations of SEF and ERCs

The Influence of Rainbands and Stratiform Heating

Many current theories for secondary eyewall formation (SEF) focus on axisymmetric processes in which convection outside the primary eyewall interacts with the vortex circulation and intensifies in a positive feedback loop to create a secondary eyewall (e.g. Rozoff et al., 2012; Huang et al., 2012; Abarca and Montgomery 2013; Kepert 2013). Prior to the feedback loop, these theories require necessary preconditioning of the azimuthal-mean vorticity profile in the outer core. Asymmetric spiral rainbands populate this outer core region and can act as vorticity anomalies that, given their sufficient projection onto the azimuthal mean, trigger axisymmetric SEF processes (Judt and Chen 2010). But the exact processes or rainband structures necessary to initiate SEF are not yet thoroughly understood. This section discusses results from observations of rainbands and secondary eyewalls that shed light on SEF mechanisms.

TC rainbands tend to form an asymmetric complex when the storm experiences environmental vertical wind shear (Willoughby et al., 1984; Hence and Houze 2012b), as shown in Fig. 1a. In this complex, convective precipitation concentrates in the right-of-shear half, where shear-induced positive anomalies of low-level vorticity and midlevel moisture tend to coincide (Corbosiero and Molinari 2002; Didlake and Houze 2009, 2013a; Reimer 2016). Here, isolated or connected convective cells are associated with an overturning circulation, convective downdrafts, and local tangential wind jets that vary in depth and strength (Barnes et al., 1983; Hence and Houze 2008; Didlake and Houze 2009, 2013a). Decaying convection and slowly falling ice crystals travel downwind and form a broad region of stratiform precipitation in the left-of-shear half of the storm (Black et al., 2002; May and Holland 1999; Hence and Houze 2012b; Didlake and Houze 2013b). The features associated with this region project more strongly onto the azimuthal mean given both the mesoscale, homogeneous nature of stratiform precipitation and the fact that these features occur at a smaller radius at the downwind end of the spiral rainband complex. Thus, the stratiform end of the rainband complex has the potential for substantial interaction with the vortex circulation and may play a more important role than the upwind convective cells in the early stages of SEF.

Didlake and Houze (2013b) examined the stratiform end of a spiral rainband complex in Hurricane Rita (2005) prior to its transition into a secondary eyewall. Within the stratiform cloud layer, upward transport associated with latent heating travelled radially outward along lines of constant angular momentum. Beneath the cloud layer, latent cooling from sublimation, melting, and evaporation created horizontal buoyancy gradients that induced a mesoscale descending inflow (MDI) pattern similar to that of the trailing stratiform region of a mesoscale convective system (Houze 2004). The negatively buoyant descending air then extended into the boundary layer.

There are two significant outcomes of the observed stratiform dynamics that likely impact SEF. The first is that the rising outflow and MDI both accelerate the outer core tangential winds and therefore contribute to the radial expansion of the overall wind field. This wind field expansion is a process that commonly precedes SEF (e.g. Sitkowski et al., 2011; Bell et al., 2012; Fang and Zhang 2012), and intense storms that do not experience SEF also do not exhibit the same degree of wind field expansion (Wunsch and Didlake 2018). Rozoff et al. (2012) examined the roles of outer core latent heating and storm expansion in SEF. They determined that increasing outer core winds improves the axisymmetric efficiency of converting heat energy released by rainband convection into increased kinetic energy, which can be manifested locally as a developing secondary wind maximum. Wunsch and Didlake (2018) found (using flight-level
data) that in a composite of 33 SEF cases, the downshear-left quadrant had the highest angular momentum and tangential wind increase in the outer core prior to the time of SEF. The stratiform rainband typically lies in the downshear-left quadrant and is thus implicated as a critical driver of wind field expansion. It remains unclear whether the expanding wind field is a causal process for SEF or a consequence of SEF mechanisms already initiated by increased rainband convection.

Figure 1. Plan view schematic of rainband and eyewall structures at two stages of secondary eyewall development: (a) the early stage with a singular eyewall and a spiral rainband complex present, and (b) the later stage with a developing circular ring of secondary eyewall convection. The environmental wind shear vector points upward and defines the four storm quadrants. Reflectivity contours (20 and 35 dBZ) show embedded convective cells in the rainband complex that collapse (gray dashes) and form stratiform precipitation traveling around the storm. Mesoscale Descending Inflow (MDI) and an enhanced updraft (white dashes) both occur in the downshear-left stratiform rainband, and the collocated gray line marks the cross section in (c). (c) Cross section schematic of the kinematics from (a). Reflectivity contours are drawn. The line arrow shows vortex-scale boundary layer inflow, and the broad solid arrows show motions associated with the stratiform rainband. The mesoscale descending inflow (MDI) occurs in a region of latent cooling and is negatively buoyant (B<0). At its end, a convective updraft occurs. Convergence and upward acceleration (∂w/∂t >0) lie along the inner side of the MDI. The plus signs indicate regions of increasing tangential velocity by the secondary circulation. The circled region indicates the location of a developing tangential jet (VT), which is located in the radial range of the developing secondary eyewall. From Figs. 17 and 18 of Didlake et al. (2018).
The second outcome of the observed stratiform dynamics is the potential triggering of secondary eyewall convection by the MDI interacting with the boundary layer. Didlake et al. (2018) explored this hypothesis in their observational study of rainband convection as it transitioned into a secondary eyewall in Hurricane Earl (2010). As in Rita, Earl’s stratiform rainband contained a robust MDI in the downshear-left quadrant, as illustrated schematically in Figs. 1a–c. In the location where the MDI extended into the boundary layer, a deep updraft occurred, originating from the boundary layer. Both the MDI and the adjacent updraft were observed prominently in multiple flight transects over the 24 hours prior to SEF. Didlake et al. (2018) proposed that the negatively buoyant MDI forced high-θe boundary layer upward to the point of becoming a buoyant updraft. The MDI and adjacent updraft were shown to persistently accelerate the low-level tangential winds in the downshear-left quadrant, contributing the most to the azimuthal-mean tangential wind acceleration compared to other quadrants. In the same radial range as the MDI/updraft, Earl eventually developed an azimuthal-mean secondary wind maximum, and this wind maximum had an asymmetry where the downshear-left quadrant was the strongest. These findings implicated the stratiform MDI as a prominent contributor to the development of the secondary eyewall.

The dynamical evolution of Earl hypothesized by Didlake et al. (2018) compared well to other observational studies of secondary eyewalls. Didlake and Houze (2011) found that the mature secondary eyewall in Hurricane Rita had an azimuthal-mean overturning circulation that included a near horizontal channel of radial outflow just above the boundary layer, which was attributed to supergradient flow. The downshear-left quadrant in Earl exhibited a similar overturning circulation as the axisymmetric secondary eyewall in Rita, while the other quadrants did not. In addition to having the strongest secondary wind maximum, the downshear-left quadrant also had the strongest updraft at the radius of the developing secondary eyewall. This asymmetry is in agreement with Hence and Houze (2012a) and Didlake et al. (2017). Hence and Houze (2012a) analysed a composite of satellite radar observations of TC concentric eyewalls and found a convective asymmetry with the highest reflectivity in the composite secondary eyewall occurring in the left-of-shear half. Didlake et al. (2017) examined airborne Doppler radar observations of Hurricane Gonzalo (2014) and found the same convective asymmetry for vertical velocity, where the strongest updrafts of the secondary eyewall occurred in the left-of-shear half. The convective asymmetry observed in these mature secondary eyewalls was likely forced by stratiform rainband convection just radially outward and was a continuation of the critical stratiform forcing leading up to secondary eyewall formation.

The results from Didlake et al. (2018) were unique in that they provided an observations-based dynamical hypothesis for connecting the asymmetric rainbands to the initiating axisymmetric perturbations necessary for the axisymmetric SEF theories. In particular, these results corroborate the “top-down” pathway of SEF described by some previous modeling studies (e.g. Fang and Zhang 2012; Leroux et al., 2013; Zhang et al., 2017; Dai et al., 2017), and illustrated in Fig. 2. These studies describe the importance of stratiform processes that sufficiently project onto the azimuthal mean, such that the negatively buoyant stratiform downdrafts induce an axisymmetric front-like zone and reduced stability in the low levels. This zone triggers and concentrates convection erupting from the boundary layer to form a secondary eyewall. Qiu and Tan (2013) found similar results, but also highlighted the importance of the supergradient wind field associated with the rainband complex as an important contributor to the forcing of secondary eyewall convection, in the manner of the axisymmetric unbalanced boundary layer hypothesis (e.g. Huang et al., 2012). Tyner et al.
(2018) and Chen et al. (2018) further emphasized the importance of negatively buoyant downdrafts by showing that secondary eyewall formation was favoured in experiments where latent cooling was amplified. Finally, the recent observational and simulation studies advocating for the importance of stratiform rainband heating in leading to SEF are broadly consistent with Moon and Nolan (2010), who used a linear vortex model along with prescribed heat sources, and found that the downwind stratiform heating contributed the most to creating a tangential wind jet that extended all the way around the vortex.

Figure 2. A multiscale schematic diagram of secondary eyewall formation in sheared tropical cyclones. The first stage shows the expansion of outer tangential wind through developing outer convection, emergence of a discrete outer updraft from boundary layer processes and axisymmetrization of outer rainbands. The second stage shows the formation and development of the secondary eyewall through extension of the outer updraft to the boundary layer and positive feedback between boundary layer processes.

From Fig. 18 of Zhang et al. (2017).

**Observed Wind Field Expansion Prior to SEF**

During the National Aeronautics and Space Administration (NASA) Hurricane and Severe Storm Sentinel experiment (HS3; Braun et al. 2016), an exceptionally large amount of aircraft observation data were collected in Hurricane Edouard (2014). Abarca et al. (2016) used NOAA P3 and G-IV dropsonde data to estimate the radius-height distribution of agradient force (defined as the sum of the centrifugal, Coriolis, and radial pressure gradient forces) during a period just prior to SEF (Fig. 3). They found a region of positive agradient force that approximately coincided with the region in which SEF occurred later on. Abarca et al. (2016) also found that the maximum spin-up tendency due to the radial vorticity flux within the boundary layer of the eyewall elongates radially outward into this same region before SEF. From these analyses, Abarca et al. (2016) argued that observations support the idea that unbalanced processes are important for SEF.
Secondary eyewall formation

Figure 3. Composite (a) tangential wind velocity (m s\(^{-1}\)), (b) agradient force (m s\(^{-1}\) h\(^{-1}\)), and (c) radial location of the dropsondes for the SEF period. In (a) and (b) the orange and red colours indicate increasingly positive values, respectively; blue colours indicate negative values. In (c) the black dots indicate the average measurement radius for each dropsonde in the analysis. The red lines indicate the radial location of the center of the bins. The bins are delimited by the locations of the vertical blue lines. The numbers superposed on the red lines indicate the number of dropsondes in each radial bin. From Fig. 4 of Abarca et al. (2016).

**SEF and ERC Observed in an Environment of Strong Wind Shear**

Dougherty et al. (2018) used flight-level, radar, dropsonde, and microwave imagery data to investigate SEF and a subsequent ERC in Hurricane Bonnie (1998). Although SEF/ERC is typically observed to take place under weak to moderate shear (Kossin and Sitkowski 2009), Bonnie was in a high-shear environment (12-16 m s\(^{-1}\)) when SEF occurred. It was also unusual that Bonnie did not appear to weaken during the ERC process. Dougherty et al. (2018) hypothesized that the large shear enhanced the outer convection from downshear rainbands, allowing for the formation of the outer eyewall. Subsequently, the asymmetric outer eyewall extended upshear, and the surface wind speeds were found to be 35% larger upshear than downshear, which is atypical. Finally, Dougherty et al. (2018) hypothesized that the relatively large size of the eyewall following ERC resulted in an increased resilience to shear and helped maintain the intensity of Bonnie.
Kossin (2015) investigated the wind-pressure relationship during and following ERCs, using the Best Track dataset for Atlantic TCs that were observed to undergo ERCs by aircraft reconnaissance. He found that at the start of ERCs, the maximum wind speeds were slightly less than the climatological value for a given minimum pressure, whereas at the end of ERCs, the maximum wind speed was much less than climatology. Therefore, the TC intensity could be substantially overestimated following an ERC, and Kossin (2015) hypothesized that this deviation from the typical wind-pressure relationship is due to the structural changes that occur during ERCs, such as the increase of the RMW and the overall expansion of the wind field.

Shimada et al. (2018) examined the RI of Typhoon Goni (2015) immediately after an inner eyewall dissipated (i.e., the completion of an ERC), by using high-temporal-resolution radar reflectivity and wind fields retrieved by the ground-based velocity track display (GBVTD) technique (Lee et al., 1999). The maximum azimuthal-mean tangential wind at 2-km altitude increased by at least 15 m s\(^{-1}\) during the first 14 h of RI (Fig. 4a). Around the onset of RI, relatively strong outflow (>2 m s\(^{-1}\)) was present both inside and outside the radius of maximum wind (RMW) above the boundary layer (Fig. 4b). A budget analysis of absolute angular momentum (AAM) showed that the outflow contributed to the decrease in AAM just outside the RMW below 5-km altitude. As a result, the low-level RMW contracted rapidly from 50 to 33 km (Fig. 4a), causing the RMW to slope greatly outward with height. The radial profile of tangential wind became more peaked with time. This wind profile is consistent with that of other intensifying tropical cyclones (Rogers et al., 2013; Martinez et al., 2017). As RI proceeded, eyewall convection was enhanced, and a well-defined eye appeared. The low-level outflow above the boundary layer changed into inflow immediately outside the RMW (Fig. 4b). Then the tangential wind field expanded radially outward (Fig. 4a), followed by the potential development of another secondary eyewall at twice the RMW (Fig. 4c).

Although the decay of an inner eyewall and replacement by an outer eyewall is considered to be the typical evolution of a TC following SEF, an ERC is not completed in a substantial fraction of cases. Yang et al. (2013) found from microwave satellite imagery that in about half of all cases in the West Pacific, either the outer eyewall decays without replacing the inner eyewall, or both eyewalls coexist for an extended period without either decaying (nearly evenly divided between these two pathways). The width of the moat and the outer eyewall were both substantially (50%) larger for cases with long-lived concentric eyewalls. To investigate the maintenance mechanism for such cases, Tsujino et al. (2017) simulated Typhoon Bolaven (2012), and they found that a sufficient supply of moist entropy existed to prevent the inner eyewall from decaying.
4.2.3 Numerical Simulations of SEF

The Influence of Symmetric vs. Asymmetric Processes on SEF

Based on an idealized numerical simulation initialized with an axisymmetric vortex embedded in a quiescent environment on an $f$-plane, Wang et al. (2016) concluded that the broadening of tangential winds within the boundary layer was exclusively attributed to the azimuthal asymmetries (Fig. 5i), because the sum of mean advection (Figs. 5c,d) and friction (Fig. 5e) yielded negative tangential wind tendencies (Fig. 5j). In contrast, using a similar model setup to Wang et al. (2016), Zhu and Zhu (2015) concluded that such resolved eddy processes are only a minor contributor to SEF, with the mean radial advection being largely responsible for spin up within the boundary layer. Above the boundary layer, both Wang et al. (2016) and Zhu and Zhu (2015) found that the symmetric dynamics are dominant (e.g. Fig. 5j), and can be satisfactorily explained by the balanced response from the Sawyer-Eliassen (Eliassen 1951) equation (consistent with many previous studies, such as Rozoff et al. 2012), and can serve as the first-order factor in the broadening of tangential winds outside the eyewall.

Figure 4. (a) Radius–time Hovmöller diagram of $\vec{u}$ (colour scale), $\avg{\vec{u}}$ (10 m s$^{-1}$, purple lines), and RMW (thick black line) at 2-km altitude. The blank areas are where the GBVTD technique could not retrieve $\vec{u}$ (i.e. during the TC's passage near Ishigaki Island and in the eye region). (b) Radius–time Hovmöller diagram of $\vec{u}$ at 1-km altitude (colour scale), radius of maximum radar reflectivity at 2-km altitude (green line), and RMW at 2-km altitude (thick black line). The blank areas are where the GBVTD technique could not retrieve $\vec{u}$. (c) Radius–time Hovmöller diagram of azimuthal mean radar reflectivity at 2-km altitude (colour), radius of maximum radar reflectivity (red line), and RMW (thick black line). The black horizontal lines indicate the boundaries of the periods defined in Table 1 of Shimada et al. (2018). From Fig. 9 of Shimada et al. (2018).
Figure 5. Radius–height cross sections of the (a) simulated tangential tendency averaged from 110 to 119 h (before SEF); (b) diagnosed tangential tendency (the sum of all the terms in the tangential wind tendency equation); and tendency of azimuthal–mean tangential wind that is contributed by the following: (c) mean radial advection, (d) mean vertical advection, (e) mean friction term, (f) the sum of the mean radial and vertical advection terms, (g) eddy radial advection term, (h) eddy vertical advection, (i) the sum of the mean eddy radial and vertical advection terms, and (j) the sum of the mean advection terms and the friction term.

From Fig. 6 of Wang et al. (2016).

The Influence of Unbalanced Dynamics on SEF

A number of studies have advocated for the importance of supergradient winds in the SEF process. Analysing data from the numerical experiment of Terwey and Montgomery (2008), Abarca et al. (2015) found significant departures from Ekman-like balance in the SEF region. In other words, in the SEF region, the subgrid-scale eddy flux divergence of horizontal momentum was insufficient to either balance the agradient force in the radial momentum
equation, or the radial flux of mean absolute vorticity in the tangential momentum equation, demonstrating the important role of the nonlinear dynamics associated with these advection terms in SEF. In a companion study, Abarca and Montgomery (2015) found that they were unable to reproduce the spin-up of the secondary wind maximum within the boundary layer when using a balanced Sawyer-Eliassen model, and so they concluded that the traditional convective ring model cannot explain ERCs. On the other hand, studies such as Heng et al. (2017) found that they were able to largely reproduce the TC secondary circulation using the Sawyer-Eliassen model, and Zhu and Zhu (2015) found that this framework succeeded for secondary eyewalls as well.

SEF in a numerical simulation of Typhoon Sinlaku (2008) was investigated in Huang et al. (2018), which followed up on the earlier studies of Wu et al. (2012) and Huang et al. (2012). Huang et al. (2018) found that in the SEF region of the simulated Sinlaku, the majority of the elevated winds are supergradient, and about two-thirds of the rapid increase in tangential wind tendencies immediately prior to SEF can be attributed to agradient wind tendencies. They argued that this suggests the importance of nonlinear, unbalanced dynamical processes in SEF in addition to the conventional axisymmetric balanced response to forcings of heating and momentum.

Analyses in Huang et al. (2018) demonstrated two distinct processes that were responsible for increasing the azimuthal-mean tangential wind within and above the boundary layer for the SEF region (Fig. 6). First, within the boundary inflow layer, the competing effect between the gain from the mean radial influx of absolute vorticity and the loss due to surface friction and subgrid turbulent diffusion yielded an increasing secondary maximum of positive tangential wind tendency prior to SEF. On the smaller-radius side of the broadening tangential wind field, the diminishing anticyclonic shear term and the slightly greater curvature term cause the azimuthal mean tangential wind to increase, demonstrating the crucial role of the mean radial flux of absolute vorticity associated with the expansion of the wind field in SEF. Second, above the inflow boundary layer, mean and eddy vertical advection act to vertically extend the tangential wind jet via the lofting of the enhanced tangential momentum farther upward.

Huang et al. (2018) also presented a budget analysis of the material derivative of the azimuthal-mean radial wind, and they found that prior to SEF, the increasingly positive net radial force (which decelerates inflowing air parcels across the SEF region), is largely attributed to the development of the mean agradient force, with a much smaller contribution from the eddy agradient force (defined as the sum of the azimuthally asymmetric centrifugal and radial pressure gradient forces; see Eq. 1-5 of Huang et al., 2018). Based on this new evidence, Huang et al. (2018) elaborated on the unbalanced dynamical pathway to SEF proposed in their two previous studies. Some other recent studies, which put emphasis on other dynamical processes, also identified the progressive growth of the secondary supergradient force/wind maximum in the region in which SEF subsequently took place (e.g. Wang et al., 2016; Ma et al., 2017; Cheng and Wu 2018).
Figure 6. The radial distribution of diagnosed contributions to the azimuthal-mean tangential wind tendency (m s⁻¹ h⁻¹) for the depth averages (a), (c), (e) at the lowest 1 km (within the boundary inflow layer) and (b), (d), (f) between 1 and 2.5 km. In the SEF region (75 – 125 km), the result demonstrates two distinct responsible processes for the increasing azimuthal mean tangential winds in the two vertical intervals. The pink curve additionally shows the mean radial flux of curvature vorticity. Time relative to the onset of SEF is given in each subplot. Different scales of the y axis are applied to the two columns.

From Fig. 13 of Huang et al. (2018).

A Balanced Framework for SEF

As alluded to above, a longstanding question regards the degree to which balanced, axisymmetric dynamics control wind structure changes and even key aspects of eyewall replacement cycles. Over three decades ago, Shapiro and Willoughby (1982) applied the transverse circulation equation developed by Eliassen (1951) for axisymmetric, balanced vortices to better understand the impact of diabatic heating in regions outside of the RMW. They distinctly noted that wind fields decaying more slowly with radius imply enhanced inertial stability outside of the RMW. While this inertial stiffness reduces low-level radial inflow, the
larger angular momentum associated with the broadened wind field more than compensates for the reduced flow, resulting in increased tangential winds in the vicinity of diabatic heating. Around the same time of the Shapiro and Willoughby publication, Schubert and Hack (1982) independently produced an elegant framework based on the Eliassen vortex model to understand the role of inertial stability on intensification driven by diabatic heating, with general results that agree with Shapiro and Willoughby’s conclusions.

In recent years, full-physics numerical simulations of TCs with SEF have displayed characteristics consistent with balanced vortex dynamics (Rozoff et al., 2012; Sun et al., 2013; Wang et al. 2016; Heng et al. 2017). Various studies have applied the Eliassen (1951) vortex model to full-physics model output to see how the transverse circulations in both frameworks compare. As an example, we will briefly explore results from Rozoff et al. (2012) in which the balanced vortex model was applied to WRF model output of a simulated TC producing SEF. They specifically used the 3-Dimensional Vortex Perturbation Analysis and Simulation (3DVPAS) method of Nolan et al. (2007) in its axisymmetric mode to diagnose the transverse circulation resulting from diabatic heating and momentum forcing on a balanced vortex. When subject to fixed heating or momentum forcing and time-integrated to a steady state, the 3DVPAS model asymptotically becomes equivalent to the Eliassen vortex model. The background vortex structure and thermodynamics and the forcing terms were taken directly from azimuthal-mean WRF output.

Figure 7 shows azimuthal-mean diabatic heating and friction from the WRF model at 10-hour increments covering the SEF period in the simulation. At early stages, there is a single eyewall with rainband activity outside of a moat consisting of diabatic cooling. Twenty hours later, the outer eyewall has fully formed and a secondary peak in diabatic heating is now more pronounced. Figure 7 also shows the 3DVPAS diagnosed vertical wind, along with the azimuthal-mean vertical wind from WRF during this time period. Overall, Rozoff et al. (2012) found that the diagnosed vertical motion closely corresponds with the radial and vertical distribution of diabatic heating. However, the peak updrafts are also coincident with regions of maximum frictional forcing, which maximizes in the inner eyewall and eventually the developing outer eyewall as well. The diagnosed and WRF vertical motions resemble each other quite closely, except in the PBL, where WRF produces more vigorous updrafts in the inner and outer eyewall regions.

Figure 8 shows a comparison of the radial flow for both 3DVPAS and the WRF for the same times in Fig. 7. Once again, there is clear qualitative agreement in the balanced and WRF frameworks, although some important differences also exist. For example, the WRF simulation produces stronger outflow just above the PBL top in the vicinity of the eyewalls, which is at least partly due to supergradient winds that were filtered out of the 3DVPAS basic state to ensure dynamical stability. Now, the linear nature of the Eliassen vortex model allows one to exactly subdivide the transverse circulation into contributions from diabatic and momentum forcing. Rozoff et al. (2012) carried out calculations showing that momentum forcing contributes to less than 10% of the eyewall updraft, and mainly at low levels, whereas diabatic heating explains most of the spatial distribution of vertical motion in the 3DVPAS solutions. In terms of radial flow, momentum forcing is significant in determining the distribution of low-level inflow, contributing to roughly half of the inflow magnitude. Diabatic heating drives inflow maxima and convergence in the vicinity of heating and also determines virtually all of the radial flow above the PBL.
Figure 7. The evolution of (a) diabatic heating $\frac{\partial T}{\partial t}$ (10⁻² K s⁻¹), (b) Friction (10⁻³ m s⁻²), (c) vertical velocity (m s⁻¹) from 3DVPAS, and (d) vertical velocity (m s⁻¹) from WRF, at 105, 115, and 125 hours.

Figure 8. The vertical motion (m s⁻¹) from 3DVPAS (a) and WRF (b) at 105, 115, and 125 hours.
The Influence of WISHE on SEF

The crucial role of the expansion of the wind field in the SEF region has been discussed in many previous studies, albeit with different interpretations. As the region of strong tangential winds expands outwards, a concurrent increase in the surface heat fluxes can be expected outside of the eyewall. The wind-induced surface heat exchange (WISHE; Emanuel 1986; Rotunno and Emanuel 1987) mechanism, describing the positive feedback between the surface wind speed and surface energy fluxes, is therefore of interest in the SEF problem.

Cheng and Wu (2018) performed a set of numerical experiments to examine the sensitivity of SEF to WISHE. The surface wind used for the surface flux calculation was capped at several designated values and over different radial intervals in different experiments. When the surface heat fluxes were strongly suppressed within and outside the region where SEF was identified in the control experiment, SEF was absent (Figs. 9a,b). When the surface heat fluxes were moderately suppressed in the same region, SEF was delayed, and the intensity of both eyewalls was weaker (Figs. 9c,d). In contrast, suppressing the surface heat fluxes in the storm’s inner-core region had limited effect on the evolution of the outer eyewall. Based on these sensitivity experiments, Cheng and Wu (2018) concluded that WISHE plays a critical role in SEF.

Figure 9. Time–radius diagrams of the azimuthal-mean vertical velocity (shaded; m s$^{-1}$) and 1-km tangential wind (contours; m s$^{-1}$) of (a) OBC-01, (b) OBC-05, (c) OBC-10, and (d) OBC-15, in which the surface wind used for the surface flux calculation is capped at 1, 5, 10 and 15 m s$^{-1}$, respectively. The black dashed line indicates the SEF time in CTL, and the red dashed line indicates the SEF time in each experiment. The blue arrows indicate the selected regions of suppressed heat fluxes. From Fig. 8 of Cheng and Wu (2018).
Environmental Influences on SEF

Idealized numerical simulations on an $f$-plane with quiescent environments have produced secondary eyewalls (e.g. Terwey and Montgomery 2008, Zhu and Zhu 2015, Tyner et al., 2018), and so it seems clear that SEF can occur through internal dynamics alone. On the other hand, some studies have found that SEF can be influenced or even triggered by environmental forcing. Fang and Zhang (2012) and Rozoff et al. (2012) both found that asymmetric convection induced by $\beta$-shear (an effect of the interaction of a TC with the meridional gradient of planetary vorticity) can be a mechanism for initiating SEF. More recently, Dai et al. (2017) conducted idealized simulations on an $f$-plane (and so there was no $\beta$-shear), with a westerly jet placed ~1500 km north of the TC in their control simulation. In simulations with such a jet, SEF occurred followed by a fairly rapid ERC; without the jet, SEF did not occur. SEF was attributed to the eddy flux convergence of absolute angular momentum associated with the jet-outflow interaction, which Dai et al. (2017) argued led to the formation of an asymmetric region of enhanced stratiform precipitation. In turn, the sustained stratiform heating outside of the primary eyewall resulted in a descending mid-level inflow, which through angular momentum advection produced a secondary wind maximum, and ultimately a secondary eyewall that encircled and replaced the primary eyewall.

Zhang et al. (2017) examined a set of simulations on an $f$-plane with moderate (6 m/s) wind shear imposed, and found that the timing and details of SEF are very sensitive to small-scale random perturbations, consistent with the large uncertainty in timing of RI for moderate-shear environments seen in the previous work of Tao and Zhang (2015). Nevertheless, they found that nearly all (38/40) of their simulations underwent SEF/ERC, usually following the completion of RI. Zhang et al. (2017) found that a mid-level region of stratiform heating associated with shear-induced outer rainbands generally formed prior to SEF. This resulted in a region of positive tangential wind tendencies that developed downward. As the wind field expanded, a local maximum in vorticity of the gradient wind formed, enhancing the boundary layer updraft through the frictional dynamics described in Kepert (2013). Finally, Zhang et al. (2017) used a boundary layer model forced by the gradient wind field from their simulation, and found that the structure of the boundary layer was relatively-well predicted, from which they concluded that the boundary layer is "slaved" to the free atmosphere, consistent with the theory of Kepert (2013).

In an observational and simulation study of Hurricane Earl (2010), Stern and Zhang (2016) found that an observed SEF/ERC was relatively well forecast at 4-5 days lead time, both in terms of the initial radius of the secondary wind maximum and overall expansion of Earl's wind field. Because this evolution occurred in multiple simulations of varying lead times (even for forecasts with poor predictions of intensity), and approximately coincided with the start of Earl’s recurvature, Stern and Zhang (2016) hypothesized that the large scale environment (which is more predictable than internal dynamics) was ultimately responsible for the wind field expansion and ERC.

Sensitivity of SEF and ERCs to Model Physics

A series of recent studies have explored the sensitivity of SEF and ERC to parameterized physics in numerical models. Zhu and Zhu (2015) found in idealized simulations that ERC evolution differed among various boundary layer parameterizations, which they attributed to differences in the magnitude of eddy viscosity. Zhu and Zhu (2015) also found that larger snow fall speeds in the microphysics parameterization resulted in increased shallow convection...
in the moat region between the rainbands and the inner eyewall, which suppressed the formation of a secondary wind maximum. Tyner et al. (2018) examined SEF in both idealized and real-case simulations, and found that by reducing the fall speed of snow in the operational HWRF, SEF and subsequent ERCs occurred that were originally absent. Tyner et al. (2018) argued that the operational HWRF is likely deficient in small and slowly falling hydrometeors, and that the modified microphysics resulted in a more realistic evolution, through enhanced radial transport of hydrometeors and increased outer rainband activity.

Tang and Zhang (2016) and Tang et al. (2017) simulated Hurricane Edouard (2014), and found that while SEF occurred in a control simulation (consistent with the observed storm), turning off the shortwave radiation parameterization suppressed SEF, primarily by preventing the suppression of convection in the moat region. Tang et al. (2017) argued that SEF therefore may be highly sensitive to the diurnal cycle of solar radiation. Nevertheless, the wind field expanded and the RMW increased with time in both simulations, with the key difference being how gradually this evolution took place.

4.2.4 Theories for SEF

The Role of the Boundary Layer in SEF and ERCs

The cloud base in tropical cyclones is observed and modelled to be low enough that cloud properties can be expected to be strongly affected by the boundary layer. For instance, the WISHE theory of tropical cyclone intensification, and Emanuel’s potential intensity theory, both have cloud thermodynamic properties depending closely on conditions within the boundary layer, including at the surface. The dynamical properties of the boundary layer are also important, since frictional convergence may favour convective development in one region over another. For instance, numerous idealized models of tropical cyclone boundary layer dynamics, of varying degrees of complexity, predict strong frictional convergence near the radius of maximum winds (Ooyama 1969, Kepert 2001, Kepert and Wang 2001, Kepert 2013, Frisius and Lee 2016). It is reasonable to assume that this convergence helps locate the eyewall convection in this area. Recently, attention has turned to whether frictional convergence within the boundary layer can either contribute to, or even create, secondary eyewall formation. Buoyant convection will always have horizontal convergence beneath it, through continuity. However, that convergence may be a consequence of the buoyancy, and quite independent of any frictional forcing – the existence of convergence within the boundary-layer is no proof that the convergence is caused by frictional processes (Raymond and Hermann 2012). Or, frictional convergence may be triggering, or perhaps locating, the convection, with buoyancy-generated vertical accelerations subsequently strengthening the convergence. Hence it is necessary to have some means of diagnosing the cause of the observed convergence.

Diagnostic models of the boundary layer provide such a tool. These models take the equations of motion and apply a pressure field or gradient wind field intended to represent the rest of the cyclone. The equations of motion are solved, with suitable parameterizations of turbulence and surface friction, to provide the boundary-layer flow corresponding to the prescribed pressure field. Since the structure and intensity of the tropical cyclone-like pressure field is prescribed, these models aim to depict one side of a two-way interaction: the rest of the cyclone can affect the boundary layer, but not vice versa. Numerous such models exist, differing mainly in the additional assumptions (such as vertical averaging, axisymmetry and linearization) used to obtain a solution (reviewed in Kepert 2010). As mentioned above, these models commonly predict strong frictional convergence near the primary radius of maximum winds.
Kepert (2013) used three such models to study concentric eyewalls. Using a nonlinear, 3-dimensional model, he showed the surprising result that in a cyclone with two wind maxima of about equal strength, the frictional updraft near the outer RMW is substantially stronger than that at the inner (Fig. 10). Using an axisymmetric linearized model, where the additional simplifications yield an analytical formula for the frictional updraft (see Eq. 22 and 24 of Kepert 2013), he showed that the updraft strength is approximately proportional to minus the radial gradient of vorticity, times the surface stress, divided by the absolute vorticity squared. The stress at the two RMWs is similar, and while the outer one has a weaker radial vorticity gradient, it is also in an environment of much lower vorticity. Dividing by the vorticity squared thus gives a stronger updraft at the outer RMW. He further showed that quite weak increases in the vorticity at several times the primary RMW could yield significant frictional updrafts.

Figure 10. Boundary layer flow simulated by the nonlinear model. (a) Radial velocity (contour interval 1 m s\(^{-1}\); multiples of 10 m s\(^{-1}\) shown as thick lines and outflow shaded). (b) Azimuthal velocity (contour interval 2 m s\(^{-1}\); multiples of 10 m s\(^{-1}\) shown as thick lines) and supergradient flow (shaded). (c) Vertical velocity (contour interval 0.1 m s\(^{-1}\); zero shown as thick lines and subsiding flow shaded). (d) Thick gray curve: prescribed gradient wind profile; dashed curve: prescribed vorticity profile; dots: azimuthal velocity at 10-m height; circles: inflow at 10-m height; thin black curve: vertical velocity at 2-km height. The inner and outer radii of maximum gradient winds are indicated by the black dots on the x-axes.

From Fig. 2 of Kepert (2013).
Based on these results, he proposed that the boundary layer contributes to secondary eyewall formation through a positive feedback between frictional convergence due to the vorticity perturbation, and increased vorticity through vortex-tube stretching in buoyant convective updrafts. The radially localized increases in vorticity are related to the well-known expansion of the wind field during secondary eyewall formation through Stokes’ theorem. A key conclusion of Kepert (2013) was that a uniform expansion of the wind field does not in itself result in a local frictional updraft; rather, it is the local enhancement of the radial vorticity gradient that can produce the updraft that is essential to the proposed feedback process.

Huang et al. (2012) had earlier proposed a different pathway by which boundary layer processes could cause secondary eyewall formation (discussed in 4.1.3 in the context of Huang et al., 2018). As with Kepert (2013), they argued that frictional convergence within the boundary layer causes convection, which forms the new outer eyewall. Their framework differs, in that the frictional convergence is caused by the outwards acceleration in the supergradient winds in the upper boundary layer, which in turn develop because of increased inflow. Abarca and Montgomery (2013) presented an analysis of a full-physics model simulation, and time-dependent simulations with a depth-averaged boundary-layer model, that further explored the mechanisms of SEF. Kepert’s (2013) simulations also contained marked supergradient flow in the upper boundary layer near the frictional updraft, suggesting that both features were together caused by vorticity changes, rather than one causing the other. Moreover, his simulations, and those of Huang et al. (2012) agree that while the supergradient flow is strongest in the upper boundary layer, the horizontal convergence is strongest in the lower boundary layer where the flow may be subgradient. From this, Kepert (2013) cast doubt on Huang et al.’s causal relationship. The relationship between the two proposed mechanisms is discussed further in Kepert and Nolan (2014) and Kepert (2017).

Kepert and Nolan (2014) and Zhang et al. (2017) applied the diagnostic models used by Kepert (2013) to WRF simulations of eyewall replacement cycles and found good agreement between the locations of the diagnosed frictional updrafts, and those in WRF. The diagnosed updrafts were, however, about half as strong as those in the WRF simulations, which they attributed to the additional effects of buoyancy in the full model.

For the proposed feedback between vorticity, frictional convergence and convection to operate, they must be in the correct relative positions. In particular, the updraft in a nonlinear boundary layer model is at smaller radius than in a linear model, and the former case is generally more favourable for the proposed feedback. Kepert (2017) showed that the updraft is displaced inwards from the radius of maximum vorticity gradient by a distance that scales as $-u_{10}/I$, where $u_{10}$ is the 10-m radial wind and $I$ is the inertial stability. He argued that when the secondary eyewall is at large radius, the updraft will be inside of the vorticity perturbation, leading to weak growth but rapid inwards movement of the perturbation. As the secondary eyewall migrates inwards, the updraft and perturbation come more into phase, leading to slower contraction and stronger growth.

The above theory of Kepert (2013, 2017), along with much of the work on secondary eyewall formation, is axisymmetric. Yet commonly, secondary eyewalls appear to form by the “wrapping up” of a principle rainband (as discussed in 4.1.2). If frictional convergence is indeed important for SEF, it is necessary to understand how the boundary layer dynamics respond during this evolution. Kepert (2018) studied the frictional response to outer spiral bands of vorticity, superimposed on an axisymmetric tropical cyclone-like vortex. Remarkably, many of the kinematic features in observed rainbands were reproduced in a model with no
moist processes. He further showed that the frictional response to such bands forms a continuum with the response to axisymmetric rings, in that both produce a frictional updraft near the band’s (or ring’s) axis, a jet of winds stronger than the local balanced flow along the band, and marked variation in the inflow strength and depth across the band (Fig. 11). In the case of a spiral band, however, the updraft is quite weak at the upwind end of the band and increases downwind. As any feedback must be weaker at the upwind end, he suggests that the frictional convergence – convection – vorticity feedback is unlikely to be the entirety of rainband dynamics.

Figure 11. Simulated boundary layer flow for a parameterized vortex with a rainband. (a) Radial velocity at 10 m; (b) azimuthal velocity at 10 m; (c) vertical velocity at 1 km; (d) the highest wind speed in the profile, divided by the balanced wind speed in that column; (e) the height of the maximum wind speed; (f) the ratio of the 10-m wind speed to the balanced wind speed, together with the streamlines of the 10-m flow; (g) the difference in direction between the 10-m flow and the balanced flow, with turning toward the center of the storm being negative; (h) vertical profiles of the radial flow 6 km inside (blue), and 6 (green) and 18 km (red) outside, of the band axis, at its midpoint, with the balanced radial flow at those points being shown by the like-coloured dots; and (i) as in (h), but for the azimuthal flow. Note that the contours in (c) are not linearly spaced but increase by factors of 2. The black dashed curve in (a)–(g) indicates the axis of the vorticity band. From Fig. 2 of Kepert (2018).
**A Linear Instability Theory of SEF**

The theory of Kepert (2013, 2017) proposes that once a large enough vorticity maximum forms in the region outside of the primary eyewall, a substantial updraft will occur from frictional convergence, driving deep convection which can amplify the vorticity and result in the above-described feedback mechanism for SEF and ERC. However, the Kepert theory starts from a pre-existing vorticity maximum, and so it does not describe how such a maximum is originally formed. Very recently, Miyamoto et al. (2018) have proposed that a linear instability of the interaction of an Ekman-like boundary layer with the free atmosphere in a vortex can lead to the exponential growth of the frictionally-forced updraft, which can serve to amplify the vorticity to a sufficient magnitude such that the convective feedback mechanism of Kepert can operate. They derived an instability condition, and found that such instability can occur for radial profiles of tangential wind where the angular velocity is large in the presence of relatively small vertical vorticity and a large negative radial gradient of vorticity. The growth rate of the instability increases with the RMW, the radius of the outer vorticity maximum, and vortex intensity, and instability can only occur at radii between 2 and 7 times the RMW. Finally, Miyamoto et al. (2018) analysed axisymmetric and three-dimensional full-physics simulations, and found that their diagnostic instability parameter increased several hours in advance of the formation of a secondary wind maximum, and thus the authors argued that SEF can be initiated by this linear instability mechanism.

**4.2.5 Summary and Conclusions**

In recent years, continued progress has been made in understanding secondary eyewall formation, eyewall replacement cycles, and the associated expansion of the tropical cyclone wind field. In particular, the typical structural evolution of SEF is now fairly well characterized, due to advancements in both observations and numerical simulations. There is broad agreement about the following aspects of SEF: (1) In real TCs, SEF generally occurs in association with initially asymmetric outer rainbands, which (at least partly) through diabatic heating enhance the vertical vorticity in a radially confined region and thereby increase the tangential winds; (2) there is a broad radial expansion of the tangential wind field that is associated with SEF (which implies a net import of vorticity), and many studies find that this expansion precedes SEF; (3) boundary layer dynamics focus convergence in the region where SEF occurs; and (4) SEF is associated with a region of supergradient flow in the upper boundary layer.

There is continued disagreement regarding the specific mechanisms that cause SEF and/or are responsible for amplifying existing wind maxima. The most prominent of these disagreements is whether enhanced boundary layer convergence is essentially a response of the otherwise-balanced vortex to friction (and the supergradient flow is itself also a consequence of the frictional response), or if instead the convergence is caused by the supergradient flow. Though such different interpretations may seem subtle, they result in very different conclusions for which processes are deemed essential to SEF. Although not as vigorously contested, there are several other ongoing debates within the literature that are noteworthy. One is that studies have reached differing conclusions on the relative importance of symmetric and asymmetric processes in driving expansion of the wind field and forming the secondary wind maximum. Another outstanding issue is the degree to which SEF is forced by purely internal dynamics as compared to external forcing from large-scale troughs/jets and/or vertical wind shear. Finally, although there is increasing evidence for top-down processes (in particular stratiform rainband
heating) leading to SEF, the relative importance of the mid- and upper-levels as compared to the boundary layer remains unclear.

At the time of the previous IWTC, there was no single widely-accepted theory for SEF, and this remains true today. Indeed, new theories of SEF continue to be developed, such as that SEF may result from a linear instability of the interaction of the boundary layer with the free atmosphere. Several studies have made distinctions between mechanisms that may be the initial trigger for SEF and mechanisms that may instead amplify some pre-existing feature (e.g. a weak local vorticity maximum). This is helpful, as it may be the case that both a trigger and an amplifying mechanism are important to SEF, and that these may be distinct. Ultimately, although some fundamental disagreements remain, most studies have concluded that SEF proceeds in some manner through feedbacks between diabatic heating in rainbands and frictional convergence in the boundary layer. In the future, we hope that continued research – observational, numerical, and theoretical – will help further refine these ideas and lead to the emergence of a more comprehensive and accepted understanding of SEF.

4.2.6 Recommendations

Our recommendations for research on SEF and wind field expansion are as follows:

1. Continue to use both idealized and real-case numerical experiments to attempt to distinguish between those mechanisms that can potentially affect SEF and those mechanisms that are actually essential to SEF. A wide range of mechanisms have been proposed for SEF, and it is possible that in real TCs, there are multiple pathways that can lead to SEF, and research should also be pursued to try to determine if this is the case.

2. There is a lack of systematic investigations into the ability of operational numerical models to skillfully forecast SEF and ERCs, although it is generally believed that such skill is currently absent. Given that idealized simulations are capable of producing secondary eyewalls, operational forecasts should in principle be able to do so as well. It is currently unclear the extent to which numerical models can predict SEF/ERCs, and the degree to which the limitations are due to model biases, initial conditions, or an intrinsic lack of predictability. Focused studies are recommended to help answer these questions.

3. All studies should make clear how they define SEF, and consider how this choice affects their analyses and conclusions in comparison to other studies. Ideally, a common definition can be agreed upon, although given the intrinsic differences between what is simulated and what can be readily observed, this may not be possible.

Acronyms Used in the Report

3DVPAS: 3-Dimensional Vortex Perturbation Analysis and Simulation
AAM: Absolute Angular Momentum
ERC: Eyewall Replacement Cycle
GBVTD: Ground-Based Velocity Track Display
HS3: Hurricane and Severe Storm Sentinel
HWRF: Hurricane Weather Research and Forecasting model
MDI: Mesoscale Descending Inflow
RI: Rapid Intensification
RMW: Radius of Maximum Winds
SEF: Secondary Eyewall Formation
TC: Tropical Cyclone
WISHE: Wind-Induced Surface Heat Exchange
WRF: Weather Research and Forecasting model

References


TOPIC 4.3 - EXTRATROPICAL TRANSITION

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Abstract
This report builds on two recent review papers in Monthly Weather Review (Evans et al., 2017, Keller et al. 2019) to document recent advances in the field’s understanding of extratropical transition. Significant advances have been made in our understanding of structural evolution during the transformation stage of extratropical transition, fostered in large part by in situ observations collected during earlier field campaigns. These in situ observations have also been leveraged to help document forecast sensitivities associated with, and the practical predictability of, extratropical transition. The last four years have also seen many of the first studies in which recent and projected changes in extratropical transition climatologies have been examined. The most substantial gains in insight since the last IWTC have arguably come, however, in the field’s understanding of midlatitude flow interaction, downstream development, and the associated high-impact weather that can result from extratropical transition events. These findings and recommendations for future research, particularly to benefit operational forecasting centers, are documented herein.

4.3.1 Introduction

The process by which tropical cyclones (TCs) transition into baroclinic cyclones as they recurve into the midlatitudes is known as extratropical transition (ET). Most affected by ET are the North Atlantic and western North and South Pacific basins during the "shoulder" seasons, when the equatorward displacement of the baroclinic westerlies favours interactions between TCs and Rossby waves propagating along the midlatitude jets or “waveguides”. Storms undergoing ET pose a particular forecasting challenge because of the rapid structural and track changes that occur during this stage of the storm lifecycle. This predictability problem is compounded by the fact that the poleward movement of transitioning storms means that they affect regions in which the infrastructure and the population is not well prepared for the severe TC-like impacts that these storms can produce.

A pair of very recent review articles serves to document the current state-of-the-art in ET research and forecasting (Evans et al., 2017; Keller et al., 2019). Although the research described in this report is necessarily based on work that was in progress during the
preparation of the review papers, the focus here on only the most recent investigations (2014 onwards) distinguishes this report from the reviews. Additionally, the design of this report departs from the structure of the review papers in a way that is intended to make the current work a useful reference for readers looking for an overview of current ET research and for proposals for near-term investigations that will advance the community’s understanding of ET going forward.

The distinguishing characteristic of ET is the structural change of the remnant TC from a symmetric, warm-core vortex to an asymmetric, cold-core circulation with well-defined frontal features. Associated with this structural change is the transition of the primary energy source for the system from surface enthalpy fluxes to the large-scale baroclinic conversions germane to midlatitude cyclones. This dramatic evolution in the nature of the storm brings with it serious predictability challenges, especially because of the sensitivity of ET to the structure of the midlatitude flow into which the TC remnant recurves. Depending on the state of the midlatitude jet, the impact of ET on this waveguide varies from a slight intensification of the jet core to the development of a high-amplitude Rossby wave train that can lead to multiple high-impact weather events downstream. The prediction of specific basin-scale outcomes from ET in both weather and climate models is at once challenging and essential, not the least because of the economic and societal costs that these events can incur.

All of these aspects of the ET problem will be addressed in this report. In section 4.3.2, we review recent work regarding the structural changes that occur during ET. This perspective is expanded to the basin scale in section 4.3.3, which considers interactions between the transitioning TC and the midlatitude waveguide, downstream development and downstream high impact weather. A discussion of the associated predictability limits and current forecast skill for transitioning storms and their downstream impacts follows in section 4.3.4. This builds towards the descriptions in section 4.3.5 of recent advances in understanding ET in a climatological context. In section 4.3.6, the report concludes with a summary of ongoing investigations, a review of gaps in our knowledge, and recommendations for research topics that may be particularly valuable to the ET research community, operational forecasters, decision-makers and stakeholders in affected areas.

4.3.2 Structural Evolution

As discussed in the recent ET review (Evans et al., 2017), a TC that travels poleward into a baroclinic environment with its attendant temperature and moisture gradients typically undergoes a structural change from a deep warm-core cyclone into either a shallow warm-core or a deep cold-core cyclone, with an asymmetric, frontal structure (e.g. Hart et al., 2006; Klein et al., 2000). Specifically, as TC moves poleward and the transformation stage of ET begins, its outer circulation encounters a midlatitude baroclinic zone, and the deep, moist convection of the inner-core becomes increasingly asymmetric. Subsequently, as the TC becomes collocated with and embedded into the baroclinic zone, the TC acquires substantial vertical tilt, develops features such as the conveyor belts characteristic of extratropical cyclones, and thunderstorm activity becomes isolated some distance poleward of the center (Klein et al., 2000; Ritchie and Elsberry 2001).

Likewise, during the transformation stage, the cyclone’s near-surface wind field becomes asymmetric and grows (Evans and Hart 2008), resulting in an increase of the cyclone’s integrated kinetic energy (Kozar and Misra 2014). Concurrently, precipitation fields become asymmetric and expand radially with increased areal coverage (Matyas 2013). The heaviest
precipitation becomes located downshear of the circulation center and may occur either left- or right-of-track (Atallah et al., 2007; Milrad et al., 2009), with left-of-track rainfall favoured in environments favouring cyclone reintensification (i.e. a negatively tilted trough upshear of the TC). The locations of heaviest precipitation during ET are further modulated by orography, with maximum amounts located in areas of upslope flow (Liu and Smith, 2016; Keighton et al., 2016) or areas of orographically driven ageostrophic frontogenesis (Milrad et al., 2013).

In the following, advances in understanding of structural evolution during ET since the last IWTC are documented. Perhaps most significant of these is the first observational confirmation of the earlier conceptual models of structural evolution, as discussed in the next subsection.

a) Observations of Structural Evolution

Several recent field campaigns have provided novel observations of transitioning TCs (Wu et al., 2005; Waliser et al., 2012; Rogers et al., 2013; Schäfler et al., 2018). Since 2014, observations from these campaigns – particularly the THORPEX Pacific Asian Regional Campaign (T-PARC; Waliser et al., 2012) – have helped confirm the validity of conceptual models of the transformation stage of ET previously developed by Klein et al. (2000) and Ritchie and Elsberry (2001).

During step 1 of the transformation stage, the TC translates poleward, its outer circulation encounters a midlatitude baroclinic zone, and the deep, moist convection of the inner core becomes more asymmetric, with an associated wavenumber-one asymmetry in the vertical motion and radar reflectivity fields with maximum ascent and reflectivity downshear-left, and maximum descent and minimum reflectivity in the upshear semicircle. Based on an analysis of Doppler radar, dropsonde, aircraft flight level, and satellite atmospheric motion vector data from western north Pacific Typhoon Sinlaku in 2008, these asymmetries have been attributed to the environmental deep-layer vertical wind shear (Foerster et al., 2014). Consistent with balanced dynamics, this deep-layer vertical wind shear led to predominantly upward mass flux downshear and downward mass flux upshear. Convective cells formed downshear-right (Fig. 4.3.2.1d), rotated cyclonically downstream, reached maximum intensity downshear-left (Fig. 4.3.2.1b), and decayed upstream (Fig. 4.3.2.1a and c). This pattern is consistent with previous theoretical, observational, and model studies of TCs in vertical shear (e.g. Marks et al., 1992; Frank and Ritchie, 2001; Black et al., 2002; Corbosiero and Molinari, 2002; Reasor et al., 2009; DeHart et al., 2014).

During step 2 of the transformation stage, the TC becomes superposed on the midlatitude baroclinic zone. Observational studies indicate that processes associated with this superposition, rather than a response to vertical wind shear, are the cause of asymmetries in the cyclone structure during this stage (Quinting et al., 2014, Katsumata et al., 2016). Warm frontal development east of the transitioning cyclone leads to forced ascent (Fig. 4.3.2.2), in turn triggering deep, moist convection and the formation of a broad stratiform precipitation region that causes heavy precipitation to the northeast of the transitioning TC. Though latent heat release due to condensation may enhance the remnant circulation of the TC aloft (Quinting et al., 2014), cooling due to evaporation and melting in the dry, cool air north of the warm front may enhance lower-level frontogenesis, potentially contributing to increased precipitation (Katsumata et al., 2016). On the western flank of the cyclone, cold frontal development is weak, and deep, moist convection is suppressed due to warm and dry air aloft and cold air near the surface.
Figure 4.3.2.1. Vertical cross-sections through Typhoon Sinlaku of radar reflectivity in dBZ (shaded), tangential wind in m s$^{-1}$ (gray contours), and in-plane wind vectors composed of radial and vertical velocity for each shear-relative quadrant. Cross-sections are taken from the corner of the domain to the center, 45° from the x- and y- axes in each quadrant: (a) upshear left, (b) downshear left, (c) upshear right, and (d) downshear right. Figure reproduced from Foerster et al. (2014).

Figure 4.3.2.2. Overview of the analysed domain and the spatial distribution of observational data. Maximum reflectivities between 0 and 15 km (dBZ; shaded) and temperature (K; contours) at 1.5 km. Wind vectors give horizontal wind at 1.5 km (m s$^{-1}$). Gray line denotes flight track of the NRL-P3 and red line denotes flight track of the USAF-WC130. Filled circles give positions of dropsondes included in SAMURAI analysis. Stars indicate positions of dropsondes in Fig. 7 in Quinting et al. (2014). Black arrows at coordinate axis show positions of cross-sections in Fig. 6 of Quinting et al. (2014).
b) Wind Field Evolution

The hazard risk from TCs is multi-faceted, with strong winds, large waves, and storm surge all posing significant threats. The nature of these threats changes during ET, however, as the wind field structure changes (Bruneau et al., 2017; Evans et al., 2017). New research since the last IWTC has sought to quantify the variability in ET-related near-surface wind field structures and develop improved parametric and statistical models for wind field structure during ET (Loridan et al., 2014, 2015, 2017).

A long-accepted framework to conceptualize TC surface level winds has been that they result from the superposition of a symmetric vortex (e.g. Holland 1980; Willoughby et al., 2006) with the TC’s forward motion. This framework depicts TCs as translating systems with strongest winds found to the right of motion in the Northern Hemisphere and to the left of motion in the Southern Hemisphere. In terms of risk assessment, this puts one side of the TC track at a much higher risk than the other. Using aircraft observations from 128 flights into tropical cyclones, Uhlhorn et al. (2014) found that while this paradigm is largely accurate at flight level, it fails near the surface where it is needed the most for risk assessment. They conclude that surface wind asymmetry is related to deep-layer shear rather than storm motion, with the strongest near-surface winds generally located downshear-left of the center. This asymmetry tends to shift downwind during ET as baroclinicity and shear increase. The limitations of the symmetric superposition framework during ET have also been highlighted by Kitabatake and Fujibe (2009) and Loridan et al. (2014). Both investigations showed that it is common for ET cases to have similar wind risk on both sides of the transitioning TC (e.g. Fig. 4.3.2.3), with approximately 67% of TCs that complete ET near Japan having winds to the left-of-track that are within 20% of those to the right-of-track (Loridan et al., 2014).

Figure 4.3.2.3. Maximum 10-m wind speed to the left of motion ($V_{\text{max, lhs}}$; y-axis) as a function of the maximum to the right of motion ($V_{\text{max, rhs}}$; x-axis) in the western North Pacific Ocean. Colour bins indicate the storm translational speed. The 1:1 (solid) and linear regression (dashed) lines are shown. See Loridan et al. (2014) for more details.
Although traditional parametric modelling solutions built for pure tropical cyclones are not adequate for ET cases, research in developing alternative methods has been limited to date. Loridan et al. (2015) propose an extension to the Willoughby (2006) model that specifically implements a left-of-track wind maximum component for the ET phase in the western North Pacific. This model is able to replicate an ET-specific surface wind structure (Fig. 4.3.2.4), yet its implementation as part of a risk assessment system is complex because it requires input from a separate model to determine if the TC is undergoing ET or not. Knaff et al. (2017) develop a hybrid statistical-dynamical model that provides skillful estimates for wind radii around storm centers for a 2-year sample of storms across the major TC basins. However, they also conclude that ET poses a unique challenge for wind field prediction.

More recently, a machine-learning model that has been trained on a large database of realistic high-resolution TC wind structures has been developed and applied to extract automatically the most relevant wind field asymmetry patterns (Loridan et al., 2017). The spatial wind distribution can then be modelled from these patterns given knowledge of the TC track, intensity, and wind field extent. Since the training database includes both pure TCs as well as ET cases, the machine-learning model learns to model both types of structure in a unified framework. However, assembling a larger, global catalog of TCs would enable the machine-learning model to learn from and better represent a broader range of TC features, including the complex wind field structures that develop during ET.

Figure 4.3.2.4. WRF-ARW-simulated 10-m wind speed (in m s\(^{-1}\)) for Typhoon Rammasun at 0600 UTC 12 May 2008 (left) and the corresponding 10-m wind speeds from the Loridan et al. (2015) ET model (right).

c) Precipitation Evolution

Rainfall with ET events may be directly – e.g. resulting from the direct interaction of the TC with the midlatitude baroclinic zone – or indirectly – e.g. such as in the case of a predecessor rain event (PRE; e.g. Galarneau et al., 2010) – related to the transitioning TC. Since the last IWTC, advances in understanding for both rainfall event types have been made. The
importance of these findings lies in their societal impacts to regions that do not necessarily receive frequent direct TC impacts. For example, a recent statistical analysis of heavy rain events in a reservoir in New York state finds that TCs are a large fraction of heavy rainfall events in the area, with ET events making up 70% of the TC total (Towey et al., 2018). In the following, advances in understanding of both direct and indirect TC-related rainfall before and during ET are discussed.

Studies during the past four years have shown that the amount of rainfall directly associated with ET events is related to environmental factors including the amount of environmental moisture (Matyas 2017), the strength of the midlatitude baroclinic zone and its proximity to the TC during ET, the strength of moisture and temperature advection during ET (and associated frontogenesis and forcing for ascent on sloped isentropic surfaces), and the alignment of the motion and vertical wind shear vectors (Deng and Ritchie 2018a).

The pattern of rainfall directly associated with ET events is also related to interaction with topography (e.g. Milrad et al., 2013, Liu and Smith 2016, Keighton et al., 2016), the strength of the midlatitude baroclinic zone and its proximity to the transitioning TC, moisture and temperature advection strength, the ascent of moist air along sloping isentropes poleward and downstream of the TC, and the alignment of the motion and vertical wind shear vectors (Deng and Ritchie 2018a). Both rainfall coverage and asymmetry (left-of-track vs. right-of-track) are affected by these factors. The latter can be quantified by a rainfall metric $B_{rain}$ (Deng and Ritchie 2018b), which is closely related to the lower-tropospheric thermal asymmetry parameter $B$ of the cyclone phase space of Hart (2003).

A case study of a heavy rainfall event directly associated with an ET event was performed for Typhoon Etau (2015) by Kitabatake et al. (2017). A meridionally oriented rainband (black bar in Fig. 4.3.2.5) became organized east of Etau (A in Fig. 4.3.2.5) after it completed ET. This rainband was responsible for heavy rainfall over eastern Japan, with total precipitation exceeding 500 mm. After Etau completed ET, two middle tropospheric cyclonic potential vorticity (PV) anomalies (B and C in Fig. 4.3.2.5) that had origins in the upper troposphere in the midlatitudes moved southeastward, were cyclonically advected around Etau, and eventually reached the area of heaviest rainfall. These disturbances were associated with mid-tropospheric dry air and forcing for ascent, resulting in the realization of potential instability and heavy rain.

Indirect rainfall, or that falling well ahead of the TC during ET, has been recently studied over the Korean Peninsula (Baek et al., 2015). Over a twenty-two-year sample, antecedent indirect precipitation ahead of the transitioning TC was found to be related to the development of middle tropospheric frontogenesis as the TC interacted with the midlatitude environment. Although Baek et al. (2015) conclude that antecedent indirect precipitation is different from the PREs defined by Galarneau et al. (2010) because frontogenesis is focused at mid-levels rather than the surface, the original definition of a PRE does not depend on the mechanism forcing ascent. This is reinforced by Galarneau (2015), who investigated the impact of an oceanic PRE on the track of TC Isaac (2012). Galarneau (2015) shows that mid- and upper-level frontogenesis provided the forcing for moist ascent in this case, with structures like those found over Korea by Baek et al. (2015). Given that there is no reason to expect that fundamentally different processes occur in different regions to trigger remote precipitation events, use of consistent terminology would avoid the divergence of studies on this form of indirect TC-related rainfall and ease future literature reviews. Because the PRE terminology appeared first in the literature, it should be preferred in future works investigating this topic.
4.3.3 Trough Interaction and Downstream Development

Prior to 2014, idealized and real case studies revealed that the phasing and interaction of a transitioning TC with an upstream trough is crucial for the development of the transitioning TC and its downstream impact (Ritchie and Elsberry 2007; Riemer and Jones 2010; Scheck et al., 2011; Grams et al., 2013b). Recent climatological studies on western North Pacific transitioning TCs (Archambault et al. 2015; Torn and Hakim 2015; Quinting and Jones 2016) corroborate these findings, emphasizing the importance of divergent outflow to downstream development.

Specifically, upper-tropospheric potential vorticity advection by the divergent component of the wind typically strengthens the local extratropical potential vorticity gradient (or waveguide), intensifying the jet streak between the upstream trough and downstream ridge, and amplifies the downstream ridge by deforming potential vorticity contours poleward. This process may impede the upstream trough’s eastward propagation, contributing to the favourable phasing of the TC with the upstream trough (Griffin and Bosart 2014; Pantillon et al., 2015; Archambault et al. 2015; Quinting and Jones 2016). This non-linear interaction results in a more poleward track of the TCs (Quinting and Jones 2016) and a stronger amplification of the downstream flow (Chen et al., 2017).

a) Downstream Development

During ET, quasi-geostrophic forcing for ascent provided by the upstream trough leads to the ascent of warm and moist tropical air masses that have been transported poleward towards the midlatitude baroclinic zone by the cyclonic TC circulation (Quinting and Jones 2016; Grams and Archambault 2016; Riboldi et al., 2018). Of note, this transport is significantly stronger than that associated with extratropical cyclones, particularly for western North Pacific TCs.
Ascent may occur several days (500-2000 km) ahead of, or in direct association with, the transitioning TC. In the former case, it is known as a predecessor rain event (section 4.3.2c). Ascent directly associated with the transitioning TC may be upright or slantwise, with the former dominating as ET begins and the latter becoming increasingly common at later times (Grams et al. 2013a; Grams and Archambault 2016). This ascent is maximized poleward of the TC and ahead of the upstream trough in the equatorward entrance region of an anticyclonically curved jet streak and is collocated with midlevel frontogenesis (Archambault et al., 2015; Grams and Archambault 2016).

The ascent resulting from the non-linear interaction between the TC, upstream trough, and the midlatitude baroclinic zone manifests itself in an upper-tropospheric divergent flow. Though it has not yet been rigorously tested, it is assumed that the divergent outflow during ET is mostly driven by latent heat release. Initial estimates using the quasigeostrophic omega equation corroborate this assumption (Quinting and Jones 2016), and poleward moisture transport (which can be thought of as a proxy for latent heat release upon ascent) is crucial to downstream ridge amplification and Rossby wave packet initiation (Riboldi et al., 2018).

The ridge amplification that often occurs downstream of transitioning TCs has been the focus of numerous recent case and composite studies (Griffin and Bosart 2014; Keller et al., 2014; Torn et al., 2015; Grams and Archambault 2016; Keller 2017), idealized simulation evaluations (Riemer and Jones 2014), and climatological studies (Archambault et al., 2015; Torn and Hakim 2015; Quinting and Jones 2016; Riboldi et al., 2018). Based on studies conducted prior to 2014 and the studies cited above, a consistent picture has emerged. In the following, this picture is described using two complementary frameworks: eddy kinetic energy and potential vorticity.

In the eddy kinetic energy framework, eddy available potential energy is converted to eddy kinetic energy through the ascent of the poleward-transported warm air mass (Keller et al., 2014; Quinting and Jones 2016; Keller 2017). The newly generated eddy kinetic energy is redistributed by ageostrophic geopotential fluxes to the downstream ridge’s flanks, with the local accumulation of eddy kinetic energy on the downstream ridge’s western flank driven by converging ageostrophic winds (due to the upstream trough) and divergent flow resulting from diabatically driven ascent along the midlatitude baroclinic zone (e.g. Chen 2015; Quinting and Jones 2016; Keller 2017). Eddy kinetic energy is subsequently dispersed by ageostrophic geopotential fluxes to downstream regions, where it contributes to the formation of further eddy kinetic energy maxima on the flanks of downstream troughs and ridges. The ageostrophic geopotential flux convergence magnitude on the western flank of the downstream ridge is directly proportional to the magnitude of the evolving Rossby wave packet (Quinting and Jones 2016; Keller 2017).

In the potential vorticity (PV) framework, divergent outflow impinges on the PV gradient coincident with the midlatitude jet stream, displaces it poleward, and thus contributes to the downstream ridge amplification (Figs. 4.3.3.1 and 4.3.3.2; Griffin and Bosart 2014; Archambault et al., 2015; Torn et al., 2015; Quinting and Jones 2016; Grams and Archambault 2016; Riboldi et al., 2018). The upstream jet streak forms due to upper-tropospheric frontogenesis as the divergent outflow strengthens the midlatitude PV gradient (Archambault et al., 2015). In the presence of a PRE, the related divergent outflow may contribute to an initial amplification of the downstream ridge, which may be thought of as environmental preconditioning (Fig. 4.3.3.2a; Grams and Archambault 2016; Bosart et al., 2017). Overall, a broad consensus in current ET research is that the upper-tropospheric divergent outflow has
the largest individual contribution to the downstream ridge building. However, as the TC approaches the midlatitude PV gradient during ET, the contribution of the transitioning cyclone’s circulation to downstream ridge amplification increases (Riemer and Jones 2014; Quinting and Jones 2016), although recent research suggests that downstream ridge amplification is not directly related to the transitioning cyclone’s intensity (Archambault et al., 2015; Quinting and Jones 2016; Chen et al., 2017; Riboldi et al., 2018).

Figure 4.3.3.1. Composite analyses showing (a) strong and (b) weak TC–extratropical flow interactions. Analyses show 500-hPa ascent (dashed green, every $2 \times 10^{-3}$ hPa s$^{-1}$, negative values only), precipitable water (shaded according to grayscale, mm), 200-hPa PV (blue, every 1 PVU), irrotational wind (vectors, >2 m s$^{-1}$; purple vectors, >8 m s$^{-1}$), negative PV advection by the irrotational wind (dashed red, every 2 PVU day$^{-1}$ starting at −2 PVU day$^{-1}$), and total wind speed (shaded according to colour bar, m s$^{-1}$). The star denotes the composite point of maximum interaction (strongest instantaneous negative PV advection by the irrotational wind). The TC symbol denotes the composite TC position. Reproduced from Archambault et al. (2015).

Further downstream, Rossby wave dispersion and the equatorward advection of anomalous cyclonic PV (induced by the anticyclonic wind field associated with the downstream ridge and the outflow anticyclone associated with the TC) result in the development of a trough downstream of the transitioning cyclone and downstream ridge (Riemer and Jones 2014; Grams and Blumer 2015; Grams and Archambault 2016). This downstream trough triggers downstream lower-tropospheric cyclogenesis, with the resulting cyclone itself associated with the poleward transport of warm and moist air (i.e. manifest as a warm conveyor belt). This contributes to ridge amplification further downstream (Fig. 4.3.3.2c; Grams and Archambault 2016), with impacts to hemispheric weather on the synoptic to sub-seasonal scales (~7-14 days; Archambault et al., 2015).

In a climatological sense, downstream development characteristics vary slightly between basins. For example, Rossby wave packets associated with downstream development are stronger (i.e. of higher amplitude) and occur more frequently than climatology downstream of transitioning TCs in the western North Pacific and southwest Indian oceans (e.g. Archambault et al. 2013, 2015; Torn and Hakim 2015; Quinting and Jones 2016), but not in the North Atlantic Ocean (Quinting and Jones 2016). This is hypothesized to result from a comparatively
short and weak climatological waveguide over the North Atlantic Ocean which may favour downstream anticyclonic Rossby wave breaking that can disrupt downstream development (Archambault et al. 2015). This is consistent with earlier case studies that were unable to systematically attribute RWP amplification to North Atlantic TCs (e.g. Agusti-Panareda et al., 2004; Pantillon et al., 2015). In the western North Pacific, it is also possible for transitioning TCs to interact with, and perturb, a zonally aligned midlatitude flow. Such a configuration is also associated with a higher-than-normal probability of downstream development as compared to climatology (Riboldi et al., 2018), although the flow perturbations are stronger and longer-lasting in the presence of a preexisting midlatitude trough (Fig. 4.3.3.3; Archambault et al., 2015; Torn and Hakim 2015; Quinting and Jones 2016).

Figure 4.3.3.2. Schematic of the three stages of ET. Red objects indicate positive PV associated with the transitioning TC and PRE. Light blue regions at upper levels indicate low-PV air in the outflow of the weather systems. The jet streaks are indicated in green, the upper-level waveguide (3 PVU) with a red contour, and orange shading is to the north. Dark blue tilted surfaces indicate low- and mid-level baroclinic zones. Trajectories of rapidly ascending air parcels are indicated by blue–red–blue lines, reflecting the diabatic PV modification. (a) Preconditioning stage of ET with contours at lower surfaces showing mean sea level pressure (black) and equivalent potential temperature (violet), as well as contours at the upper surface showing 3 PVU at 200 hPa at t+12 h. (b) The TC–extratropical flow interaction stage of ET showing the same fields as in (a), but at t+60 h and 3 PVU at 335 K. (c) The downstream flow amplification stage of ET showing the same fields as in (b), but at t+108 h.

From Grams and Archambault (2016).

b) High-Impact Weather

To date, most investigations of high-impact weather resulting from downstream development associated with ET have been case studies of individual events, with most focusing on transitioning western North Pacific and North Atlantic TCs. In the western North Pacific, a systematic relationship between ET events and downstream high-impact weather has not yet
been established; however, in the Atlantic, the magnitude of – and the area affected by – heavy precipitation in downstream regions is significantly enhanced 2-3 days after the interaction of North Atlantic TCs with the midlatitude flow (Fig. 4.3.3.4; Pohorsky 2018). However, there is some indication that downstream impact of ET in the North Atlantic may shift the location of high-impact weather events rather than causing them to occur when they otherwise would not have occurred (Pantillon et al., 2015).

Figure 4.3.3.3. Meridional wind anomalies averaged between 35° and 55°N for western North Pacific (WNP) ET cases (a) with and (b) without preceding upper-level trough as a function of longitude and time (shading, m s⁻¹), where stippled regions denote where the value is statistically significant at the 95% level. From Torn and Hakim (2015).

Figure 4.3.3.4. Time series of precipitation extremes in a box 60° to 83° east of the maximum interaction point between a TC and the midlatitude flow. (a) Horizontal line represents the time lag after TC-jet interaction onsets. The vertical axis represents the fraction (%) of the box covered by precipitation extremes at a given time after the interaction. (b) Vertical axis represents the summed exceedances of the climatological 99th percentile at each grid point in the box. The red line is the average of 147 recurving north Atlantic TCs. Light and dark gray shadings respectively represent the 1st-99th and the 10th-90th intervals of precipitation extremes obtained from bootstrapping. From Pohorsky (2018).
Selected case study analyses of the downstream impact following the ET of western North Pacific and North Atlantic TCs include:

- **Super Typhoon Nuri (2014)**
  The extratropical transition of Super Typhoon Nuri (2014) led to the formation of an omega block over western North America and several cold air outbreaks on its eastern flank (Bosart et al., 2015b).

- **Tropical Storm Meari (2011)**
  The interaction of Meari (2011) with the midlatitude flow resulted in the amplification of a Rossby wave packet that dispersed across North America. Its dispersion contributed to the development of a trough-ridge couplet over western and central North America and the formation of two severe mesoscale convective systems over the Upper Midwest of the United States (Cordeira et al., 2017).

- **Typhoon Choi-Wan (2009)**
  Using a TC removal technique, Keller and Grams (2014) demonstrated that the ET of Choi-Wan (2009) altered the severity and location of a heat wave, heavy precipitation, and a cold surge over North America.

- **Typhoon Lionrock (2016)**
  Late in its lifecycle, Lionrock (2016) interacted with an unusually strong early-season baroclinic trough of Asian origin and associated extratropical cyclone, underwent ET, triggered a strong PRE, and generated widespread flooding across parts of Japan, Korea, China, and Russia (Bosart et al. 2018).

- **Hurricane Katia (2011)**
  Using a TC removal technique, Grams and Blumer (2015) demonstrated that a European high-impact weather event was caused by the downstream impact of a transitioning North Atlantic TC. The interaction of Katia (2011) with the midlatitude flow caused strong upper-tropospheric ridge-building and the development of a PV streamer downstream. Deep convection and heavy rain developed in the warm and moist environment ahead of this PV streamer.

- **Hurricanes Leslie, Rafael, and Sandy (2012)**
  Each of Leslie, Rafael, and Sandy locally impeded the forward progression of an upstream trough, then reintensified as an extratropical cyclone as the trough wrapped up. Downstream propagation characteristics of each TC’s impact to the midlatitude flow vary between cases, with the common thread that all led to downstream high impact weather events that were sampled as part of SOP1 of the HyMeX field campaign (section 4.3.4a).

Further analyses of several of these cases are presented below.
Super Typhoon Nuri (2014)

Nuri is notable for achieving a post-ET minimum sea-level pressure estimated at 924 hPa in the Bering Sea, which at least tied the record for the deepest extratropical cyclone observed over the North Pacific Ocean. Bosart et al. (2015a) show that prior to ET, Nuri’s diabatically driven upper-tropospheric outflow helped to strengthen the north Pacific jet by increasing the meridional temperature gradient (Fig. 4.3.3.5a). Post-ET, diabatically driven outflow downstream of Nuri contributed to ridge building and omega block formation over northwestern Canada and eastern Alaska (Fig. 4.3.3.5b). This ridge building event and its subsequent evolution resulted in a deep upper-tropospheric trough developing over western and central North America, which led to three surges of cold, dry Arctic air into the United States over the subsequent week (Fig. 4.3.3.5c and d). In conjunction with these cold surges, 2,677 daily minimum temperature records were broken over the conterminous United States. Medium-range global numerical model guidance from NCEP failed to reliably forecast Nuri’s downstream impact until 144 h prior to Nuri’s peak extratropical intensity, and the 0-month NCEP Climate Prediction Center temperature forecast for the conterminous United States was nearly 180° out of phase from the verifying temperature pattern (not shown).
Typhoon Lionrock (2016)

Lionrock is notable for a series of binary and trinary interactions with other western North Pacific TCs that took place before the storm interacted with a strong early-season baroclinic trough and associated cyclone, underwent ET, triggered a strong PRE, and generated widespread flooding in northeastern Asia (Bosart et al., 2018). Diabatically driven ridge-building occurred with both Lionrock and its associated PRE (Fig. 4.3.3.6a). The orientation of the upper-tropospheric irrotational wind is consistent with frontogenetically forced ascent and diabatically driven ridge building due to negative PV advection (Fig. 4.3.3.6b). This pattern continues through Lionrock’s ET as the upstream trough acquires a significant negative tilt (Fig. 4.3.3.6c and d). The upstream trough with which Lionrock interacted during its ET was highly anomalous for late summer, exceeding -6 standard deviations for 500 hPa geopotential height at its core on 30 August (not shown).

4.3.4 Predictability and Predictions of Extratropical Transition

One of the ultimate goals of ET research is to improve our ability to predict the transition of TCs and their effects on the midlatitude flow, most notably those related to downstream high-
impact weather events. In this context, it is important to distinguish between predictability (the intrinsic uncertainty in the system) and predictions (our ability to forecast an event), noting that predictability establishes an upper limit on our deterministic predictive skill (Melhauser and Zhang 2012). Studies of intrinsic predictability rely heavily on the combination of analysis, modeling and observational data sources, while those related to predictive skill often focus more directly on guidance, forecasts from RSMCs, and the optimal use of observations in data assimilation systems. Recent investigations of all of these elements that contribute to the forecasting challenges associated with ET will be discussed in this section.

a) Intrinsic Predictability of ET

Numerous earlier studies have shown that the phasing between the upstream trough and the recurving TC has a dramatic impact on ET and the downstream impacts thereof [see Jones et al. (2003) for a review]. However, more recent work has highlighted the fact that other midlatitude features can also have an important impact on the predictability of downstream flow evolution. The climatological analysis of TCs interacting with nearly straight zonal jets by Riboldi et al. (2018) reveals that Rossby wave initiation is more likely to occur during ET in the presence of weak jets. This is because stronger jets prevent significant ridge building through the downstream advection of the PV anomalies produced during TC-jet interaction.

Furthermore, Torn and Hakim (2015) suggest that reduced predictability following ET might be the result of ET generating new waves rather than amplifying existing waves that can be sampled by upstream observations. This argument agrees with recent findings of enhanced predictability associated with long-lived Rossby wave packets (Grazzini and Vitart 2015). Torn (2017) also demonstrated that elevated forecast spread emanates downstream from a transitioning TC regardless of whether there is an upstream wave packet. Because the downstream response to ET is primarily related to Rossby wave packets propagating along the midlatitude waveguide (Wirth et al., 2018), these studies suggest that uncertainties associated with the initiation of wave packets during ET can lead to the growth of downstream forecast errors even in the absence of phasing uncertainties with the upstream trough.

Partly as a result of such studies documenting the importance of basin scale cyclone-waveguide interactions, the North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX) field campaign was designed to explore the impact of processes that disturb the jet stream, including ET, and their impact on downstream high-impact weather (Schäfler et al., 2018). The campaign's intensive observing period (IOP) took place from mid-September to mid-October 2016, over which time numerous extratropical and tropical cyclones were sampled. The overall conditions were quite favourable for investigations of diabatic heating, cyclone and jet stream interactions over the North Atlantic. Four research aircraft were used during NAWDEX, each equipped with state-of-the-science remote-sensing and in situ instruments, along with numerous ground-based measurements. In all, the aircraft carried out 49 NAWDEX flight missions.

Of the six tropical cyclones that were sampled during the NAWDEX IOP, three underwent ET: Ian, Karl and Nicole. Despite Karl’s minimal intensity as a TC, the observational dataset for this storm is particularly unique because coordination with NOAA's tropically focused Sensing Hazards with Operational Unmanned Technology field campaign (Dunion et al., 2018) meant that Karl and its large-scale environment were heavily sampled throughout the cyclone’s life cycle. Schäfler et al. (2018) highlight the key stages of the Tropical Storm Karl ET event: i) an upstream trigger, in this case TS Karl, ii) the dynamical interaction of ex-Karl with the jet
stream, iii) downstream evolution of the ex-Karl disturbance, and iv) subsequent high-impact weather over Europe. In the Karl case, the 5-day forecasts exhibited relatively low predictability (Fig. 4.3.4.1).

![Image](image_url)

**Figure 4.3.4.1.** Time series of the anomaly correlation of day-5 guidance from ECMWF for 500 hPa geopotential over an area from 35°N to 75°N and from 60°W to 0° (shown at the initial time of the forecast). The deterministic model is shown with the black line, the ensemble-mean with a red line, 50% of ensemble members with an orange line, and all ensemble member with yellow shading. The grey boxes represent weather regimes as described by Schafler et al. (2018). Individual ET events are noted at the top of the plot. Adapted from Schafler et al. (2018).

While NAWDEX took a broad view of basin-scale features and processes that limit predictability, the Hydrological cycle in Mediterranean eXperiment (HyMeX) field campaign focused on the eastern North Atlantic where the bulk of downstream high-impact weather associated with ET is expected to occur. The local dynamics and the predictability of such events at short range were investigated during the HyMeX first Special Observation Period (SOP1) in autumn 2012 (Drobinski et al., 2014; Ducrocq et al., 2014). Despite the clear dynamical linkage and consistent seasonality (Pinto et al. 2001), few studies have directly addressed the connections between ET, reduced predictability in the Mediterranean sector, and high-impact weather events.

The gap in our understanding of downstream North Atlantic ET impacts and associated predictability issues motivated Pantillon et al. (2015) to investigate the link between tropical cyclones and Mediterranean weather during HyMeX SOP1. The authors performed five-day simulations of hurricanes Leslie, Rafael and Sandy with the Meso NH model in a domain encompassing the North Atlantic and the Mediterranean. Control simulations were compared to simulations in which the hurricanes were filtered out from the initial conditions. Pantillon et al. (2015) conclude that there is large case-to-case variability in downstream high impact weather (section 4.3.3b), but suggest that the interaction of tropical cyclones with the midlatitude flow over the western North Atlantic may be considered a perturbation to, rather than a source of, downstream wave breaking. These findings are also indicative of the fact that more research is needed to identify systematic differences between ET cases that amplify the downstream wave pattern and induce extreme weather and those that do not.
Although the HyMeX and NAWDEX field campaigns provide valuable observational evidence of the complex processes and interactions that limit predictability during ET and its potential downstream impacts, the necessarily restricted coverage of IOPs means that much of the resulting research focuses on a limited number of case studies. In an effort to place such studies in a broader context, recent research has adopted ensemble techniques to establish forecast climatologies that facilitate the comparison of downstream forecast uncertainty during ET to typical forecast spread for that time of the year. On average, recurving TCs are associated with comparatively higher forecast standard deviation, with cases in the western North Pacific cases being the least predictable (Aiyyer 2015; Quinting and Jones 2016; Torn 2017). The region of enhanced standard deviation originates from where the TC enters the midlatitudes and spreads downstream at the Rossby wave group velocity. However, enhanced forecast uncertainty remains confined to the region of the transitioning TC in the absence of downstream development, highlighting the importance of Rossby wave packets to downstream forecast uncertainty (Fig. 4.3.4.2). With a reduction of the forecast skill horizon of approximately two days (Grams et al., 2015), predictability problems associated with ET appear to be larger than those related to baroclinic cyclones that occur in the same region during both winter and autumn seasons (Torn 2017).

![Figure 4.3.4.2. Recurvature-relative composites of the anomaly of 250-hPa geopotential height ensemble standard deviation (shading, gpm) averaged between 20°N and 80°N relative to June-November climatology for western north Pacific ET cases (a) with and (b) without downstream Rossby wave packets. Black thick line indicates the mean recurving track. From Quinting and Jones (2016).](image)

Although universally applicable statements about the intrinsic predictability of ET remain elusive, the combination of climatological, modelling, observational and ensemble strategies have yielded important improvements in our understanding of the key processes and features that occur before, during and after ET. Such insights help us to assess the predictability of the ET process, particularly with regard to downstream high impact weather. This intrinsic predictability appears to be more limited than that of any of the individual components because the complex interactions between the “key ingredients” of ET occur over a broad range of spatial and temporal scales.
b) Assessing Predictability Limits: ET Sensitivity

The predictability of ET and its associated downstream impacts is naturally limited by the sensitivity of the features involved in the ET process to small perturbations. These initial seeds of uncertainty may develop on relatively small scales, but grow rapidly in sensitive regions during ET to affect both the environment in which the transition is occurring and the structure of the remnant TC itself.

i) Environmental Sensitivity

Cases and scenarios with large forecast errors during ET have motivated a number of recent modeling investigations, many of which focused on the transition, landfall, and downstream impacts of Hurricane Sandy (2012). Studies underscored strong sensitivity in track and ET timing (Munsell and Zhang 2014), and in the downstream midlatitude ridge amplification influenced by diabatic processes (Torn et al., 2015). Several studies have also highlighted the sensitivity of Sandy’s forecast tracks to the model configuration itself (Bassill 2014; Magnusson et al., 2014). In cases of especially high forecast sensitivity, such as Sandy, multiple factors often influence the forecast. In some cases, large sensitivity is associated with a bifurcation (Scheck et al., 2011) that occurs when a small change in one interaction parameter (e.g. midlatitude trough or TC vortex structure) results in a significant change in the storm’s track during transition. Bifurcation points are associated with the regions of strong deformation that can arise when the local relative velocity is zero, often in the base of a trough or along the apex of a ridge [see Riemer and Jones (2014), their Fig. 11]. As a TC approaches, the bifurcation point influences the likelihood of recurvature and eventual ET, as well as reduced the predictability of its post-transition outcome (Grams et al., 2013b; Riemer and Jones 2014; Keller et al., 2019).

Another example of a transitioning TC whose track was highly sensitive to the presence of such a structure in the environmental flow was Hurricane Nadine (2012), a storm that was also notable for its large forecast uncertainty (Munsell et al. 2015). Operational ensemble forecasts showed a bifurcation in Nadine’s track, with a significant fraction of members predicting landfall over the Iberian Peninsula, and large spread in the synoptic conditions downstream. This limited predictability was not only a major issue for planning observations during HyMeX SOP1, but also for modeling Nadine’s evolution and of the synoptic conditions over the Mediterranean in numerical experiments (Pantillon et al. 2015). Pantillon et al. (2016) clustered the ECMWF ensemble forecast into two scenarios for interaction between Nadine and an Atlantic cut-off low, which controlled both the track of Nadine and the synoptic conditions downstream. The forecast bifurcation appears to have been related to the strength of the interaction between the transitioning TC and the cut-off low, with weaker interactions leading a westerly cyclone track and stronger interactions leading to a higher potential for landfall on the Iberian Peninsula (Fig. 4.3.4.3). Pantillon et al. (2016) found that the high forecast sensitivity to this vortex–vortex interaction resulted in the lowest predictability over the Mediterranean observed during HyMeX SOP1.
Figure 4.3.4.3. Scenarios of (a) weak and (b) strong interaction between Hurricane Nadine and a cut-off low. Tracks of Nadine (thick curves) and the cut-off low (thin curves) in ECMWF ensemble members from 20 through 25 September 2012. The ECMWF analysis (black curve), deterministic forecast (grey curve) and control forecast (green curve) are also marked in (a). From Pantillon et al. (2016).

In order to assess such sensitivity to the environment in which ET is occurring, new ensemble-based diagnostic frameworks have been used to quantify uncertainty associated with the near-ET state and upstream features. In the case of Typhoon Choi-Wan (2009), Keller et al. (2014), and Keller (2017) identify different forecast scenarios using clustering techniques. They show that the different scenarios are associated with different rates of baroclinic energy conversion as the system undergoes ET (particularly to the east of the surface cyclone), leading to varying intensities of downstream waveguide amplification. Most of their sensitivity targets relate to the confluence region between the TC and the midlatitude trough immediately upstream. Other features further upstream of ET were found to be less important to the downstream flow response. They conclude that this case appears to be very sensitive to how the TC-midlatitude interaction modulates energy conversion from the background flow.

The evolution of the downstream state can also be sensitive to the interaction between the TC and the midlatitude flow itself, including nearby upper-tropospheric cyclones (Pantillon et al., 2016). From a forecasting perspective, Grams et al. (2015) showed that initializing TCs in the incorrect position can degrade the skill of a 3-day forecast of the downstream 500-hPa anomaly correlation to that of an 8-day forecast when the TC is initialized in the correct position. This study also highlights the sensitivity of the downstream response to ascending warm conveyor belts ahead of the transitioning TC. The importance of such features in amplifying the downstream flow pattern and limiting the downstream predictability following ET were also emphasized by Grams and Archambault (2016). As a consequence, it appears that downstream forecast variability associated with ET events is case-specific. It is therefore important to expand these types of analyses to a larger set of cases and to consider the potential utility of simplified or idealized frameworks. Such studies will help us to understand why some ET events are more sensitive to in situ baroclinic and diabatic processes, while others are particularly sensitive to how the TC remnant interacts with the midlatitude flow.
ii) Storm-Scale Sensitivity

Although environmental conditions play an important role in establishing the limits of predictability during ET, the TC cannot be considered a passive player in the transition process because of both the remnant cyclonic potential vorticity and the large envelope of warm, moist air that the cyclone transports to higher latitudes. Sensitivity to these structures was exemplified during Hurricane Sandy’s transition, during which Torn et al. (2015) show that NCEP’s global forecast variability was characterized by large sensitivity to the interaction between diabatic outflow from convection associated with Sandy and the waveguide to the northwest. This result suggests that ET position forecasts are not solely attributable to upstream features: the TC and its associated convection can have a significant impact on the subsequent ET evolution.

Recent studies have also used adjoint and related singular vector sensitivity diagnostics to identify phenomena that influence storm evolution during ET. An adjoint model (the transpose of the tangent linear forecast model) allows for the efficient calculation of the sensitivity of a particular forecast aspect, or response function, to changes in the initial state under the tangent linear assumption. The related singular vector analysis permits the identification of the fastest growing perturbations to a given forecast. Magnusson et al. (2014) perform an evaluation of the ECMWF forecasts of Hurricane Sandy as it underwent ET, including a singular vector sensitivity analysis. They calculate the leading singular vector optimized for 48-h forecast total perturbation energy inside a box centered on Sandy as it is approaching the US east coast (Fig. 4.3.4.3) on 25 October 2012. The initial singular vector structure indicates that the forecast of Sandy is most sensitive to the structure of the subtropical ridge to the north and northeast of the storm. Part of the evolved singular vector structure stretches to the northwest of Sandy and is associated with the TC outflow as it starts to interact with midlatitude flow. The singular vector results are consistent with the ensemble analysis that they performed in the same study, which also highlights the importance of the strength of the subtropical ridge in determining if Sandy would make landfall along the eastern United States seaboard.

Doyle et al. (2014) further examined the sensitivity of Hurricane Sandy near landfall using the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) moist adjoint. At short lead times, the forecast is most sensitive to moisture in the immediate vicinity of the TC and to vorticity in the area between the storm and the ridge to the north (Fig. 4.3.4.4). The sensitivity also extends towards the trough to the west, with some sensitivity associated with the low to the northeast. At longer lead times, the adjoint calculation indicates that the forecast was sensitive to the ridge directly to the north of the storm, the immediate upstream trough, as well as a mid-Pacific trough well upstream of the storm (not shown). These complex sensitivity patterns illustrate how the Sandy forecasts were sensitive to several different local and remote features, and shed light on why the forecast uncertainty for Sandy was so large.
Figure 4.3.4.3. Leading singular vector [(a) initial and (b) evolved] calculated for 0000 UTC 25 Oct (shaded) and targeted for Sandy after 48 h. Geopotential height averaged for 700, 500, and 300 hPa (thin contour lines) from the analysis at the valid time for the singular vector. The observed track (thick, black line) and position at the valid time for the singular vector (black triangle). From Magnusson et al. (2014), their Fig. 8.

Figure 4.3.4.4. The initial adjoint sensitivity from the 48-h 45-km COAMPS forecast initialized at 0000 UTC 27 October 2012. Left panel shows the analysed 850-hPa heights (m), contours, and sensitivity to 850-hPa water vapour (m$^2$ s$^{-2}$ [g kg$^{-1}$]-1), shaded. Right panel shows analysed 500-hPa heights (m), contours, and sensitivity to 500-hPa vorticity (10$^{-5}$ m$^2$ s$^{-1}$), shaded. Adapted from Doyle et al. (2014).
Another COAMPS adjoint study, this one for Super Typhoon Lupit (2009), also finds highly complex sensitivity patterns during the ET. Reynolds et al. (2014) show that very short-range (12 h) forecast sensitivity to moisture extends from the area in the immediate vicinity of the storm along the developing frontal boundaries to the north and northeast of the storm (Fig. 4.3.4.5). They also found that the sensitivity patterns align with areas of strong frontogenesis and high PV. These adjoint results are complementary to ensemble-based tools and allow for quantitative identification of the processes and phenomena that influence storm evolution during ET. Their consistency with the results of sensitivity studies of storms observed during the T-PARC field campaign (section 4.3.2a) lends additional credibility to this analysis technique and demonstrates its potential utility for observation targeting.

![Figure 4.3.4.5](image.jpg)

Figure 4.3.4.5. The initial adjoint sensitivity from the 12-h 15-km COAMPS forecast initialized at 00Z 26 October 2009. Left panel shows the analysed 925-hPa potential temperature (K). Left panels show the COAMPS simulated 925-hPa radar reflectivity (gray shading), and sensitivity to 850-hPa water vapour (ci=0.05 m² s⁻² [g kg⁻¹]⁻¹), shaded. Adapted from Reynolds et al. (2014).

As a result of the observational relevancy of TC sensitive regions, NOAA undertook a concerted effort to use research aircraft to observe TCs undergoing ET without any direct influence from land as part of the Intensity Forecasting Experiment (Rogers et al., 2013). To date, five Atlantic TCs have been sampled [Hurricanes Earl (2010), Thomas (2010), Sandy (2012), and Arthur (2014) and Tropical Storm Karl (2016)] by multiple aircraft at multiple times during the transition period. The Karl observations are of particular interest because they dovetail with the NAWDEX basin-scale sampling described in section 4.3.4a. Additional NOAA aircraft missions that were conducted in the East Pacific sampled Hurricane Patricia (2015) during its encounter with a region of high baroclinicity over very warm water [with additional dropwindsonde observations from the Tropical Cyclone Intensity experiment (Doyle et al., 2017)]. Similar missions documented Hurricanes Dora (2011), Hilary (2011), and Simon (2014) as they encountered the cool sea surface in regions of high baroclinicity. Analyses of such datasets will help to evaluate the impacts of cool water and high baroclinicity on TCs, two elements to which the transition process appears to be particularly sensitive.
c) Practical Predictability of ET

The most direct measure of the current limits of practical predictability during ET is the quality of forecasts issued by operational centers before and during the event. It is this form of predictability, naturally limited by the intrinsic predictability described in section 4.3.4a and heavily influenced by the sensitivities discussed in section 4.3.4a, that has the largest direct effect on those who are affected by ET and its potential downstream impacts.

A linear discriminant analysis approach has been used to provide a climatological baseline TC classification to aid in the evaluation of operational and numerical model forecast skill (Aberson 2014). The predictors include position and intensity, as well as the 12-h trend of these two quantities and the current day of the year. Cyclone classification forecasts from NHC were found to be skillful at all lead times. However, ET forecasts could not be analysed due to the small sample size, and as a result ET forecast skill relative to the baseline has yet to be quantified for forecasts from operational centers.

Recent improvements in deterministic and ensemble numerical guidance (e.g. Aberson et al., 2015; Zhang and Weng 2015; Weng and Zhang 2016), as well as observational capabilities, have benefited operational centers. An operational center’s ET forecasts should be assessed within the context of expected numerical model forecast skill, including insight as to when skill is likely to be either anomalously high or low. An example of this is given by Sandy (2012), wherein members of the United States’ global ensemble system with inaccurate track forecasts simultaneously had inaccurate cyclone classification forecasts (Kowaleski and Evans 2016).

Further intercomparison studies have focused on cases in which large disparities in guidance quality exist between operational centers. Key storm metrics computed by Magnusson et al. (2014), again for Hurricane Sandy (2012), illustrate such behavior (Fig. 4.3.4.6). Overall, the forecasts from ECMWF (gray dashed) are more consistent across initialization times. All ensembles show a positive bias (too weak) in the central pressure; however, the resolution of the forecasts in the TIGGE archive is inversely correlated with the central pressure bias (Davis 2018). All centers also underestimate the strength (maximum wind speed) of the cyclone. The CMC has the fastest-moving cyclones with too early landfalls, while ECMWF and UKMO have in general the slowest-moving cyclones.

Using a larger sample of events, Leonardo and Colle (2017) verify 1-5 day multi-model ensemble forecasts of North Atlantic TCs verified against NHC’s best tracks for the 2008-2015 seasons. They document an overall slow along-track bias, most of which occurs during the ET phase of the storm life cycle (Fig. 4.3.4.7). All models show a 25%-40% reduction in the slow bias when the extratropical phase of the storms is excluded from the evaluation. Guidance from the ECMWF shows the most significant improvement, with the magnitude of the day-5 along-track slow error decreasing from 200 km to 120 km when the ET cases are ignored. Leonardo and Colle (2017) note that the small sample size of ET cases prevents them from determining whether the improvements that they also observed over the 8-year study period were due to improved ET track forecasts, or to changes in the frequency of ET events.
Figure 4.3.4.6. Statistics for TIGGE ensemble forecasts from different initial times (x-axis). The ticks on the x-axis represent 0000 UTC. ECMWF (gray, dashed), UKMO (black, dashed), NCEP (black, dotted), CMC (black, solid), and JMA (gray, solid). Figure from Magnusson et al. (2014).

Figure 4.3.4.7. Average 2008-2015 along track errors when (a) including and (b) excluding forecasts in which the observed TC was extratropical. Figure from Leonardo and Colle (2017).
4.3.5 Extratropical Transition and Climate

As long-period historical reanalyses become more available and the effects of climate change become increasingly felt by the general population, studies of ET in long-term contexts and under different climate-change scenarios have become more prevalent. These investigations help us to understand changes in the nature and frequency of ET over time, and to begin to assess current and future risks for vulnerable coastal populations.

a) Climatology of ET

One of the fundamental questions surrounding ET, and indeed TCs more generally, is whether there are any detectable trends in frequency-of-occurrence in the observational record. However, the relatively short length of the satellite era and the large interannual variability of ET frequency have made teasing out long-term trends in the historical record difficult. Mokhov et al. (2014) found a slightly positive trend in the fraction of TCs undergoing ET globally over the 1970-2012 period despite a slight decreasing trend in the North Atlantic. This result underscores the influence of large inter-basin differences on such analyses and suggests that more research efforts are required to identify secular trends in the ET record.

Considering all global basins, Bieli et al. (2018a,b) present an ET climatology from 1979 to 2017 using the Cyclone Phase Space [CPS; Hart (2003)], best-track and two reanalysis datasets (Fig. 4.3.5.1). They show that the basins with the highest fractions of ET are the North Atlantic and the western North Pacific (around 50%), and that the lowest relative frequency of occurrence is found in the eastern North Pacific and North Indian Ocean regions. The authors ascribe much of this inter-basin variability to the geography of the regions and to differences in mean steering flow. The western North Pacific and the North Atlantic are also the basins with the highest landfalling rates, followed by the Australian region. Bieli et al. (2018a,b) also note strong differences in seasonality between the basins. In the western North Pacific and the North Atlantic, storms are more likely to undergo ET late in the TC season. In contrast, the seasonal cycle in the Southern Hemisphere ET fraction is generally weak.

It is important to notice that the ET climatology is sensitive to the reanalysis used to calculate CPS, as well as the best-track dataset considered. ET fractions are higher when the CPS is calculated from the ERA-Interim reanalysis compared to the JRA-55 reanalysis (Fig. 5.1). Bieli et al. (2018b) suggest that JRA-55-derived CPS analyses better agree with best-track designations that do the corresponding ERA-Interim-derived analyses, with significant differences appearing in the eastern and central North Pacific regions. In these areas, the ERA-Interim reanalysis has a large number of false positives in which the CPS calculated using ERA-Interim fields suggests ET, but there is no ET label in the best-track dataset. Overall, ET classifications using CPS in both reanalysis datasets agree best with the best-track designations in the North Atlantic and western North Pacific basins, perhaps in part because the CPS is used operationally by the RSMCs in these regions. In contrast to Mokhov et al. (2014), Bieli et al. (2018a) did not find any statistically significant trends in ET fraction except in the South Indian Ocean.
Such focused studies of the ET climatology remain rare, and much of our understanding of recent trends in TC-midlatitude interactions is gained indirectly from studies of the tropical phase of the TC life cycle. For example, Kossin et al. (2014) found an increase in the latitude of maximum intensity of TCs over the last 30 years, associated with a poleward shift in genesis locations (Daloz and Camargo 2018; Studholme and Gulev 2018; Sharmila and Walsh 2018), which is projected to continue (Kossin et al. 2016). Shaw et al. (2016) also highlight the uncertainty of predictions of the complex spatial patterns of baroclinicity and displacements in extratropical storm tracks. Predicted changes in these features appear to vary by both season and hemisphere, implying that changes in ET may be regional in nature.

b) Extratropical Transition in Climate Models

Despite the uncertainty in the recent historical record surrounding ET, projections of the frequency-of-occurrence and spatiotemporal characteristics of TC recurvature and ET are required by decision makers, insurers, and other groups that seek to understand and mitigate risks associated with ET. With issues in the length of the historical record and reporting biases such as those outlined in Landsea et al. (2010), high-resolution climate models have been used with increasing frequency to study TC-climate interactions (Walsh et al., 2015; Wehner et al., 2015; Camargo and Wing 2016; Yoshida et al., 2017). The current consensus projection is that globally, TCs will become less frequent but intense storms will become stronger (the tail of the intensity distribution is extended) with heavier precipitation (Knutson et al. 2010; Walsh et al. 2016). Despite the increasing volume of published literature regarding potential changes of TCs in an evolving climate, ET has received relatively little attention.

Recent efforts have been undertaken to apply traditional ET metrics [including the Hart (2003) CPS] to climate model output. Generally, TCs are handled in a Lagrangian, storm-following framework. However, with climate integrations, no observational track record exists, necessitating the need for objective, automated detection and tracking algorithms. TC climatology and projections are sensitive to the thresholds used in these tracking algorithms, especially for low-resolution models and weak TCs (Horn et al., 2014; Zarzycki and Ullrich 2017).
Notwithstanding this limitation, Liu et al. (2017) investigated North Atlantic ET events in high-resolution simulations from the Geophysical Fluid Dynamics Laboratory’s Forecast-Oriented Low Ocean Resolution model that followed Representative Concentration Pathway 4.5 (RCP4.5) scenario protocols. They found that despite a decrease in TC frequency in the North Atlantic basin under RCP4.5, the number of storms undergoing ET increased slightly (Fig. 4.3.5.2). This results in a projected increase in the ET ratio that Liu et al. (2017) propose to be a response to the shifts in TC genesis described in section 4.3.5a. With a more favourable storm formation environment over the eastern North Atlantic, the preferred recurvature track lies in the western North Atlantic at the expense of storms forming and tracking into the Caribbean Sea and Gulf of Mexico. In a follow-up study using the same simulations, Liu et al. (2018) analysed rainfall along the eastern United States seaboard associated with both ET and non-ET TC events. They found an increase in the rainfall associated with ET events in the northeastern United States due an increase in transitioning storm frequency, but prior to ET onset itself. It is important to note that these results are based on single-model studies and focused only on the North Atlantic basin. Multi-model studies targeting the global climatology of ET are needed to produce a more complete picture of ET in a changing climate.

Fig. 4.3.5.2. The climatological TC density of storms undergoing ET events in (a) present-day and (b) RCP4.5 global warming simulations using GFDL FLOR. TC events not undergoing ET are shown in (d) and (e). The future change of annual TC density of ET and non-ET events are shown in (c) and (f). Reproduced from Liu et al. (2017).

A drawback of using the Hart (2003) CPS in a climate modelling context is that it requires output to be saved on multiple vertical levels with high temporal frequency. For long-term, high-resolution simulations completed over the past decade, many groups have opted for reduced output data streams at sub-daily timescales. Baatsen et al. (2015) develop a
simplified ET algorithm that detects collocated equivalent potential temperature anomalies and potential vorticity centers associated with cyclones in the North Atlantic. They find that a warmer Atlantic Ocean decreases the duration of ET and results in an increased frequency of post-ET reintensification that has clear implications for Western Europe.

Zarzycki et al. (2017) are able to apply the full CPS ET detection technique to high resolution simulations from the NCAR Community Atmospheric Model. They find systematic differences between the model results and diagnostics from the Climate Forecast System and ERA-Interim reanalyses for North Atlantic storms over the 1980-2002 period. The largest number of ET events occurs in September in both the model simulations and reanalyses; however, the month with the 2nd largest number of ET occurrences in the simulations is October, as opposed to July in the reanalyses and IBTrACS (Knapp et al., 2010). They also find that the ET process extends for a longer time period in the model simulations than in the reanalyses. While the simulations show ET onset at about the same latitude as the reanalyses, ET completion occurs further north and east in the model than in the reanalyses (Fig. 4.3.5.3).

Figure 4.3.5.3. Objectively tracked storm trajectories from 1980 to 2002 for (a) a 55 km version of the NCAR Community Atmospheric Model, (b) a 28 km version of the model, (c) the Climate Forecast Systems Reanalysis, and (d) the ERA-Interim reanalysis. In the panels (a) through (d), gray lines indicate the full trajectory from TC genesis to extratropical cyclone decay, red circles indicate the beginning of ET, and blue squares indicate the completion of ET. IBTrACS trajectories are shown in (e) with instantaneous ET being denoted by black triangles. Reproduced from Zarzycki et al. (2017).
They further find that the simulations have a higher fraction of ET events following the “asymmetric then cold-core” pathway compared to the “cold-core then asymmetric” pathway than is found in the reanalyses. The “long” bias in ET duration is primarily tied to the former pathway bias. This implies that the modelled TCs take longer than analysed to become cold-core after becoming asymmetric, which the authors hypothesize may be due to differences in the mean flow or parameterized physical processes. In either case, biases in event duration suggest that there may be systematic structural errors present during ET in climate models, a finding that needs to be investigated in other modelling systems and basins before any general conclusions can be drawn.

c) Extratropical Transition Sensitivity to Climate Change

Another framework that has received attention recently for studying climate impacts on weather-scale phenomena is the application of background anthropogenic “fingerprints” to model simulations in a case-study context. Sometimes referred to as “detection and attribution” or “pseudo-global warming” configurations (Schär et al., 1996), these experiments seek to understand storm-level sensitivity to climate perturbations within a constrained synoptic setup.

Although pseudo-global warming work has primarily been focused on TCs [for example Knutson et al. (2008) and Wehner et al. (2018)], a few recent case studies in the North Atlantic have relevance to the ET community. Lackmann (2015) noted that, when using pre-1900 large-scale climate deltas, Hurricane Sandy became weaker and made landfall further south along the Eastern Seaboard (while undergoing ET) than observed. Conversely, when post-2100 climate increments were applied, Lackmann (2015) found that the storm was stronger and made landfall at a higher latitude. More recent work applying the pseudo-global warming framework to an idealized simulation of Hurricane Irene shows that super-Clausius–Clapeyron scaling of precipitation rates during ET may occur (due to increases in dynamical moisture convergence and surface fluxes), and that the duration of the transitioning phase may increase (Jung and Lackmann 2018). This extension of the transition period would permit tropical impacts to persist further poleward in a warming climate.

In one of the few ongoing pseudo-global warming projects that directly addresses the ET process, Michaelis and Lackmann (2018) have applied this framework to study ET changes using NCAR’s Model for Prediction Across Scales. It is clear that demand for information about the climate sensitivity of ET from decision makers and the general public will only increase over time, and that a concerted effort on the part of the ET research community is required to be able to respond with robust and general statements about this important subject.

4.3.6 Summary and Recommendations

Since the last IWTC four years ago, notable advances have been made in our understanding of ET, particularly as it relates to the collection of in situ observations of structural change, and indirect and downstream impacts from ET events. However, there remain many fruitful directions for future research, as posed in Evans et al. (2017) and Keller et al. (2019). These and other recommendations are synthesized here.

A universally applicable definition for extratropical transition does not exist, a fact that harms the community’s ability to make robust, general statements about both specific cases and the ET climatology. Although the cyclone phase space of Hart (2003) has become the de facto
classification standard, it does not resolve the transitioning cyclone’s inner core, is reliant on model-derived analyses and forecasts, suffers from ambiguity with warm-seclusion events and requires information that may be difficult to obtain in a climate modelling context. A discussion is recommended as to whether a universally applicable alternative definition is necessary and achievable. Such a definition would prove particularly useful in developing an internally consistent global ET climatology and for comparisons between studies based on reanalysis data and climate model output.

Much of the research documented here and in Evans et al. (2017) and Keller et al. (2019) is primarily fundamental in nature. There have been few advances in operational/applied research as it relates to ET in recent years. Representative examples include the “no skill” model for cyclone phase classification of Aberson (2014) and a regression-based adjustment to the Advanced Dvorak Technique remote intensity estimation method based in part on Manion et al. (2015). Recent high-impact ET events such as North Atlantic TC Sandy (2012) highlight forecast communication issues during ET events, as discussed in the IWTC-8 report, and suggest that further work is needed to improve our ability to effectively communicate evolving cyclone threats during ET to the public. Further, recent advances in geostationary and polar-orbiting satellite technology enable us to observe transitioning cyclones better than ever before, and suggest that further research on how to best leverage these technologies in the advisory and forecast (both operational and numerical) process is warranted. The optimal use of such observations also involves data assimilation systems, an important component of the forecasting system that has received relatively little ET-focused attention in recent years.

Although recent years have seen the collection of the first in situ observations of structural change during ET, the sample size of cyclones for which such observations exist is very small, and more observations are necessary to document and understand case-to-case variability. This also applies to the direct impacts (wind, waves, and rainfall) that accompany ET, downstream development, and other indirect impacts of ET events including downstream high impact weather events. Detailed analyses of data from the recent NAWDEX, HyMeX and NOAA sampling campaigns may prove fruitful in these regards.

Data from these field campaigns are already being used in process studies that will help to quantify the intrinsic predictability of ET by identifying sources of sensitivity and documenting the complex interactions between the features involved in the transition. The combination of such investigations with ensemble- and adjoint-based methods for estimating predictability will help to estimate an upper bound for potential forecast improvements. Approaching this problem simultaneously from multiple directions is particularly useful because the detailed data from field campaigns are necessarily limited to a small number of cases, while the modelling and analysis frameworks can be extended to larger sample sizes. The natural extension of these studies into investigations of practical predictability mandates the use of such larger datasets because of the relatively small number of ET events annually and large case-to-case variability. Accordingly, the increased use of ensemble reforecast datasets for studies of forecast skill may help to establish a baseline for the practical predictability of ET in current numerical guidance.

Research conducted over a decade ago (Hart et al., 2006) documented the conditions under which transitioning TCs would decay or intensify post-ET; however, the sample sizes for each set of cases were very small, and post-ET intensity change remains a forecast challenge. For example, earlier studies (e.g. Hart et al. 2006; McTaggart-Cowan et al., 2007; Pantillon et al., 2013) suggest that intensification is generally associated with a negatively upstream tilted
middle-tropospheric trough and associated strong middle tropospheric cyclone vorticity advection over the TC. Though this is generally thought of as a first-order qualitative influence on extratropical cyclone intensity, crucial details of this process remain to be quantified and warrant further investigation.

Significant advances in understanding of the downstream impacts of recurving TCs have been made in recent years, particularly for the western north Pacific and Atlantic basins. However, most studies have emphasized individual case studies, with comparatively few studies (e.g. Grams and Archambault 2016; Archambault et al., 2013, 2015) focusing on climatological or composite analyses. The systematic investigation of linkages between ET events in all basins and downstream high-impact weather constitutes an intriguing research opportunity, whether for individual basins or in comparing differences between basins (e.g. such as may arise due to different climatological states of the midlatitude waveguide between the western north Pacific and Atlantic). Further, the idea that a transitioning TC may indirectly precondition the midlatitude waveguide (e.g. through a PRE) and thus impact their subsequent interaction and downstream response is relatively recent, and further investigation is recommended to quantify the extent to which preconditioning occurs and its attendant impacts to the downstream response and hemispheric-scale predictability. Finally, most downstream development studies have focused on the synoptic scales. Preliminary research suggests that some ET events may have impacts extending to the sub-seasonal to seasonal scales, and further study is warranted to document these impacts, better understand the underlying physics and dynamics, and quantify the predictability changes associated with such events.

At even longer time scales, recent years have seen the publication of the first studies with the goal of document or predicting the influence of climate change on ET climatologies and impacts, particularly in downstream regions. Given the apparent presence of persistent differences between reanalysis datasets and systematic model errors during ET, more studies in this vein are required to allow the community to make clear and compelling statements about the presence or absence of secular trends in ET in both the historical record and in climate projections. Such an effort is also required in the realm of attribution studies, not the least to assess whether current “fingerprint” technique is reliable for such studies given the complex dynamical interactions involved in the ET process. One thing that is certain about this emerging component of the ET field is that the results of these studies will be of significant interest to decision makers and the general public both in regions that currently experience ET and in those that are predicted to begin to feel the effects of transitioning storms in the future.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Expansion</th>
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<tbody>
<tr>
<td>CMC</td>
<td>Canadian Meteorological Centre</td>
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<tr>
<td>COAMPS</td>
<td>Coupled Ocean/Atmosphere Mesoscale Prediction System</td>
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<tr>
<td>CPS</td>
<td>Cyclone phase space</td>
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<tr>
<td>ECMWF</td>
<td>European Centre for Medium-Range Weather Forecasts</td>
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<td>ERA-Interim</td>
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<td>HyMeX</td>
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<td>IBTrACS</td>
<td>International Best Track Archive for Climate Stewardship</td>
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**Acronym** | **Expansion**
--- | ---
IOP | Intensive Observing Period
JMA | Japanese Meteorological Agency
NAWDEX | North Atlantic Waveguide and Downstream impact EXperiment
NCAR | National Center for Atmospheric Research
NCEP | National Centers for Environmental Prediction
NHC | National Hurricane Center
NOAA | National Oceanographic and Atmospheric Administration
PRE | Predecessor rain event
PV | Potential vorticity
PVU | Potential vorticity unit
RSMC | Regional Specialized Meteorological Centre
RWP | Rossby wave packet
SOP | Special Observing Period
TC | Tropcial cyclone
THORPEX | THe Observing system Research and Predictability EXperiment
TIGGE | THORPEX Interactive Grand Global Ensemble
T-PARC | THORPEX Pacific-Asian Regional Campaign
UKMO | United Kingdom Met Office

**References**


Bosart, L. F., D. Keyser and A. C. Winters, 2015a: An investigation of the skill of week-two extreme temperature and precipitation forecasts at the NCEP-WPC. Presentation at the NGGPS Annual Meeting and External FFO PI Meeting, College Park, MD, USA.


Abstract

In the last four years there has been significant changes in the tropical cyclone community’s ability to analyse and diagnose tropical cyclones, which are impacting research understanding and forecast operations. To highlight some of the recent progress, three sub topics are briefly discussed in this report. These subtopics include new and existing methods to estimate TC surface wind structure, next generation geostationary satellites for TC monitoring, and new developments and science using aircraft-based reconnaissance.

5.0 Introduction

This special topic highlights a few developments in the areas of tropical cyclone analysis and remote sensing that have occurred in the last four years.

New capabilities are being tested and demonstrated to increase our ability to estimate surface wind speeds/vectors. Some of these data also have become available to operational forecasters. New techniques include passive L-band (0.5 to 1.5 GHz) based techniques, C-Band (4 to 8 GHz) Synthetic Aperture Radar (SAR), Geographical Positioning System (GPS) reflectometry, and those developed using infrared (IR) imagery. These new techniques nicely complement operational scatterometry and microwave sounder-based methods that continue to improve. Some progress has also been made combining the various estimates to provide improved initial assessments of TC surface wind fields (e.g. TC Vitals). Members have also worked together to make some of these data available with lower latency. The European Space Agency (ESA) and National Aeronautics and Space Administration (NASA), and several research groups have not only developed wind estimate algorithms, but have begun sharing wind speed estimates with operational centres.

In the last four years, two “next generation” geostationary satellite systems have become available (Himawari-8/9 and GOES-16/17), and several similar systems are planned in the next four years. These new satellites provide higher frequency (spectral, spatial, and temporal) observations and present both new opportunities and challenges to forecasters.
There are also new capabilities that come with these data, but there are also capabilities that remain unaddressed.

At every IWTC there has been a recommendation of some sort to develop new aircraft reconnaissance-based observational capabilities. Such observations have begun to occur in the western North Pacific region with both low and upper-level aircraft. Observations are being collected and used for operational decisions and in numerical weather prediction models. It is also important to state that three IWTC-8 recommendations are either directly or indirectly addressed in this topic.

5.1 New and Existing Methods to Estimate TC Surface Wind Structure

This subtopic discusses improvements in the ability to estimate surface winds in the hostile environment of TCs. Because most TCs occur over the ocean and are rarely well observed by conventional observations, the methods discussed are based on satellite data. This subtopic covers both methods based on newly available data and those that are based older data and methods where capabilities have improved.

5.1.1 Methods based on newly available data

In the last four years, several methods based on new (to the TC community) data and new methods have become available. These include (1) the L-band passive microwave data from Soil Moisture Active Passive (SMAP) and Soil Moisture Ocean Salinity (SMOS) missions, which were initially designed for soil moisture research, (2) the SAR data, which in the past was difficult to collect, and (3) GPS reflectometry. The time latency of SMOS, SMAP and SAR data are also small enough that wind speeds and vectors should be available to operational centres for evaluation in the next several years.

Passive L-Band data is only minimally affected by rain or frozen precipitation (Wentz, 2005; Reul et al., 2012). L-Band microwave emission from the wind roughened ocean surface is caused by sea-foam (whitecaps) keeps increasing approximately linearly with wind speed (Nordberg et al., 1971; Monahan and O’Muircheartaigh, 1980; Reul and Chapron, 2003; Anguelova and Webster, 2006). This same signal is the basis for visible estimation of surface wind speeds (Neumann, 1952). This signal also remains sensitive to increasing wind even in wind speeds up to 70 m s⁻¹, and the methods used to estimate high wind speeds using SMOS and SMAP data are similar (Reul et al., 2016; Fore et al., 2016; Meissner et al., 2017 and references therein). For wind speeds below 15 m s⁻¹, the performance of L-band radiometers to measure scalar wind speeds is not as good as that of higher frequency radiometers or scatterometers due to larger radiometer noise and lower sensitivity to weaker winds. However, at high wind speeds, particularly above 25 m s⁻¹, L-band radiometers have a distinct advantage over most of these other instruments because they are nearly insensitive to heavy precipitation, show no sign of saturation or sensitivity loss, even in extreme winds. The two downsides to these estimates is their roughly 40 km horizontal resolution and the width of their data swaths, which are relatively narrow. Nonetheless, these sensors are able to provide some of the structural aspects of the highest winds in TCs without aircraft reconnaissance; nicely complementing other techniques that often struggle to estimate the highest wind speeds.

The C-Band SAR systems are the only active microwave sensors able to observe ocean surface night and day and through clouds at high resolution (50 m) with a wide, for this horizontal
resolution, coverage (400 km swath). This unique combination can be used to characterize the
inner core storm structures, such as, the eye-wall and radius of maximum wind speed, and the
rain band locations. Its high resolution also allows measurements in coastal areas without any
land contamination. SAR wind measurement principle is thus very similar to scatterometers -
it relies on the sensitivity of the backscattered intensity from the ocean sea surface to the
ocean surface wind speed and direction. Consequently, most SAR sensors suffered from a
decrease in sensitivity for winds higher than 35 ms\(^{-1}\). More recent SAR sensors (Radarsat-2,
Sentenal-1), however, have the capability to measure the signal both in co-polarization and
cross-polarization (antenna emits in V polarization and receives in H; or vice versa). This
improvement provides higher sensitivity to the ocean surface wind speed for extreme winds
enables to improve the wind speed accuracy in TCs (Zhang et al., 2012; Horstmann et al.,
2015; Hwang et al., 2015). Currently, the impact of rain on measurements of extreme wind is
still uncertain and a research topic, but this does not negate the main advantage of these new
SAR missions - to infer local information about the TC structure. Finally, thanks to the space
component of Copernicus (the European Union's Earth Observation Programme), two SARs
(Sentinel-1A and Sentinel-1B) are operational and Sentinel-1C and -1D are planned; ensuring
continuity of this data until the end of 2030. As with SMAP and SMOS, the SAR data latencies
are being reduced and there are hopes of automating wind speed estimates for TC
applications.

Examples of SMAP and Sentinel-1 SAR are shown in Figure 1, where ocean surface wind speed
retrievals are compared in Lionrock (2016/08/27). The SAR retrievals follow the algorithm
from Mouche et al. (2017) that combines both co- and cross- polarizations to measure ocean
surface wind vector at 3-km resolution over TCs and the SMAP algorithm is documented in
Meissner et al. (2017).

![Figure 1](image.png)

**Figure 1.** Wind speed (m s\(^{-1}\)) as obtained (a) with SAR using the two polarization
channels at 3-km resolution, (b) at 40-km resolution with the SMAP radiometer wind
speed from the RSS algorithm (Meissner et al., 2017). From Mouche et al. (2017).
Global Navigation Satellite System-Reflectometry (GNSS-R) is a remote sensing technique that uses navigation signals—specifically, those that reflect from a surface—opportunistically for science applications (Zavorotny et al., 2014). The Cyclone Global Navigation Satellite System (CYGNSS) is the first science-driven GNSS-R satellite mission. It employs a constellation of eight microsatellites, each with a 4-channel GNSS-R radar receiver capable of measuring GPS Level 1 signals scattered from the surface (Ruf et al., 2016a,b, 2018). CYGNSS provides frequent observations of near-surface ocean wind speed in all precipitating conditions without signal saturation, even in very high wind speeds. The CYGNSS observations of wind speed, appear as single lines that track across the ocean surface corresponding to the GPS reflections between two orbiting satellites (i.e. one CYGNSS and one GPS) during a relatively short period of time.

Using these data, Morris and Ruf (2017a,b) developed methods that objectively estimate TC intensity, wind radii, radius of maximum wind speed, and integrated kinetic energy from simulated CYGNSS Level-2 wind speed estimates. Morris and Ruf’s parametric model algorithm, based on Emanuel and Rotunno (2011), smartly interpolates across tracks of CYGNSS observations through a storm, leading to objective estimates of TC metrics. Figure 2 shows a preliminary example of a CYGNSS storm overpass, with the resulting parametric model retrieval. The methods developed in Morris and Ruf (2017b) are currently being applied to on-orbit data. CYGNSS datasets are available about one week following the observations. We expect more GPS-R satellite capabilities will be developed in the next four years, possibly impacting operational interests.

**Figure 2. A CYGNSS overpass of Hurricane Florence on 11 September 2018.** Left: In color, CYGNSS YSLF (Young Seas Limited Fetch) wind speed (knots). A dashed-cross line denotes the best track center location, with the red dots denoting the interpolated center position at the CYGNSS coverage time for this plot. Middle: CYGNSS YSLF wind speed, again in knots, but projected in storm centric coordinates, with the closest-in-time best track wind radii estimates visualized for comparison. Right: An example of a CYGNSS parametric model retrieval in the SE quadrant.

### 5.1.2 Methods based on previously existing data

In this section we review current methods available to estimate surface wind structure. These include, scatterometry, microwave sounder, and IR applications. We ask readers to examine the sub-topic report for a more comprehensive discussion of these methods.
Scatterometry has become a standard for estimating gales. Currently there are three operational scatterometers, SCATSat (India), ASCAT-A (EUMETSAT), and ASCAT-B. The former is a Ku-band (13.515 GHz) and ASCATs are C-band (5.255 GHz). These data are available in real-time from Royal Netherlands Meteorological Institute (KNMI) and others. Microwave sounders have been updated in the last four years and legacy algorithms, now the Hurricane Intensity and Structure Algorithm (HISA) based on microwave sounder derived temperature and moisture profiles has been created to estimate TC intensity (max winds and minimum sea level pressure) as well as the radial extent of 34-, 50- and 64-knot winds or “wind radii” (Chirokova et al., 2017; Demuth et al., 2004, 2006; Bessho et al., 2006). Microwave Integrate Retrieval System (MIRS) – based 3-D profiles of temperature, moisture and cloud liquid water called the Microwave Integrated Retrieval System (MIRS) (Boukabara et al., 2013).

In the last four years, a couple of methods to estimate gales via information provided by IR imagery have been developed. These include the method documented in Dolling et al. (2016), that makes use of the deviation angle variance (DAV) technique (DAV-T; Piñeros et al., 2008) combined with sea surface temperature, TC age, and current intensity, to estimate wind radii. Similarly, Knaff et al. (2016) uses IR based estimates of TC size (Knaff et al., 2014), TC motion and current intensity to estimate wind radii. This latter is method is used at Joint Typhoon Warning Center (JTWC), where operational Dvorak intensity/center fixes provide inputs, and in the latest version of the Advanced Dvorak Technique (Velden and Olander, 2018).

Finally, to help forecasters put all this TC structure information together, JWTC uses a recently developed objective wind radii best tracking (OBTK) procedures. OBTK combines several estimates of current surface wind structure including forecaster-estimated, satellite-based-automated-objective estimates, and six-hour model-forecasts. OBTK estimates of gales have mean absolute errors of roughly 15% when compared to ASCAT wind radii (Sampson et al. 2017, 2018). OBTK calculations are performed on the Automated Tropical Cyclone Forecasting (ATCF; Sampson and Schrader, 2000). ATCF is also used at NHC and The Central Pacific Hurricane Center. More information can be found the sub-topic 7.2 report (Meissner et al., 2018).

5.2 New generation geostationary satellites for TC monitoring

In the last four years, several next generation satellites were launched by member states and have become operational. These include the Japanese Himawari-8, and Himawari-9 (spare), the United States of America’s GOES-16 (GOES-EAST) and GOES-17 (GOES-WEST replacement). There are also several next generation geostationary satellites that will become operational in the next four years including China’s FY-2, Korea’s GeoKOMPSAT-2A, and EUMETSAT’s MTG, which have similarly improved imager features. These functions and specifications are notably improved from those of the imagers on the previous satellites. Some of the satellites also have or will have optical lightning mappers and hyperspectral infrared sounders. These four years have also allowed researchers and forecasters to use and exploit these new capabilities. Below we briefly discuss how these data have been used to aid decision making, advance applications, and improve TC analysis and forecast guidance. More details can be found in the subtopic 7.2 report (Bessho et al., 2018).
5.2.1 Improved decision making

With the new capabilities of these next generation geostationary satellites, namely improved temporal sampling, spectral resolution (i.e. number of channels), spatial resolution, and navigation, these satellites lend themselves to improved decision making.

Center fixing is improved primarily by the higher temporal and spatial resolutions, but also aided by the different visible and near-IR channels. Center determination is further aided by special rapid scan operations and improved navigation. Reducing errors in location lead to improved assessment of geneses/formation potential, intensity and structure, and Numerical Weather Prediction (NWP) initialization. Continuous TC genesis assessment is also aided as important features like subtle changes in outflow boundaries, are more easily tracked. Therefore, while the methods have not changed dramatically, the available information has improved in quantity and quality, in some cases dramatically.

Routine subjective Dvorak analyses are either being replaced or supplemented by objective techniques (Olander and Velden, 2018; Kishimoto et al., 2013). The increased resolutions have, in some cases, increased the intensity estimates, as the eye is viewed as being warmer. JMA is now using spatial average of eye temperature instead of the warmest eye pixel to adjust for the higher eye temperatures. However, the increased temporal resolution is greatly beneficial, generally resulting in better scene identification, improved center location, and more frequent observations, especially in the Southern Hemisphere. The more frequent observations also lend themselves to temporal averaging, which acts to reduce noise and increase accuracy.

Multiple visible, near-IR, and water vapour channels have also improved analyses. The co-viewing of visible and near-IR channels helps discriminate the phase and thickness of cloud features, allowing improved interpretation and, in particular, better discrimination of low-level clouds, as shown in Fig. 3. Similarly, the multiple water vapour channels provide a poor man’s water vapour sounder, allowing for the local tracking of dryer air masses, when animated, and vital information about how water vapour is distributed/stratified vertically.

![Figure 3. Comparison of VIS (left) and NIR (right) imagery of Typhoon Yutu (2018) as viewed by Himawari-8. Notice how the eyewall region appears much darker in the NIR (A) and that the low-level (non-frozen) clouds appear much brighter in the NIR image at the low to high cloud transition point (B).](image-url)
5.2.2 Advanced Applications

The newer generation of geostationary satellites, Meteosat Second Generation, GOES-16/17, and Himawari 8/9 has led to wider use of Red Green Blue (RGB) image combinations to display satellite imagery. RGB combinations have been created to aid the tracking of temperature and water vapour in the atmosphere, cloud top microphysics and water phase, provide cloud top pressures/heights and better detect surface features. Advanced workstations can overlay model output/analyses and conventional data on top of this imagery to further increase information content. These RGB combinations are in use at most RSMCs, though there does not seem to be a consensus set of products or usage. While strictly not an RGB, the Saharan Air Layer product, with GOES-16 and 12-µm imagery, can now be produced again.

Navigation, spatiotemporal, and spectral resolution have all increased with the next generation geostationary satellites. Each of these plays a role in improving Atmospheric Motion Vectors (AMVs). The availability of multiple water vapour channels helps with tracking of mid-level cloud motions, the higher precision near infrared and infrared channels are being used to track low-level features at night and provide better height assignments. The high-resolution visible imagery is also being used to track fine-scale features during daylight hours. These higher quality AMVs are being used in research and operations. Operationally, JMA is using near-surface AMVs to provide surface wind estimates and help with tracking and estimates of gales (Fig. 4), while NHC is just starting to utilize these new capabilities. Research has also been investigating the relationships between cyclonic outflowing winds and TC intensity, showing that the latter is highly correlated to the maximum tangential wind of upper tropospheric AMVs (Oyama et al., 2018). The higher quality AMVs are also making their way into models via data assimilation (section 7.2.3). New methods, like optical flow algorithms are also being tested for AMV estimation.

Figure 4. The surface AMVs (coloured arrows) retrieved from Himawari-8 imagery of Full-Disk (left) and target area (right) at 00:00 UTC 1 August 2017 for Typhoon Noru. Background is a Band 3 (0.64 µm) Visible image. The colour of arrows indicates the wind speed (kt).
GOES-16 and GOES-17 also have incorporated a new instrument: The Geostationary Lightning Mapper (GLM). The GLM allows forecasters to continuously monitor total lightning (cloud-to-ground + intracloud) in TCs beyond the range of current ground-based lightning detection networks with a high detection efficiency (Goodman et al., 2013). Prior research using ground-based networks (mostly cloud-to-ground) showed that lightning can help improve intensity forecasts (DeMaria et al., 2012). Stevenson et al. (2018) also showed intense lightning activity is often associated with deep active convection, which favours TC intensification when located within the radius of maximum wind. The GLMs are relatively new and NHC forecasters have only recently gained access to GLM data from GOES-16 on their operational workstations. Given the prior work with ground-based lightning, the GLM is expected to help TC forecasters, and be used by the research community.

5.2.3 Data Assimilation Efforts

With the tremendous investment in geostationary satellites, much effort has been spent trying to assimilate AMVs and radiances in hurricane models. Results from such studies are optimistically showing generally that AMVs and radiance data assimilation helps the initial state estimate and can lead to improved forecasts. Given the lack of other data where TCs form, such activities have enormous potential returns, but data assimilation in the hurricane scene remains a difficult task as TCs are extreme phenomena with heavy rainfall, highly curved inflowing and outflowing winds, and dense cloud cover. In the TC environment, both new/improved data treatment techniques and more sophisticated NWP methods are required to have the most successful data assimilation and forecast improvement outcomes. We ask the reader to review the report Bessho et al. (2018) for more information.

5.2.4 Coming capabilities of future geostationary satellites

The capabilities of emerging and near-future geostationary meteorological satellites are quite promising. China’s FY-4 series (the first satellite was launched in 2017) includes a hyperspectral IR sounder and a lightning mapper. The payloads of the Meteosat Third Generation satellites also plan to include a hyperspectral sounder. The U.S. GOES-R series will continue with the launches of GOES-T and -U. However, GOES-T and -U will be delayed as the cooling system needs to be upgraded. These satellites will carry the GOES-16/17 legacy instruments which include the high-resolution imager (i.e. the Advanced Baseline imager) and lightning mapper (i.e. GLM). Korea plans to launch its new Kompsat series -2A and -2B, with much improved imagers and a hyperspectral sounder on -2B. India will also launch Insat-3DS that will continue the successful Insat-3 series. Finally, JMA is designing the Himawari-8/9 replacement and expect to begin manufacturing in 2023 with operations set to begin in 2029. Of these future capabilities, hyperspectral sounders may be a topic at the next IWTC, as they provide superior precision and higher temporal frequencies and may be able to better depict the rapidly changing conditions associated with TC environments. Eye soundings may also be possible in TCs with cloud-free eye structures.

5.3 New developments and science using aircraft-based reconnaissance

It has been a recurrent recommendation of past IWTCs to call for an extension of regular and coordinated aircraft reconnaissance missions in other TC basins than those covered by the long-standing U.S. program. We are happy to report that in recent years there has been significant progress toward this goal in the western North Pacific. In the last four years, new
airborne observational technology has also emerged, and refined strategies for designing optimal aircraft flight patterns meant to maximize the impact of these observations on NWP-based forecasts of track and intensity have been tested. Below we provide an overview of the current status of airborne observing technologies and strategies, highlight some applications of these aircraft-based observations to improve analysis of TC intensity and structure, and discuss what efforts are planned in the future. All details will be found in the subtopic 7.3 report (Wong et al., 2018).

5.3.1  TC aircraft reconnaissance and field campaigns

5.3.1.1  Advances in the U.S. aircraft reconnaissance program

The U.S. TC scientific community, and in particular the National Oceanic and Atmospheric Administration (NOAA), continues to improve and update its airborne capabilities designed to make in-situ observation of TCs. To this end, new observation platforms or instruments have been recently tested.

New platforms include large and small Unmanned Aerial Vehicles (UAVs) such as NASA’s Global Hawk and unmanned aerial systems (UASs) like the Coyote (Cione et al., 2016). The Global Hawk, an unmanned aircraft for high-altitude, long-duration Earth science missions, has been used in several TC field campaigns. The Coyote, on the other hand, is a small remotely-piloted device launched from dropsonde tube on the WP-3D aircraft that is able to fly and make observations at very low altitudes, where manned aircraft cannot fly. Such capability allows the Coyote to be used for a real-time assessment of near-surface/boundary layer winds and minimum sea level pressure. Coyote UASs were successfully deployed in Hurricanes Edouard (2014) and Maria (2017). Further development of the Coyote technology is ongoing. Those efforts will add additional instrumentation, and extend the flight duration (now being only 1 to 2 h).

Among the full array of instruments and devices deployed or operated on U.S. weather reconnaissance aircraft are floats and profilers for oceanic sampling, Tail Doppler radar, for 3-D winds and rain rate, the SFMR (Stepped Frequency Microwave Radiometer), for surface wind speed and rain rate, and the dropsondes. One of the more exciting observational capabilities is the addition of the Wide-swath Scanning Radar Altimeter (WSRA), which can provide near-real-time reporting of ocean directional wave spectra, significant wave height, rain rate, and the mean square slope of the ocean surface. It is also noteworthy that older NCAR/Vaisala RD-94 dropsondes are now being replaced by the newer/better designed NCAR/Vaisala RD-41 dropsondes.

One of the new instruments, the Doppler Wind LIDAR (DWL), detects and tracks the relative movement of aerosols via laser light and provides wind vectors in regions where there is a lack of precipitation scatterers. As such, the DWL provides a complement to wind measurements obtained with the tail Doppler RADAR, which is reliant upon precipitation scattering. Such capability can prove valuable in situations with pronounced precipitation asymmetries, such as TCs in vertical wind shear (Zhang et al., 2018) and/or for improved boundary layer wind observations.
Concurrent with these steady technology improvements, innovative strategies are being tested to take the most advantage of the whole set of aircraft-based observations. A new targeting strategy for the aircraft flight planning discussed in Torn (2014) was tested during reconnaissance flights associated with Hurricane Michael (2018) and Central Pacific Major Hurricane Lane (2018), before being implemented operationally for the first time in Hurricane Florence. The strategy relies on the computation of numerical model uncertainty fields based on ensemble model output (from the EC model). The flight tracks are then designed to sample coherent regions where there is the maximum uncertainty. It still remains to be demonstrated if this strategy systematically reduces model uncertainty and thus improves forecasts.

The philosophy and motivations of the NOAA’s airborne sampling program for TCs is contained within the NOAA Intensity Forecasting Experiment (IFEX; Rogers et al., 2006, 2013) which aims at tackling the challenge of intensity forecasting, particularly for rapid intensity change events. Through IFEX, significant advances have been made in the real-time display of aircraft data for NHC forecasters. Analyses of reflectivity and winds from the tail Doppler radar are now available within approximately 20 minutes following the completion of the aircraft’s pass through the TC center. These observations can also be accessed online like the example shown in Fig. 5.

In 2018, and for the first time, real-time Doppler radar analysis data has been ingested into the software that NHC forecasters use to visualize TC structure as they prepare their forecasts. This data can now be co-viewed and combined with other data sources, e.g. from GOES-16, to provide forecasters an unprecedented look at the TC inner-core and to assess features such as deep convection, vortex tilt, radius of maximum wind or the presence of secondary eyewalls (Fig. 6).

![Figure 5. Real-time tail Doppler radar analyses from Hurricane Florence (2018). (a) Reflectivity (shaded, dBZ) and winds (barbs, kt) at 2 km altitude sampled during 1512-1840 UTC 10 Sept.; (b) As in (a), but for wind speed (shaded, kt), streamlines at 2 km (black) and at 5 km (grey) altitude, and radar-derived diagnostics in text. Black x’s in (b) denote locations where the peak vertical velocity in the 4-16 km layer is > 1 ms⁻¹.](image-url)
5.3.1.2 Aircraft reconnaissance advances in the North-West Pacific

A pioneering program for aircraft-based Typhoon surveillance missions in the western North Pacific was the Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) program. Starting in 2003, DOTSTAR has investigated 63 typhoons in 2017 (conducting 79 flights and releasing 1291 dropsondes). The targeted observations conducted by DOTSTAR have resulted in a robust (10 to 20%) improvement in model forecasts of typhoon tracks in both the National Center for Environmental Prediction’s (NCEP) Global Forecast System and European Center for Medium Range Weather Forecasts’ (ECMWF) Integrated Forecast System (Chou et al., 2011) and has shed light on typhoon dynamics. DOTSTAR was an active partner of the Tropical cyclone-Pacific Asian Research Campaign for Improvement of Intensity estimations/forecasts (T-PARC) field campaign conducted in collaboration with Japan and the United States of America, and more recently (2017-2018) in the T-PARC-II campaign. The T-PARC project, funded by Japan for the 2016-2020 period, aims to improve estimations and forecasts of TC intensity as well as storm track forecasts. For T-PARC-II, a new dropsonde and multi-channel receiver has been developed with very light weight and without the parachute. A newer version of this light weight dropsonde that uses more environment-friendly materials is currently under development.

Hong Kong, China, has also joined the global regional aircraft reconnaissance effort. In collaboration with the Government Flying Service (GFS), Hong Kong Observatory (HKO) commenced reconnaissance flights for TCs over the northern part of South China Sea in 2011, providing high-resolution wind, temperature and relative humidity data along the flight paths (Chan et al., 2011). The flight-level observations were used to analyse the TC position, intensity and structure in a near-real-time manner. These observations also contributed positively to TC forecast track improvements in the next 2-3 days, as well as improved analysis and forecast of TC structure in a mesoscale NWP model (Wong et al., 2013). In 2016,
a dropsonde measurement system was installed on board a new jet GFS aircraft. Since the first mission, about 20 flights have been conducted. The near-real-time dropsonde observations were disseminated using the GTS. HKO has also contributed to the TC surveillance flight data acquisition in various international and regional projects, including T-PARCII and the Experiment on Typhoon Intensity Change in Coastal Areas (EXOTICCA), among others. An example of how these dropsonde data from different field projects can be combined is shown in Fig. 7, where DOTSTAR and HKO’s dropsondes are combined in an analysis.

EXOTICCA started in 2014 being coordinated by the Shanghai Typhoon Institute of China Meteorological Administration (STI/CMA) and HKO. The major objectives of EXOTICCA are to conduct: (a) field campaigns on the intensity and structure characteristics of the target offshore and landfalling TCs using integrated and novel observation techniques; and (b) demonstration research on the utilization of the synergized field observation data with the aim of deepening the understanding of the mechanism of structure and intensity changes, to improve the relevant capability of operational analysis, NWP model forecasts, reliable storm surge and flooding and associated risk assessment (Lei et al., 2017).

Several new observation platforms have been implemented by STI/CMA during the observational field campaign experiments, including low-altitude/lower boundary layer (400-600m) UAV observations of winds and temperatures. In order to obtain in-situ observations of the TC structure, particularly the vertical profiles of wind, temperature, pressure and moisture of the inner-core or in different quadrants of the storm at same time, a “rocket-dropsonde” system was also developed by STI/CMA. This system uses a rocket platform to release dropsondes over targeted areas. The positions of dropsondes are determined by the Beidou satellite, which also transmits the dropsonde observations to the ground operation centre. This rocket-dropsonde system was used to investigate Severe Typhoon Mujigae in October 2015. The rocket was launched from Hainan Island, about 330 km west-southwest to the center of Mujigae and four dropsondes were released in the periphery of Mujigae’s inner-core. Nearly simultaneously, HKO conducted a surveillance flight, passing through the centre of Mujigae a little earlier. This collaborative operation provided a valuable opportunity to validate the
airborne observations of the typhoon from different platforms or techniques and to analyse the inner-core structure of Mujigae (Fig. 8).

Figure 8. The schematic of rocket-dropsonde (top left) and vertical profiles of wind speed [ms⁻¹] collected around ST Mujigae by STI/CMA on 3 October 2015. Comparison of wind profile of rocket-dropsonde versus those collected by the HKO reconnaissance flight (top right), and estimated surface winds along the HKO reconnaissance flight’s path (bottom right).

5.3.2 Applications of aircraft-based observations

5.3.2.1 Collecting observations that span the TC life-cycle in a variety of environments for model initialization, sensitivity studies and evaluation

Many of the IFEX missions have targeted TCs in the early stages of their life-cycle, as this has the potential to capture many important features in a TC’s intensity evolution, including genesis and rapid intensification. The data collected in these missions are used to improve TC intensity forecasting in several ways. First, data is transmitted in real-time to the NOAA Environmental Modeling Center (EMC), where it is assimilated into the operational regional Hurricane Weather Research and Forecasting (HWRF) model. Earlier efforts were successful in developing the capability of transmitting airborne Doppler radar data in real-time to EMC. Those efforts showed some success in reducing forecast error when those data were assimilated into the Weather Research and Forecasting (WRF) model. There are many recent studies that show that forecast errors can be reduced by assimilating/using aircraft data, including flight-level observations, dropsonde observations, and airborne Doppler RADAR-based wind estimates (Zhang and Weng, 2015; Aberson et al., 2015; Weng and Zhang, 2016; Tong et al., 2018). Similarly, dropsondes from the Global Hawk UAV have also been shown to improve TC analyses and forecasts (Christophersen et al., 2017, 2018a,b).
Another way aircraft data improves TC intensity forecasting is by facilitating model evaluation, which can lead to improvements in the representation of physical processes in the model (Zhang et al., 2013a,b). The impact of using observations to improve the representation of vertical eddy diffusivity was shown in Gopalakrishnan et al. (2013) and Zhang et al. (2015, 2017). Using this improved eddy diffusivity results in a shallower and stronger TC boundary layer inflow layer, more consistent with observations, as well as differences in other boundary layer properties such as stability, convergence, and angular momentum advection. These changes have been shown to produce better forecasts of rapid intensification (Zhang et al., 2017), as well as providing a better representation of TC size (Bu et al., 2017). Zhang et al. (2018) used aircraft observations to reduce the horizontal mixing length in HWRF forecasts of Hurricane Earl and found that many structural aspects were improved, including storm size, boundary layer heights, warm-core height, and eyewall slope. Biases in both storm intensity and storm size were significantly reduced with the modified horizontal mixing length. It is also important to mention that these manned aircraft, UAV and UAS based data are critical for development of satellite-based techniques. For instance, there are few conventional observations of extreme winds from which SMOS, SMAP, SAR and GPS-R methods can be validated against. So aircraft-based data remain critical for nearly every aspect of TC research, development and forecasting.

5.3.2.1 Improve the understanding of physical processes driving intensity changes of a TC at all stages of its life-cycle

The third IFEX goal is primarily concerned with hypothesis-driven research aimed at better understanding intensity change processes within the TC inner core and its environment. Much of the recent work has focused on the TC response to vertical shear and the structure and distribution of precipitation and its relationship to TC intensity change. The understanding gained from these observationally-based studies is being used to guide the development of forecasting tools and model improvements that hold the potential to improve TC intensity forecasts. For more details on this topic refer to topic 5.3 report, Wong et al. (2018).

5.4 Recommendations

1. Support the growing number of research and operational programs that are providing accurate validation data for satellite-derived surface wind speeds/vectors outside the Atlantic TC basin. Including validation of new observational capabilities (how good?) and the real-time sharing and exchange of aircraft/UAV based observational data. (for WMO)
2. Support efforts to make current and future research and development satellite data and products available in real-time or near real-time to permit operational applications after successful cal/val. (for WMO)
3. We recommend further investigation of the use of GNSS-R data for determining TC size, strength and structure. (for Researchers)
4. Encourage the use and evaluation of wind fields from L-band radiometers (SMOS and SMAP) for determining intensity and 34-, 50, and 64 kt radii in TC. (for Forecasters and Researchers)
5. Encourage the use and evaluation of SAR-derived ocean surface wind speeds. These complement other techniques, but provide invaluable inner-core wind structure information. (for Forecasters and Researchers)
6. Encourage the global community to collaborate on the optimal mix of legacy satellite sensors along with those coming from small satellites and CubeSats. (for WMO)

7. To encourage and support for another International Workshop on Satellite Analysis of Tropical Cyclones (IWSATC) in the near future; expanding the role to better reach underdeveloped TC-prone countries. (for WMO)

8. To support/continue to support the development of new aircraft observation platforms such as dropsondes, UAS/UAV, RADAR/LIDAR instruments on board the flight vehicles and provide quality observations with high resolution in both space and time (for WMO, and researchers)

9. To support technique development and applying aircraft observations in analysis of TC intensity, wind distribution, boundary layer structures during the whole TC lifecycle (to researchers)

10. Support enhanced nowcasting and/or forecasting techniques of TC intensity, rapid intensity change and associated high-impact weather using combinations of the aircraft reconnaissance-based data, satellite-based data, other meteorological observations (for WMO, Forecasters and Researchers)

11. Support the application of new aircraft observational data for data assimilation activities in NWP models, for improving model physics in those models, and for improved validations of model output and physical processes (for Researchers)

12. Document (and/or through training opportunities) how aircraft (new and old) can be used by RSMC/TCWC forecasters to improve their analysis of TC intensity and surface wind structure, and leading to more accurate, effective assessment or communication of uncertainty of potential impacts to the users and general public (to WMO and Forecasters)

13. To support / organize coordinated field campaigns of various aircraft observation missions and experiments for gathering observation datasets of the whole TC lifecycle and intensity evolution (to WMO)

Acknowledgments

The Topic Chairs would like to thank our Rapporteurs Kotaro Bessho, Jack Beven, Thomas Meissner, Lucrezia Ricciardulli, and Wai Kin Wong and their team members for their great work and help with this topic. We also thank our organizations (NOAA, Meteo France, Remote Sensing Systems, JMA, and the Hong Kong Observatory) for allowing us time to complete the work.

Acronyms used in the report

AMV  Atmospheric Motion Vector
ATCF  Automated Tropical Cyclone Forecast system
AWIPS-II Advanced Weather Interactive Processing System-II
CYGNSS Cyclone Global Navigation Satellite System
DAV  Deviance Angle Variance
DOTSTAR Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region
DWL  Doppler Wind LIDAR
EMC  Environmental Modeling Center (USA)
ESA  European Space Agency
EXOTICCA Experiment on Typhoon Intensity Change in Coastal Areas (China)
GFS Government Flying Service (China)
GLM GOES Lightning Mapper
GNSS-R Global Navigation Satellite System-reflectometry
GOES Geostationary Operational Environmental Satellite
GPS Global Positioning System
GTS Global Telecommunications System
HISA Hurricane Intensity and Structure Algorithm
HKO Hong Kong Observatory
HWRF Hurricane Weather Research and Forecasting model
IFEX Intensity Forecasting Experiment (USA)
IR Infrared
IWTC International Workshop on Tropical Cyclones
JMA Japanese Meteorological Agency
JTWC Joint Typhoon Warning Center
LIDAR Light Detection and Ranging
KMNI Royal Netherlands Meteorological Institute
MIRS Microwave Integrated Retrieval System
NASA National Aeronautics and Space Administration
NCAR National Center for Atmospheric Research (USA)
NOAA National Oceanic and Atmospheric Administration
NWP Numerical Weather Prediction
OBTK Objective Best Track
RADAR Radio Detection and Ranging
SAR Synthetic Aperture Radar
SFMR Stepped Frequency Microwave Radiometer
SMAP Soil Moisture Active Passive
SMOS Soil Moisture Ocean Salinity
STI/CMA Shanghai Typhoon Institute of China Meteorological Administration
UAS Unmanned Aerial System
UAV Unmanned Aerial Vehicle
WRF Weather Research and Forecasting model
WSRA Wide-swath Scanning Radar Altimeter
YSLF Young Seas Limited Fetch

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TOPIC 5.1 - NEW AND EXISTING METHODS TO ESTIMATE TC SURFACE WIND STRUCTURE

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Abstract
The rapport describes and compares various existing and new methods to estimate tropical cyclone (TC) surface wind structure from spaceborne sensors. We discuss scatterometers, L-band radiometers, C-band synthetic aperture radars, reflectometers and microwave sounders. We describe the TC wind structure analysis at the JTWC and the DAV technique for determining wind radii.

5.1.1 Introduction
The report is organized as follows: Section 5.1.2 deals with the classical co-polarized C-band and Ku-band scatterometers. L-band radiometers (SMOS and SMAP), which are a relative new technology for determining intensity and size of TC, are described in Section 5.1.3 and their capabilities are compared to the classical co-polarized scatterometers. The subject of Section 5.1.4 is the dual polarized C-band synthetic aperture radar and its capability to determine TC structure. Another new technology, reflectometry, with focus on the CYGNSS instrument, is described in Section 5.1.5. Section 5.1.6 deals with the microwave sounding technique. Section 5.1.7 gives an account of how these sensors are used in the TC wind structure analysis at the Joint Typhoon Warning Center. Section 5.1.8 describes the DAV technique of estimating wind radii. Summary and conclusions are given in Section 5.1.9 and some recommendations are made in Section 5.1.10.

5.1.2 Scatterometers
Scatterometers are spaceborne radars used to measure the ocean surface wind speed and direction. They operate at microwave frequencies/wavelengths of about 14 GHz/2 cm (Ku-band, VV and HH-pol: NSCAT, QuikSCAT, OSCAT-1, RapidScat, ScatSat), 5 GHz/5 cm (C-band, VV-Pol: ERS, ASCAT). Some of these instruments and missions are described in detail in Naderi et al. (1991), Attema (1991), Lungu and Callahan (2006), Figa-Saldana et al. (2002), Durden and Perkovic-Martin (2017), Wentz et al. (2017). The incident waves resonate via
Bragg scattering with ocean capillary waves, whose wavelengths range from a few millimeters to a few centimeters, and a signal is backscattered to the scatterometer. The intensity of the backscatter relative to the transmitted intensity depends on the wind speed and direction, and on frequency, polarization and Earth incidence angle. The National Aeronautics and Space Administration (NASA) mission QuikSCAT operated continuously from 1999 to 2009 and has been very useful for wind data assimilation in Numerical Weather Prediction (NWP) models. Current scatterometer missions used in NWP are the EUMETSAT ASCAT on MetOp-A (since 2007) and MetOp–B (since 2012), and the ISRO ScatSat. The actual resolution of these data is 25-50 km.

The scatterometer wind retrieval algorithms are based on empirical models which are developed by matching the observed backscatter signal as a function of frequency, polarization, and Earth incidence angle to collocated ground truth wind measurements (Wentz and Smith, 1999; Verspeek et al., 2010; Ricciardulli and Wentz, 2015; Soisuvan et al., 2012; Stoffelen et al., 2017). At wind speeds below 30 ms\(^{-1}\), the ground truth is represented by buoys, by other well-calibrated satellite measurements or by NWP models, e.g. NCEP GDAS or ECMWF. For very high winds (above 30 ms\(^{-1}\)) the model is typically extrapolated and tuned to make the retrieved winds match winds in storms observed by aircraft-mounted instruments.

Scatterometer measurements are impacted by rain (Stiles and Yueh, 2002; Tournadre and Quilfen, 2003; Draper and Long, 2004; Hilburn et al., 2006; Weissman and Bourassa, 2008; Portabella et al., 2012). At winds greater than 20 ms\(^{-1}\), rain significantly attenuates the backscattered signal, and it distorts the wind vectors by artificially shifting them to a direction perpendicular to the satellite track. For this reason, scatterometer wind measurements are of limited use for TCs as a significant portion of the wind field in the storm is affected by rain. This has been a shortcoming for the QuikSCAT and RapidScat observations in TCs, but less for ASCAT, as rain affects the high frequencies measurements (Ku-band) much more than lower ones (C-band).

Another important issue is that the wind speed signal of single polarized scatterometers (VV or HH-pol) loses sensitivity and starts to saturate above 35 ms\(^{-1}\) (Donelan et al., 2004; Hwang et al., 2013; Hwang and Fois, 2015; Sapp et al., 2016), which makes accurate wind speed estimates in intense TCs difficult. This shortcoming will be mitigated by adding a cross-polarization channel (VH-Pol) to the C-band scatterometers, as on the Sentinel-1 SAR and on the future MetOp SG, planned for launch in 2022 (c.f. Section 4).

### 5.1.3 L-Band Radiometers

It has been a long-standing challenge for satellite sensors to accurately measure high wind speeds, as found in tropical or extratropical cyclones. The reasons are: 1) in most sensors, the signal saturates when wind speed reaches ~33 ms\(^{-1}\) - the strength of category-1 hurricanes, and 2) the signal is attenuated by heavy rainfall that typically accompanies the majority of high wind events. Both of these factors can result in large errors at very high wind speeds.

The recent availability of spaceborne L-band radiometers, which operate in the low range microwave frequencies (1 – 2 GHz), overcomes the shortcomings which affect TC observations from most of the currently operating instruments. L-band radiometers are minimally affected by rain or frozen precipitation (Wentz, 2005; Reul et al., 2012). The signal they receive remains sensitive to increasing wind even in wind speeds up to 70 ms\(^{-1}\) (Reul et al., 2012; Yueh et al., 2013; Meissner et al., 2014; Reul et al., 2016; Fore et al., 2016; Meissner et al.,...
2017), the strength of category-5 tropical cyclones. Both the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) and the NASA Soil Moisture Active Passive (SMAP) L-band radiometers are able to provide very reliable measurements of extreme ocean wind speeds at a spatial resolution of 40 km (Reul et al., 2016, 2017; Yueh et al., 2016, Meissner et al., 2017).

SMOS (Kerr et al., 2010, Mecklenburg et al., 2012) is a synthetic aperture radiometer that measures effectively the spatial Fourier transform of the emitted brightness temperature, which is referred to as **visibility**. This visibility function is then converted into scene brightness temperatures, from which the surface wind speed can be retrieved. SMAP (Entekhabi et al., 2010, 2014) has a real aperture consisting of a spinning mesh antenna of 6-meter diameter. Achieving the desired spatial resolution of 40 km with the low L-band frequency requires either a large antenna or the utilization of the synthetic aperture technique. Wind speeds are processed and distributed for both sensors (www.smosstorm.org, ftp://podaac.jpl.nasa.gov/allData/smap/L3/JPL/V4/, www.remss.com/missions/smap).

Figure 5.1.1 Time series of intensity, 34-kt (gale force), 50-kt (storm force) and 64-kt (hurricane force) wind radii of Hurricane FLORENCE in September 2018. The red circles are the values from SMAP (40 km spatial resolution), and the blue squares from RSS ASCAT (25 km). The green dashed lines are the Best Track (BT) estimates from the U.S. National Hurricane Center (NHC). The BT intensity values have been scaled from 1-minute to 10-minute sustained winds (Harper et al., 2010). The radii are shown for the NE sector.

For wind speeds below 15 ms\(^{-1}\), the performance of L-band radiometers to measure scalar wind speeds is not as good as that of higher frequency radiometers or scatterometers (QuikSCAT, ASCAT, RapidScat, ScatSat). The L-band radiometers have larger radiometer noise and lower sensitivity to wind speed below 15 ms\(^{-1}\). However, at high wind speeds, above 25 ms\(^{-1}\), L-band radiometers have a distinct advantage over most of these other instruments. This applies, in particular, under heavy precipitation, as found in TCs. The signal of the L-band radiometer
shows no sign of saturation or sensitivity loss even in extreme winds. The reason for this is that the microwave emission from the wind roughened ocean surface is caused by sea-foam (whitecaps), which keeps increasing approximately linearly with wind speed (Nordberg et al., 1971; Monahan and O’Muircheartaigh, 1980; Reul and Chapron, 2003; Anguelova and Webster, 2006) and for many years was the basis for visible estimation of surface wind speeds (Neumann, 1952). This advantage of radiometers at low-frequency over scatterometers in measuring extreme wind speeds had already been suggested by Jones et al. (1981) in their pioneering aircraft flight into Hurricane Allen.

Figure 5.1.2 Surface wind speed retrieved from SMOS data (40 km resolution) as the satellite swath intercepted Super-Typhoon JEBI on 02 SEP 2018. The wind speed contours from SMOS wind (pink) at 34-kt (left), 50-kt (middle) and 64-kt (right) are superimposed with ATCF wind-radii forecasts (thick black).

Figure 5.1.3. Rapid intensification of Typhoon TRAMI observed by SMAP (40 km spatial resolution). The observed intensity changed from 43 ms\(^{-1}\) (Category 2) on 2018-09-23 08:47 to 61 ms\(^{-1}\) (Category 4) on 2018-09-24 09:25 within less than 25 hours. The lines show the 34-kt, 50-kt and 64-kt wind radii in the various sectors.
Figure 5.1.1 shows the time series of intensity and radii of Hurricane Florence observed by SMAP and RSS ASCAT (Ricciardulli, 2016; Ricciardulli and Wentz, 2016) and compared to Best Track (BT) data. The maximum winds need to be sustained for at least 10 minutes in order to produce the roughness that the satellites observes. Therefore, the Best Track intensity data have been scaled down from 1-minute to 10-minute sustained winds to be representative of the scales observed by satellite (Harper et al., 2010). Further examples are shown in Figure 5.1.2 (SMOS wind field of Super-Typhoon JEBI) and Figure 5.1.3 (Rapid intensification of Typhoon TRAMI from SMAP).

The L-band radiometers are able to detect the phases of rapid intensification at least up to wind speeds of 60 ms⁻¹ and show good correlation with the BT intensities and radii. Currently, the major limiting factor of the L-band radiometers to measure winds in tropical cyclones is their spatial resolution (~ 40 km). In many cases, this does not allow to resolve the structure around the eye of the tropical cyclone, in particular for small compact systems. It also puts a limitation on how close to the coast accurate ocean wind speed measurements can be performed. However, combined data from SMOS and SMAP do provide new and very regular estimates of wind radii at 34-kt, 50-kt and 64-kt for each given storm (Reul et al., 2017).

Estimates of storm intensity and sizes are being produced in near-real time from SMOS (www.smosstorm.org) and SMAP (www.remss.com/missions/smap). The Joint Typhoon Warning Center has started using these in their forecasting via their Automated Tropical Cyclone Forecasting Systems (ATCF) (Sampson and Schrader, 2000). These estimates (e.g. Figure 5.1.1–5.1.3) are critical for both real-time estimates of wind radii (Bender et al., 2017) and guidance development (Knaff et al., 2018).

### 5.1.4 C-Band Synthetic Aperture Radar

The C-Band Synthetic Aperture Radar (SAR) systems are the only active microwave sensors able to observe ocean surface night and day and through clouds at high resolution (50 m) with a wide coverage (400 km swath). This unique combination opens perspectives to characterize the inner core storm structures, such as, the eye-wall and radius of maximum wind speed, and the rain band locations. High resolution also allows measurements in coastal areas without any land contamination.

Since the launch of the first satellite SAR mission SEASAT in 1978, the application of SAR for ocean surface wind retrieval has become mature for moderate wind speeds (Monaldo et al., 2003; Dagestad et al., 2012), with noticeable efforts for hurricane monitoring (Gonzales et al., 1982; Katsaros et al., 2000). Up to very recently, and as for scatterometer missions, most of the SAR were only operating in co-polarization (antenna emits in V or H polarization and receives in H or V polarization). SAR wind measurement principle is thus very similar to scatterometers. It relies on the sensitivity of the backscattered intensity from the ocean sea surface to the ocean surface wind speed and direction. Consequently, SAR suffers from the same limitation for extreme winds: a decrease in sensitivity for winds higher than 35 ms⁻¹. Yet, several improvements and new methodologies have been seen in recent years. Radarsat-2 (launched in 2007 by the Canadian Space Agency) pioneered the capabilities to measure the signal both in co-polarization and cross- polarization (antenna emits in V polarization and receives in H; or vice versa). In particular, the higher sensitivity (with no apparent saturation) of the cross-polarization (w.r.t. to co-polarization) to the ocean surface wind speed for extreme winds enables to improve the wind speed accuracy in TCs (Zhang et al., 2012; Horstmann et al., 2015; Hwang et al., 2015).
Thanks to the space component of Copernicus (the European Union’s Earth Observation Programme), a constellation mission consisting of two SARs is now operational since April 2014 for Sentinel-1A and April 2016 for Sentinel-1B. The extension of Sentinel-1 mission is already planned and agreed by the European Commission and the ESA with Sentinel-1C and -1D. They will ensure the continuity of Copernicus service at least until the end of 2030. As it was the case with Radarsat-2, the Sentinel-1 SARs can acquire simultaneously over the same area in both co- and cross- polarizations. Mouche et al. (2017) focused on the quality assessment of the new cross-polarization channel and its possible benefits for extreme wind measurements. They propose to combine both co- and cross- polarizations to measure ocean surface wind vector at 3-km resolution over TCs. When compared to SMAP radiometer measurements, very consistent results have been obtained with bias and RMS respectively lower than 3.5 and 5.0 ms$^{-1}$ for wind speeds larger than 30 ms$^{-1}$ (Mouche et al., 2017). At the same resolution (40 km), the linear relationship found between L-band ocean surface roughness brightness temperature and C-band cross-polarized backscattering over extreme winds explains the similar performances of the two different sensors (Zhao et al., 2018).

Figure 5.1.4. shows a comparison between Sentinel-1 SAR and SMAP radiometer ocean surface wind speed retrieved in the case of Typhoon Lionrock (2016/08/27) as obtained (a) with SAR using the two polarization channels at 3-km resolution and (b) SMAP radiometer wind speed from the RSS algorithm (Meissner et al., 2017). As observed, typical parameters such as TC eye diameter or radius of maximum wind can only be accurately derived from high resolution products. Recent work has also shown the capability of Sentinel-1 to measure wind speeds up to 75 ms$^{-1}$ over Irma the 7th of September 2017 in close agreement with SFMR (Stepped Frequency Microwave Radiometer) airborne measurements (Mouche et al., 2018). Finally, the analysis of backscattered signal can also provide information on the wind rolls alignments in the TC (Foster et al., 2004).

The differing sensitivity between contemporaneous co- and cross-polarized SAR signals is thus the main advantage of new SAR missions to infer local information about the TC structure. To first order and because of its high-resolution capabilities, SAR measurements can thus accurately document the ocean surface response in and around TC eyes. However, at C-Band and at high resolution, the impact of rain in case of extreme wind is still uncertain with possible increase or decrease of the backscattered signal.
Figure 5.1.1. Wind speed as obtained (a) with SAR using the two polarization channels at 3-km resolution, (b) at 40 km resolution with the SMAP radiometer wind speed from the RSS algorithm (Meissner et al., 2017).

5.1.5 Reflectometry

Global Navigation Satellite System-reflectometry (GNSS-R) is a remote sensing technique that uses navigation signals—specifically, those that reflect from a surface—opportunistically for science applications (Zavorotny et al. 2014). The Cyclone Global Navigation Satellite System (CYGNSS) mission employs a constellation of eight microsatellites, each with a 4-channel GNSS-R radar receiver capable of measuring Global Positioning System (GPS) L1 signals scattered from the surface (Ruf et al. 2016a,b; 2018). CYGNSS provides frequent observations of near-surface ocean wind speed in all precipitating conditions and represents the first science-driven GNSS-R satellite mission.
Contrasting the large swaths provided from scatterometers and radiometers, CYGNSS delivers wind speed observations via collections of tracks across the ocean surface (See Figure 5.1.5) (CYGNSS, 2017; Ruf and Balasubramaniam, 2018; Ruf et al., 2018) The sampling properties of the CYGNSS constellation are a function of the orbit properties of the spacecraft and GPS satellites, and are therefore a function of latitude, and time and space window choices (Bussy-Virat et al., 2018). Morris and Ruf (2017a,b) developed methods that objectively estimate TC intensity, wind radii, radius of maximum wind speed, and integrated kinetic energy from simulated CYGNSS level-2 wind speed estimates. Morris and Ruf’s parametric model algorithm smartly interpolates across tracks of CYGNSS observations through a storm, leading to objective estimates of TC metrics. Using the best-track datasets as validation, these methods are applied and validated using the first set of CYGNSS TC observations (Morris, 2018; Chu et al., 2002; Landsea and Franklin, 2013). Figure 5.1.5 shows a preliminary example of a CYGNSS storm overpass, with the resulting parametric model retrieval. In the example shown in Figure 5.1.5, Hurricane Florence is not completely sampled, but where there are observations, objective estimates of TC metrics are possible. Notably, CYGNSS wind speed estimates capture the storm structure asymmetry documented in the closest best-track analysis. The methods developed in Morris and Ruf (2017b) are currently being applied to on-orbit data, with one retrieval example shown in Figure 5.

5.1.6 Microwave Sounders

A Hurricane Intensity and Structure Algorithm (HISA) based on microwave sounder derived temperature (T) and moisture (Q) profiles has been created to estimate TC intensity (max winds [Vmax] and minimum sea level pressure [MSLP]) as well as the radius of 34 (gale), 50 (damaging), and 64 (hurricane/typhoon) kt surface winds. This Cooperative Institute of Research in the
Atmosphere (CIRA) technique (Chirokova et al., 2017) was initially developed in 2004 to produce TC intensity estimates using low earth orbiting (LEO) microwave sounder data (Advanced Microwave Sounding Unit – AMSU) (Demuth et al., 2004, 2006; Bessho et al., 2006). 3-D profiles of T, Q and cloud liquid water (CLW) (Boukabara et al., 2013) provide the environmental thermodynamics in and around the TC regardless of cloudy conditions (a major advantage over Infrared (IR) based sounders) and map the warm core temperature anomaly aloft that is highly correlated with storm intensity.

Figure 5.1.3. Block diagram of statistical model to estimate surface values

NOAA’s Microwave Integrated Retrieval System (MiRS) provides T and Q profiles from multiple AMSU sensors (NOAA-15, 16, 18, 19, MetOp A, B) and the Advanced Technology Microwave Sounder (ATMS, SNPP, JPSS1-soon) in near real-time once the Automated Tropical Cyclone Forecasting (ATCF) aid tells it the TC’s location. Using NOAA’s global model (GFS) data for boundary conditions, a downward hydrostatic integration is performed, a geopotential height field is derived and subsequently a 3-D wind field is produced at standard pressure levels for a 12- degree TC centered box. Finally, a statistical model is used to estimate surface values, including Vmax, MSLP, R34, R50, and R64 as noted in the block diagram Figure 5.1.6.

Note the T and Q profiles can capture TC asymmetries that can be caused by a variety of environmental influences (interactions with ridges, troughs, island/land terrain, other TCs, shear, sea surface temperatures, dry air entrainment, etc.). A 2-D wind field at standard pressure levels is then available for multiple applications. Figure 5.1.7 highlights an example of 850 hPa winds from TC Marcus illustrating the asymmetric winds.

Verification of these satellite-derived wind radii have been done using NHC and JTWC “best track” data sets from 2012-2016 for TCs in the Atlantic, East Pacific, and Western Pacific basins (Table 5.1.1). The sample storms range from tropical storms to Cat 5 (Super Typhoons). Note the number of cases for gale wind radii (> 34 kt) will be larger than either R50 or R64 cases, since not all TCs reach 50 or 64 kt respectively. Ongoing work is focused on adding TC structure predictors and updating coefficients using a much larger data set. Note that ATMS’s superior resolution can better handle smaller storms and compact gradients.
Tropical Cyclone Wind Structure Analysis at the Joint Typhoon Warning Center

JTWC generates and distributes Significant Tropical Weather Advisories, Tropical Cyclone Formation Alerts, and TC track, intensity, and wind field forecasts for U.S. Government customers in the North Pacific, South Pacific, and Indian Ocean basins. Significant Tropical Weather Advisories classify the potential for monitored disturbances to develop into significant TCs within a 24-hour forecast period as “low,” “medium,” or “high.” Tropical Cyclone Formation Alerts provide a geographical area for potential TC formation of each disturbance at the “high” classification level. TC warnings cover a 120-hour forecast period unless dissipation, subtropical transition (STT) or extratropical transition (ETT) is expected to occur earlier. If dissipation, STT or ETT is predicted, the JTWC warning will cover the period up to and including the anticipated dissipation, STT or ETT. Forecasts are issued every six hours. The maximum sustained wind speed for initiating TC warnings is 25 knots in the North Pacific and 35 knots in the North Indian Ocean and Southern Hemisphere, with allowance to “warn early” for timely protection of resources and human life.

JTWC forecasters analyse the radius of 34-knot, 50-knot and 64-knot winds (R34, R50 and R64, respectively) in the northeast, southeast, southwest and northwest quadrants of all North Pacific, South Pacific and Indian Ocean basin TCs. These wind radii represent the maximum over-ocean area within which TC-induced sustained wind speeds equal to or greater than the indicated threshold may be observed. Estimating wind radii for TCs that develop within such an expansive geographic area that encompasses large, data sparse regions, without the
aid of aerial reconnaissance, is a major challenge. However, JTWC has made solid progress toward improving the accuracy of these estimates over the past several years with the ongoing support of various researchers and partner organizations. Because accurate verification data are essential to statistical analyses of existing and potential wind radii estimation techniques, JTWC has partnered with the Naval Research Laboratory to conduct post-storm reviews of 34-knot wind radii for all western North Pacific TCs since 2013 (Sampson et al., 2017).

Figure 5.1.5. ATCF interactive wind radius analysis radial display plot for TC 25W (2018) showing 34-, 50- and 64-knot best track wind radii, by quadrant, along with a variety of individual 34 knot wind radius estimates (top). ATCF interactive 34-knot, northeast quadrant wind radius time history plot for TC 25W (2018) (bottom).

1 Aircraft observations for TCs that pass near Taiwan are occasionally available from the DOTSTAR program. More information on DOTSTAR is provided later in this report.
JTWC uses the Automated Tropical Cyclone Forecasting (ATCF) system to analyse TC best track wind radii estimates for current and past cyclones (Sampson and Schrader, 2000). ATCF provides an interactive radial display of 34-, 50- and 64-knot best track wind radii and individual wind radii estimates derived from various techniques and methods. Interactive, single-quadrant time history plots of 34-knot wind radii, which also include the individual wind radii estimates displayed on the radial plot, are also available to the forecaster in ATCF (Figure 5.1.8). ATCF calculates and pre-populates first-guess R34/R50/R64 values using an automated, objective consensus of available wind radii estimates (OBTK) at each synoptic time (every six hours), which is displayed as a dashed line on the time-history plots. Forecasters use both the radial and time history displays to view available data and “hedge” best track wind radii to be slightly larger or smaller than the objective consensus based on the concentration of available guidance.

Deviations from the consensus may be larger when high-quality data, such as wind observations from on-shore stations, ships or buoys or wind speeds derived from a scatterometer (e.g. ASCAT, WindSat or ScatSat-1) overpass, are available around the analysis time. Indeed, scatterometers provide more routinely available, high-accuracy TC wind field data than any other data source in the JTWC forecast area, and mean OBTK errors are reduced when scatterometer-based wind radii estimates are incorporated (Sampson et al., 2018). Additionally, forecasters often visually compare their best track wind radii estimates with available satellite imagery, particularly images derived from microwave sensors and scatterometers, to determine whether best track wind radii estimates are consistent with a cyclone’s overall convective structure (Figure 5.1.9).
Individual, real-time wind radii estimates available in ATCF for active cyclones may include:

- 34-, 50- and 64-knot wind radii estimates manually derived from ASCAT, WINDSAT or ScatSat-1 scatterometer data by JTWC Satellite Analysts (included in OBTK).
- 34-knot wind radii estimates objectively derived from ASCAT scatterometer data (included in OBTK) (Sampson et al., 2018).
- 34-, 50- and 64-knot wind radii estimates derived from GFS, HWRF and COAMPS-TC model six-hour forecasts (included in OBTK) (Sampson et al., 2017).
- 34-, 50- and 64-knot wind radii estimates based on Microwave Humidity Sounder (MHS) and Advanced Technology Microwave Sounder (ATMS) data (included in OBTK) (Bessho et al., 2006).
- 34-, 50- and 64-knot wind radii estimates derived from combined, multiple-satellite-platform TC surface wind analyses (included in OBTK) (Knaff et al., 2011).
- 34-, 50- and 64-knot objective wind radii estimates derived from subjective Dvorak fix intensity and structure evident in coincident infrared-satellite imagery (included in OBTK) (Knaff et al. 2016).
- 34-, 50- and 64-knot wind radii estimates derived from Soil Moisture Active Passive (SMAP) sensor data (included in OBTK) (Meissner et al., 2018; Meissner et al., 2017).
- Surface and upper-air observations, including planetary boundary layer wind speed data measured by dropwindsondes launched from DOTSTAR program aircraft, which sample the peripheral flow around tropical cyclones near Taiwan (Wu et al., 2005).

Additionally, NRL and JTWC will examine wind field data from the TROPICS (https://tropics.ll.mit.edu/CMS/tropics/Mission-Overview), CYGNSS (Morris and Ruf, 2017), SMOS (Kerr et al., 2010; Reul et al., 2017) and other missions for potential future ingest into ATCF as they become available within the next few years. Although R50 and R64 are more challenging to accurately estimate than R34 due to the low density of TC core observations, remote-sensing signal attenuation and other issues, JTWC is optimistic that access to additional data from L-band sensors will enable forecasters to improve inner TC wind radii estimates.

### 5.1.8 Wind Radii Estimation: DAV Technique

The deviation angle variance (DAV) technique (DAV-T; Piñeros et al., 2008) objectively evaluates the axis-symmetry of a tropical system via infrared brightness temperatures by comparing the temperature gradient vector at each pixel to a radial line. The radial reference center is the center of a tropical disturbance or TC, and the metric is the variance of all deviation angles within a preset distance. Lower DAV values correspond to more axisymmetric structures and thus stronger TCs. This metric has been applied to estimate TC intensity (e.g. Ritchie et al., 2012, 2014), detect tropical cyclogenesis (Wood et al., 2015), and track cloud clusters over time (Rodríguez-Herrera et al., 2015).

The DAV application has recently been expanded to estimate the extent of TC wind fields (Dolling et al., 2016). By using each pixel in a satellite image as the reference center, the DAV-T produces a map of variances, and this map exhibits high correlation with the two-dimensional wind field. Via linear regression of these values in combination with sea surface temperature, TC age, and current intensity, wind radii values are estimated with relatively low errors compared with other techniques. Ongoing work with DAV-T wind radii estimates has
supported a reanalysis of TC wind fields in the Australian region with the eventual goal of producing an objective, consistent, satellite-derived best track dataset (Stark et al., 2018).

### 5.1.9 Summary and Conclusions

Radiometers are an important spaceborne remote sensing tool for determining TC features complimentary to the classical co-polarized scatterometers. L-band radiometers (SMOS, SMAP) do not suffer from signal saturation at high wind speeds and are minimally affected by rain.

Although reflectometry is a less mature technique compared to others, CYGNSS provides valuable rapid revisit, high resolution, near-surface wind speed data, which are uninhibited by rain contamination.

The spatial resolution of research-grade microwave imagers remains 2-3 times better than operational sensors. Microwave sounder resolutions need improvement to adequately resolve warm core anomalies associated with smaller TC eyes.

CubeSats have shown value recently in specifying TC wind fields and multiple missions in the next 1-5 years will greatly aid in identifying their true capabilities and future roles.

### 5.1.10 Recommendation

We recommend considering using wind fields from L-band radiometers (SMOS and SMAP) for determining intensity and 34-, 50, and 64 kt radii in TC. Proper scaling of the intensity of the satellite measurement to 10-minute sustained winds is necessary.

SAR-derived ocean surface wind speed can complement radiometer measurements for a better sampling. However, the high resolution of SAR images makes this sensor unique for inner core analysis, including the estimate of the radius of maximum wind speed or the TC eye diameter and morphology.

We recommend further investigation of the use of CYGNSS data for determining TC size, strength and structure. While CYGNSS data are currently not available with a latency to support real-time, operational activities, the Naval Research Laboratory, serving as liaisons to the Joint Typhoon Warning Center, plan to jointly validate and assess potential impact of CYGNSS-derived size and structure estimates if they were available in an operational, real-time environment.

Accurate validation of satellite-derived surface wind speeds are sorely needed to calibrate algorithms, thus we strongly support the growing WPAC programs sponsored by multiple countries.

Temporal sampling is problematic using LEO sensors, thus we encourage the global community to collaborate on the optimal mix of legacy sensors along with small satellites and CubeSats.

Current satellite platforms are a mix of operational and R&D, thus future research efforts should include near real-time data streams to permit operational applications after successful cal/val.
Acknowledgments

We acknowledge funding by NASA contracts NNH17CA04C (SMAP Science Utilization), NNH14CM09C (Ocean Vector Wind Science Team), by ESA SEOM, element of EOEP4 program, and by the CYGNSS science team. SMOS NRT winds are developed under ESA contract N°4000122821/17/I-EF. Results and conclusions regarding C-Band Synthetic Aperture Radar are based on Sentinel-1 data (2016-2018) from Copernicus and RADARSAT-2 data from the Canadian Space Agency. RADARSAT-2 data have been obtained by GIS-BreTel. A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

Acronyms used in the report

AMSU - Advanced Microwave Sounding Unit
ASCAT - Advanced Scatterometer
ATCF - Automated Tropical Cyclone Forecasting
ATMS - Advanced Technology Microwave Sounder
BT - Best Track
CIRA - Cooperative Institute of Research in the Atmosphere
CLW - Cloud Liquid Water
CYGNSS - Cyclone Global Navigation Satellite System
DAV-T - Deviation Angle Variance Technique
ECMWF - European Centre for Medium-Range Weather Forecasts
ESA - European Space Agency
ETT - Extra-Tropical Transition
GNSS-R - Global Navigation Satellite System - Reflectometry
GFS - Global Forecast System
GPS - Global Positioning System
HISA - Hurricane Intensity and Structure Algorithm
JTWC - U.S. Joint Typhoon Warning Center
MetOp - EUMETSAT Meteorological Operational satellites
MiRS - Microwave Integrated Retrieval System
MSLP - Minimum Sea Level Pressure
NASA - National Aeronautics and Space Administration (USA)
NCEP - U.S. National Centers for Environmental Prediction
NHC - U.S. National Hurricane Center
NRL - U.S. Naval Research Laboratory
NWP - Numerical Weather Prediction
OBTK - Objective R34, an equally weighted average of R34 estimates
Q - atmospheric moisture profile
R34, R50, R64 - 34-ft (gale force), 50-kt (storm force), 64-ft (hurricane force) wind radii
SAR - Synthetic Aperture Radar
SFMR - Stepped Frequency Microwave Radiometer
SMAP - Soil Moisture Active and Passive (NASA mission)
SMOS - Soil Moisture and Ocean Salinity (ESA mission)
STT - Sub-Tropical Transition
T - atmospheric temperature profile
TC - tropical cyclone
Vmax - maximum wind speed
References


TOPIC 5.2 - NEW GENERATION GEOSTATIONARY SATELLITES FOR TC MONITORING

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Abstract
On 7 July 2015, the door to a new era of TC analysis was opened by Himawari-8 which is a lead-off unit of new generation geostationary meteorological satellites. In this review, innovative aspects of TC analysis which are newly available with the state-of-the-art observation function of the satellites are introduced. At first, operational advancement of TC monitoring brought by the enhanced observations is shown. As a second topic, the impact on TC analysis from the new satellite products including RGB images, AMVs and so on is reviewed. From the point of view of the analysis for NWP, the results of data assimilation experiments using the new observational data are also referred. Finally, expected contributions of future satellites to TC analysis are mentioned.

5.2.1 Introduction
On 7 October 2014 the Japanese new generation geostationary meteorological satellite, Himawari-8, was successfully launched. JMA successfully commenced the unit's operation from 7 July 2015 (Bessho et al., 2015). Himawari-9 was also launched on 2 November 2016 as an in-orbit standby and successor satellite of Himawari-8. The first satellite in the GOES-R series, which are collaborative programs between NOAA and NASA, was launched on 19 November 2016 and named GOES-16 (GOES-EAST) (Schmit et al., 2017). GOES-17 (GOES-WEST) was launched on 1 March 2018. CMA also launched FY-4A on 10 December 2016, which is the first satellite of the FY-4 programme (Yang et al. 2017). These new generation meteorological satellites including GEO-KOMPSAT-2A of KMA, which will be launched very soon, and MTG of the EUMETSAT, have the same imager features such as an increased number of spectral bands, high spatial resolution and high frequency. These functions and specifications are notably improved from those of the imagers on previous satellites. Some of them also equip or will equip lightning mappers and hyperspectral infrared sounders. In this report, the contribution to TC analysis and forecasts from these satellites will be shown.

5.2.2 Contributions to TC analyst’s decision-making
In this section, it will be discussed how Himawari-8 and GOES-16 serve the TC analyst, concentrating on new capabilities of the imagers for TC center fixing, TC genesis detection, TC
intensity estimation, and how they are improved over the legacy (5 bands) imagers. The new capabilities aiding forecaster interpretation are also discussed.

1) **TC center fixing and TC genesis detection**

A center position of TC is generally estimated based on the Dvorak techniques; by analyzing the center position of an eye or the CDO as well as the curvature of a surrounding band detected in meteorological satellite imagery. To estimate the center position of a circulation of low-level clouds, TC analysts pick low-level clouds around TC from stationary or animated imagery and seek the circulative movement.

Using novel observational features of imagers on the new generation of geostationary satellites such as higher spatial and temporal resolution, TC analysts are now better able to locate the center of circulation and observe low-level organization to determine TC genesis. Higher spatial resolution makes it easier to identify and classify cloud system features. Higher image frequency allows the analyst to distinguish between features that are transitory and those likely to be synoptically significant (for example, an emerging eye). Higher image frequency also allows the movement of cloud features to be more easily tracked, allowing greater confidence in estimating the cloud system circulation center. This is particularly true for weaker systems where the center is often estimated by looking for the center of rotation of cloud features. The added confidence in center fix location will benefit initial analyses in NWP, and to guide reconnaissance aircraft. The combination of improved spatial and temporal frequency improves the analyst's ability to identify and track low-level cloud lines. This can help the analyst assess how cyclogenesis is progressing and organizing. During early stages of cyclogenesis, a dry mid-level environment often causes strong downdrafts that produce low-level outflow cloud lines that have a component of motion away from the system center. This feature quite often signifies arrested development. As cyclogenesis progresses, the mid-levels become moist, downdrafts are reduced, and less outflow-induced low-level cloud lines are observed.

2) **Intensity estimation**

The combination of improved spatial resolution and temporal frequency allows greater confidence in Dvorak intensity estimates especially for defining scene types (see “eye” scene in Fig. 5.2.1). In these figures, the sharper depiction of the emerging eye and eyewall structures are notable.

On the other hand, the difference in spatial resolution between newer and older imagers can result in differences between Dvorak intensity analysis results from these imagers. JMA compared subjective Dvorak analysis results of 15 typhoons in 2015 using satellite images from MTSAT-2 and Himawari-8. In “eye” scenes, T-numbers from Himawari-8 are sometimes 0.5 higher than those from MTSAT-2 because maximum brightness temperatures in the eye of Himawari-8 imagery can show up to 5 degrees higher than those of MTSAT-2 imagery. Because JMA takes the average brightness temperature in the eye for their Dvorak analysis, their operational results are generally congruent between new and old imagers. The results of objective Dvorak analysis in JMA (Kishimoto et al. 2013) also show a slight bias between new and old imagers. JMA tuned their algorithm of the objective Dvorak analysis to retrieve comparable results. In the latest version of the objective ADT (Olander and Velden 2018), intensity estimates of TCs are also slightly higher (but comparable) for some scene types using GOES-16 vs. GOES-13.
Until the start of operations of Himawari-8, typhoons in the western North Pacific basin were observed every 30 minutes, and cyclones in the South Pacific basin were observed every 1 hour. Consequently a Dvorak analyst usually used the satellite image from 20 minutes or 40 minutes before the operational TC analysis cycle time in each basin. Nowadays, Himawari-8 provides images every 10 minutes for both basins. Hence, the analyst can perform a Dvorak analysis with the satellite image just before or at analysis time. The higher frequency of Himawari-8 images also strengthens the confidence of Dvorak analysis results. Due to time constraints, most TC analysis centers do not routinely perform a Dvorak analysis on every image. However, when there is uncertainty in the analysis, or the system is undergoing rapid change, the analyst can average the results over a larger number of images to gain greater confidence. This can be particularly useful in highly sheared systems where the critical distance from the low-level center to the edge of the dense overcast often varies strongly over short periods as convection develops near the center and is advected downshear.

3) **Rapid scans**

The AHI on Himawari-8/9 is capable of frequent and flexible observation, providing full-disk images of the earth every 10 minutes and regional images with shorter intervals. In regional monitoring, Target Area observation mode provides imagery covering an approximately 1,000 km x 1,000 km area every 2.5 minutes with flexibility for location changes. This rapid observation provides better insight for extreme events such as TCs. JMA utilizes Target Area observation mode for typhoon monitoring with automatic tracking system using the typhoon track forecast. Typhoon images obtained through Target Area observations are provided to users through their dissemination system.

JMA also launched the HimawariRequest service in January 2018, allowing NMHSs in WMO RA-II and RA-V to request Target Area observation. The requests from NMHSs in RA-V are submitted to JMA in collaboration with the BoM. This service enables each registered NMHS
user to request a position and period of Target Area observation, including for TCs in the South Pacific and southeast Indian Ocean, if there is no typhoon in the western North Pacific.

BoM has not yet made use of the facility to request Himawari-8 Target Area observations for TCs, but they have recently tested the process in preparation for the 2018/19 TC season. They plan to make use of this facility just prior to or during landfall of intense TCs on heavily populated areas; and it is expected to improve their ability to keep track of rapid changes in intensity and structure during this critical part of the TC lifecycle.

The ABI on GOES-16/17 provides for up to two special targeted meso sectors with 1-min. image frequency. These rapid-scanning sectors often target TCs in the Atlantic and eastern Pacific basins. They are being used at NHC for better center and circulation detection, “first-light” imagery, and to monitor rapidly-evolving convective characteristics. Researchers at the UW- CIMSS are also experimenting with super-high-resolution AMVs over the storm core region using the 1-min. rapid scans,

4) **Near-infrared band (1.6 µm)**

For TC analysis, visible (VIS) imagery (0.64 µm) is used during the daytime, while infrared (IR) imagery (10.4 µm) emphasizing areas of high brightness temperature or differential IR imagery (10.4 – 12.4 µm) are used during the night. However, in VIS imagery, it is often difficult to distinguish low-level clouds from upper- or middle-level thick clouds generated from a cumulonimbus because they all have similarly high albedos. Near-infrared (NIR) imagery (1.6 µm) from the new satellites can help solve this problem. The albedo of water clouds and ice clouds differ significantly in NIR imagery from Himawari-8; the former is almost the same as the albedo in VIS imagery, while the latter is much lower (Fig. 5.2.2). Therefore, as low-level clouds are water clouds and upper- or middle-level clouds are usually ice clouds, they can be easily distinguished from each other by using NIR imagery from Himawari-8. When it comes to low-level clouds and upper-level thin clouds, reflection of low-level clouds can penetrate through the upper-level thin clouds in VIS imagery while it is not distinguishable in NIR imagery. Therefore, it is more effective to use both VIS and NIR imagery.

![Figure 5.2.2. Conceptual diagram of VIS and NIR satellite imagery. Yellow arrows indicate the sunlight, and blue and red arrows indicate the reflection in 0.64 and 1.6 µm bands, respectively, of water and ice clouds. The length of arrows shows the strength of the reflection in each band schematically.](image-url)
Fig. 5.2.3 shows a side-by-side VIS and a NIR image for Typhoon Yutu (2018). Areas near the center of Yutu, “A” in the figure for example, are covered with developed cumulonimbus and upper-level thick clouds generated by cumulonimbus. Both the cumulonimbus and upper-level thick clouds are seen as bright white in the VIS imagery, while the upper-level thick clouds are seen as gray in the NIR imagery due to lower albedo. As for the surrounding area marked “B”, low-level clouds and upper-level thin clouds are mixed. The albedo of upper-level thin clouds is relatively low in VIS imagery and they are translucent imagery, i.e. low-level clouds under the upper-level thin clouds are detectable. On the other hand, the NIR imagery depicts uniform gray in that region.

![Figure 5.2.3. Comparison of VIS (left) and NIR (right) imagery of Typhoon Yutu (2018)](image)

JMA usually uses animated imagery to track low-level clouds and estimate a center position of the circulation. It is possible that low-level clouds happen to be hidden temporarily under middle- or upper-level clouds in some situations. Animated multispectral imagery can help interpret these occurrences. Also, the direction and speed of upper-level thin clouds are different from those of low-level clouds in most cases. The differences can be recognized in animated image sequences which make it easier to track low-level clouds.

In this way, low-level clouds are captured, and the direction and speed of low-level winds can be estimated from their movement. Then, a center position of a tropical disturbance, i.e. that of a low-level circulation, is more easily obtained from the low-level winds, whose direction and speed will be analysed more precisely with shorter observation intervals. Target-Area observations with 2.5 minute intervals are ideal for this application.

5) **Water vapour bands**

When no cloud exists, water vapour (WV) imagery is more effective in depicting the state of atmosphere, compared with VIS or NIR imagery. Water vapour images are obtained in the wavelength band of 6.2 – 7.3 µm; which is most strongly affected by water vapour absorption. If water vapour exists in areas with no clouds, its extent, height and movement, i.e. the state of the atmosphere, can be analysed with these images. In detail, radiation from the sea or ground surface is absorbed in overlying atmospheric water vapour and re-radiated with the temperature of the water vapour. If the amount of water vapour is large in the upper troposphere, radiation from the low- and middle-troposphere is all absorbed and re-radiated with the temperature of the upper levels. So only the information of water vapour in the upper levels can be obtained from the satellite sensor looking down (the amount of water vapour in low- and middle-level cannot be analysed). In the case that the upper level air is dry, radiation
from the middle-levels is detectable, so when the brightness temperature obtained in WV imagery is around the temperature of the middle troposphere, it is identified that the upper air is dry. Also, when the brightness temperature increases with time, it is considered that there is evidence of subsidence.

The AHI (Himawari-8) and ABI (GOES-16/17) have three bands for water vapour observation at 6.2 µm, 6.9 µm and 7.3 µm (Fig. 5.2.4). As the wavelength increases, the absorption rate gets lower (transmission increases) and the average height of detectable water vapour becomes lower as a result. Taking advantage of these characteristics, the extent and thickness of dry air from upper- to middle-levels can be roughly estimated through the comparison of water vapour imagery from these three bands (Fig. 5.2.5).

A tropical cyclone forms and develops mainly based on release of latent heat of water vapour; however, it may weaken or at least the development can be arrested when dry air exists in upper- or middle-levels. The amount of water vapour in upper- or middle-levels can be analysed with upper air rawinsonde observations or microwave observations by a low-earth orbit satellite, but it is not always possible to obtain these observations in the vicinity of a tropical cyclone at sea; therefore, the water vapour imagery from geostationary meteorological satellites is very useful for analysing the storm environment.

Figure 5.2.4. Example of tropospheric contribution functions for a typical atmosphere from the 3 AHI/ABI water vapour bands
5.2.3 Advanced applications to TC monitoring

The improved spatiotemporal and spectral sampling from the new generation of geostationary meteorological satellites is also enabling superior derived products to improve the TC analysis process. The advanced imagers can provide tailored RGB imagery and improved Level-2 products such as AMVs, aerosol detection and so on. New instruments such as lightning mappers are expanding the observing tool box with new products that can be used in both the forecast and research communities.

1) RGB image products

With the advent of the AHI and ABI, the increase in spectral resolution has allowed for multispectral combinations and RGB image products that go beyond the seminal EUMETSAT recipes (Lensky and Rosenfeld 2008) of the older geostationary imagers. Applications of RGB products to TCs include tropical wave monitoring, TC-environmental interactions, TC genesis and extratropical transition.

In particular, the Airmass and Dust RGBs have seen the most operational use at the National Hurricane Center over the last decade as they have helped forecasters identify the types of air masses that surround and sometimes envelope tropical cyclones. The Airmass RGB shows boundaries between warm, moist tropical air and drier mid-latitude air. The Dust RGB highlights the dust plumes associated with the SAL that emanate off the west African coastline into the Atlantic each year. In addition, the Aerosol Optical Depth product has been very
popular for detecting the areal extent and relative thickness of the SAL. For dust analysis applications, these and other satellite-derived products are used to track the dust component and the dry air associated with the SAL as it advects off the west African coast (Fig. 5.2.6). The presence of a strong SAL over the Atlantic has been shown to modulate TC activity (Dunion and Velden 2004, Evan et al. 2006 and many others). The various split-window and multispectral geo-based products that can detect the dust-laden dry air can be useful for tracking the SAL and TC interactions.

Figure 5.2.6. An example of a 4-panel display from AWIPS II that allows a forecaster to view multiple time-synchronized products at once. The Dust RGB (upper left), the GOES-16 Aerosol Optical Depth product (upper right), the Airmass RGB (lower left), and the GOES-16 7.3 µm water vapour imagery (lower right).

The use of the Water Vapour RGB product in addition to original three water vapour bands, which were already mentioned above, is more effective to grasp the extent and height of dry air. JMA has been developed this RGB recipe and employs this image to interpret the environmental dry condition surrounding a typhoon which usually brings negative impact to its development (Shimizu 2019). Fig. 5.2.5 shows the Water Vapour RGB imagery for Typhoon Yutu (2018) at 00 UTC on 29 October 2018. In this case, thick clouds in surrounding areas weakened rapidly after the area of dry air became clear in the Water Vapour RGB.

The AHI and ABI with 16 bands each has led to the development or improvement of many other RGBs including the Day Convective Storm RGB, Night-time Microphysics RGB, and True Color Reproduction imagery (Miller et al. 2016; Murata et al. 2018) among others that have shown some early indications of improved environmental and near-storm analysis. The 2016 typhoon season and 2017 Atlantic hurricane season in particular featured increased RGB usage to look for early indications of tropical cyclogenesis or improved organization.

2) AMVs

Higher quantity and quality of AMV wind estimates are being enabled by improved spatiotemporal image sampling. Finer quality TC wind analyses (inflow, outflow) are producing better initial conditions for TC-scale numerical models leading to improved model forecasts of
TC track and intensity. Improved AMVs also provide better analysis tools to understand the condition of TCs. The usages of AMVs for numerical model prediction will be shown in next section. Below are some examples of using AMVs retrieved from AHI and ABI for TC analyses.

As AHI on Himawari-8 is capable of more accurate and frequent observation for AMVs, JMA is using sea-surface AMVs, estimated from low-level AMVs derived from Himawari-8 Full-Disk imageries, for analyses of TCs genesis and strong wind areas operationally in RSMC Tokyo – Typhoon Center. The scheme to estimate sea surface AMVs from low-level AMVs of Full-Disk imageries are applied to Target Area imageries with 2.5-minute intervals. Detailed information for the method of estimating sea-surface AMVs from Full-Disk imageries is described in the Topic 4 of IWTC-9 “TC Structure Analysis and Change” and Nonaka et al. (2019). Using sea-surface AMVs of Target Area is very effective for monitoring and analysis of typhoon as it enables to observe wind direction and movement more clearly and in detail (Fig. 5.2.7). JMA also operationally uses sea-surface AMVs from Target Area imageries to estimate the radius of gale force wind of typhoon. JMA is now planning to provide sea-surface AMVs to related NMHSs through their data dissemination system. Combination of the HimawariRequest service and sea-surface AMVs from Target Area imageries for TCs will become a truly practical application of Himawari-8 observational data, one that will prevent and/or reduce the TCs risks and impacts.

![Himawari-8 imagery](image)

**Figure 5.2.7.** The sea-surface AMVs (colored arrows) retrieved from Himawari-8 imagery of Full-Disk (left) and Target Area (right) at 00:00 UTC 1 August 2017 for T1705. Background is visible image of Band #3 (0.64 μm). Colour of arrows shows the wind speed (kt).

Oyama et al. (2018) identified the characteristics of cloud-top winds that indicate TCs intensification by analysis of the upper tropospheric MTSAT AMVs of TCs occurring in the western North Pacific basin. Their results show that the maximum tangential wind of upper tropospheric AMVs was highly correlated with the maximum sustained wind of TCs, and suggested that the variations of cyclonic circulation near the cloud top was caused by the upward transport of the varying absolute angular momentum from the surface to the upper troposphere within TC inner core. Meanwhile, the radial outflow near the cloud top captured by the AMVs represented the outward movement of upper tropospheric clouds such as anvils from
deep convection in TC inner core. The case study using Typhoon Lionrock showed a capability of Himawari-8 high-resolution AMVs to support TC intensity and structure analyses. JMA will conduct a further investigation to estimate typhoon intensity from the upper tropospheric AMVs for operational utilization.

The increased spatial, temporal, and spectral information provided by the GOES-16/17 ABI are also resulting in improved AMVs and derived products for TC analysis, and better initial conditions for numerical model forecasts. Advanced AMV algorithms (Bresky et al., 2012) and processing methodologies (Velden et al. 2005, 2018) designed to take full advantage of the higher spatial and temporal resolution are resulting in increased quantities and quality of AMWs in TC environments (Fig. 5.2.8). In addition, the ABI’s improved geolocation capability allows higher-temporal image sampling that reduces AMV tracking errors.

![Image of GOES-16 AMWs for 2017 Atlantic Hurricane Irma]

**Figure 5.2.8.** GOES-16 AMWs for 2017 Atlantic Hurricane Irma. The blue (yellow) wind barbs represent the upper (lower) level winds.

### 3) Geostationary Lightning Mappers

In addition to the new and improved cloud and moisture data provided by the ABI, forecasters now have access to continuous high detection efficiency lightning data over oceanic regions from the Geostationary Lightning Mapper on GOES-16. This new instrument is allowing forecasters to continuously monitor total lightning (CG+IC) in TCs out of range of current ground-based lightning detection networks with a high detection efficiency (Goodman et al. 2013). Prior research using ground-based networks (mostly CG) showed that lightning can help improve intensity forecasts (DeMaria et al. 2012). Stevenson et al. (2018) also showed intense lightning activity is often associated with deep active convection which favours TC intensification when located within the radius of maximum wind. The geostationary lightning mappers are expanding these capabilities (Fig. 5.2.9).
Figure 5.2.9. The GOES-16 GLM observed Maria’s inner core lightning burst inside the RMW 24 h before it rapidly intensified from an 80-kt (Cat 1) to a 135-kt (Cat 4) hurricane.

5.2.4 Data assimilation into numerical models

Advancing data assimilation methods along with improved instruments are enabling greater positive impacts from geostationary meteorological satellite data in TC prediction models. Superior sampling strategies (spatiotemporal, spectral, signal-to-noise) leads to lower observation errors and increased impact in the model initializations, which can result in improved forecasts of TC behavior (Wu et al., 2014, 2015; Velden et al., 2017; Kim et al., 2017; Zhang et al., 2018). For example, rapid-scan sectors (now routinely available from Himawari-8/9, GOES-R series, and more) can focus on TC events and provide high-density (spatial and temporal) datasets to help initialize high-resolution TC models. Fig. 5.2.10 below shows two recent studies that assimilated enhanced AMVs from rapid-scan GOES data into the Hurricane WRF model.

Furthermore, Kunii et al. (2016) assimilated rapid-scan AMVs derived from 15-min interval imagery of Himawari-8 and found greater benefit than AMVs from 60-min interval imagery for a severe rain event in Japan caused by TC induced moist air flux.

Incredible detail of the TC CDO and outflow can be resolved with dense AMVs which will be retrieved by new "optical flow" techniques in near future. These dense AMVs can in principle be created every 2.5 minutes via Himawari-8 over the western North Pacific and even every 1 minute via GOES-16 over the Atlantic. These very high spatiotemporal resolution AMVs currently cannot be effectively assimilated into models, as NWP centers either use data thinning, super-obing, or strict quality control which results in a loss of much of the detailed information content. An experimental framework to incorporate dense AMVs data set, which was still retrieved from traditional technique, not optical flow, via dynamic initialization scheme is proposed in Elsberry et al. (2018). The final new technology application is to upscale the analyses into the United States Navy’s NAVGEM global model system, which will improve the initial conditions and thus the NAVGEM forecasts of TCs. Better initial and lateral boundary
conditions for the COAMPS-TC model from these improved short-term NAVGEM forecasts should improve the COAMPS TC predictions as well.

Other studies have shown how assimilation of multispectral IR radiances from polar-orbiting satellites can improve the depiction of TC moisture and thermodynamic environments. However, IR observations have limitations in clouds, and of course TCs are cloudy events. Therefore, until very recently only radiances in clear skies and limited radiances in cloudy skies from advanced IR sounders are assimilated in the current NWP systems. Wang et al. (2014, 2015, 2017) propose a new approach to make use of ample partially cloudy scenes to take advantage of the assimilation of cloud-cleared IR radiances. By assimilating more IR sounder information from partially cloudy regions, significant improvement in the NWP forecasting for Hurricane Sandy (2012), Hurricane Joaquin (2015) and Hurricane Matthew (2016) was demonstrated by reduced track forecast errors.

Another approach is assimilating all-sky IR radiances by explicitly including cloud effects. Honda et al. (2018) demonstrated the value of rapid scanning all-sky IR radiance assimilation (10 minute) from Himawari-8 by improving the humidity analysis and intensity forecast for Typhoon Soudelor (2015) (Fig. 5.2.11). The assimilation of cloud-cleared and all-sky sounder IR provides critical moisture and thermodynamic information in the generally cloudy atmosphere around TCs. More frequent sampling will only enhance this impact, and as we will see in the next section, this may come from emerging geostationary satellite hyperspectral sounders.

**Hurricane Maria—Enhanced AMVs**

*Tropical Cyclone research and high-res modeling applications*

Two recent studies using enhanced AMVs in the Hurricane WRF (HWRF) model

![Figure 5.2.10. Assimilated enhanced AMVs lead to stronger vortex zonal wind component increments in the HWRF cycle during Hurricane Joaquin (2014), and subsequently improved intensity forecasts (top). Assimilating enhanced AMVs in all HWRF nested domains including the inner vortex region yields better Hurricane Joaquin intensity forecast impacts (blue) vs. control (no enhanced AMVs, red) and vs. assimilation of AMVs only in the outer HWRF domains (green) (bottom).](image-url)
Figure 5.2.11. (a) Time series of MSLP forecast for Typhoon Soudelor (2015) when assimilating all-sky Himawari-8 IR radiances every 10 minutes (Him8), every 30 minutes (Him8-30min), or no radiances (NoHim8). Thin lines are forecasts from the ensemble mean analyses at different initial times. (b) The forecast MSLP errors verified against the best track averaged 13 forecasts (Honda et al., 2018).

Improved TC analysis with the enhanced instruments also gives us additional positive impacts on model performance. For example, as shown earlier, the new generation geostationary imagers enable us to improve the analysis of the center location and intensity estimate of TCs. Because these properties are used for TC relocation and bogus-generation procedures, the improvement of their quality is expected to lead to improved initial analyses and ultimately superior numerical model forecasts of TCs.

5.2.5 Frontier of new geostationary satellites and coming capabilities of future satellites

As mentioned above, new generation geostationary satellites have already made big improvement in TC monitoring and forecasting. But there are still some unexplored regions for operation and research of TC using the satellite data. One big challenge is targeted observation by the satellites with the information of sensitive regions as estimated from ensemble forecasts, where these additional observation data will be effective in improving prediction results (Bessho et al. 2015). The targeted observations have been already implemented in a variety of field experiments including THORPEX/T-PARC. In T-PARC, JMA executed MTSAT-2 rapid-scan operations. Rapid scan observation by Himawari-8/9 and GOES-R series offers significant opportunities for operational targeted observation with dense AMVs data set.

The other big theme using satellite observation data for TC monitoring is an application of AI to TC genesis and intensity estimation. In operational centers, subjective or objective Dvorak analysis has been widely used for the estimation. Using a huge amount of past analysis result as teaching data, there is a big possibility to develop an algorithm of deep machine learning for TC genesis and intensity estimation. JMA has already started the preliminary study of the
algorithm with the cooperation of Yokohama National University. Once the fully automated analysis of TC genesis and intensity estimation using AI algorithm is established, homogeneous TC analysis results will be retrieved with high frequency. This will bring immeasurable impact on operational TC monitoring.

What new observations will be available in the next 4 years from geostationary orbit? The capabilities of emerging and near-future geostationary meteorological satellites are quite promising. The FY-4A includes a hyperspectral IR sounder and a lightning mapper. The payloads of the MTG satellites also plan to include a hyperspectral sounder. The sounders provide superior signal-to-noise and will enable improved radiance assimilation at a higher temporal frequency to depict rapidly changing conditions associated with TC environments. Eye soundings may also be possible in TCs with cloud-free eye structures. These soundings data will be also useful for nowcasting of TC with some atmospheric instability parameters.

The U.S. GOES-R series will continue with the launches of GOES-T and -U. These will carry the GOES-16/17 legacy instruments which include the high-resolution imager and lightning mapper. Korea plans to launch its new GEO-KOMPSAT series -2A and -2B, with much improved imager on -2A, and air pollution and ocean color imagers on -2B. India will launch Insat-3DS that will continue the successful Insat-3 series. In 2018, JMA has started considering the next geostationary satellite program. In their plan, by 2023 JMA will start manufacturing the next geostationary satellites that will be the successors to Himawari-8/9, aiming to put them into operation around 2029.

Looking to the near-future and beyond, it is clear that improving global satellite observing systems will benefit TC detection and analysis. This is critical since remote sensing is the primary observation tool of TCs over oceanic regions, and the advancing data assimilation systems demand better and more data to improve forecasting of these high-impact weather events.

### 5.2.6 Summary and Conclusions

The latest generation of meteorological geostationary satellites is already proving to greatly augment TC analysis and forecasting. From improved imagery to enhanced derived products, the investments in satellite remote sensing capabilities are leading to new observations and insights into TCs, which ultimately translate to improved forecasts and public safety. The TC research community working on satellite applications will continue to employ the latest generation geo-satellite observations towards developing improved algorithms to derive existing products, as well as novel methods to extract information content from the multispectral imagery. TC forecast centers as well as NWP centers are becoming better equipped to obtain, view and use the full suite of new-generation-sensor high-spatiotemporal outputs, imagery and products. It is truly an exciting era in observing tropical cyclones.

### 5.2.7 Recommendation

That the WMO considers the continuation of the IWSATC series. Two very successful workshops have been held, roughly at 4-5 year intervals. This workshop series is designed to bring TC forecasters and researchers together to learn about new satellite capabilities and how these can meet TC forecaster and research needs. All global TC operational analysis centers as well as TC research institutes are invited, with focus on research applications updates, training sessions and exchange of information in discussion sessions. We recommend that WMO
encourage and support another IWSATC in the near future, with an expanded role in reaching out especially to underdeveloped TC-prone countries.

**Acronyms used in the report**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ABI</td>
<td>Advanced Baseline Imager</td>
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<tr>
<td>ADT</td>
<td>Advanced Dvorak Technique</td>
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<tr>
<td>AHI</td>
<td>Advanced Himawari Imager</td>
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<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
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<td>AMV</td>
<td>Atmospheric Motion Vector</td>
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<td>AWIPS</td>
<td>Advanced Weather Interactive Processing System</td>
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<td>CG</td>
<td>Cloud-to-Ground</td>
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<tr>
<td>BoM</td>
<td>Australian Bureau of Meteorology</td>
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<tr>
<td>CIMSS</td>
<td>Cooperative Institute for Meteorological Satellite Studies</td>
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<tr>
<td>CIRA</td>
<td>Cooperative Institute for Research in the Atmosphere</td>
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<tr>
<td>CDO</td>
<td>Central Dense Overcast</td>
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<td>CMA</td>
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<td>COAMPS</td>
<td>Coupled Ocean/Atmosphere Mesoscale Prediction System</td>
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<td>CSU</td>
<td>Colorado State University</td>
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<tr>
<td>FCDI</td>
<td>Four-dimensional COAMPS Dynamic Initialization</td>
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<td>GEO-KOMPSAT</td>
<td>GEOstationary KOrea Multi-Purpose SATellite</td>
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<td>GOES</td>
<td>Geostationary Operational Environmental Satellite</td>
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<tr>
<td>EUMETSAT</td>
<td>European organization for the exploitation of METeorological SATellites</td>
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<td>FY</td>
<td>Feng-Yun</td>
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<td>HWRF</td>
<td>Hurricane WRF</td>
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<td>IC</td>
<td>Intra-Cloud</td>
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<td>IR</td>
<td>InfraRed</td>
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<td>IWSATC</td>
<td>International Workshop on Satellite Analysis of Tropical Cyclones</td>
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<td>Japan Meteorological Agency</td>
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<td>KMA</td>
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<td>MRI</td>
<td>Meteorological Research Institute</td>
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<td>MSLP</td>
<td>Minimum Sea Level Pressure</td>
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<td>MTG</td>
<td>Meteosat Third Generation</td>
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<tr>
<td>MTSAT</td>
<td>Multi-functional Transport SATellite</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>Navy Global Environmental Model</td>
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<td>NWP</td>
<td>Numerical Weather Prediction</td>
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<td>Red-Green-Blue</td>
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<td>SAL</td>
<td>Saharan Air Layer</td>
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<td>TC</td>
<td>Tropical Cyclone</td>
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<td>The Observing system Research and Predictability Experiment T-PARC</td>
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TOPIC 5.3 - NEW DEVELOPMENTS AND SCIENCE USING AIRCRAFT-BASED RECONNAISSANCE

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Abstract
The recent advances in the development of aircraft reconnaissance of tropical cyclones (TCs) in support of real-time monitoring and field campaign experiments are presented in this report. While TC track forecasts have been improving over the past decade, the intensity forecast, in particular rapid intensification and rapid weakening, remains challenging. Aircraft observations provide indispensable data in the monitoring and analysis of TC intensity and structure. Current and emerging technologies of airborne observation platforms being employed in several TC centers or field campaigns, such as unmanned aerial system and rocket dropsondes, are introduced. Aircraft observational strategies were reviewed that were employed in the observation of three major TCs in 2018, namely Hurricanes Florence and Michael and Typhoon Trami in the Western North Atlantic (NATL), Gulf of Mexico (GoM) and Western North Pacific (WPAC) respectively. The three TCs were observed by five different aircraft types representing the latest in airborne observational technology and using the latest strategy for designing optimal aircraft flight patterns for maximizing their impact on NWP model prediction of track and intensity. Examining these observations provides some insight into the present-day status of airborne observing technology and strategy. Applications of aircraft observations to improve analysis of TC intensity and structure and future developments of forecasting techniques will be discussed.

5.3.1 TC Aircraft Reconnaissance Operations and Field Campaigns

5.3.1.1 NOAA Air Reconnaissance

The U.S. National Oceanic and Atmospheric Administration (NOAA) has two four-engine turboprop WP-3D aircraft and one twin-engine Gulfstream (G-IV) jet, operated by the NOAA Aircraft Operations Center, whose primary area of operations is the Atlantic and East Pacific basins. TC missions are typically conducted under guidance from the NOAA/Atlantic Oceanographic and Meteorological Laboratory’s Hurricane Research Division (HRD). The current motivation for NOAA’s airborne sampling program for TCs is contained within the NOAA Intensity Forecasting Experiment (IFEX; Rogers et al., 2006, 2013). IFEX owes its origins to the fact that, while TC track forecasts have continued to improve over the past 15-20 years and there have been some improvements in intensity forecasts in recent years (DeMaria et al., 2014), the challenge of intensity forecasting remains, particularly for rapid intensity change events. IFEX is defined by its three primary goals, which map onto nowcasting, forecasting and research objectives.
New observational platforms are under trial to develop improved techniques for observing TC inner-core structure and providing this information in real-time to the NOAA National Hurricane Center (NHC) and Environmental Modeling Center (EMC). One such instrument being tested is the Coyote unmanned aerial system (UAS; Cione et al. 2016). The Coyote is a remotely-piloted aircraft launched from the WP-3D that takes in situ measurements of temperature, moisture, winds, and pressure for 1-2 h at very low altitudes, enabling it to sample regions of the TC that cannot be safely sampled using manned aircraft. Such a capability allows the Coyote to be used for a real-time assessment of near-surface winds and minimum sea level pressure. Coyote UASs were successfully deployed in Hurricanes Edouard (2014) and Maria (2017). Further development is ongoing to add additional instrumentation and to extend the duration Coyotes can remain airborne.

Another new instrument being tested is a Doppler Wind Lidar (DWL). The DWL uses a laser to detect aerosols that can provide wind vectors where there is a lack of precipitation scatterers. As such, the DWL can provide a complement to measurements of winds provided by the tail Doppler radar, which is reliant upon precipitation scatterers. Such a capability can prove valuable in situations with pronounced precipitation asymmetries, such as TCs in vertical wind shear (Zhang et al., 2018). The DWL has successfully collected measurements in Tropical Storm Erika (2015), Hurricane Earl and Tropical Storm Javier (2016), Hurricane Maria (2017), and Hurricane Lane (2018).

As mentioned above, the aircraft utilized in the NATL and GoM regions, as well as Eastern and Central Pacific regions (EPAC, CPAC), are the NOAA Gulfstream IV (G-IV) flying at altitudes ranging from 12 to 14 km for surveillance of the TC near and extended environment, including rings of 150-165 km and 500-600 km radius, and the NOAA WP-3D aircraft for mid- and low-level reconnaissance of the inner core region of the storm, at a typical altitude of 1.5 to 3 km. In addition to the NOAA aircraft, the Air Force Reserve Command (AFRC) 53rd Weather Reconnaissance Squadron (WRS) operates WC-130J aircraft with similar capabilities as the NOAA WP-3D.

Noteworthy TCs flown by these aircraft in 2018 were Hurricanes Florence, Michael, and Lane. For Hurricane Florence (Fig. 5.3.1), there were 9 G-IV surveillance flights that deployed 281 of the new RD-41 dropsondes over five days. There was about 64 hours of data collected by the Stepped Frequency Microwave Radiometer (SFMR) and tail Doppler radar (TDR) for evaluation, but not yet ready for real-time operational transmission. There were 3 WP-3D flights before it was diverted to fly Isaac, that deployed 82 of the old RD-94 dropsondes and 20 AXBTs for ocean profiling. Also, TDR data was transmitted operationally as was 24 hours of SFMR surface wind data. There were also 8 WC-130J reconnaissance flights which deployed 196 of the RD-94 dropsondes and also provided 64 hours of SFMR surface wind data. As part of the TROPIC ocean profiler operational demonstration project, 20 AXBTs and 10 Woods Hole Oceanographic Institution (WHOI) Alamo floats were deployed, which provided data in near real-time. The AXBT data was sent in real time and assimilated by the Navy coupled COAMPS-TC model.

For Hurricane Michael, there were 3 G-IV flights and deployed 87 dropsondes, 6 WP-3D flights that deployed 102 dropsondes, and 74 ocean profilers. There were 8 WC-130J flights that deployed 81 dropsondes and one WC-130J flight in which 8 drifting buoys from Scripps Oceanographic institution (SOI) were deployed along with 3 EM/APEX ocean profiling floats (current, temperature and salinity profiles). There was a total of 270 dropsondes deployed in Michael.
A new U.S. observing strategy for the aircraft flight track planning was implemented for the first time in Central Pacific Major Hurricane Lane (2018), and operationally for the first time in Hurricane Florence, was the technique developed by Dr. Ryan Torn (SUNY/Albany) of computing numerical model uncertainty fields for track and intensity utilizing ensemble model output, which in this case was the ECMWF global model. The flight tracks were then designed to sample the coherent regions of maximum uncertainty within in an effort to reduce model uncertainty. It still remains to be shown if this would be in fact the case.

5.3.1.2 DOTSTAR

The DOTSTAR (Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region) program was carried out during 2003 - 2013 (Wu et al., 2004, 2005, 2006, 2007a-b; Chou and Wu, 2008; Chen et al., 2009; Yamaguchi et al., 2009; Wu et al., 2009a-c; Chou et al., 2010; Wu et al., 2010; Chen et al., 2011; Chou et al., 2011; Liang et al., 2011; Weissmann et al., 2011; Yen et al., 2011; Huang et al., 2012; Jung et al., 2012; Wu et al., 2012a,b). A special collection issue named “Targeted Observation and Data Assimilation for Improving Tropical Cyclone Predictability” was published in Monthly Weather Review in 2009 and 2010. During 2003-2017, 79 surveillance flight missions were conducted for 63 typhoons, with 414 flight hours and 1291 dropwindsondes released in the DOTSTAR project (Fig. 5.3.2). The result is a robust 20% improvement in numerical models, such as NCEP GFS, that represents significant contribution to the study of typhoons (Chou et al., 2011).

Widely recommended as a fully-developed program, DOTSTAR was included in the international THORPEX/PARC initiative under the World Meteorological Organization (WMO) and in collaboration with the Japanese program – Typhoon Hunting 2008 (TH08), led by Dr Tetsuo Nakazawa of JMA/MRI; and the US program – Tropical Cyclone Structure 2008 (TCS-08) led by Dr Patrick Harr of Naval Postgraduate School. This was the first field observation program in which four airplanes including two jets for surveillance, a P-3 and a C-130 for reconnaissance were used to observe tropical cyclones in the western North Pacific. The unprecedented data collected are highly valuable for understanding the physics and dynamics of the genesis, structure change, recurvature, extra-tropical transition, targeting observation, and predictability of tropical cyclones.

A mesoscale model coupling the Weather Research and Forecasting model and the three-dimensional Price-Weller-Pinkel ocean model have been used to investigate the dynamical
ocean response to Megi (2010). It is found that Megi induces sea surface temperature (SST) cooling very differently in the Philippine Sea (PS) and the South China Sea (SCS). The results are compared to the in situ measurements from the Impact of Typhoons on the Ocean in the Pacific (ITOP) 2010 field experiment, satellite observations, and ocean analysis field from Eastern Asian Seas Ocean Nowcast/Forecast System of the U.S. Naval Research Laboratory (Wu et al., 2016) The continuing work in DOTSTAR has shed light on typhoon dynamics, improved the understanding and predictability of typhoon track through the targeted observations, placed the DOTSTAR team at the forefront of international typhoon research, and has made a significant contribution to the study of typhoons in the northwestern Pacific and East Asia region.

Starting from 2013, the DOTSTAR team transferred the standard operation procedure of DOTSTAR to the Central Weather Bureau and the Taiwan Typhoon and Flood Research Institute. More details can be found at: http://typhoon.as.ntu.edu.tw/DOTSTAR/en/. In 2017-2018, collaborating with DOTSTAR, the targeted aircraft observation of TCs have also been developed in both Japan under T-PARCII (section 7.3.1.5), and with Hong Kong, China (next section).

5.3.1.3 TC reconnaissance flights in South China Sea by Hong Kong Observatory

Hong Kong Observatory (HKO) commenced the reconnaissance flight for TCs over the northern part of South China Sea in 2011. In collaboration with the Government Flying Service (GFS), flight missions were conducted in the Flight Information Region (FIR) of Hong Kong using a fixed-wing aircraft equipped with a data probe and a meteorological measurement system to provide high resolution winds, temperature and relative humidity data along the flight path (Chan et al., 2011). The flight observations were used to analyse the position, intensity and structure in near real-time basis to support the assessment of weather changes associated with the passage of TCs (Fig 5.3.3). The flight data also contributed positively to TC track forecast for the next 2-3 days, as well as analysis and forecast of TC structure in mesoscale NWP model (Wong et al., 2013).
In 2016, a dropsonde measurement system was installed on board a new jet aircraft of GFS (Bombardier Challenger 605; link: https://www.gfs.gov.hk/eng/aircraft.htm). Since the first dropsonde mission conducted on 27 September 2016 during the approach of Megi, about 20 flight missions with more than 130 dropsondes were deployed to collect vertical profiles of temperature, dew point, wind speed and wind direction of TCs in the northern part of South China Sea up to September 2018. Dissemination of dropsonde observation through GTS in a near-real-time basis has also been implemented.

HKO also contributed the TC surveillance flight data to various international and regional projects including ESCAP/WMO Typhoon Committee EXOTICCA (see next sub-section), WMO/WWRP Research Demonstration Projects (RDPs), namely SCMREX (Southern China Monsoon and Rainfall Experiment) (Luo et al., 2017) and UPDRAFT (Understanding and PreDiction of Rainfall Associated with landFalling Tropical cyclones). On 15 September 2018, reconnaissance flights were conducted in cooperation with DOTSTAR team (Fig. 7.3.4) to obtain vertical profiles of observations in Mangkhut that were useful for analysis of TC structure, intensity and future NWP modelling studies or model validation.

Figure 5.3.3. Reconnaissance flight for Severe Typhoon Utor during 09-11 UTC on 13 Aug 2013 with two photographs taken near its centre (left) and estimated near surface winds overlaid on flight path. The range of gale force wind over northeastern quadrant was analysed to be about 290 km that compared favourably with the wind distribution from the NOAA multi-platform wind analysis (155 nm highlighted in yellow near the bottom of right panel).

Figure 5.3.4. Near-surface winds sampled within the circulation of Mangkhut on 15 September 2018 by dropsonde missions of HKO (northwest quadrant) and DOTSTAR (northeast quadrant) together with other surface wind observations.
5.3.1.4 EXOTICCA

The Experiment on Typhoon Intensity Change in Coastal Area (EXOTICCA) was commenced in 2014 and coordinated by the Shanghai Typhoon Institute of China Meteorological Administration (STI/CMA) and the Hong Kong Observatory (HKO). The major objectives of EXOTICCA are to conduct: (a) field campaigns on the intensity and structure characteristics of the target offshore and landfalling TCs using integrated and novel observation techniques; and (b) demonstration research on the utilization of the synergized field observation data with the aim of deepening the understanding of the mechanisms of structure and intensity change, to improve the relevant capability of operational analysis, numerical weather prediction (NWP) models forecast, reliable storm surge and flooding and associated risk assessment (Lei et al., 2017).

Several new observational platforms have been implemented by STI/CMA during the observational field campaign experiments. The low-altitude (400-600m) UAV observation targeting tropical cyclone Chanhom (1509) was conducted on 10 July 2015 where wind and temperature data along the flight path were collected to analyse profiles in the lower boundary layer (Fig. 5.3.5).

To obtain in-situ observations of the TC structure, particularly the vertical profiles of wind, temperature, pressure and moisture of the inner-core or in different quadrants of the storm at the same time, a “rocket-dropsonde” system was developed by STI/CMA by using a rocket platform to release dropsondes over target areas. The positions of dropsondes are determined by the Beidou satellite and the dropsonde observations are transmitted to the ground operation centre through the Beidou satellite.

A special field campaign using the rocket-dropsonde system was conducted by STI/CMA for Severe Typhoon Mujigae (1522) in October 2015. The rocket was launched at Wanning located in the southeast coast of Hainan Island, about 330 km west-southwest to the center of Mujigae, at 15 UTC on 3 October 2015. Four dropsondes were released in the periphery of the inner-core of Mujigae (Fig 5.3.6) where vertical profiles of wind, temperature, pressure and
humidity were collected. HKO also conducted a surveillance flight passing the centre of Mujigae earlier that evening. This collaborative operation provided a valuable opportunity to validate the air-borne observations of TC from different platforms or techniques to analyze the inner-core structure of Mujigae.

5.3.1.5 T-PARCII

The T-PARCII (Tropical cyclone-Pacific Asian Research Campaign for Improvement of Intensity estimations/forecasts) project (website: [http://www.rain.hyarc.nagoya-u.ac.jp/~tsuboki/ kibanS/index_kibanS_eng.html](http://www.rain.hyarc.nagoya-u.ac.jp/~tsuboki/ kibanS/index_kibanS_eng.html)) aims to improve estimations and forecasts of tropical cyclone intensity as well as storm track forecasts since 2016. The T-PARCII project is funded by the Japanese Grant-in-Aid for Scientific Research (KAKENHI) program for the period from 2016 to 2020. The basic and important facility for in-situ observations using aircraft is a dropsonde system. For an effective observation of tropical cyclones, a multi-channel dropsonde receiver and easy-to-use dropsonde are necessary. In the T-PARCII project, a new dropsonde and four-channel receiver has been developed by the Nagoya University and the Meisei Electric with very light weight and without a parachute, which often causes trouble when being launched from an aircraft. The terminal fall-speed is approximately 13 m s\(^{-1}\) in the lower atmosphere. The flight mission is conducted using the Gulfstream II aircraft operated by the Diamond Air Services (DAS) based in the Nagoya City Airport. A test flight with the new system was performed on 27 July 2017 to the north of the Noto Peninsula, Japan. The temperature sensor is furthermore improved to increase its response. Although a dropsonde is disposable, the newer version of a dropsonde using environment-friendly materials is under development.
The first flight missions of T-PARCII were performed around 06 UTC on 21 October and around 01 UTC on 22 October 2017 to observe the very large and intense Typhoon Lan (2017) to the southeast of Okinawa. This observation was performed as a joint observation with the Taiwan DOTSTAR team which observed Typhoon Lan around 12 UTC October 21, 2017. Dropsondes were released from a height of 43,000 ft. The eyewall was penetrated twice on 21 and once on 22 October. During the two flight missions, 4, 5, and 17 dropsondes were deployed in the eye, eyewall, and surrounding region, respectively (Fig. 5.3.7). The observation provides very important data for the improvements of intensity estimation and forecast as well as for studies of the typhoon (Ito et al., 2018).

On 25-28 September 2018, four reconnaissance flights occurred across the inner core of Typhoon Trami by the jet aircraft of Nagoya University and the DOTSTAR project. A total of about 80 dropsondes were deployed by the two aircrafts in 4 days to collect meteorological profiles over Trami’s inner core, eye and eyewall regions.

![Dropsonde locations deployed in T-PARCII over an infrared satellite image from 06:52:30 UTC 21 October 2017. The closest surface dropsonde observation time to the satellite image time is indicated by a rectangle. (b) Same as (a) but at 01:15:00 UTC 22 October 2017.](image)

**Figure 5.3.7**

5.3.2.1 Development of measurement strategies and technologies for improvement of monitoring TC intensity, structure and environment

Recent advances have been made in observational technology: (a) experimental use of new Unmanned Aerial Vehicles (UAVs) of various sizes such as the NASA / Northrup-Grumman Global Hawk, used during the HS3, SHOUT and EPOCH campaigns from 2012-2017, the NOAA/Raytheon Coyote, and (b) improvements in aircraft expendable instrumentation such as improved dropsonde technology with the NCAR/Vaisala RD-41 dropsonde, the Meisei Electric dropsonde and the Yankee Environmental Systems HDSS/DDS rapid/multi-sonde deployment system and (c) air-deployable ocean floats (Alamo, EM-APEX), drift buoys (Scripps) and ocean profilers (AXBTs, AXCPs, AXCTDs).
Transition of airborne remote sensing technology to operations has also been made such as on: SFMR for surface wind speed and rain rate, Tail Doppler Radar for 3-D winds and rain rate, and Wide-swath Scanning Radar Altimeter (WSRA) for wide swath ocean surface wave spectra. Research development are underway in the development of aircraft remote sensing systems for future operational observations: (a) HIRAD and HIWRAP/IWRAP for wide-swath surface wind vector and vertical Doppler wind and rain profiles to complement the Tail Doppler Radar (TDR); (b) HAMSR for 3D mapping of the TC inner core temperature and moisture fields; (c) Doppler Wind Lidar for improved boundary layer wind observations; and (d) expendable ocean profiler for high altitude deployment.

In IFEX, significant advances have been made in the real-time display of aircraft data for NHC forecasters. Analyses of reflectivity and winds from the tail Doppler radar are now available within around 20 minutes of completion of an aircraft pass through the TC center and can be accessed online (Fig. 5.3.8).

**Figure 5.3.8.** Real-time tail Doppler radar analyses from Hurricane Florence (2018). (a) Reflectivity (shaded, dBZ) and winds (barbs, kt) at 2 km altitude from 1512-1840 UTC 10 Sept.; (b) As in (a), but for wind speed (shaded, kt), streamlines at 2 km (black) and 5 km (grey) altitude, and radar-derived diagnostics in text. Black x’s in (b) denote locations where the peak vertical velocity in the 4-16 km layer > 1 m s⁻¹.

In 2018, for the first time, data from the Doppler radar has been ingested into the software in real time that NHC forecasters use to visualize TC structure as they prepare their forecasts. This data can be combined with other data sources, e.g. from GOES-16, to provide an unprecedented look at the TC inner-core for forecasters in real-time (Fig. 5.3.9) to assess features such as vortex tilt, radius of maximum wind and secondary eyewalls, and the presence of deep convection.
5.3.2.2 Collecting observations that span the TC life cycle in a variety of environments for model initialization, model sensitivity studies and evaluation

Many of the IFEX missions have targeted TCs at the early stages of their lifecycle, as this has the potential to capture many important features in a TC’s intensity evolution, including genesis and rapid intensification. The data collected in these missions is used to improve TC intensity forecasting in two ways. First, data is transmitted in real-time to the NOAA Environmental Modeling Center (EMC), where it is assimilated into the operational regional Hurricane Weather Research and Forecasting (HWRF) model. Earlier efforts were successful in developing the capability of transmitting airborne Doppler data in real-time to EMC, with some success in reducing forecast error shown after assimilating this data into the Weather Research and Forecasting (WRF) model using an ensemble Kalman filter (EnKF; Zhang et al., 2009). More recent efforts have continued to show improvements in reducing forecast error using aircraft data, including flight-level, dropsonde, and airborne Doppler radar (Zhang and Weng 2015; Aberson et al., 2015; Weng and Zhang 2016; Tong et al., 2018). Dropsondes from the unmanned Global Hawk aircraft have also been shown to improve TC analyses and forecasts (Christophersen et al., 2017, 2018a,b).

Another way aircraft data improves TC intensity forecasting is by facilitating model evaluation, which can lead to improvements in the representation of physical processes in the model (Zhang et al., 2013). The impact of using observations to improve the representation of vertical eddy diffusivity was shown in Gopalakrishnan et al. (2013) and Zhang et al. (2015, 2017). Using this improved eddy diffusivity results in a shallower and stronger TC boundary layer inflow layer, more consistent with observations, as well as differences in other boundary layer properties such as stability, convergence, and angular momentum advection. These changes have been shown to produce better forecasts of rapid intensification (Zhang et al. 2017), as well as providing a better representation of TC size (Bu et al., 2017). Zhang et al. (2018) used aircraft observations to reduce the horizontal mixing length in HWRF forecasts of
Earl and found that many structural aspects were improved, including storm size, boundary layer heights, warm-core height, and eyewall slope. Biases in both storm intensity and storm size were significantly reduced with the modified horizontal mixing length.

In T-PARCII, the impact of dropsondes through the aircraft missions on forecast skill, data assimilation (DA) and following forecast experiments were conducted using a Japan Meteorological Agency non-hydrostatic model (JMA-NHM) and its mesoscale 4D-VAR system. The DA experiments were performed over twelve 3-h cycles without and with 26 dropsonde observations (CTRL and TPARCII, respectively). The subsequent 36-h forecast experiments were also performed with the initial condition obtained at the end of each DA cycle. The GPS-derived horizontal displacement was considered as the dropsonde drops because the dropsonde may orbit around the TC center significantly (Aberson et al., 2017).

Dropsonde data improved track forecasts across all the forecast hours (Fig 5.3.10 (a)). The maximum improvement rate of 16% was achieved at T+27h to T+30h in the TPARCII experiment. This improvement was consistent with magnitudes of changes in the steering flow. Likewise, the threat score of heavy rainfall events became higher by adding dropsonde observations into the DA system. These results show the potential usefulness of the airborne dropsondes for more accurate track and rainfall forecasts through the high-resolution DA and forecast systems.

Figure 5.3.10. Forecast errors in the CTRL and T-PARCII experiments. (a) Track forecast error against BTA data averaged over the forecasts. The results are shown for CTRL (in blue) and TPARCII (in red). (b), (c) Same as (a) but for root-mean-squared error of Pmin and Vmax against BTA, respectively. (d-f) Same as (a-c) but against RTA.
It is noted that, however, TC intensity forecast skill against the best track analysis (BTA) was generally degraded in the TPARCII experiment. However, this may be an artifact of the quality of BTA. When real-time analysis (RTA) – i.e. warning intensity from RSMC is used as the verification baseline, intensity forecasts in TPARCII yielded comparable or better skill than CTRL. This resulted from better agreement in the central pressure ($P_{\text{min}}$) between RTA and the dropsonde-based analysis, implying that what we think of as “intensity forecast errors” against BTA is just an uncertain estimate of forecast errors. In other words, the inner-core observations are needed not only for the accurate TC intensity analysis but also for evaluating the intensity forecast skill (Fig. 5.3.10).

5.3.2.3 Improve the understanding of physical processes important in intensity change for a TC at all stages of its life cycle

The third IFEX goal is primarily concerned with hypothesis-driven research aimed at better understanding intensity change processes within the TC inner core and its environment. Much of the recent work has focused on the TC response to vertical shear and the structure and distribution of precipitation and its relationship to TC intensity change. HRD has built up a fairly substantial database of airborne Doppler and dropsonde observations over the years. This database has been exploited to examine the composite mean response of the TC kinematic, precipitation, boundary layer, and surface wind field to vertical shear (Reasor et al., 2013; Zhang et al., 2013; Cione et al., 2013; DeHart et al., 2014; Uhlhorn et al., 2014; Hazelton et al., 2015) and to compare vortex- and convective-scale structural differences between intensifying and steady-state TCs (Rogers et al., 2013; Martinez et al., 2017). A recent composite study examines shear-relative structural variations in deep convection as it relates to TC intensity change (Wadler et al., 2018). Numerous case studies have also been conducted that examine the vortex-, convective-, and boundary-layer scale structure of TCs and how they are related to intensity change (Molinari et al., 2013; Stevenson et al., 2014; Montgomery et al., 2014; Rogers et al. 2015, 2016. 2017; Susca-Lopata et al., 2015; Zawislak et al., 2016; Guimond et al., 2016, 2018; Nguyen et al. 2017) and processes important in secondary eyewall formation and eyewall replacement cycles (Didlake et al. 2017, 2018; Dougherty et al. 2018). The understanding gained from these observationally-based studies is being used to guide the development of forecasting tools and model improvements that hold the potential to improve TC intensity forecasts.

5.3.3 Summary and Recommendation

The recent advances in aircraft reconnaissance for tropical cyclones are presented in this report. With new observing techniques, research development and operational applications have been explored that enhance real-time monitoring, analysis and forecast of tropical cyclone intensity and structure, as well as the understanding of their dynamical and physical mechanisms. The following developments of aircraft-based reconnaissance or other airborne observations are recommended with a view to improving nowcasts and forecasts of intensity, rapid intensity changes, and related high-impact weather such as extreme rainfall, high winds and storm surges, for the betterment of disaster-risk preparedness and mitigation:

- to support / organize coordinated field campaigns of various aircraft observational missions and experiments in multiple ocean basins for gathering observational datasets of the whole TC lifecycle and intensity evolution;
to continue development of new aircraft observation platforms such as dropsondes, UAS/UAV, radar/lidar instruments on board the flight vehicles and provide quality observations with high resolution in both space and time;

- to encourage real-time exchange of aircraft observation data;
- to carry out validation of new observation data to understand the data quality of new instruments;
- to conduct technique development and application of aircraft observations in the analysis of TC intensity, wind distribution, and boundary layer structures during the whole TC lifecycle;
- to enhance nowcasting or forecasting techniques of TC intensity, rapid intensity change and associated high-impact weather using the aircraft reconnaissance data or in combination with other meteorological observations;
- to apply new aircraft observation data in NWP model data assimilation, improving model physical processes, intensity and rainfall forecasts and model validation; and
- to document or through training opportunities to enhance capacity of forecasters in RSMCs / TCWCs to apply new aircraft data for improving analysis of TC intensity and structure in supporting more accurate, effective assessment or communication of uncertainty of potential impacts to the users and general public.

**Acronyms used in the report**

- **BTA**: best-track analysis
- **DOTSTAR**: Dropsonde Observation for Typhoon Surveillance near the TAiwan Region
- **EXOTICCA**: Experiment on Typhoon Intensity Change in Coastal Area
- **G-IV**: NOAA Gulfstream IV jet
- **GoM**: Gulf of Mexico
- **HRD**: Hurricane Research Division, NOAA
- **IFEX**: Intensity Forecast Experiment, NOAA
- **NATL**: Western North Atlantic
- **NHC**: National Hurricane Center, NOAA
- **RDP**: WMO/WWRP Research Demonstration Project
- **RTA**: real-time analysis
- **UAS / UAV**: unmanned aerial system / vehicle
- **UPDRAFT**: Understanding and PreDiction of Rainfall Associated with landFalling Tropical cyclones
- **WMO/WWRP**: WMO World Weather Research Programme
- **WPAC**: Western North Pacific

**References**


TOpIC 6. COMMUNICATION OF FORECAST UNCERTAINTY AND WARNINGS USING PROBABILISTIC HAZARD INFORMATION

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Abstracts of Sub-topics

6.1 Understanding TC impacts on society for the purposes of advancing the total warning system concept

Early warning systems (EWSs) for tropical cyclones and other hazards are a major component in disaster risk reduction through the emphasis on disaster preparedness. Despite considerable advances in predictive technologies, disasters associated with hydro-meteorological and geo-hazards particularly tropical cyclones continue to claim many thousands of lives, and causing irreparable damage upon homes, business, property, livelihood and critical infrastructure. These disasters leave impoverished economies in their destructive wake. Rapid and accurate information communication is essential for an effective EWS for disaster risk reduction. This information can be delivered through identified institutions, informing individuals exposed to tropical cyclones and other hazards to take action to avoid or reduce their risk and prepare for effective response. However, as organisational structures increase in complexity so does the distribution of response roles and responsibilities among authorities. The end-to-end early warning system for disaster risk management (DRM) for tropical cyclones and other hazards is comprised of ten individual elements (see description below and accompanying diagram) or systems that work together to create the entire system, a ‘system of systems.’ The integration of each element with appropriate strength is critical for the success of the EWS. One weak element can cause failure of the overall system.

6.2 Communicating Risk & TC Forecast Uncertainty

Over recent years, science and technological advancement in research has rapidly improved data observation, modelling and analysing natural hazards forecast improvement for disaster risk and reduction. Unfortunately, many of these innovations and research advances have not been tailored to benefit communities at risk. These improved forecasts are only as good as they are communicated to the communities they will affect. When communicating warnings, the information suppliers need to use language that is not overly technical or scientific. The suppliers need to keep the audience of the warnings in mind, including their level of understanding and knowledge, to ensure maximum clarity is achieved. Appropriateness and effectiveness of being culturally sensitive should be considered when communicating warning signals. Firstly, understanding embedded indigenous traditions and knowledge of the land can
help authorities gain insight into the hazard characteristics of a certain area. But secondly, due to their in-depth local land knowledge, indigenous people may react defensively to warnings or orders, this should be accounted for with appropriate sensitivity warnings.

6.3 Current and potential use of ensemble forecasts in operational TC forecasting

In order to understand the current and potential use of ensemble forecasts in operational TC forecasting, a questionnaire survey on the use of dynamic ensemble forecasts was conducted to operational TC forecast centers. The results of the questionnaire including areas of research and development that would help TC forecasters to make increased use of ensemble forecast information in the future are presented. Secondly, research and operational progress since the last IWTC in areas of ensemble-based TC/TC-induced track, intensity, genesis, wind, precipitation and flooding, and storm surge forecasting are summarized. Thirdly, the results of a survey on the use of TIGGE in academic papers are presented.

Acknowledgements

The topic co-chairs gratefully acknowledge the efforts and contributions of the Subtopic Rapporteurs (Bapon Fakhruddin, Vikash Prasad, Linus MAGNUSSON, Helen TITLEY & Munehiko YAMAGUCHI) and their respective Working Group members.
TOPIC 6.1 - ADVANCING THE TOTAL EARLY WARNING SYSTEM FOR TROPICAL CYCLONES AND OTHER HAZARDS

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Context

Early warning systems (EWSs) for tropical cyclones and other hazards are a major component in disaster risk reduction through the emphasis on disaster preparedness. Despite considerable advances in predictive technologies, disasters associated with hydro-meteorological and geo-hazards particularly tropical cyclones continue to claim many thousands of lives, and causing irreparable damage upon homes, business, property, livelihood and critical infrastructure. These disasters leave impoverished economies in their destructive wake.

Rapid and accurate information communication is essential for an effective EWS for disaster risk reduction. This information can be delivered through identified institutions, informing individuals exposed to tropical cyclones and other hazards to take action to avoid or reduce their risk and prepare for effective response. However, as organisational structures increase in complexity so does the distribution of response roles and responsibilities among authorities. The end-to-end early warning system for disaster risk management (DRM) for tropical cyclones and other hazards is comprised of ten individual elements (see description below and accompanying diagram) or systems that work together to create the entire system, a 'system of systems.' The integration of each element with appropriate strength is critical for the success of the EWS. One weak element can cause failure of the overall system.

The ten essential elements that combine to build an effective multi-hazard early warning system are:

- Institutional arrangements, which reflect how regulatory frameworks, policies and plans enable and prioritise DRM;
- Earth observation data includes the methods and/or infrastructure available for obtaining earth observation information;
- Data information and collection describes the methods and/or infrastructure for collecting global and regional information;
- Hazard detection includes the data analysis software that are available for detecting hazards based on the information provided;
- Hazard decision support is comprised of the availability of hazard models and understanding whether a threat is imminent or not;
- Warnings and other infrastructure products include how the hazard information are presented in the form of watches, advisories or statements;
Impact based forecasting/warnings use hazard, vulnerability, impact and risk assessments to communicate useful likely impacts, rather than generic hazard information such as wind speeds;
Dissemination and notification includes all methods that pass on hazard and warning information;
Risk communication is the ability for the system to be able to appropriately warn all people and communities who might be impacted; and,
Finally, community connection and response incorporates how the community is able to respond to hazard/impact information and whether the appropriate response is carried out.

The institutional arrangement incorporates how regulatory frameworks, policies and plans enable and prioritise DRM. It can be seen that EWSs are most effective in countries where the government has invested in building a strong regulatory framework and a clear mandate for agencies involved in preparedness (Sendai Framework for Disaster Risk Reduction 2015-2030). A suitable data observation system is critical for detecting tropical cyclones and other hazards to inform the early warning notification. Earth observation data includes the methods and/or infrastructure available for obtaining earth observation information.

Data information and collection describes the methods and/or infrastructure for collecting global and regional information. Global, regional and national data feed into the data and information collection to inform the local hazard warning.

Hazard detection tools include human observation, electronic hardware, operating systems, and data analysis software required to process and analyse signals. Consideration should be taken to ensure compatibility with both the local and global data networks.

Hazard decision support information enables a meaningful interpretation of risk. Determination of the extent to which the hazard will affect should be developed such as through models. Warnings and other infrastructure products include how the hazard information is presented in the form of watches, advisories or statements. These are required to be updated at a frequency which is appropriate to the warning lead time relevant to the particular hazard. Impact based forecasting/warning expresses the impact associated with the forecast. This enables users to interpret the hazard warning in a more meaningful way that relates to their needs.

Systems to disseminate and notify of hazards are becoming increasingly sophisticated due to technology advances such as the internet, social media, and text messages, which can be extremely effective.

Systems of risk communication must be well established, ensuring all stakeholders are effectively notified, including government, decision makers, public, local community, community leaders and tourists. Channels of communication and procedures for providing the warning must be clearly understood by all parties and systems should be regularly checked. Of critical importance in the effectiveness of the Multi-Hazard Early Warning System (MHEWS) is the consideration of community response. This component emphasises the importance of working with the community to understand local knowledge, raise public awareness, tailor warnings to ensure their usefulness and accurate community interpretation of the key message as well as to ensure appropriate response plans and safe evacuation procedures are adequately resourced. Community connection is a two-way network, both receiving...
information and helping to inform decision makers of local constraints through tools such as pre-impact assessments.

Like the links on a chain, the overall system is only as strong as its weakest link. The failure of any one of these individual systems can lead to the overall failure of the entire early warning system and likely increase the adverse impacts to life and infrastructure during an event.

**Recommendations to advance the total early warning system concept for tropical cyclones and other hazards**

Over recent years, science and technological advancement have rapidly improved data observation, modelling and analysis of natural phenomena resulting in forecast improvements. However, there are recent advances in research that have not been transposed to the operational domain and neither are many of the research for operations tailored to serve communities at risk. Accurate forecasts are only effective if they are truly useful and communicated in an effective and efficient manner to the communities that will be affected. Scientific data, predictions and warnings therefore need to be useful by using understandable terminology for a spectrum of users.

In light of the above, the following are offered as recommendations:

- Ensure that the needs of various users are considered. Different stakeholders have different information requirements, thus a thorough understanding of their individual needs can help ensure that they are equipped with relevant and valuable information to properly respond to warnings. When communicating warning alerts, predicted events and the corresponding uncertainty, the communicating authority should consider background information, personal experience, and culture of the warning recipients. Warnings that are tailored to the receiving group can add to the effectiveness of the warnings, e.g. if the population affected has experienced a similar hazard previously. A framework is needed to strengthen and build the individual's capacity to understand suitably and effectively respond to warnings. Bias, non-confidence may lower the ability of the individual or even the community to respond to warnings such as those associated with tropical cyclones, and may even at times doubt the severity of the warnings.

- Population groups with minimal or no access to technical support (e.g. cell phones, internet access, education, support groups) could be more vulnerable when receiving warnings. The consequences of these limitations must be taken into account when designing warning systems at the community level.

- When communicating warnings, the information suppliers need to use language that is not overly technical or scientific. Those communicating the warnings needs to ensure that maximum clarity and usefulness are achieved by careful consideration of the level of understanding and knowledge of the recipients of the warnings. The general public may often not understand the uncertainties associated with a forecast. The public’s possible lack of knowledge and consequent inability to interpret information correctly, can lead to contradicting expectations between themselves and the experts behind the warnings.
• Culturally sensitivity should be considered when communicating warning signals. Firstly, understanding embedded indigenous traditions and knowledge of the land can help authorities gain insight into the hazard characteristics of a certain area. Secondly, due to their in-depth local land knowledge, indigenous people may react defensively to warnings or orders, this should be accounted for with appropriate sensitivity in the warnings.

• A participatory approach should be encouraged when designing maps to communicate tropical cyclone warnings. The maps will only be effective and useful if they encourage the public to take appropriate action. Misinterpretations of probability maps are common among the public, as they generally require prior knowledge to recognise and make sense of the symbols.

• Working collectively with all stakeholders could improve the communication of tropical cyclone warnings. Tropical cyclone warnings should be seen as a system which consider the community’s perception of risk, social norms, and resource availability.

• Foster dialogue between different actors in improving warning systems by providing a platform for stakeholders to raise challenges they have with the EWS. The information providers/authorities can use this feedback mechanism to improve the EWS and make it more user-friendly. The procedures to be implemented during a tropical cyclone event should be discussed in advance and in-depth with relevant stakeholders. Regular meetings with key stakeholders will improve the progress of effective communication.

• Recognition and in-depth understanding of the specific roles and responsibilities of the various agencies/organisations/groups responsible for different levels or components of the EWS. are essential for EWS success. The effectiveness of tropical cyclone EWSs is highly dependent on the knowledge and experience of the governing body and authority. Even though the scientists provide the information, it is the government’s responsibility to understand and therefore act on the warnings and communicate to the public.

• Emergency guidelines should not totally rely upon past experience as past events for various reasons may not at all times provide good guidelines for future events and response plans.

• Develop targeted lessons in schools/ educational facilities as the youth can serve as active agents that could help propagate cyclone knowledge to the broader community.

• Authorities must remember that media outlets may often have the same minimal technical understanding as the general public and thus should ensure that warning information is conveyed to the media correctly.

• Explore new communication platforms/channels such as the public’s updates posted on social media to map the impacts of events as they occur. There is an increasing demand for event monitoring through this medium of communication. Posts and photos can help strengthen the credibility of warning updates.
<table>
<thead>
<tr>
<th><strong>World Meteorological Organisation (WMO) – Climate Risk Early Warning System (CREWS)</strong></th>
<th><strong>Pacific Resilience Program (PREP) – Multi-Hazard Early Warning System (MHEWS)</strong></th>
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<tr>
<td>The Climate Risk and Early Warning Systems (CREWS) initiative, launched in 2015, has been operating in 19 countries in Africa and the Pacific. It is improving early warning systems to protect the most vulnerable populations against hazards like tropical cyclones and floods in Least Developed Countries and Small Island Developing States. CREWS is a multilateral fund that supports the most vulnerable countries by helping people understand the risks they face, monitor hazards, issue simple warning messages that reach everyone at risk, and know how to respond. (CREWS Initiative, 2017)</td>
<td>The development objective of the Pacific Resilience Program Project for Pacific Islands including Samoa is to strengthen early warning, resilient investments, and financial protection of Samoa. The project comprises of four components. The first component, strengthening early warning and preparedness (estimated cost including contingencies) objective is to increase the resilience of the participating phase one countries and the Pacific region as a whole to natural hazards such as cyclones, coastal and riverine flooding, volcanic eruptions, tsunamis, and earthquakes by improving the quality of forecasting and warning services as well as disaster preparedness. The second component, risk reduction and resilient investments (estimated cost including contingencies will finance entry level resilient investments, such as the retrofitting of public buildings (for example, schools, health centres) to meet internationally accepted building standards for resilience (including appropriate consideration of gender requirements)). The third component, disaster risk financing objective is to strengthen the financial resilience of the participating Pacific Island countries (PICs) to disaster events by enabling them to secure access to immediate liquidity post disaster for low, medium, and high risk events. The fourth component, project and program management objective is to provide efficient and effective implementation support to the projects in each country, including staff, operating costs, monitoring and evaluation, and the cost of audits. (World Bank, 2018)</td>
</tr>
</tbody>
</table>
TOPIC 6.2 - COMMUNICATION OF RISK, UNCERTAINTY & IMPACT ASSOCIATED WITH TROPICAL CYCLONES

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(NOTE: Only powerpoint slides available)
Uncertainty, Risk and Impact

Topics

- Why do we need to communicate these?
- Challenges
- Opportunities
  - Recent trends – Social Media
  - Future possibilities – role of forecasters
Customers are varied

- Intelligence (plus evolving)
- Risks - exposure and vulnerability
- Impact
- Needs/demands and requirements – hence need for tailored, personalised, location specific products and services – delivered through User Centered Design

Uncertainty, Risk and Impact
Knowledge of customer requirements

Uncertainty, Risk and Impact
Knowledge of customer requirements (Customer Matrix)

<table>
<thead>
<tr>
<th></th>
<th>7-28 days</th>
<th>3-7 days</th>
<th>1-2 days</th>
<th>Within 24 hrs</th>
<th>IMPACT</th>
<th>Post impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal</td>
<td>Outlook</td>
<td>Watch</td>
<td>Warning</td>
<td>Alert</td>
<td></td>
<td>Recovery</td>
</tr>
<tr>
<td>Pre-planning</td>
<td>Highest value decisions are made to pre-position resources</td>
<td>Need for probabilistic or “what-if” scenarios to refine plans</td>
<td>Rapid warning updates, identify highest risk zones</td>
<td>Pre-assessment of impact areas, location-specific push notifications</td>
<td>Lack of situational awareness</td>
<td></td>
</tr>
</tbody>
</table>

Decision support is required – communicating risk, uncertainty and impact
Uncertainty, Risk and Impact
Challenges – Public perceptions

- Peter Otto’s paper starts off by saying, "we didn’t do anything because we thought, it’s just another… (Honor, 2015)"

- Hurricane Florence (Fox News)
  - Wayne Mills, from North Carolina mentions, “If the storm stayed a Category 4, I definitely would have left”
  - Famous Roberts, a corrections officer from Trenton, “Like a lot of people (we) didn’t think it was actually going to be as bad,” he said. “With the category drop ... that’s another factor why we did stay.”

- Cyclone Debbie field survey in Mackay –
  - "I didn’t go because the guy living two doors down is a SES volunteer and he didn’t go."
  - "We have seen it before. Debbie was going to make landfall (referring to the track forecast) 200 km to the north. We knew she’ll be alright."

---

Uncertainty, Risk and Impact

![5-Day Forecast vs. Observed Rainfall](image-url)

As Hurricane Florence approached the North Carolina coast last Thursday, Sep. 13, 2018, the NWS was forecasting extreme rainfall and catastrophic flooding in the coming days. Here’s a look at how the forecast compares with the observed rainfall.
Uncertainty, Risk and Impact
Challenges (Typhoon Haiyan - 2013)

- The tendency for citizens to respond to risk information and ultimately survive the threat is influenced by many factors that go beyond receiving accurate and timely information. (Morrow and Lazo, 2015).

- When Typhoon Yolanda/Haiyan hit the Philippines, over 6,300 people were killed despite consistent forecasts of a severe threat to the region for several days before the event. (Otto et al, 2016).
Uncertainty, Risk and Impact

Opportunity – Social Media

For more information go to https://www.weather.gov

The information from the National Oceanic and Atmospheric Administration shows the potential areas affected by Hurricane Florence. Residents in the affected regions should prepare for heavy rain, strong winds, and potential flooding. It is important to stay updated with the latest forecasts and follow any advice given by local officials.

2. Large swells affecting Bermuda and portions of the U.S. East Coast will continue this week. These swells will result in life-threatening surf and rip currents.

Uncertainty, Risk and Impact

Opportunity – Social Media

Storm surge will be a huge factor for Hurricane Florence. Check out what it might look like with @TWCErikaNavarro:

The real surge. Brilliant and important work by @weatherchannel illustrating the impact of storms: https://www.weatherchannel.com/surge-prediction
Uncertainty, Risk and Impact

Opportunity - Forecaster's role

Changing forecaster role - Focus on higher value function - providing Customer Decision Support
(Communicating insight, knowledge, wisdom, threat, risk, impact, uncertainty, urgency and hazard severity)

Right tools - right processes - right capability - right delivery

Principles

EFFICIENT, Robust, Resilient, Interoperable, Scalable, Standardized, Nationally consistent, Flexible and Reliable

Thank you

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TOPIC 6.3 - CURRENT AND POTENTIAL USE OF ENSEMBLE FORECASTS IN OPERATIONAL TC FORECASTING

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Working Group members: Matthew Boterhoven, BoM, Australia, Mark DeMaria, NHC, USA, Nadao Kohno, MRI/JMA, Japan, Marie-Dominique Leroux, RSMC La Reunion, France, Ryan Torn, State University of New York, USA, Hui Yu, STI, China

Abstract
In order to understand the current and potential use of ensemble forecasts in operational TC forecasting, a questionnaire survey on the use of dynamic ensemble forecasts was conducted to operational TC forecast centers. The results of the questionnaire including areas of research and development that would help TC forecasters to make increased use of ensemble forecast information in the future are presented. Secondly, research and operational progress since the last IWTC in areas of ensemble-based TC/TC-induced track, intensity, genesis, wind, precipitation and flooding, and storm surge forecasting are summarized. Thirdly, the results of a survey on the use of TIGGE in academic papers are presented.

6.3.1 Introduction

Over the past 25 years dynamical ensemble forecasts have been routinely produced by NWP centers. Ensemble forecasting can help to capture situation-dependent uncertainty in the track, intensity and hazard forecasts for existing tropical storms, and provide probabilistic information about TC genesis. Many global NWP centers produce TC track and intensity forecasts based on their ensemble prediction systems, share these via the TIGGE cyclone exchange program, develop TC forecast products, and perform verification. In many operational TC forecast centers ensemble forecasts are available and consulted by forecasters. This sub-topic aims to document the current availability and use of ensemble forecasts in operational TC forecasting, and also suggest recommendations for where to focus future research and development in order to unlock their potential benefit and increase the use of this probabilistic ensemble forecast information in operational TC forecasts and warnings. This report contains the results of a questionnaire to operational TC forecast centers on their use of dynamic ensemble forecasts (5.3.2), a summary of research and operational progress in this topic since the last IWTC, compiled with the help of the working group members (5.3.3), a
survey of the use of TIGGE forecasts in academic papers (5.3.4) and a summary and recommendations (5.3.5).

6.3.2  Questionnaire on the use of dynamic ensemble forecasts in operational TC forecasting

6.3.2.1  Introduction and aims of the questionnaire

WMO’s 10-year high impact weather research project, HIWeather, aims to enable increased global resilience to severe weather by improving forecasts of severe weather and its impacts, and the communication of information to users, especially emergency managers (WMO, 2014). As a project within HIWeather, and in association with the WMO/WWRP PDEF Working Group, a group of international researchers started a collaboration aimed at enhancing collaboration amongst the research and operational community on the topic of ensemble forecasting and verification of TCs. The first activity was to design and circulate a questionnaire to all operational TC forecasting centers around the world asking about their use of dynamical ensemble forecast information. The questionnaire aimed to report to IWTC-9 a baseline on the current use of ensembles at global operational TC forecast centers, and help shape future research and development. Its more detailed objectives were as follows:

i) To document the current availability of ensemble forecasts in TC forecast centers, and their use by operational forecasters.

ii) To ascertain how uncertainty is represented in the operational warnings for track, intensity, genesis and hazards from their center, and whether or not this uncertainty information is taken from dynamical ensemble forecasts.

iii) To obtain examples where probabilistic forecasts have been successfully integrated in to operations, but also occasions where hurdles have prevented them from being fully utilized.

iv) To collate forecaster feedback on where they would like to see future research and development focused to enable them to make wider use of ensemble forecasts.

A total of 60 questionnaire responses were received from 25 different centers around the world (see Figure 1). There is a good balance globally, with at least 14 respondents having forecast interest in each of the global basins. The majority of respondents were operational forecasters, but there were also inputs from managers, researchers, and others such as technical developers. The results will now be summarized with respect to the four main objectives of the questionnaire.

6.3.2.2  Current availability and use of ensemble forecasts

Dynamic ensemble forecasts were used by nearly all respondents (95%). Figure 2 shows that they are viewed as particularly important in track and genesis forecasting, with most respondents also using them in hazard forecasting and impact-based forecasting. They are less well used in intensity forecasting, and are used least in forecasting TC size/structure and extra-tropical transition (although this result may be influenced by not all of the forecasters being involved in predicting this process). Over half of respondents were able to use ensemble-based products created at their center, but even larger numbers looked at online products from other centers or products sent by global NWP centers, either in combination with those produced in-center, or in many cases being reliant on these external sources of ensemble forecast information. The most frequently used ensemble models worldwide are the NCEP
GEFS and the ECMWF ENS ensemble, followed by MOGREPS-G from the UK Met Office, JMA’s global ensemble and the Canadian global ensemble. A range of other ensembles are used by a smaller number of respondents.

Figure 1. Organization of respondents (including RSMC/TCWC where applicable)

Figure 2. Responses to the question: “How important would you say ensemble forecasts are in each area of TC forecasting?”

Over 90% of respondents used multi-model ensemble forecasts (multiple dynamical ensembles), with around half using a full probabilistic multi-model ensemble combination and half mainly by comparing one ensemble with another, but less than half use any calibrated ensemble forecasts. Figure 3 shows that the product type used most regularly was the
ensemble mean track, followed by the tracks from the ensemble members, which were used more regularly than the strike probabilities created from them. This reflects how the ensembles may sometimes be being used in a deterministic-focused environment, where individual tracks can be overlain and compared to the deterministic tracks, as opposed to focusing on the full probabilistic forecast information. However, the probabilistic information in the genesis products is well-used. It was noticeable that many respondents were keen to have future access to additional ensemble-based products such as landfall probability, storm surge, river discharge, flood risk and impact-based products.

Figure 3: Responses to: “Which ensemble-based or probabilistic products do you use?”

More than half of people for track, and a third for intensity, said that they mainly used ensemble forecasts to compare the ensemble mean forecasts to the deterministic forecasts. Half of the respondents stated that they used the full probabilistic forecast information provided by the ensemble in their operational forecasting. For track 77% found the spread useful to provide situation-dependent uncertainty, falling to 33% for intensity.

6.3.2.3 How is uncertainty represented in operational warnings?

Tables 1-4 detail how forecast uncertainty is represented in operational forecasts and warnings issued from each separate center (where this information was available from respondents).

Table 1 shows that for track forecasting, there is a clear discrepancy between the number of operational TC forecasters who use and value ensemble forecast information, as shown in the previous section, and the pull-through in to operational forecast products of the probabilistic guidance that ensembles can provide. Although uncertainty is generally shown (via a circle, cone or error swath), this is based only on historical forecast error statistics in forecasts from
most centers, with only two RSMCs (La Reunion and Tokyo) and two other centers (TCWC Wellington and MeteoFrance New Caledonia) including ensemble forecasts in the calculation. There is no standard forecast length or frequency and rather than a standard global definition, each center chooses its own uncertainty definition for the percentage of storms contained in the cone/swath/circle (between 66 and 80%). Table 2 shows how only RSMC Honolulu and RSMC Miami said that uncertainty was included in their intensity forecasts, with this being in the form of wind speed probabilities from a statistical model in both cases. Dynamical ensemble forecasts are however often included alongside consensus forecasting, climatological information, and forecaster judgement in operational TC genesis forecasts (Table 3). Table 4 shows that the expression of uncertainty and the use of ensembles in operational hazard forecasts varies considerably, with products often taking the form of named or colour-coded categories assigned based on probabilities (statistical or dynamical).

Table 1. Operational track forecasts from each TC forecasting center

<table>
<thead>
<tr>
<th>Center name</th>
<th>Forecast length / frequency</th>
<th>How is uncertainty represented?</th>
<th>How is it calculated?</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSMC Tokyo</td>
<td>5 days / 8 times a day</td>
<td>Circle containing 70% of TCs</td>
<td>Historical forecast error statistics (up to 72 hours) and ensemble spread (after 96 hours)</td>
</tr>
<tr>
<td>RSMC Honolulu</td>
<td>5 days / 6 hourly</td>
<td>Cone containing 67% of TCs</td>
<td>Historical forecast error (5 year)</td>
</tr>
<tr>
<td>RSMC La Reunion</td>
<td>5 days / 6 hourly</td>
<td>Cone containing 75% of TCs</td>
<td>Based on both ensemble spread and historical forecast error, (Dupont et al. 2011)</td>
</tr>
<tr>
<td>RSMC Miami</td>
<td>5 days publicly, 7 days internally / 6 hourly (more frequent when necessary)</td>
<td>Cone containing 67% of TCs</td>
<td>Previous 5 years of track error for that basin</td>
</tr>
<tr>
<td>RSMC New Delhi</td>
<td>5 days / 6 hourly (and 3 hourly updates for intervening)</td>
<td>Cone containing 72% of TCs</td>
<td>Historical forecast error statistics</td>
</tr>
<tr>
<td>TCWC Jakarta</td>
<td>3 days / 6 or 12 hourly</td>
<td>Cone containing 80% of TCs</td>
<td>Consensus spread. Patterns obtained from wind model forecasts, and sometimes the form is modified manually to make the shape smoother.</td>
</tr>
<tr>
<td>TCWC Perth</td>
<td>7 days / 1, 3, or 6 hourly</td>
<td>Cone</td>
<td>Situation dependent, usually either consensus spread or climatological uncertainty but can be manipulated.</td>
</tr>
<tr>
<td>TCWC Wellington</td>
<td>24 hours, but up to 5 days if a threat to NZ / 6 hourly</td>
<td>Cone containing 70% of TCs</td>
<td>Calculated based on consensus spread, ensemble spread and climatological uncertainty.</td>
</tr>
<tr>
<td>Joint Typhoon Warning Center (JWTC)</td>
<td>5 days / 6 hourly</td>
<td>Error swath</td>
<td>Calculated by adding the JTWC 5-year running mean forecast track error to the forecast 34-knot wind radii at each forecast time.</td>
</tr>
<tr>
<td>PAGASA</td>
<td>5 days / 6 hourly</td>
<td>Cone / circle containing 70% of</td>
<td>Historical forecast error statistics</td>
</tr>
</tbody>
</table>
### Table 2. Operational intensity forecasts from each TC forecasting center

<table>
<thead>
<tr>
<th>Center name</th>
<th>Forecast length / frequency</th>
<th>Is uncertainty represented, and if so how?</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSMC Tokyo</td>
<td>3 days / 8 times a day</td>
<td>No</td>
</tr>
<tr>
<td>RSMC Honolulu</td>
<td>5 days / 6 hourly</td>
<td>Yes, wind speed probabilities for 34/50/65 knots – Monte Carlo simulation</td>
</tr>
<tr>
<td>RSMC La Reunion</td>
<td>5 days / 6 hourly</td>
<td>No</td>
</tr>
<tr>
<td>RSMC Miami</td>
<td>5 to 7 days / 6 hourly</td>
<td>Yes, wind speed probabilities</td>
</tr>
<tr>
<td>RSMC New Delhi</td>
<td>5 days / 6 hourly (3 hourly updates for intervening)</td>
<td>No</td>
</tr>
<tr>
<td>TCWC Jakarta</td>
<td>3 days / 6 hourly</td>
<td>No</td>
</tr>
<tr>
<td>TCWC Perth</td>
<td>7 days / 1, 3 or 6 hourly</td>
<td>No</td>
</tr>
<tr>
<td>TCWC Wellington</td>
<td>24 hours but up to 5 days if a threat to NZ / 6 hourly</td>
<td>No</td>
</tr>
<tr>
<td>Joint Typhoon Warning Center (JTWC)</td>
<td>5 days / 6 hourly</td>
<td>No (only qualitatively in discussions)</td>
</tr>
<tr>
<td>PAGASA</td>
<td>Only forecast the TC by category / 6 hourly</td>
<td>No</td>
</tr>
<tr>
<td>WFO Guam</td>
<td>5 days / 6 hourly</td>
<td>No</td>
</tr>
<tr>
<td>Center name</td>
<td>Forecast length / frequency</td>
<td>How is uncertainty represented?</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>----------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>Thai Meteorological Department</td>
<td>3 days / 3, 6, 12 hourly depending on situation</td>
<td>No</td>
</tr>
<tr>
<td>MetMalaysia</td>
<td>7 days / 6 hourly</td>
<td>No</td>
</tr>
<tr>
<td>Meteo-France New Caledonia</td>
<td>3 days / 6 hourly</td>
<td>No</td>
</tr>
<tr>
<td>Meteo-France - Martinique</td>
<td>5 days / 6 hourly</td>
<td>No</td>
</tr>
<tr>
<td>Hong Kong Observatory</td>
<td>5 days / 24 hourly</td>
<td>No</td>
</tr>
<tr>
<td>Canadian Hurricane Center</td>
<td>5 days / 6 hourly</td>
<td>No</td>
</tr>
<tr>
<td>RSMC Tokyo</td>
<td>1 day / 8 times a day</td>
<td>Not represented</td>
</tr>
<tr>
<td>RSMC Honolulu</td>
<td>5 days / 6 hourly</td>
<td>High/medium/low categories with assigned probabilities</td>
</tr>
<tr>
<td>RSMC La Reunion</td>
<td>5 days / daily</td>
<td>Probability categories (very low, low, moderate, high, very high)</td>
</tr>
<tr>
<td>RSMC Miami</td>
<td>5 days / 6 hourly</td>
<td>Percentages to nearest 10% that are grouped into high/medium/low categories</td>
</tr>
<tr>
<td>RSMC New Delhi</td>
<td>5 days / daily</td>
<td>Nil, low, Fail, Moderate, High corresponding to 00, 1-25, 26-50, 51-75, 76-100% of probability</td>
</tr>
<tr>
<td>TCWC Jakarta</td>
<td>3 days / 6 hourly</td>
<td>high/medium/low</td>
</tr>
<tr>
<td>TCWC Perth</td>
<td>3-7 days / daily</td>
<td>High/moderate/low/very low</td>
</tr>
<tr>
<td>TCWC Wellington</td>
<td>5 days / daily</td>
<td>Low potential/moderate potential/ high potential</td>
</tr>
<tr>
<td>Joint Typhoon Warning Center (JTWC)</td>
<td>14 days / 12 hourly</td>
<td>Using terms like (less likely, very likely)</td>
</tr>
<tr>
<td>PAGASA</td>
<td>48 hours / daily</td>
<td>Using terms like (less likely, very likely)</td>
</tr>
</tbody>
</table>
Table 4. Operational hazard forecasts from each TC forecasting center

<table>
<thead>
<tr>
<th>Center name</th>
<th>In hazard forecasts e.g. precipitation, winds, storm surge, flooding, how is uncertainty represented?</th>
<th>How is the uncertainty calculated?</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSMC Tokyo</td>
<td>Hazard forecasts not currently included in our service</td>
<td>n/a</td>
</tr>
</tbody>
</table>
| RSMC Honolulu                | Wind speed probability graphics for 34/50/65 knots  
Category and colour coded hazard threat index:
- Little to None
- Elevated (changed from Low)
- Moderate
- High
- Extreme                      | Probabilistic according to the hazard e.g. wind speed probabilities                              |
<p>| RSMC La Reunion              | No probabilistic data available for public                                                    | n/a                               |
| RSMC Miami                   | Varies depending on hazard, most common is &quot;worst case scenario&quot;, &quot;most likely&quot; and &quot;best case scenario&quot; (10%, 50%, 90%) | Generally ensemble based, either statistically or direct from ensemble output |
| RSMC New Delhi               | Forecast for heavy precipitation is given in range (7-11 cm, 12-20 cm and more than 20 cm in 24 hrs) and likelihood of occurrence (likely: 26-50%, very likely: 51-75% and most likely: 76-100%). The winds, storm surges and flooding are also mentioned in ranges with above probability of occurrence. | Uncertainty is calculated based on likelihood of occurrence and confidence level of forecast based on various deterministic and ensemble models. Accordingly the colour codes of green, yellow, orange and red are used in increasing order of severity based on confidence level and likelihood of occurrence. |
| TCWC Perth                   | Probabilistic language (likely, possibly etc)                                                 | Assigned by forecaster             |
| TCWC Wellington             | High/medium/low risk in severe weather outlooks.                                              | Subjective assessment based on analysis of system and |</p>
<table>
<thead>
<tr>
<th>Organization</th>
<th>Methodology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Typhoon Warning Center (JTWC)</td>
<td>n/a</td>
<td>Environment, deterministic forecasts, and ensemble outlooks.</td>
</tr>
<tr>
<td>PAGASA</td>
<td>In description e.g. we say that the hazard is possible to happen.</td>
<td>Based on daily observations and deterministic forecast from other models</td>
</tr>
<tr>
<td>WFO Guam</td>
<td>Descriptively</td>
<td>Forecast accuracy and type of system</td>
</tr>
<tr>
<td>Thai Meteorological Department</td>
<td>Show on Map</td>
<td>Risk matrix</td>
</tr>
<tr>
<td>Meteo-France New Caledonia</td>
<td>There is no graphical representation of hazard forecasts. They mentioned in bulletins with key words (“probably”, “risk”, “certainly” etc).</td>
<td>Ensemble-based and multi-model</td>
</tr>
<tr>
<td>Meteo-France - Martinique</td>
<td>Not available for the public.</td>
<td>ECMWF EPS and ARPEGE PEARP</td>
</tr>
<tr>
<td>Hong Kong Observatory</td>
<td>Uncertainty in the change of tropical cyclone warning signal, which is related to local wind forecast, is represented in five categories of probability for government departments.</td>
<td>Based on the probabilistic relationship between local winds and position/intensity of tropical cyclone.</td>
</tr>
<tr>
<td>Canadian Hurricane Center</td>
<td>Listing the worst case scenario and the sensitivity of forecast errors. Qualitatively in free form text discussion.</td>
<td>Empirically, plus local effects and criteria (i.e. known flooding levels for storm surge)</td>
</tr>
</tbody>
</table>

### 6.3.2.4 Examples of successful integration of probabilistic forecasts in to operations, and occasions where hurdles have prevented them from being fully utilized

There were numerous excellent examples of where probabilistic forecasts have been pulled through in to operational forecasts and warnings, including the ensemble-based RSMC La Réunion operational track uncertainty cone, the multi-model ensemble TC track and activity forecast products made available from JMA to Typhoon Committee members, and the successful integration of ensemble probabilities in the production of Tropical Cyclone Potential Bulletins at TCWC Wellington.

Just over half of respondents stated that they now placed more emphasis on using dynamical ensemble forecast information rather than using the traditional consensus approach using multiple deterministic forecasts. Of the consensus-favouring group, several said this was mainly due to habit, tradition, or because they had neither the desired access to, understanding of, nor the tools required to use the dynamical ensemble forecasts. Others felt the consensus approach was more skillful, particularly at shorter lead times and for intensity and structure forecasts, due to the higher resolution and the different model physics, biases, and parameterizations when combining multiple deterministic models. Several people felt that they would have liked to have answered that both were equally important, with the consensus forecasts better suited to the required deterministic components of the products and warnings, and ensembles being more useful for probabilistic forecasts and communicating uncertainty,
while others requested research into approaches that combine and maximize the benefit from both approaches.

The main hurdles experienced that prevent ensemble forecasts from being fully utilized were a) lack of access to different ensemble data at their center, lack of inclusion of ensembles in their key operational or visualization tools, and late availability time in an operational context; b) concerns about, or lack of information on, the performance of the ensemble forecast models; c) lack of familiarity with the interpretation of ensemble and probabilistic forecasts by forecasters, and d) the challenge of communicating uncertainty and probabilistic forecasts to the public.

6.3.2.5 Forecaster feedback on where they would like to see future research and development focused to enable them to make wider use of ensemble forecasts

In the product section of the questionnaire the products that had the highest proportion of respondents saying that they were desired but not currently available were: landfall probability, storm surge, river discharge, flood risk/inundation and impact-based products. Hazard-based and impact-based products also featured strongly when asked for specific details of a particular product that they would like to be able to see. Other requests were an operational ensemble-based cone of probability, more useful intensity guidance including probability of intensity change and bias corrected intensity forecasts from multiple ensembles, and ensemble clustering with probabilities.

In the verification section of the questionnaire, it was clear that some ensemble-based verification metrics such as economic value plots, are not as well used or understood as others, and may need to be communicated more clearly. The respondents gave several ideas for verification information that they would like to see that are more relevant to their day to day forecasting experience. For example, only including members that had a similar track to the actual event in intensity verification, metrics that translate ensemble spread into categorical estimates of forecast confidence in comparison to the widely used historical forecast error statistics and then verify this performance, and regularly updated or real-time performance metrics comparing the performance and skill for all types of models (deterministic, consensus and ensemble models) for the current storm, basin, and season-to-date.
Figure 4. The questionnaire asked respondents which of the above statements would help them make better use of ensemble forecast information in the future, rating each idea from 1 (not important) to 5 (very important).

When asked to score which areas of research and development would help them make better use of ensemble forecast information in the future (Figure 4), the top five scoring answers were:

1. Improvement in the skill of the ensemble forecasts (intensity)
2. Greater access to ensemble forecast data
3. Improvement in the skill of the ensemble forecasts (track)
4. Better understanding of best practice in ensemble-based forecasting of TCs
5. The development of hazard-based ensemble products

At the end of the questionnaire respondents were asked what specific developments they would like to see. The key themes coming through these responses are detailed below:

- Several responses talked of the challenge and the need to focus on how to communicate uncertainty to the general public, and explain how the public can use probabilistic information.
- Others felt the development of new tools, products and visualizations to allow
forecasters to rapidly and efficiently view and interpret ensemble data should be the main goal in the coming years.

- **Collaboration between NWP centers and forecasting centers** to share ensemble data (in standard formats), products, verification packages and results, and expertise on interpreting ensemble forecast data and including ensemble information in forecast and warning products, was requested.

- **Training of forecasters on the utilization of ensembles** to encourage and support a change in operational working practice towards using probabilistic information was mentioned by several respondents as essential, with one respondent summing up that the key challenge for the future was to implement changes to operational products and workflows that utilize ensemble forecasts better while balancing the communication of a clear and concise warning product.

- Several users requested a focus on the development of ensemble-based hazard-based forecasts e.g. storm surge, coastal inundation, inland flash flood and river flooding, especially where the risk is focused remotely (away from the center of the cone).

- The development of impact-based ensemble products was seen as crucial by a number of respondents, with access to and/or collection of socio-economic data sources being one key issue here.

- **Improvement in the skill of ensemble forecasts**, in particular for TC intensity and structure was seen as a key priority. Improved availability of bias-corrected ensemble forecasts, or methods to do so, was also requested.

- **User-oriented and basin-specific verification comparing ensemble guidance across models** was seen as important to help forecasters gain confidence in using ensemble forecast information.

The results of the questionnaire should help to provide guidance to NWP centres, researchers working in this area, and managers in the operational forecasting centers, on where further development should focus to maximize the potential benefit of ensemble forecasting in operational TC forecasting.

### 6.3.3 Progress in this field since the last IWTC

This section describes the research and operational progress in the ensemble forecasting of TCs since the last IWTC and is put together from a combination of working group member contributions and literature reviews. It is split in to the main areas of TC forecasting: track, intensity, genesis and hazard-based forecasts (wind, precipitation and flooding and storm surge).

#### 6.3.3.1 Track

As described in previous IWTC reports (e.g. Elliott and Yamaguchi, 2014), a consensus approach (A mean of TC forecast positions from multiple deterministic NWP models) is currently an essential element in issuing deterministic TC track forecasts at operational centers worldwide. A review paper of the WGNE intercomparison of TC forecasts by operational NWP models confirmed the usefulness of consensus TC track forecasts worldwide (Yamaguchi et al. 2017). The ensemble mean track forecast from dynamic ensembles are often included in these consensus forecasts, where they have been found to be provide useful guidance, in particular for extended range track forecasts. Some of the efforts to further improve consensus forecasts include an addition of new forecasts, bias correction, unequal weighting and discarding forecast
members. Cangialosi (2018) shows the improvement of consensus TC track forecasts at NHC by applying bias corrections and unequal weighting based on Williford et al. (2003). The impact of assigning unequal weights is also demonstrated by Simon (2018) under HFIP (Gall et al. 2013). Nishimura and Yamaguchi (2015) verified a selective consensus approach where among 11 operational global deterministic forecasts, those with large position errors at short lead times are discarded from forecast members making the consensus. Similar to the results of Qi et al. (2014), which originally proposed this discarding approach and applied it to a single-model ensemble including ECMWF ensembles, the usefulness of this method was limited to a short lead time (e.g. 48 hours). Dong and Zhang (2016) showed that a reduction in the errors were achieved by 5%–10% for lead times of 24–120 hours with this approach, and this approach has been used operationally at the CMA Typhoon and Marine Forecast Center since 2015.

As the results of the questionnaire in section 5.3.2 show, there is great potential to increase the use of the situation-dependent uncertainty information provided by dynamic ensemble forecasts in the operational forecasts of track uncertainty. Dupont et al. (2011) showed that a method, now used operationally at RSMC La Reunion, using the ensemble spread to take into account the meteorological synoptic context, proved to be more skillful than just using the climatological distribution of position error. Du et al. (2016) showed the usefulness of a multi-center ensemble-based probability circle, especially for long lead times. Zhang and Yu (2018) described a new probabilistic TC track forecast scheme named PROTRA at STI, which is a combination of creating a deterministic TC track forecast from ECMWF and NCEP ensembles with member selection and mean track shifting, and probability ellipse from an ECMWF ensemble (see Fig. 5).

![Flowchart of PROTRA](image)

**Figure 5.** (Left) Flowchart of PROTRA. The essential steps are highlighted in blue. (Zhang and Yu, 2017). (Right) Real time PROTRA forecast for TC Jebi initialized at 12UTC 1 Sep, 2018 (blue star). The red stars are observed positions of Jebi before 12UTC 1 Sep, 2018. The coloured ellipses are for 70% probability at different leading time.

By converting the track forecasts from dynamic ensemble members in to strike probability forecasts, the full probabilistic skill of the ensemble can be utilized and evaluated. Leonardo and Colle (2017) found that for North Atlantic TCs, ensemble forecasts from ECMWF ENS and a
multi-model ensemble of ECMWF ENS, MOGREPS-G and NCEP GEFS have more probabilistic skill than the EC deterministic model and comparable skill to the official cone forecast. They found a slow bias in TC’s along-track direction to be a common feature in many NWP models, especially (but not exclusively) when TCs undergo extratropical transition. Titley and Stretton (2018) verify strike probability forecasts for named storms in all TC basins, from the same three global ensembles and their multi-model combination, and demonstrate that additional skill and value is gained by using a multi-model ensemble compared to the best-performing individual ensemble.

Combined ensemble track and intensity displays can help forecasters better understand the relationships between the ensemble track and intensity forecasts. For example, NHC forecasters found that in the GFS ensemble forecasts for Hurricane Florence, the members with more southerly tracks tended to be weaker than those to the north, especially those that made a sharp turn toward the southwest just prior to landfall.

### 6.3.3.2 Intensity

A consensus approach is also often used in issuing deterministic TC intensity (maximum surface wind and minimum sea level pressure) forecasts (e.g. DeMaria et al., 2014). Consensus forecasts of TC track heavily rely on dynamical model outputs. Meanwhile, statistical-dynamical models such as SHIPS (e.g. DeMaria et al., 1994) are widely used in consensus forecasts of TC intensity, though a use of direct outputs from NWP models such as HWRF has recently shown promising results (e.g. Cangialosi, 2018). Although some progress has been made in the ability to forecast TC intensity, anticipating rapid intensity changes remains a challenging problem. A new DTOPS model for forecasting RI is now available to NHC forecasters. DTOPS combines the deterministic intensity predictions from the GFS and ECWMF global models, the HWRF regional model and the statistical D-SHIPS and LGEM intensity models in a logistic regression algorithm (Onderlinde and DeMaria 2018).

As the results of the questionnaire survey show, none of the centers issue forecast uncertainty in terms of maximum surface wind and minimum sea level pressure. However, some studies have been conducted to estimate the forecast uncertainty of TC intensity since the last IWTC. These include Chen et al. (2016) that developed an objective PCIF for TCs over the western North Pacific basin. Another study by Alessandrini et al (2018) developed an Analog Ensemble (AnEn) technique to predict TC intensity in both the eastern Pacific and Atlantic Ocean basins. The AnEn is an inexpensive, naturally calibrated ensemble prediction of TC intensity derived from a training dataset of deterministic HWRF forecasts. Magnusson et al. (2018) is a study pursuing a more dynamical approach. It demonstrated that ECMWF ensembles could provide better probabilistic forecasts of TC intensity by refining the model resolution, adopting ocean-coupling and making better use of observations around TCs in the data assimilation. Torn (2016) showed that adding initial-time SST uncertainty that originates from taking random samples from climatology resulted in a 10-20% increase in the intensity standard deviation, which could result in providing more reliable probabilistic forecasts. It also pointed out that more skillful ensemble predictions would likely require more sophisticated treatment of model uncertainty through stochastic physics elements. Ensemble forecasts with limited area models including HWRF- and HMON-based ensembles developed under HFIP (e.g. Zhang et al., 2014), COAMPS-TC ensemble (Doyle et al., 2012, 2014), the convection-permitting tropical configuration of the UK Met Office ensemble (MOGREPS-CP), and French AROME-based ensembles (Seity et al., 2011) also have a great potential for improving not only deterministic but also probabilistic forecasts of TC intensity. One of the challenges would be a stability of...
forecasts as such model outputs sometimes vary considerably from one initial time to another, which prevents forecasters from trusting them.

WANI technique proposed by Tsai and Elsberry (2014, 2015a, 2015b) is another example of a statistical model to estimate the uncertainty of TC intensity forecasts. Goerss and Sampson (2014) developed a statistical-dynamical model to estimate TC intensity forecast errors with forecast members used in TC track consensus forecasts at NHC and JTWC. One of the future challenges in this field would be a systematic comparison of statistical, statistical-dynamical, dynamical approaches and a combination of them in terms of reliability and sharpness of the ensembles. The dynamical approaches can include single- and multi-model dynamical ensembles from global and regional NWP systems.

6.3.3.3 Genesis

As shown in the results of the questionnaire, a probabilistic approach is employed at all the weather centers issuing TC genesis forecasts. A multi-model ensemble is one of the approaches to estimate forecast probabilities and thus is widely used in many centers. An example is a guidance product developed by Florida State University. Using diagnostics from several global models, areas of possible TC formation based on low shear, low-level cyclonic rotation, and vertical stability are identified (Halperin et al. 2017). A logistic regression is trained on several years of model forecasts to provide a quantitative estimate of the probability of TC formation in the following 48- and 120-hour, given the model diagnostic input parameters. NHC runs this algorithm on the deterministic GFS, ECMWF, UKMO and Canadian global models, and combines the probabilities in consensus forecast. NHC also provides a Tropical Weather Outlook (TWO) product that includes a quantitative estimate of the probability of TC formation at 48- and 120-hour lead times. Several graphical products were developed from the GFS, ECMWF and UKMO ensembles as guidance for the TWO. Figure 6 shows an example that identifies regions favourable for TC formation, which includes individual ensemble member low-level vorticity and a combined probability of high relative humidity and low vertical wind shear. Yamaguchi and Koide (2017) developed a statistical-dynamical TC genesis guidance using Early stage Dvorak analysis (EDA) and global ensembles. The EDA is a scheme that enables the analysis of tropical disturbances at earlier stages by adding T numbers of 0.0 and 0.5 to the conventional Dvorak technique. The probabilities that a tropical disturbance analysed with T numbers of 0.0, 0.5, and 1.0 reaches tropical storm intensity within 2 days are 15%, 23%, and 57%, respectively. FAR is found to decrease if the global ensembles simulate the tropical disturbance analysed with the EDA in the models. In addition, it tends to decrease with the increasing number of such ensemble members.
Figure 6. Example of a product derived from the combined GFS and ECMWF ensemble forecasts for guidance to NHC’s Tropical Weather Outlook. The contours should areas of high 850 hPa vorticity and the colour fill area indicates the probability of a region having low vertical shear and high low-level relative humidity. This example was from the 48 hour ensemble forecasts initialized at 00 UTC on 6 October, 2018, just prior to the formation of Hurricane Michael in the western Caribbean.

6.3.3.4 Hazards

The importance of increasing the focus on the probabilistic forecasting of downstream hazards has been recognized by key international programs such as the Hurricane Forecast Improvement Project (HFIP), and the WMO High-impact weather (HiWeather) program (WMO, 2014). Often the location of the greatest hazards and impacts can be displaced from the storm landfall location, and can spread far inland, with consequences for evacuation and recovery programs. The importance of multi-hazard warning systems taking in to account concurrent and cascading hazards is also recognized, as is the need to consider the vulnerability and exposure of the areas likely to be affected, in order to move towards risk and impact-based forecasting. Recent research and operational progress in the use of ensembles to forecast wind, precipitation, flooding and storm surge hazards is given below.

6.3.3.4.1 Wind

NHC’s Wind Speed Probability (WSP) products are a good example that has achieved a transition to the development of hazard-based products and a gradual use of ensemble information. NHC has long-recognized the need to convey the uncertainty in their official forecasts. NHC’s first quantitative uncertainty product was the Strike Probabilities, which was first issued for Hurricane Alicia in 1983 (Sheets 1985). This product estimated the probability that the TC center would be within 60 nmi of selected locations in the vicinity of the NHC official track forecast out to 72 hr. Limitations of the Strike Probabilities were that they only
considered track forecast uncertainty, and did not directly address the TC wind hazard. For these reasons, the Strike Probability product was replaced with the wind speed probability (WSP) product in 2006, which provides estimates of the probability of 34, 50 and 64 kt winds occurring at a given location at 12-hr intervals out to 5 days (DeMaria et al., 2009). The WSP model takes into account track, intensity and wind structure uncertainty. However, due to the lack of availability of an ensemble system that can provide reliable measures of that intensity uncertainty, a Monte Carlo method was used, where 1000 plausible realizations of TC track and intensity are generated by randomly sampling from the previous 5-year history of NHC’s official forecast errors. Wind structure uncertainty is estimated from a simple climatology and persistence wind radii model and its error characteristics.

Beginning in 2010, the WSP model was upgraded to make the track uncertainty a function of dynamical model spread (DeMaria et al., 2013). This was accomplished through GPCE, which estimates the track error from the spread of a multi-model ensemble and the official intensity forecast (Goerss 2007). The 5-year NHC official track errors used in the Monte Carlo WSP are stratified into terciles based on the GPCE values. In real-time the appropriate tercile is sampled based on the GPCE values. The GPCE values are a function of forecast time, so, for example, a low-error tercile distribution could be sampled at an early forecast lead time and a high-tercile distribution could be sampled at longer forecast lead times in the same WSP model run. The WSP model could also be transitioned to include more input from ensemble systems. The current version uses historical track error distributions stratified by model spread. The next step in that development would be a hybrid method where the tracks from an ensemble modelling system are used directly, but the intensity and structure perturbations are still from statistical error distributions. A version of that hybrid method is described by Schumacher and DeMaria (2018) where the tracks from the GFS, ECMWF, UKMO, Canadian and Navy global model ensembles are used in place of the statistically generated tracks. In the longer term, the WSP model could be replaced by a consensus approach and/or dynamical ensemble systems once those are able to reliably estimate the range of possibilities in track, intensity and structure (e.g. Sampson and Knaff 2015, Holman et al., 2018). A first step in that direction is to add an option to the WSP model that uses the GFS ensemble system for cases undergoing extra-tropical transition.

6.3.3.4.2 Precipitation and flooding

Table 4 in the questionnaire results section showed that several operational forecasting centers do include ensemble forecast information in their TC hazard forecasts. For example, RSMC New Delhi give probabilistic forecasts of heavy precipitation from TCs (for 7-11 cm, 12-20 cm and more than 20 cm in 24 hours) and the likelihood of occurrence (likely: 26-50%, very likely: 51-75% and most likely: 76-100%). Uncertainty is calculated based on various deterministic and ensemble models, and colour codes of green, yellow, orange and red are used in increasing order of severity based on confidence level and likelihood of occurrence. At JMA, in their post-processing of quantitative precipitation forecasts they make use of the ensemble member from JMA GEPS whose track is the closest to the official TC track forecast.

Downstream hazards from TC precipitation include landslides caused by the extreme rainfall like in the case of Wipha (2013) and Mangkhut (2018), flash floods or river flooding as seen for Harvey (2016). However, there are few studies looking at the skill of dynamic ensemble forecasts in forecasting precipitation and flooding from TCs, or how these forecasts could be utilized in operational TC forecasting.
The ECMWF ENS precipitation forecasts for hurricane Harvey (2013) are evaluated in Julina et al. (2018) using a new combined meteorological and land-surface index, and showed skill at least 4 days in advance of the 3-day period 26-28 August 2017. The ECMWF ensemble precipitation forecasts are used in the Global Flood Awareness System (GloFAS) provided by the Copernicus Emergency Management Service. Figure 7 shows an example of forecast issued 3 days before the landfall of Florence (2018) on the shores of North and South Carolina. Wu et al. (2013) and Fang and Kuo (2013) both look at ensemble-based forecasts of precipitation for TCs in Taiwan. Wu et al. use ensemble-based simulations for Typhoon Sinlaku to highlight that the uncertainties in rainfall patterns and amounts can be assessed from ensemble track variations, thus providing better insights into rainfall predictability. Fang and Kuo develop a modified probability-matching technique using ensemble forecasts at dual resolutions and show that this substantially reduces or eliminates the intrinsic model rainfall bias and leads to better quantitative precipitation forecasts (QPF) guidance for landfalling typhoons over Taiwan.

Figure 7. Flood forecast from Glofas (http://www.globalfloods.eu/) issued 3 day prior the landfall of Florence. Probability for exceedance of 20-year return period of river discharge (map) and river discharge for a river point close to Georgetown, South Carolina.

6.3.3.4.3 Storm Surge

The extent to which ensemble information is used for storm surge forecasts varies from one forecasting center to another. The underlying basis for the storm surge watch/warnings of the US NWS is the probabilistic surge (P-surge) modelling system that forces a simplified ocean model (SLOSH model) with a large ensemble (~1000 members) of plausible, statistical surface wind forcing. The Australian BoM has also developed an ensemble storm surge system (Greenslade et al., 2017). Based on an official TC forecast track, the storm surge model is run with 200 ensemble members that are randomly chosen from possible tracks. BoM also conducts ensemble storm surge simulations with ensemble members of a dynamical model. SMN of Mexico calculates storm surges with three scenarios, center and right and left most paths of the uncertainty cone, with parametric TC forcing (i.e. gradient wind balance). Meteo-France in La Reunion has developed an original method, soon to become operational, to generate ensemble scenarios around the RSMC’s official track forecast in the SPICY project (Bonnardot et al., 2016). Storm surge forecasts are issued on an ensemble scenario of TC track and intensity based on climatological errors as well as EPS members realigned on the official
RSMC forecast. Japan Meteorological Agency started multi-scenario storm surge predictions with six typical typhoon tracks in 2016 (Hasegawa et al., 2017). In the system, five typical TC courses are extracted from the JMA global ensemble prediction system using cluster analysis (K-mean method). After adding the official forecast track scenario, storm surge predictions are carried out. TC conditions such as location are obtained from the dynamical ensemble, but TC intensity is modified with parametric models because current operational ensemble models do not have sufficiently fine grid resolution to resolve TC intensity and structure. However, even current ensemble models give skillful TC track forecasts, and more importantly landfall probabilities, which can be utilized in storm surge predictions in order to give more practical storm surge risk information. An example is a study by Bloemendaal et al. (2018) that showed promising results for storm surge forecasts based on current atmospheric ensemble resolution.

In many TC cases, flood impacts are caused by compound events of precipitation and/or storm surges leading to flooding in coastal areas. An ultimate goal would be to be able to predict the flood inundation in a fully probabilistic system based on precipitation, river modelling and storm surge. Example of such system is outlined in Saleh et al. (2017) and showcased for the impact of mainly precipitation-driven floods during Irene (2011) and mainly storm-surge driven flood during Sandy (2012) in New York City.

6.3.4 TIGGE article survey

TIGGE (The International Grand Global Ensemble) was a major component of THORPEX (Parsons et al., 2017) research program, whose aim was to accelerate improvements in forecasting high-impact weather (Swinbank et al., 2016). TIGGE was established to support a range of THORPEX research activities by providing operational medium-range global ensemble forecast data to the international research community. Since the TIGGE archive started on 1 October 2006, the TIGGE dataset have been utilized for a wide range of scientific studies over the world. The WMO/WWRP PDEF Working Group carries out an annual literature search on the AMS and Wiley websites for papers using TIGGE data.

TIGGE is found to have been utilized for a wide range of scientific studies all over the world. Seventy eight research papers including an overview (Bougeault et al., 2010) and a review paper of TIGGE (Swinbank et al., 2016) have been published in the AMS journals, while forty research papers were found on the Wiley website. Figure 8 show the time series of the annual number of the TIGGE papers and which journals they were published in. Since 2010/11, the number of TIGGE papers has increased and TIGGE papers have been published at a pace of approximately 15 papers per year. Figure 9 shows that tropical cyclones are the most studied research area, followed by heavy precipitation.
NWP-TCEFP is a good example that achieved a R2O transfer with TIGGE. NWP-TCEFP was launched in 2009 as a RDP of WMO/WWRP and TCP (Yamaguchi et al. 2014). The objective of the project is to explore the utility of ensemble forecasts of TCs, including MCGEs, and to promote such products for operational TC forecasting. The project started from creating ensemble TC track predictions using TIGGE and putting them on a project website. As these products were confirmed to be highly appreciated by the Typhoon Committee Members through a questionnaire survey and Yamaguchi et al. (2012) demonstrated the relative benefits of MCGEs such as an improved spread–error relationship of TC track predictions, RSMC Tokyo Typhoon Center started providing ensemble TC track predictions from ECMWF, JMA, NCEP and UKMO global ensembles to the Typhoon Committee Members in real time from.
2016. Yamaguchi et al. (2015) showed that global ECMWF, JMA, NCEP, and UKMO ensembles are capable of providing guidance on TC activity (genesis plus the subsequent track) forecasts that extends into week 2 and that MCGEs tend to have better forecast skill (larger BSSs) than the best single-model ensemble. These TC activity products have also been provided to the Typhoon Committee Members in real time since 2016.

6.3.5 Summary

The questionnaire results show that dynamic ensemble forecasts are currently used by nearly all forecasters and at TC forecast centers around the world. They are seen to be particularly important in track and genesis forecasting, but are less well-used in intensity and structure forecasts, where the inability of current global dynamical ensembles models to capture the range of probabilities limits their full use. There are several examples of excellent pull-through of ensemble forecasts in to the operational TC forecasting process, but overall there remains a striking difference between the high number of operational TC forecasters who use and value ensemble forecast information, and the slower pull-through in to operational forecast warnings and products of the probabilistic guidance and uncertainty information that ensembles can provide. The survey highlighted the following as areas of research and development that would help TC forecasters to make increased use of ensemble forecast information in the future: a) an improvement in the skill of the ensemble forecasts (in particular for intensity); b) improved access to ensemble forecast data, tools, visualizations and user-orientated verification; c) better understanding of best practice in ensemble-based forecasting of TCs; d) the development of hazard-based and impact-based ensemble products; e) a change in operational working practices towards using probabilistic information, including a focus on how to communicate uncertainty to the general public.

The inventory of the progress since the last IWTC shows development of the use of ensembles in different directions, with several new and innovative ideas for how to utilize ensemble forecast information in TC forecasting. For example, CMA has deployed a method to select ensemble members based on their short-range performance. However, there is a risk of a negative impact on the ensemble reliability here by reducing the ensemble spread more than the skill, and it is important to continue to utilize the full probabilistic information from the ensembles alongside these new approaches. There has also been development of more limited-area ensembles from the operational side. As these km-scale models are expensive, Meteo-France is applying a clustering algorithm to select global ensemble members to downscale. There has also been some progress on the downstream hazard modelling in terms of wind, storm-surge and flood modelling, and the use of an ensemble framework is encouraged, including the gradual transition from statistical to dynamical ensembles as dynamical forecast skill improves.

Dynamical ensemble data such as TIGGE is a great data source to evaluate the usefulness of ensembles for TC forecasting and promote a Research to Operations (R2O) transfer in TC forecasting.

6.3.6 Recommendations

- Researchers are encouraged to promote research activities to evaluate and improve probabilistic TC intensity and structure forecasts (e.g. Magnusson et al., 2018).
Researchers are encouraged to promote research activities to demonstrate the usefulness of dynamical ensemble forecasts for hazard-based products such as for strong wind, precipitation, flooding and storm surge, and the use of ensembles in impact-based forecasting for TCs.

In order to facilitate the use of ensembles, greater access to forecast data including deterministic/ensemble forecast data and global/regional forecast data would be beneficial. Research is encouraged to evaluate how best to combine the information from these models, in order to maximize forecast skill and reliability.

The research community should recognize the value and importance of access to forecast data such as TIGGE and further promote the use of such data. We recommend the community to build a code repository for product generation and verification to facilitate the operational use of ensemble forecasts.

There is a need for greater collaboration both amongst the operational forecast centers, and between operational forecast centers, NWP modelling centers, and researchers, in order to co-ordinate the development of new ensemble-based tools and methods, and develop and share best practice on the use of ensemble forecasts in operational TC forecasting.

The operational forecasting community are encouraged to facilitate a change in operational working practice towards using ensemble-based uncertainty and probabilistic information in forecasts and warnings, including a focus on how best to communicate uncertainty to the general public.

Acknowledgements

The co-rapporteurs would like to thank:

- The working group members for their contributions.
- The respondents from the operational TC forecast centers who completed the questionnaire.
- All those who assisted the working group members in preparing their contributions.

Acronyms

AMS: American Meteorological Society
AROME: Application of Research to Operations at Mesoscale
ASL: Atmospheric Science Letters
AnEn: Analog Ensemble
BAMS: Bulletin of American Meteorological Society
BoM: Bureau of Meteorology
COAMPS-TC: Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones
DSHIPS: Decay SHIPS
DTOPS: Deterministic To Probabilistic Statistical
ECMWF: European Centre for Medium-Range Weather Forecasts
EDA: Early stage Dvorak analysis
FAR: False Alarm Ratio
GEFS: Global Ensemble Forecast System
GEPS: Global Ensemble Prediction System
GPCE: Goerss Predicted Consensus Error
GRL: Geophysical Research Letters
HFIP: Hurricane Forecast Improvement Project
HMON: Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic
HWRF: Hurricane Weather Research and Forecasting
IWTC: International Workshop on Tropical Cyclones
JAOT: Journal of Atmospheric and Oceanic Technology
JAS: Journal of Atmospheric Sciences
JC: Journal of Climate
JGR: Journal of Geophysical Research
JMA: Japan Meteorological Agency
JTWC: Joint Typhoon Warning Center
LGEM: Logistic Growth Equation Model
MA: Meteorological Applications
MCGE: Multicenter Grand Ensemble
MOGLEPS: Met Office Global and Regional Ensemble Prediction System
MRI: Meteorological Research Institute
MWR: Monthly Weather Review
NCEP: National Centers for Environmental Prediction
NHC: National Hurricane Center
NWP: Numerical Weather Prediction
NZ: New Zealand
PAGASA: Philippine Atmospheric, Geophysical and Astronomical Services Administration
PCIF: Probabilistic Climatology-based Intensity Forecast
PDEF: Predictability, Dynamics and Ensemble Forecasting
PROTRA: Probabilistic Track
QJRMS: Quarterly Journal of the Royal Meteorological Society
QPF: Quantitative Precipitation Forecasts
RDP: Research and Development Project
RSMC: Regional Specialized Meteorological Center
S.D.: Standard Deviation
SHIPS: Statistical Hurricane Intensity Prediction Scheme
SMN: Servicio Meteorológico Nacional
SST: Sea Surface Temperature
STI: Shanghai Typhoon Institute
TC: Tropical Cyclone
TCP: Tropical Cyclone Programme
TCWC: Tropical Cyclone Warning Center
THORPEX: The Observing System Research and Predictability Experiment
TIGGE: The International Grand Global Ensemble
TWO: Tropical Weather Outlook
UKMO: UK Met Office
WANI: Weighted-analog intensity
WF: Weather and Forecasting
WFO: Weather Forecast Office
WGNE: Working Group on Numerical Experimentation
WMO: World Meteorological Organization
WSP: Wind Speed Probability
WWRP: World Weather Research Programme
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[Available online at www.wmo.int/pages/prog/arep/wwrp/new/documents/Topic1_AdvancesinForecastingMotion.pdf.]


TOPIC 7 - TROPICAL CYCLONE VARIABILITY BEYOND THE SYNOPTIC SCALE

Abstract

Over the past four years, efforts to understand the influence of anthropogenic climate change on tropical cyclone (TC) activity have progressed. There is some evidence that an observed poleward migration of the latitude of maximum TC intensity in the western North Pacific is highly unusual compared to expected natural variability and may be partly due to anthropogenic forcing. Projections of TC activity changes for late 21st century global warming scenarios continue to indicate increased storm surge risk due to sea level rise (all other factors assumed equal), increased TC rainfall rates due to a warmer atmosphere holding more water vapor, and increased TC intensities. Confidence on TC frequency projections is still limited by some divergent results across studies.

For seasonal forecasting of TCs, the number of groups issuing seasonal forecasts has continued to expand over the past few years, with several of these institutions/agencies now providing landfall or region-specific predictions as well. Different statistical, dynamical, and statistical-dynamical models were developed by various research groups in predicting the seasonal TC activity. These methodologies and verification summaries are reviewed in the Rapporteur’s Report. Some research groups have also attempted to extend predictions beyond the seasonal timescale to the multi-annual timescale in recent years. While decadal TC forecasting is still in an experimental stage at present, there are some plans to develop decadal/multi-annual TC prediction towards operational use, particularly in the North Atlantic basin.

On subseasonal timescales, recent observational studies have better documented the physical links between the Madden-Julian Oscillation (MJO) and TC activity. There is emerging evidence of modulation of TCs by other types of equatorial waves, including convectively coupled atmospheric Kelvin waves, and by extratropical influences, including Rossby wave breaking—which also lowers predictability of TC genesis. The Sub-seasonal to Seasonal (S2S) research...
initiative led to the establishment of the S2S database, to help assess and improve forecast skill, gain mechanistic understanding, and promote operational use of S2S forecasts. Products and skill assessments derived from the database, as obtained from a number of centers and research groups, and from the “The International Grand Global Ensemble (TIGGE)” are reviewed. Early results from such efforts overall are encouraging, though more verification and calibration studies are needed.

**Introduction**

This topic reviews the research progress over the past four years for TC variability and change at timescales beyond the usual weather forecast timescale of order one week. While error growth in forecast models usually results in little weather forecasting skill beyond 7-10 days, certain features of the earth’s weather and climate system allow for the possibility of extending predictability beyond this range for certain phenomena and regions. In the tropics, the Madden and Julian Oscillation (MJO) organizes tropical convection on the near global scale and, in conjunction with other tropical waves and extratropical influences (including Rossby wave breaking), modulates TC activity in certain regions affected by the oscillation. This leads to the possibility of extended range predictions of TC activity beyond the current operational 5-day forecasts, to timescales of about 10-30 days. El Niño-Southern Oscillation (ENSO) modulates large-scale tropical convection on interannual timescales and offers the possibility of seasonal TC forecasting skill using state-of-the-art statistical and/or dynamical models. On multi-year timescales, any skill associated with internal variability (initial conditions) will presumably eventually be lost, but both low-frequency internal variability and forced (mainly anthropogenic) climate change may be important for TC prediction. On decadal and longer timescales, the climate change caused by anthropogenic forcings may have significant influence on TC activity as well. At this scale, the forecasting problem is essentially a boundary value problem (for assumed emission scenarios) as opposed to an initial value problem. Studies to identify observable trends and changes, understand whether TC activity has changed significantly in the past due to anthropogenic climate change, and how TC activity may change over the coming century continue to be key topics of intense research.

**7.0.1 Tropical Cyclones and Climate Change**

Global mean temperature and sea level have increased significantly over the past century. IPCC concluded that it is extremely likely that anthropogenic forcing has been the dominant cause of global climate warming since the mid-20th century, and there has very likely been a substantial anthropogenic contribution to sea level rise (IPCC AR5, 2013). As TCs are one of the most destructive weather systems on Earth, the connection between climate change and TC activity, in particular the possible influence of human activities, have been a subject of intense research. Generally speaking, TC and climate change studies can be divided into two main categories: those focused on the past (including past data analysis, model historical simulations, etc.) and those focused on the future (model projections for assumed future emission scenarios). Studies on past data include analysis of observable trends and variations and exploring for evidence that TC activity is already changing significantly due to anthropogenic forcing. However, with significant decadal and spatial variations in TC activity, data/observational challenges, and uncertainties in the expected forced signal and internal variability (noise) levels, detecting a human influence on TC activity has proven to be much more challenging than for global mean temperature and sea level rise. The future TC projection studies take projected climate change simulations for the 21st century from climate
models and attempt to either directly or indirectly infer changes in TC activity that accompany the global climate change.

7.0.1.1. Exploring Past Data and Historical Simulations: Detection and Attribution of Climate Changes

Efforts to reconstruct prehistoric TC activity using various geologic proxy records continued to improve our understanding of how TC activity varied from century to century in the distant past and to provide clues about the expected range of TC variability essentially from natural causes alone, since anthropogenic forcing of climate was believed to be rather limited in the preindustrial era.

For recent studies on historical data, analysis of best track and satellite-based datasets have indicated a poleward trend in the latitude of TC maximum intensity, a change which is most robustly observed in the western North Pacific. A methodology of inferring a detectable (non-natural) change by regressing out expected natural variability contributions using key climate variability indices has been employed to explore the possible causes for the observed poleward migration (Kossin et al., 2016). Other studies have explored an intriguing apparently global slowdown of TC propagation speeds (Kossin 2018) and decadal shifts in TC tracks and occurrence in the western North Pacific, as well as the increase in the intensity of landfalling typhoons in East and Southeast Asia. However, these changes have yet to be confidently linked to anthropogenic forcing. In the Atlantic basin, which is a basin characterized by pronounced multidecadal variability of TC activity, debate continues on whether these variations are predominantly due to internal variability associated with ocean circulation changes, or to multidecadal changes in the magnitude and geographical distribution of aerosol forcing (Booth 2017; Vecchi and Delworth 2017). Over the North Indian Ocean, a new study presents evidence that the recent occurrence of a number of extremely severe post-monsoon season TCs in the Arabian Sea is linked to anthropogenic forcing, though the record being examined is relatively short, only extending back to 1998 (Murakami et al., 2014).

Various research efforts using GCMs to elucidate the relationship between climate and TC formation continued, with some progress. Some statistical studies on the relationship between climate and TC intensity suggested a trade-off between increases in TC intensity and fewer TCs (e.g. Kang and Elsner, 2016).

A relatively new area of research has been on event attribution: either for individual TCs (e.g. Super Typhoon Haiyan, Hurricane Sandy, Hurricane Harvey) or individual TC seasons. For the latter, in the Pacific basin, modelling studies suggest that anthropogenic forcing may have enhanced recent unusually active seasonal TC activity near Hawaii and in the western North Pacific. However, these event attribution studies are typically based on model simulations. Observed data analyses that fully support the notion of a significant (unusual compared to natural variability) anthropogenic influence in any of these regions have not yet been identified.

7.0.1.2. Developments in Tropical Cyclone Long-term Projection Research

Over the past four years, a substantial number of additional studies have been published on TC climate change projections applicable to late 21st century global warming scenarios. On the whole, these additional studies support previous findings, with a few exceptions as noted below.
The projection with highest confidence is that anthropogenic sea level rise will exacerbate storm surge levels, all other factors equal, and this has been supported by new surge modelling sensitivity studies. The plausible increase in extreme wind waves due to a projected increase in TC intensity may further aggravate the impacts of storm surge and sea level rise on coastal structures.

The next most confident projection, which been simulated across a wide range of modelling studies, is the projected substantial increase in TC rainfall rates in a warming climate—projected to be about 6-22% for a 2°C global warming. New moisture budget analyses demonstrate that this modeled change is due primarily to enhanced moisture convergence resulting mainly from enhanced atmospheric moisture content with a secondary contribution from enhanced convergence.

Models and theory continue to project increased TC intensity in a warmer climate, with about 1-10% higher intensities projected for a 2°C global warming. Recent developments include a finding of increased TC intensification rates in a few studies which have examined this metric. One study using a modified form of potential intensity theory concluded that enhanced vertical temperature gradients in the upper ocean would mitigate some of the projected intensification of TCs (Huang et al., 2015). Follow-up studies suggest that the magnitude of this effect would be relatively small—order 10 to 15 percent reduction in the projected intensification compared to simulations without the effect included (Emanuel 2015; Tuleya et al., 2016). A few relatively high resolution fully coupled ocean-atmosphere GCM studies have become available. These report mixed results, with some tending to indicate similar results to the atmosphere-only models and others indicating an even larger increase of intense TC numbers.

While the vast majority of projection studies indicate fewer TCs globally in a warming climate, two new studies project at least slight increases. More recent studies have continued to explore the mechanisms for climate-induced changes in TC frequency, though important issues remain unresolved. This remains an issue that limits our confidence in projections of future TC track and occurrence.

The interaction of future TC activity with possible future anthropogenically induced changes in El Niño-Southern Oscillation and other forms of climate variability is a new topic being explored.

Recommendations for future emphasis include:

- improving climate-quality data sets of various TC metrics and related environmental variables;
- improving climate models for projecting future TC metrics and simulating past climate forcing changes as well as verifying the realism of model-simulated TCs;
- event attribution studies for TCs and climate change with peer review;
- more cross-disciplinary studies on the changes of TC impacts in the context of climate change.

### 7.0.2 Seasonal tropical cyclone forecasting

A summary of seasonal TC forecasting techniques used by a substantial number of forecasting groups and operational centers has been included in the Rapporteur’s Report (Section 7.2). Currently, a substantial and growing number of groups are making such forecasts for individual
or multiple TC basins. Different modelling methods, including statistical, dynamical, and statistical-dynamical approaches, were developed and adopted by various research groups in predicting the seasonal TC activity. ENSO and related SST indices were also key predictors in the forecast models of a number of research groups. Basin-wide TC counts (storms and hurricanes), number of landfalling TCs, and intensity metrics (e.g., ACE index) are some of the common forecast products.

In addition to strictly objective methods, individual forecast groups also incorporate subjective (forecaster expert opinion) methods to make seasonal forecasts. An advantage of the objective methods is the opportunity to objectively evaluate a method’s performance on historical data prior to its operational use, provided that independent data (not used to develop the model) are available for verification. The subjective methods allow forecasters to include a variety of evolving information in their forecasting deliberations, in an attempt to provide the best possible forecast. Verification will typically begin for these techniques once the center begins issuing the seasonal forecasts in real time.

Among the TC basins, North Atlantic was the most actively studied basin, with over 25 different forecast groups issuing seasonal forecasts for this basin. Efforts have been made to collate the large variety of forecast products into a consolidated website (http://www.seasonalhurricanepredictions.org), and there is a future plan to expand the website to a one-stop-shop portal of seasonal TC forecasts for all ocean basins. Recent progress in the development of decadal climate prediction systems with a view to filling the information gap between seasonal forecasts and climate change projections was reported. Since decadal variations of TC activity are impacted by both internally generated variability and externally forced components, incorporation of future changes in external forcings into the modelling is required. With relatively low skill levels compared to seasonal TC forecasts, decadal TC forecasting is still in an experimental stage at present. However, as recent studies have reported some skill in forecasting Atlantic hurricane activity at the multi-annual timescale (e.g., Caron et al., 2018), together with the strong interest of user needs, there are some plans to develop decadal/multi-annual TC prediction towards operation use, in particular in the North Atlantic basin.

Future recommendations include:

- new techniques for seasonal prediction (e.g., machine learning techniques);
- moving from basinwide to regionally-based predictions;
- improving skill of statistical models by utilizing new and longer period re-analysis/historical datasets; and
- further research on decadal/multi-annual predictions.

7.0.3 Tropical cyclone prediction on subseasonal timescales and the S2S database

On subseasonal timescales, research has progressed toward a better understanding of mechanisms producing potential extended range predictability, and in the development of models and prediction methods for exploiting some of this potential predictability. More observational studies have documented links between the MJO and TC activity. There is emerging evidence of modulation of TCs by other types of equatorial waves, including convectively coupled atmospheric Kelvin waves (Schreck 2015; 2016), and by extratropical
influences in the Atlantic, including Rossby wave breaking (Zhang et al., 2016)—which also lowers predictability of TC genesis.

The Sub-seasonal to Seasonal prediction project (S2S), jointly launched by WWRP and WCRP, led to establishment of the S2S database (Vitart et al., 2017), which is now being used to help assess and improve forecast skill, gain mechanistic understanding, and promote operational use of S2S forecasts. Assessment studies (e.g. Lee et al., 2018) show that models with more accurate representations of the MJO tend to have better extended-range forecasting skill for TC activity.

The International Grand Global Ensemble Experiment (TIGGE; Swinbank et al., 2016) provides a multi-center grand ensemble that has been assessed as providing skillful TC activity forecast guidance in most basins extending to week 2. Skill assessments from some individual models are also providing promising examples of skill and predictability, with MJO skill in one model assessed as extending to 27 days (Xiang et al., 2015). The northward-propagating Boreal Summer Intraseasonal Oscillation has somewhat less skill lead-time than the eastward propagating MJO.

While many forecast agencies currently predict genesis with a lead time up to 5 days, operational forecasts of TC track and intensity with a typical lead time of 5 days are only available after confirming TC genesis. With a view to providing further forecasting guidance for operational forecasting, some numerical prediction centers produce ensemble system generated forecast products which extend from before the moment of TC genesis to after it. This includes “strike probability maps” extending out to 10 to 15 days produced by the ECMWF and other centers. The US National Hurricane Center (NHC) forecasts for individual TCs do not extend beyond 5 days, though NHC has begun issuing forecasts for “potential TCs” in some time-critical instances.

Subseasonal TC forecasting products and skill assessments for several operational forecasting efforts and for research-mode forecasts were summarized. These included the Colorado State University Atlantic basin forecasts, ECMWF public and nonpublic global/basin forecast products, derived forecasts products from ECMWF ensemble members, Australian Bureau of Meteorology trial southern hemisphere forecasts, China Meteorological Administration western North Pacific and China landfalling TCs forecast. The private sector’s ongoing efforts in developing subseasonal TC forecast products are also noted.

Recommendations for future emphasis include:

- guidance on specific consistent metrics for verification and measures of skill
- move toward regional-scale predictions
- improve understanding of tropical-extratropical interactions
- possibly develop a “Severe Weather Forecasting Demonstration Project” focused on subseasonal TC forecasts.
Acknowledgements

The topic co-chairs gratefully acknowledge the efforts and contributions of the Subtopic Rapporteurs (Kevin Walsh, Phil Klotzbach, and Suzana Camargo) and their respective Working Group members.

Acronyms used in the report

ACE : Accumulated Cyclone Energy
ECMWF: European Centre for Medium-Range Weather Forecasts
ENSO : El Niño-Southern Oscillation
GCM : General Circulation Model
IPCC AR5: Intergovernmental Panel on Climate Change Fifth Assessment Report
MJO: Madden-Julian Oscillation
SST : Sea Surface Temperature
S2S: Subseasonal to Seasonal
TC: Tropical Cyclone
WWRP : World Weather Research program
WCRP : World Climate Research program

References


TOPIC 7.1 - TROPICAL CYCLONES AND CLIMATE CHANGE

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Abstract

Since IWTC-8, progress has been made in our understanding of the relationship between tropical cyclone characteristics, climate and climate change. New analysis of observations has revealed trends in the latitude of maximum TC intensity and in TC translation speed. Climate models are demonstrating an increasing ability to simulate the observed TC climatology and its regional variations. The limited representation of air-sea interaction processes in most climate simulations of TCs remains an issue. Consensus projections of future TC behaviour continue to indicate decreases in TC numbers, increases in their maximum intensities and increases in TC-related rainfall. Future sea level rise will exacerbate the impact of storm surge on coastal regions, assuming all other factors equal. Studies have also begun to estimate the effect on TCs of the climate change that has occurred to date.

7.1.1 Introduction

Recent reviews of this general topic include Walsh et al. (2015), Camargo and Wing (2016), Sobel et al. (2016) and Knutson et al. (in preparation). Important advances in the past four years have been the increasing number of paleoclimate records that have been analysed to determine past tropical cyclone (TC) incidence; a number of new results obtained from homogeneous records derived from satellite observations that point to the possibility of an increasing anthropogenic influence on aspects of tropical cyclone climatology; progress on understanding the links between climate and tropical cyclone formation using increasingly realistic climate model simulations; a recognition that future substantial increases in tropical cyclone rainfall might be one of the more robust predictions of climate change relevant to tropical cyclones; and the advent of attribution of the influence of climate change on individual tropical cyclone events and seasons.

7.1.2 Observations of tropical cyclones

7.1.2.1 Paleotempestology

Paleoclimate records representing periods prior to the beginning of observational records, such as overwash deposits and stalagmites, are increasingly being used to constrain past tropical cyclone variations at specific locations (e.g. Frappier et al., 2014, Donnelly et al., 2015, Van
Hengstum et al., 2016, Baldini et al., 2016; Bregy et al., 2018). For instance, Burn and Palmer (2015) reconstruct Atlantic hurricane activity over the past millennium from a lake sediment record in Jamaica and find an increase in hurricane activity since the late 18th century, but this change is not outside the range of variability over the millennium. While confirming that centennial-scale variations in TC incidence do exist in various regions, Muller et al. (2017) note that there appears to be some inconsistency between the relationships with ENSO identified in the paleo records and those relationships identified with modern data.

### 7.1.2.2 Historical and satellite era

#### 7.1.2.2.1 Global

Shipwreck rates have been used to examine variations in TC incidence in the past few centuries, with Trouet et al. (2016) showing that TC activity in the North Atlantic appeared to be suppressed during the Maunder Minimum. Yan et al. (2017) try to relate variations in simulated TC-related climate variables over the past millennium in the western North Pacific (WNP) to historical typhoon archives but find important differences between them.

More recently, satellite-based data have indicated a poleward trend in the latitude of TC maximum intensity (LMI; Kossin et al., 2014) that is projected to continue into the future (Kossin et al. 2016a). Following the analysis of Kossin et al. (2014), which removed the contribution from interbasin frequency variability from the global analysis, Moon et al. (2015) found that removing this contribution and omitting data from the southern hemisphere causes the statistical significance of the rate of poleward migration to fall below 95%. Kossin et al. (2016b) argue that this result does not obviate the presence of a significant global trend, nor does it challenge the presence of significant poleward trends found in individual basins.

Kossin et al. (2016a) and Kossin 2018 suggest that the poleward shift of LMI in the western North Pacific is particularly robust and is unlikely to be due to natural variability alone. Further study by Zhan and Wang (2017) suggested that this poleward migration over the WNP consists mainly of TCs with intensity below typhoon strength, although this result relies on the accuracy of heterogeneous TC intensity data. Song and Klotzbach (2018) infer that both the Interdecadal Pacific Oscillation and basin SST warming and related potential intensity increase are factors affecting the poleward migration in the western North Pacific, by influencing genesis latitude and latitudinal distance from genesis to the LMI, respectively. Studholme and Gulev (2018) and Sharmila and Walsh (2018) followed up on the work of Daloz and Camargo (2018) to identify a relationship between an observed poleward movement of tropical cyclone formation and corresponding changes in various climate variables. Knapp et al. (2018) found that the regions where TCs have eyes have expanded poleward, which provides a somewhat independent check on the poleward TC migration deduced from best-track data. A recent study (Altman et al. 2018) that employs a tree-ring network in the western North Pacific finds a rapid increase in the destructive effects of TCs over the 20th century, which is associated with poleward TC migration. The changes are argued to be outside the range of natural variability and may be associated with climate change.

Kossin (2018) also found a global slowdown in translation speeds of TCs of 10% from 1949 to 2016, with greater slowdowns over land regions of Australia, the western North Pacific, and Atlantic, but the causal mechanism behind these trends is still unclear and support from numerical simulations is presently lacking.
Klotzbach and Landsea (2015) find a recent slowing of the observed upward trend from 1970 to 2004 in the global numbers of Saffir-Simpson category 4 and 5 storm numbers. They also find a continuation in the increasing trend in the proportion of these storms, but that this trend is not statistically significant during the more recent period 1990–2014. Holland and Bruyère (2014) find a significant increase in proportion of category 4 and 5 storms globally in recent decades, and confirmed that an increase also is seen using homogenized satellite-derived intensity data of Kossin et al. (2013) that begins in 1982.

### 7.1.2.2.2 Western North Pacific (WNP)

Mei et al. (2015) and Mei and Xie (2016) show that, over the past 37 years, landfalling typhoons that strike East and Southeast Asia have intensified by 12–15%, due to locally enhanced surface warming. Li et al. (2017) also found that TCs making landfall over East China have tended to be more destructive in recent decades. Lin and Chan (2015) examined recent trends in typhoon Power Dissipation Index (PDI) in the WNP, finding compensating decreases in typhoon frequency and duration combined with increases in intensity. Zhao and Wu (2014) reported a pronounced northwestward shift in TC tracks over the WNP after late 1980s. He et al. (2015) also analyzed a pronounced decadal shift in WNP TC activity after the late 1990s, including genesis number, prevailing tracks and occurrence frequency. A number of subsequent studies have analyzed the implications of this decadal shift for the increase in the proportion of TCs undergoing rapid intensification in WNP (Zhao et al., 2018a) and the occurrence of intense TCs in the coastal regions along East Asia (Zhao et al., 2018b).

### 7.1.2.2.3 North Atlantic

There have been significant recent trends in TC incidence in this basin, whose causes remain controversial. Wing et al. (2015) found robust trends of TC potential intensity (Emanuel 1988) in North Atlantic over the period 1980-2013 but the results are sensitive to the choice of input dataset. There have been a number of studies aiming to identify the reasons for these and other TC trends. An important, though uncertain, possible mechanism is variations in aerosols (Booth et al., 2012; Dunstone et al., 2013; Ting et al., 2015; Sobel et al., 2016; Booth 2017; Zhang et al., 2017; Malavelle et al., 2017), along with internal (natural) decadal variability and associated atmospheric and oceanic conditions (Zhang et al. 2013; Camargo et al., 2013; Ting et al., 2015; Vecchi and Delworth 2017; Yan et al., 2017b; Sutton et al., 2018; Zhao et al., 2018).

### 7.1.2.2.4 North Indian

Mohapatra et al. (2016) found during the satellite period (1961–2010), TCs and severe TCs over the NIO and BOB show significant decreasing trends for the monsoon and post-monsoon seasons and for the year as a whole. No significant trend is observed over the Arabian Sea during the same period. Balaji and Chakraborty (2018) use accumulated cyclone energy (ACE) to demonstrate an upward shift of this quantity in this basin in 1997, caused by increase in number and duration of hurricanes over the period 1997-2014. Murakami et al. (2017a) reported the first documented occurrence of post-monsoon season severe TCs in the Arabian Sea during 2014 and 2015, but this conclusion is based on records extending only back to 1998. Model simulations indicate a potential anthropogenic contribution to the increase.
7.1.2.2.5 South Indian and South Pacific

Dowdy (2014) found a decrease in TC numbers in eastern Australia during the satellite era, after removing the substantial effects of ENSO variations on TC incidence in this region. Fitchett and Grab (2014) find few trends in landfalls in south-east Africa, but with an increasing number of TCs tracking south of Madagascar. Nash et al. (2016) compared documentary 19th century records of TCs with post-satellite-era occurrence and found few TC landfalls in the 19th century.

7.1.2.3 ENSO, tropical cyclones and climate change

While Cai et al. (2015) delineate the anticipated changes in ENSO behavior due to climate change, there have been few recent studies that focus specifically on the implications for tropical cyclones. Chand et al. (2017) suggested that substantial changes in El Niño-driven tropical cyclone incidence might occur in the 21st century in the central Pacific. In addition, it is critical to understand future changes in the diversity of ENSO events (Capotondi et al., 2014), as TC activity in the North Atlantic and Eastern and Western North Pacific depends strongly on the spatial pattern of warming during El Niño (Patricola et al., 2016, 2018; Wu et al., 2018). A new metric that for the first time uniquely describes the diversity of ENSO reveals future increases in La Niña, El Niño, and Modoki events by accounting for the non-linear response of deep convection to SST (Williams and Patricola 2018). Finally, paired with ENSO, Atlantic SST variability can drive constructive or compensating influences on seasonal TC activity in the Atlantic and Eastern North Pacific (Patricola et al., 2014, 2017), indicating the importance of understanding future changes in the probabilities of SST patterns in each basin, rather than changes in mean SST, for future TC projections.

7.1.2.4 Relationships between tropical cyclone formation and climate

GCM studies have helped elucidate some of the relationships between climate change and tropical cyclone activity (e.g. Ballinger et al., 2015). Sugi et al. (2015) showed that it was not necessarily the case that a cooler climate would mean fewer tropical cyclones. In contrast, Yoo et al. (2016) simulated similar TC numbers during the last glacial maximum to the current climate. Merlis et al. (2016) used globally uniform-SST aquaplanet simulations to show that increased SST caused increases in intensity but decreases in numbers. The experiments of the Hurricane Working Group (Walsh et al. 2015) separately changed SST and CO2 to understand their influence on tropical cyclone climate, with the idea that these contribute to the reduction in mass flux proposed to be associated with reduction in TC frequency (Sugi et al., 2012). This has relevance to projections of 21st century TC numbers. Satoh et al. (2015) proposed that an average TC intensity increase combined with a climate-related constraint for the total TC mass flux leads to a reduction of TC numbers. An alternative view (e.g. Camargo et al., 2014) holds that reduced global TC frequency with climate warming in at least one model (GFDL HiRAM model) is statistically related to the degree of column saturation deficit and changes in potential intensity of the environment. Tory et al. (2013) diagnosed a global decrease in TC frequency in climate model warming scenarios (CMIP5 models) using an alternative TC detection method not based on modelled storms but rather on large-scale dynamical and thermodynamical conditions. In addition, idealized models have been used to investigate the impact of varying meridional temperature gradients on TCs (Federov et al., 2018), finding that a decreased gradient generally leads to more TCs.
Genesis potential indices (GPIs, e.g. Camargo 2013; Camargo et al., 2014) have been used to explore statistical relationships between climate and tropical cyclone formation rates. Important uncertainties remain in the best representation and also how changes in GPI values in a different climate compare with changes in TC numbers directly simulated by GCMs (that is, which is more likely to represent real-world behaviour). Recent applications include the use of GPIs in the construction of a tropical cyclone hazard model (Lee et al., 2018) and for diagnosing the interannual variability of tropical cyclone formation in the Atlantic in millennia-long model runs (Lavender et al., 2018). Along these lines, Tory et al. (2018) used some novel diagnostics to establish some threshold relationships for geographical regions of tropical cyclone formation.

7.1.2.5 Theoretical relationships between climate and intensity

The links between climate and TC intensity are largely through the successful theory of maximum potential intensity (Emanuel 1988). Further refinements by Chavas (2017) have clarified some of the constraints on this theory. Kang and Elsner (2015, 2016) used statistical analysis to suggest a trade-off between increases in tropical cyclone intensity and fewer tropical cyclones.

7.1.3 Projections of future TC climatology

Climate models with horizontal resolutions of around 50 km are now able to simulate the spatial climatology and interannual variability of tropical cyclone formation reasonably well (Camargo and Wing 2016). Nevertheless, finer horizontal resolution models (in some cases as fine as 6 km grid spacing for regional models or 25 km for global climate models) tend to show improved simulation of intensities (e.g. Knutson et al., 2015; Bhatia et al., 2018; Gettelman et al., 2018).

7.1.3.1 TC numbers and occurrence

A large majority of GCM simulations project future decreases in global tropical cyclone numbers (Knutson et al., in preparation). An unresolved issue at present are the reasons why a smaller subset of models project increases in numbers (e.g. Emanuel 2013; Bhatia et al., 2018). There remains limited confidence in the geographical details of projections of future TC track and occurrence.

7.1.3.2 TC intensity

A projected increase in TC intensity with climate warming by about 1-10% for a 2 degree Celsius global warming scenario (Knutson et al. in preparation) is generally consistent with potential intensity (PI) theory (e.g. Emanuel 1988) which also predicts such an increase in a greenhouse-warmed climate based on CMIP5 model results (Sobel et al., 2016). The prediction from PI theory is generally supported by the results of most fine-resolution global climate models, regional dynamical downscaling models, and other modelling systems (Knutson et al., in preparation). Bhatia et al. (2018) reported using a 25-km-mesh high-resolution GCM that TC intensification rate is projected to be higher at the end of this century relative to the present-day, resulting in more major hurricanes globally. Increases in the proportion of tropical cyclones that reach category 4 and 5 intensity are projected by some models (e.g. Holland and Bruyere 2014). A relatively robust feature of models is a simulated future increase in the proportion of relatively intense storms and decrease in the proportion of
relatively weak storms (e.g. Zhang and Wang 2017; Knutson et al., in preparation). Recent studies have begun to consider future changes in additional TC characteristics including TC size and destructiveness (Sun et al., 2017; Schenkel et al., 2018).

### 7.1.3.3 Air-sea interaction

A limitation in the majority of GCM projections of future tropical cyclone incidence is the lack of realistic air-sea interaction processes in most simulations, as these tend to employ specified SSTs rather than coupled ocean-atmosphere GCMs, due to the very considerable saving in computer time. In addition, prescribed SST simulations are often preferred due to the problem that tropical SST biases common to coupled models (e.g. Richter 2015; Zuidema et al., 2016) can introduce substantial errors into the simulated TC climatology (Hsu et al., 2018). Lack of atmosphere-ocean coupling can produce greater simulated TC number and intensity compared to coupled simulations (Li and Sriver 2018). For TC-climate simulations performed in downscaling mode, rather than within a global climate simulation, there is potential for overestimating the impact of climate warming on TC intensity due to the influence of ocean coupling (Huang et al., 2015), though according to more recent studies, this moderating impact of the ocean vertical temperature gradient change is estimated to be relatively minor (Emanuel 2015; Tuleya et al., 2016). The limited number of fully coupled ocean-atmosphere GCM studies that have been performed give mixed results, with some tending to indicate similar results to the atmosphere-only models (Kim et al., 2014) and one study indicating that inclusion of ocean-atmosphere coupling can lead to an even larger increase of intense tropical cyclone numbers than a case without ocean coupling, at least in some basins (Ogata et al., 2016).

### 7.1.3.4 TC rainfall and other impacts

Projected future increases in TC rainfall rates can be quite substantial (Villarini et al., 2014; Wright et al., 2015; Scoccimarro et al., 2017; Patricola and Wehner 2018), with values sometimes being larger than that expected simply from the increase in atmospheric moisture content (roughly 7% per degree Celsius of local surface warming). Increases in TC rainfall rates of about 6 to 22% are projected for a 2°C global warming scenario (Knutson et al., in preparation). The physical mechanism for this increase is reasonably well understood (e.g. Wang et al., 2015), being primarily related to increased moisture convergence--due to increased water vapor and secondarily to an enhanced convergence-- and with a smaller contribution from increased evaporation.

The greatest impact from tropical cyclones in coastal regions is from storm surge, which is almost certain to be exacerbated by future sea level rise, all other factors assumed equal, and will also be influenced by regional changes in tropical cyclone characteristics (Woodruff et al., 2013). The effects of storm surge vary strongly from location to location, and so the numerous studies that have been performed on this issue have usually been focused on specific locations (e.g. Garner et al., 2017). Moreover, the plausible increase in TC induced extreme wind waves due to the projected increase in TC intensity may further aggravate the impacts of storm surge and sea level rise on coastal structures (Timmermans et al., 2017, 2018). A challenge in performing this kind of study is the relative impact of highly confident projections of sea level rise compared with rather less confident projections of changes in tropical cyclone characteristics. In some locations, the sea level rise contribution is expected to dominate (McInnes et al., 2014).
7.1.3.5 Event Attribution Studies

A new development in the field has been the advent of event attribution of climate change studies for TCs. For example, these explore how the climate change that has occurred to date may have influenced individual TCs, including storm surge (e.g. Lackmann 2015; Takayuba et al., 2015; Risser and Wehner 2017; Oldenborgh et al., 2017; Emanuel 2017; Wang et al., 2018; Patricola and Wehner 2018; Wehner et al., 2018), with some studies performed in real time (Reed 2018). These studies can also explore how anthropogenic climate change may have influenced a particular TC season (e.g. Murakami et al., 2015; 2017a,b; 2018; Zhang et al., 2016). An issue with establishing confidence levels for such studies is whether a significant observed trend in a TC metric or closely related metric can be identified to support the model-estimated anthropogenic influence. If not, then the inference about anthropogenic influence is based on the model simulation and will typically have lower confidence than for a case where a closely related significant observed climate trend has also been identified.

7.1.4 Future research

Methods of performing event attribution studies are likely to be further refined in future studies. Producing a regionally and globally comprehensive paleotempestology record that is consistent with known physical relationships between current climate and TCs remains a research challenge. Increasingly, coupled ocean-atmosphere climate models will be employed that more realistically simulate both the air-sea interaction processes that are known to be important to tropical cyclone intensification, as well as the basin-scale SSTs that influence basin-wide TC activity. Community modelling efforts, such as HighResMIP (Haarsma et al., 2016), will provide valuable datasets for understanding and improving the representation of TCs in high-resolution coupled climate models. A large ensemble simulation with a TC-permitting model can also be useful for isolating the effect of anthropogenic forcing from the effect of natural variability on any observed change or trend in TC metrics. Future research should be able to resolve the issue of why some climate models are predicting future increases in tropical cyclone numbers rather than the majority prediction of decreases. Detection and attribution studies will continue to search for evidence of human influence on tropical cyclone activity, through a combination of observational and modelling studies. Research to assess changes in TC impacts at specific locations (e.g. coastal megacities) will also be valuable for climate change adaptation and resilience.

7.1.5 Recommendations

1) Efforts should continue to develop, improve, and maintain climate-quality data sets of various TC metrics and related environmental variables, for use by the weather and climate change research communities for detection and attribution-related research. A particular focus should be the continued maintenance and creation of observational data sets that remove as much as possible the effects of temporal inhomogeneities in observing practices.

2) Modelling groups should continue to improve climate models for projecting future TC-relevant environmental conditions, for simulating past conditions and their response to past climate forcing changes, and for directly simulating TC activity within the climate models, or as an offline downscaling step, preferably including the influence of ocean coupling.
3) Event attribution studies for TCs and climate change are more valuable scientifically when they have gone through peer review, as opposed to ‘real-time attribution’ studies. This is to take advantage of the peer-review system which has proven valuable for maintaining and improving the scientific quality of studies. Rapid assessments have value for media exposure but a potential shortcoming is the lack of peer review.

4) Cross-disciplinary research to better understand and assess the possible changes in multi-hazard impacts of TCs to coastal cities in the context of climate change (e.g. coastal inundation caused by the combined effect of heavy rain, storm surge and wind waves) should be encouraged for further improvement of critical infrastructure design and the formulation of effective emergency preparedness measures.

5) Further efforts should be made to improve our theoretical understanding of the relationship between climate and TCs. For instance, a quantitative climate theory of TC formation would improve our confidence in future projections of TC numbers.

Acknowledgments

The rapporteur would like to thank the members of the working group for their valuable contributions to this section.

Acronyms used in the report

ACE - Accumulated cyclone energy
CMIP5 - Coupled model intercomparison project version 5
ENSO - El Niño/Southern Oscillation
GCM - General circulation model
GPI - Genesis potential index
PDI - Power dissipation index
TC - Tropical cyclone

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Zhao, J., R. Zhan, and Y. Wang, 2018b: Global warming hiatus contributed to the increased occurrence of intense tropical cyclones in the coastal regions along East Asia. Scientific Reports, 8, 6023.

Abstract
This report summarizes several of the current research techniques used in operational seasonal forecasts of tropical cyclone (TC) activity issued around the globe. In addition to discussing current techniques used by several of the forecasting groups issuing predictions for various portions of the globe, the report also examines forecast products that extend beyond predicting basinwide activity levels. Several dynamical and hybrid statistical/dynamical models now predict TC track density as well as landfall likelihood. A summary of recent research into forecasting TC activity beyond seasonal (e.g. multi-year) timescales is also included.

5.2.1 Introduction
Seasonal tropical cyclone (TC) forecasts have been issued for the North Atlantic basin operationally by Colorado State University since 1984, starting with the pioneering work of Gray et al. (1984a, b). Since that time, many other forecast groups have begun issuing forecasts for the North Atlantic basin. In addition, several groups now issue operational forecasts for other TC basins around the globe, including the NW Pacific and the Australian region. This report summarizes several of the current operational seasonal forecasts available for various TC basins. For additional discussion of the mechanisms driving TC variability on seasonal timescales, please refer to Vitart et al. (2014).

We do note that many groups other than those discussed here issue forecasts for the Atlantic basin, with several groups not listed here issuing predictions for other TC basins as well. Over 25 different forecast groups including government agencies, private sector weather companies and universities are currently contributing seasonal forecasts for the North Atlantic to a collation website http://www.seasonalhurricanepredictions.org. This collation website also provides brief descriptions of each North Atlantic forecast group’s methodology and provides links to their websites where more details are included. The goal is to expand this website to include seasonal TC forecasts for all ocean basins in the future.
In addition to seasonal forecasts for entire TC basins, some of these forecasts now go beyond predicting basinwide TC activity and highlight areas where TC tracks are more or less likely. The report also briefly discusses outlooks issued beyond seasonal (e.g. multi-year) timescales and finishes with a summary and some ideas for areas of future research.

5.2.2 Seasonal Tropical Cyclone Forecasts

Colorado State University (CSU)

CSU has been issuing Atlantic basin seasonal hurricane forecasts since 1984. Forecasts are currently issued in early April, with updates then provided in early June, July and August. These forecasts use a blend of statistical modelling based on historical atmosphere/ocean data such as the Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010), the European Center for Medium Range Weather Forecasts Interim Reanalysis (ERA-Interim) (Dee et al., 2011), and the National Oceanic and Atmospheric Administration (NOAA) optimum interpolation (OI) SST (Banzon et al., 2016). In addition, CSU incorporates an analog year selection process whereby observed and projected climate indices are compared with prior hurricane seasons. Lastly, CSU examines dynamical model predictions of El Niño-Southern Oscillation (ENSO) and Atlantic SST and sea level pressure (SLP) patterns and qualitatively adjusts its predictions based on these outlooks.

Most of CSU’s predictors relate closely to ENSO and Atlantic SSTs, with more active Atlantic hurricane seasons associated with warmer than normal waters in the tropical Atlantic and cooler than normal waters in the central and eastern tropical Pacific. This combination of water temperature anomaly patterns also tends to reduce vertical wind shear in the Atlantic. Too much vertical wind shear is known to be detrimental for hurricane formation and intensification (e.g. Klotzbach et al., 2017 and references therein).

CSU’s forecasts have been issued in real-time since 1984 and have shown skill since their inception (Klotzbach and Gray 2009) when compared to climatology or the previous 5-year and 10-year means. CSU’s forecasts have also shown competitive skill to those demonstrated by Tropical Storm Risk and NOAA in recent years (Klotzbach et al., 2017). Figure 1 displays early August seasonal forecasts for the number of named storms from CSU compared with observations.
Figure 1. Real-time named storm forecasts from CSU issued in early August compared with observations from 1984-2017

National Oceanic and Atmospheric Administration (NOAA)

The NOAA seasonal hurricane forecasts for the Atlantic and Northeast Pacific basins are based on a suite of statistical prediction tools and dynamical model forecasts. The primary statistical aids for the Atlantic are based, in part, on research detailed in Bell and Chelliah (2006). One of these aids is the Climate Prediction Center (CPC) statistical analog regression. A range of forecast August–October (ASO) Nino 3.4 temperatures, ASO tropical Atlantic SSTs, and the forecast ASO tropical Atlantic difference from global tropical SSTA (usually a range of 0.5°C is used) are considered. The Northeast Pacific CPC statistical analog regression is based on a range of projected ASO Nino 3.4 and Nino 3 SSTs. These predictors are then regressed upon years with similar climate conditions to provide one statistical forecast, along with a likely range. The skill of NOAA’s operational seasonal forecasts compared to that of Tropical Storm Risk and CSU is discussed in Klotzbach et al. (2017).

One unique aspect of the NOAA forecast is its use of the high-resolution CFS-T382 model. The model is run for 2-3 weeks prior to the May and August forecasts, and these forecasts are collected as an ensemble of large-scale predictions, including shear and SST, along with a count of TCs and overall activity. Finally, the GFDL-Flor and Hi-Flor forecasts, plus the ECMWF, NMME, and UKMET seasonal forecast models are also used for both ASO climate conditions and total storm and activity counts in making the seasonal hurricane forecast. After all of these forecast aids are compiled, subjective adjustments are made, and the forecast is a
consensus of 6 forecasters throughout NOAA offices in the Climate Prediction Center, National Hurricane Center and the Hurricane Research Division. The Atlantic seasonal forecasts are issued in mid-May and updated in early August. The Northeast Pacific seasonal forecast is issued in mid-May.

**Tropical Storm Risk (TSR)**

TSR, based at University College London in the UK, has issued public outlooks for seasonal TC activity in the North Atlantic and Northwest Pacific basins since 2000. TSR forecasts basinwide TC activity (comprising numbers of storms of different strengths and the Accumulated Cyclone Energy (ACE) index) and U.S. landfalling TC activity. The TSR forecast models are statistical in nature and are underpinned by predictors that have sound physical links to contemporaneous TC activity. Outlooks are issued in deterministic and tercile probabilistic form. For the North Atlantic, TSR issues seasonal forecasts in early December, early April, late May, early July and early August. For the Northwest Pacific, TSR issues seasonal outlooks in early May, early July and early August. All historical TSR seasonal TC forecasts are available online at [www.tropicalstormrisk.com/forecasts.html](http://www.tropicalstormrisk.com/forecasts.html) thereby allowing assessments to be made of the TSR real-time forecast skill for the period 2000-2018. TSR’s real-time forecast skill was also shown to slightly exceed those of CSU and NOAA for ACE based on data from 2003-2014 (Klotzbach et al., 2017).

The TSR seasonal model for North Atlantic TCs is sophisticated for a statistical model. The model divides the North Atlantic basin into three regions: (1) the tropical North Atlantic; (2) the Caribbean Sea and Gulf of Mexico; and (3) the ‘rest’ region which comprises the North Atlantic area outside regions (1) and (2). TSR employs separate outlook models for each of the three regions before summing the regional hurricane outlooks to obtain an overall North Atlantic hurricane outlook. The two main predictors used by TSR in making its seasonal outlooks are: (1) The forecast speed of the trade winds for July-August-September for the region 7.5-17.5°N, 100-30°W. The trade winds blow westward across the tropical Atlantic and Caribbean Sea and influence cyclonic vorticity and vertical wind shear over the main hurricane track region; (2) The forecast SST for August-September for the region 10-20°N, 60-20°W between West Africa and the Caribbean where many hurricanes develop during August and September. Waters here provide heat and moisture to help power the development of storms within the hurricane main development region. The nature of the TSR model is shown in Figure 2 and is described further in Lea and Saunders (2004, 2006), Saunders (2006) and Saunders and Lea (2008). The basis for the trade wind speed being the environmental field that best replicates long-term hurricane activity is given in Saunders et al. (2017).

TSR outlooks for US landfalling TC activity issued between December and July employ a historical thinning factor between ‘tropical’ North Atlantic activity and US landfalling activity. The TSR outlook for US landfalling activity issued in early August employs the persistence of July steering winds (Saunders and Lea, 2005). These winds either favour or hinder evolving hurricanes from reaching US shores during August and September.

TSR outlooks for Northwest Pacific TC activity are made as follows. Predictions of intense typhoon numbers and the ACE index are made using the forecast value for the August-September Niño 3.75 region (5°S-5°N, 140°W-180°W) SST and the current year-to-date ACE index (July and August outlooks). Typhoon numbers and tropical storm numbers are forecasted using the Niño 3 region SST from the prior September and the forecast number of intense typhoons. Above average (below average) Niño 3.75 SSTs are associated with weaker
(stronger) trade winds over the region 2.5-12.5°N, 120°E-180°. These in turn lead to enhanced (reduced) cyclonic vorticity over the Northwest Pacific region where intense typhoons form.

![Figure 2](image)

**Figure 2.** Nature of the TSR statistical model for replicating North Atlantic seasonal hurricane activity. The figure displays the two August-September environmental field areas that the TSR model employs most often in producing a seasonal hurricane outlook. The figure also displays the anomalies in August-September SST (colour coded in °C) and 925 hPa wind (arrowed) linked to active Atlantic hurricane years. Figure taken from Saunders and Lea (2008).

**Geophysical Fluid Dynamics Laboratory (GFDL)**

GFDL has been conducting retrospective and real-time dynamical seasonal forecasts for every month since 2014 using the Forecast-Oriented Low Ocean Resolution version of CM2.5 (FLOR; ~50 km-mesh horizontal resolution in the atmosphere and 1° in the ocean; Vecchi et al., 2014) and the high-resolution version of FLOR (HiFLOR; ~25 km horizontal resolution in the atmosphere; Murakami et al. 2015) for both research purposes and as a contribution to the North American Multi-Model Ensemble (NMME; Kirtman et al., 2014). HiFLOR shows skillful prediction for frequency of major hurricanes in the North Atlantic a few months in advance (r=0.74; Fig. 3a) and landfalling storms in the United States (r=0.53; Fig. 3b) in the retrospective seasonal forecast (1980–2016; Murakami et al., 2016a). Real-time predictions by the dynamical models are shared with experts at the National Hurricane Center and the Climate Prediction Center to assist with the NOAA seasonal hurricane outlook.

GFDL has also been developing new statistical-dynamical models to improve prediction skill relative to the dynamical seasonal forecasts by FLOR. Murakami et al. (2016b) and Zhang et al. (2016, 2017) constructed new statistical-dynamical models for landfalling storms over the United States and East Asia, respectively, showing higher skill in predictions of landfalling storms than FLOR does. Specifically, Murakami et al. (2016b) showed that a new statistical-dynamical model retains forecast skill up to lead month 5 with a correlation coefficient of 0.5 and a forecast error of 2.0 for landfalling storms for the United States. Zhang et al. (2017) reported a correlation coefficient between predicted and observed TC landfall over southern East Asia of 0.52 (0.64) for forecasts initialized in January (June).
The UK Met Office has been providing seasonal TC forecasts for the North Atlantic annually to the public since 2007 (Camp et al., 2015). These forecasts are produced using the Met Office's Global Seasonal forecast system GloSea5 (MacLachlan et al., 2015), which is a fully coupled ocean-atmosphere-land ensemble prediction system with ~60 km horizontal resolution in the atmosphere and 0.25° in the ocean. This system provided useful guidance on the extremely active 2017 North Atlantic hurricane season, in particular predicting the enhanced frequency of observed TC tracks across the northeast Caribbean at more than 3 months lead time (Camp et al., 2018a).

In 2015, the Met Office expanded its seasonal TC forecasts to include all ocean basins around the world (Camp et al., 2015). These are made available to forecasters internally at the Met Office, as well as to meteorological agencies, including the National Hurricane Center. Forecasts include the number of TCs, hurricanes and the ACE index, as well as spatial track anomalies, for the forthcoming 6-month period, updated on a monthly or weekly basis. GloSea5 shows significant skill over the hindcast period 1993-2015, with correlations exceeding 0.8 (0.7) for predictions of the ACE index in the eastern Pacific (North Atlantic) for June-November. GloSea5 shows significant skill for predictions of TC landfall in the Caribbean (Camp and Caron, 2017) and the western Pacific (Camp et al., 2018b), with trial forecast products of TC landfall risk now being developed for East Asia.

**European Centre for Medium-Range Weather Forecasts (ECMWF)**

ECMWF seasonal forecasts of TCs have been issued monthly since 2001 (Vitart and Stockdale, 2001). At the seasonal range, the TC products include the number of tropical storms.
(maximum wind speed exceeding 17 m s\(^{-1}\)), number of hurricanes, and ACE over several TC basins (North Atlantic, Northeast Pacific, Northwest Pacific, South Indian Ocean, Australian Basin and South Pacific), tropical storm density anomaly and standardized tropical storm density for a six-month period. The TCs are detected using the tracker as described in Vitart et al. (1997) and the statistics of detected TCs are calibrated using the seasonal re-forecasts.

Figure 4 shows the climatology of tropical storm track density over the period 1990-2014 in observations (from IBTrACS), System 4 and System 5. According to Figure 4, System 5 displays a much more realistic tropical storm climatology than System 4. System 4 severely underestimated the number of tropical storms. System 5 still underestimates tropical storm activity, but the number of detected tropical storms is significantly higher than in System 4. The higher horizontal resolution of System 5 is likely to be a main reason for this improvement in the tropical storm climatology.

![Tropical Storm density](image)

Tropical Storm density
(Max wind > 17 m/s)

Figure 4. Tropical storm track density over the period 1990-2014. This figure shows the annual number of TCs passing within 500km in observations (top panel), in System 4 (middle panel) and in System 5 (lower panel).
The improvement in tropical storm climatology does not necessarily translate into more skillful forecasts of TC inter-annual variability. System 5 displays significant skill in predicting the interannual variability of TC ACE over the North Atlantic ($r = 0.65$ from 1990-2014), Northeast Pacific (May and June start dates only), Northwest Pacific and South Pacific (October and December start dates). System 5 displays generally lower skill than System 4 over the Atlantic ($r = 0.72$ from 1990-2014) and Northeast Pacific but higher skill over the Northwest Pacific (particularly from April to June) and over the South Pacific.

**Australian Bureau of Meteorology / The University of Melbourne**

Tropical cyclone (TC) season outlooks are issued operationally by the Australian Bureau of Meteorology (BoM) for November to the end of April (Southern Hemisphere TC season) for the Australian Region (AR) since 2009 (http://www.bom.gov.au/climate/cyclones/australia/archive.shtml) and for the South Pacific Ocean (SPO) since 2010 (http://www.bom.gov.au/climate/cyclones/south-pacific/archive.shtml).

The statistical seasonal TC forecast model used by the BoM described in Kuleshov et al. (2009) applies linear discriminant analysis (LDA) to identify the historical relationship between observed numbers of TCs and indices (predictors) describing the state of ENSO. The ENSO predictors employed in the Bureau’s statistical prediction model are the Southern Oscillation Index (SOI) and equatorial sea-surface temperature anomalies in the Niño 3.4 region (N34). The LDA technique is applied in the Bureau model to identify the relationship between the JAS mean of an ENSO predictor (either SOI or N34) and the observed number of TCs in a TC season in a region/sub-region over a training period. The resulting statistical relationship is then applied to a predictor value for a JAS period subsequent to the training period to yield predictions for the probability that the number of TCs in the forthcoming season is greater than the median over the training period and for the number of TCs in that season. The skill of the predictions was evaluated over a 30-year hindcast period using a leave-one-out cross validation approach. TC predictions show some skill for the western Australian sub-region (5°-40°S, 90°-125°E) and the Australian region as a whole (5°-40°S, 90°-160°E), however the value over climatology can be small.

The use of support vector regression (SVR) models, exploring new explanatory variables and the non-linear relationships between them, the use of model averaging, and lastly the integration of forecast intervals based on a bias-corrected and accelerated non-parametric bootstrap have been investigated, aiming to improve skills of operational TC seasonal forecasts issued by the BoM for the Australian region and the South Pacific Ocean, as well as sub-regions therein (Wijnands et al., 2015). Hindcasting analyses showed that the SVR model outperforms several benchmark methods. Analysis of the generated models shows that the Dipole Mode Index, the 5VAR index (an index that combines the mean sea level pressure from Tahiti and Darwin as well as the Niño 3, Niño 3.4, and Niño 4 indices) and the Southern Oscillation Index are the most frequently selected as explanatory variables for TC seasonal forecasting in all regions. For both the AR and the SPO, normalized root mean squared error (nRMSE) statistics for the hindcast analyses for 2003/2004 to 2013/2014 indicates that SVR has better skill than LDA: in the AR, nRMSE was 0.93 and 1.25 for SVR and LDA, respectively; in the SPO, nRMSE was 0.83 and 0.94 for SVR and LDA, respectively (Wijnands et al., 2015). Overall, the new SVR methodology is an improvement over the current linear discriminant analysis models and has the potential to increase the accuracy of seasonal TC forecasts in the AR and the SPO.
City University of Hong Kong

Since 2000, the Guy Carpenter Asia-Pacific Climate Impact Centre (GCACIC) of the City University of Hong Kong has been issuing a seasonal forecast for TC activity for the Northwest Pacific. For the period 2000-2011, the forecast was for annual Northwest Pacific TC activity based on a statistical model developed by Chan et al. (1998) and later modified (Chan et al., 2001). However, because of the decreasing trend in Northwest Pacific TC activity since 1997, the statistical model generally over-predicted such activity. Therefore, the statistical forecast was stopped in 2011.

Huang and Chan (2014) then developed a dynamical seasonal TC activity forecast model based on Regional Climate Model Version 3 (RegCM3). In addition to the TC activity for the entire Northwest Pacific, the model also produces forecasts of the number of landfalling TCs in East Asia. Three regions are defined: South (southern China, Vietnam and Philippines), Middle (eastern China) and North (Korean Peninsula and Japan). Because the model uses as both initial and lateral boundary conditions the US Climate Forecast System (CFS) global model forecasts, which has only seven months from the initial time, the forecasts can only be issued for six months (with the initial month used as spinup).

Using this setup, the GCACIC has been issuing six-month forecasts for the months of May to October (based on the 1 April run of CFS) for:

- Northwest Pacific TC activity
- Number of landfalling TCs in each of the three regions

No formal verification of these predictions has been conducted as of yet, but a quantitative evaluation of the forecasts is forthcoming.

Lok and Chan (2017) extended the Huang and Chan (2014) study to predict the annual power dissipation index (APDI) for South China. For every TC that the RegCM3 predicts to make landfall in south China, the position of this TC at three days before landfall was used as the center of the grid of a nested version of the Weather Research and Forecasting (WRF) model. The WRF model uses the forecasts from the RegCM3 as initial and lateral boundary conditions to predict the landfall intensity of the TC, from which the PDI can be calculated. For every season, values of the PDI of all TCs that are predicted to make landfall in south China are then summed to obtain the APDI. This metric gives the expected “damage” to a particular region in a given year. Hindcasts show that this setup is able to predict APDI quite well, especially if there are not too many weak or very intense TCs. No operational forecast of the APDI has been issued yet.

Hong Kong Observatory

The Hong Kong Observatory started issuing experimental seasonal forecasts of TC activity affecting Hong Kong, i.e. TCs necessitating issuance of local signals, in the early 2000s. The annual number of TCs within 500km of Hong Kong was later adopted as the predictand because it was a more objective criteria and had the same long-term mean as the annual number of TCs affecting Hong Kong. The forecast is given in terms of a range, e.g. 4-7. Among other things, the annual forecast is publicized every March at a press conference and is available on the Observatory's website (https://www.hko.gov.hk/wxinfo/season/anlf.htm).
The initial forecast methodology was primarily based on the statistical analysis of ENSO’s impacts on Hong Kong TCs. Over the years, the methodology has evolved, and the performance has gradually improved. A statistical-dynamical approach has been developed, using principal components extracted from dynamical climate model output as predictors. Currently, model data from NCEP’s Climate Forecast System and the Japan Meteorological Agency’s climate model are used. Simple Poisson regression models using predicted sea surface temperature over the Niño 3.4 region and large-scale 500-hPa zonal wind over the western North Pacific as predictors are also considered. In recent years, tropical storm density anomaly maps published by the European Centre for Medium-Range Weather Forecasts are used to qualitatively assess anomalous TC activity in the northern part of the South China Sea. All of the afore-mentioned information are taken into account when formulating the annual forecasts of TC activity.

In the past decade, 60 percent of the forecasts issued were verified to be correct. It is noted that the objective quantitative forecast generated by the statistical-dynamical approach achieves more than a 20 percent error reduction against climatology during the past nine years, though the sample may be too small to be conclusive. In the next step to improve forecasting skill, machine learning techniques will be explored.

Japan Meteorological Agency

The Japan Meteorological Agency (JMA) started developing seasonal TC prediction products with atmosphere-ocean coupled models more than ten years ago, and prototype products are used for internal demonstration and evaluation. An objective detection and tracking algorithm used for this application is based on a technique described in Takaya et al. (2010). Currently, there are several internal products including TC genesis number, accumulated TC probability, ACE, and mean latitude and longitude of TC genesis in the Northwest Pacific (WNP). There are also map products of TC genesis number, accumulated TC probability and ACE. These predictions have been verified using hindcasts and best track analyses in the WNP as well as other basins such as the Atlantic and the South Pacific. The predictive skill of the latest system has turned out to be comparable with published results of other seasonal prediction systems. For example, the correlation between predicted and observed ACE in the Atlantic and WNP during 1996-2009 were 0.65 and 0.74, respectively, which are similar to correlations reported in Camp et al. (2015) of 0.56 and 0.74 for the Atlantic and WNP, respectively).

The underlying mechanisms of the seasonal predictability of TC location and genesis potential in the WNP were discussed by Takaya et al. (2010) and Takaya et al. (2017). Tropical Pacific and Indian Oceans (Indian Ocean Capacitor effect) control seasonal TC activity by modulating the WNP monsoon (monsoon trough), providing seasonal predictability for TC activity.

Shanghai Typhoon Institute (STI) of China Meteorological Administration

STI began making operational forecasts of seasonal TC activity over the NW Pacific in the middle 1990s, based on a statistical technique and an analog-year analysis. These initial forecasts were paused in 2000 and were then restarted in 2005 (Zhan et al., 2012). The current forecasts include the number of tropical storms forming in the NW Pacific and making landfall in China, the number of TCs affecting all of China, East China, South China, and Shanghai City, as well as the number of intense TCs, ACE, and TC track density over the NW Pacific. The forecasts are currently issued in late March of each year, with updates in late June, late July and late August.
At present, the operational seasonal TC forecasts issued by STI are mainly based on statistical, dynamical and hybrid statistical-dynamical techniques, as well as climate-based analogs. The final forecast is a combination of these approaches. The statistical schemes were built using mean generation functions (MGF), stepwise regression (SWR), and optimal subset regression (OSR). The predictors in the latest two regression models include sea level pressure (SLP), SST, vertical shear of zonal wind, 500-hPa geopotential height and convective activity, all of which are believed to be closely related to seasonal TC activity over the NW Pacific (Ying and Wan 2011). The STI dynamical forecast is based on a regional atmospheric model (iRAM) developed at the International Pacific Research Center (IPRC) at the University of Hawaii (Zhan et al., 2011; Wu et al., 2012), in which initial and lateral boundary conditions are obtained from the seasonal prediction of the National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFSv2). The hybrid statistical-dynamical forecasts (STI-HSD) of TC activity over the WNP are made in a three-step procedure (Zhan and Wang 2016). First, the predictors are obtained from various ensemble members of the NCEP CFSv2 seasonal forecasts. Second, a statistical regression model is used for predictions. Third, ensemble forecasts are produced. Most of STI-HSD’s predictors are closely related to SST anomalies in the Nino3.4 region and the East Indian Ocean (EIO) (Zhan et al., 2011), the SST gradient between the Southwest Pacific and the western Pacific warm pool (SSTG) (Zhan et al., 2013), and vertical wind shear over the equatorial western Pacific (Zhan and Wang 2016).

All forecasts issued by STI show positive skills relative to climatological persistence (Figure 5). Using the CFSv2 retrospective forecasts from different initial forecast months for the period 1982–2010, significant skills are found in predicting seasonal TC number and ACE starting from January. The correlation coefficient between the STI-HSD predicted TC number and the observed ranges from 0.62 to 0.80, and that between the STI-HSD predicted ACE and the observed ranges from 0.58 to 0.81. The prediction experiments for 2011-2015 using the hybrid dynamical-statistical model showed better skill and longer lead times than that using pure statistical models.

Figure 5. (a) Time series of the observed and hindcast ACE over the NW Pacific in the typhoon seasons based on the CFSv2-predicted ENSO and SWP SST predictor model with initial months from January to March, on the CFSv2-predicted Ushear and SSTG predictor model with April initial conditions, and on the CFSv2-predicted Ushear with May initial conditions and observed April SSTG, and (b) correlation coefficients of the corresponding seasonal ACE between observations and CFSv2 forecasts for each initial condition listed in (a).
National Typhoon Center/Korea Meteorological Administration

Seasonal western North Pacific TC activity is monitored and forecast by the National Typhoon Center (NTC) at the Korea Meteorological Administration (KMA). The targeted period for the seasonal forecasts is divided into June-July-August (JJA) and September-October-November (SON). The NTC produces seasonal forecasts of TC frequency in late May for JJA, and in late August for SON. The forecast output is issued to the public, and some of the products are shared with fourteen countries under the ESCAP/WMO Typhoon Committee's perennial operating plan.

The forecast is subjectively arranged based on a combination of statistical and numerical prediction sources. Among other techniques, a statistical-dynamical model has been developed based on previous studies on the environmental connections with western North Pacific TCs (Kang and Elsner 2015, 2016; Yang et al., 2018). Multiple linear regression of the forecast TC frequency using environmental factors as explanatory variables is used to find the range of the forecast uncertainty. Here, the GloSea 5 model is utilized for the ensemble predictions of the seasonal environment, and then each set of predicted environments is interpreted into the climatological TC activity. The probability distribution of the forecast includes the uncertainty of the numerical predictions and their statistical TC outputs as well. The seasonal forecast is assigned to a category of either 'Below Normal', 'Normal', or 'Above Normal' which is referenced with probability information.

The statistical-dynamical approach is characterized by a statistical interpretation of the environmental predictions made by GloSea5 into seasonal TC frequency. Then, the operational forecast performance of this model is verified by a correlation analysis between the observed and interpreted TC frequency. The correlation between observed and predicted TC frequency is \( r = +0.69, [0.36, 0.87] \) with the 95% confidence interval highlighted in brackets for JJA and is \( r = +0.71, [0.40, 0.88] \) with the 95% confidence interval highlighted in brackets for SON over the past 20 years (1991-2010).

5.2.3 Beyond Seasonal Timescales

Recently developed decadal climate prediction systems attempt to fill the information gap that exists between seasonal forecasts and climate change projections. As such, decadal prediction can be considered an extension of dynamical seasonal forecasts wherein climate models are initialized by introducing observation-based data and run for multiple years under the influence of contemporaneous changing external forcings (for instance, with rising greenhouse-gas concentration), as in climate projection. In this case, incorporating changes in external forcings is necessary since at this timescale the evolution of the climate is impacted by both internally generated variability and externally forced components.

At present, the skill level for these forecasts is generally considered to be relatively low, but the Atlantic basin stands out as one region where decadal forecasts consistently return significant and positive skill. As a consequence, a few recent studies have reported significant skill in forecasting Atlantic hurricane activity at the multi-annual timescale. Using a direct detection technique, Smith et al. (2010) were the first to show predictability of TC frequency beyond the seasonal timescale. This positive skill was linked by Dunstone et al. (2011) to the ability of their forecast system at predicting a number of atmospheric variables over the main development region. They also identified the North Atlantic sub-polar gyre as a key region driving the skill in their model. Relying on hybrid statistical-dynamical techniques, subsequent
studies have confirmed the ability of these forecast systems at predicting not only the number of basin-wide hurricanes (Caron et al., 2014, Vecchi et al., 2013), but also some landfalling statistics (Caron et al., 2015; Camp and Caron, 2017). In a recent comparative study, Caron et al. (2018) showed that these decadal prediction systems offer an improvement over climatological forecasts and, in some cases, over a 10-year persistence forecast.

While decadal forecasting is still considered experimental, the Grand Challenge on Near-Term Climate Prediction (GC-NTCP) is aiming to facilitate the development of decadal prediction towards its operational use through, amongst other things, the production and dissemination of climate outlooks for the forthcoming years based on real-time forecasts produced by a number of institutions (Smith et al., 2013). Currently, the Met Office displays the forecasts from the individual contributors in graphical format as part of an informal exchange, but only for a few selected climate variables. Because of the encouraging results highlighted here and the strong interest for such a product, Atlantic hurricanes are a prime candidate to be added to the list of climate variables being forecasted operationally.

5.2.4 Summary and Conclusions

This report summarizes several of the seasonal forecast models available today for various TC basins around the globe. The number of groups issuing seasonal forecasts has continued to expand over the past few years, with several of these agencies now providing landfall or region-specific predictions as well. There also has been an expansion of efforts to extend predictions beyond the seasonal timescale to the multi-annual timescale in recent years, with skill at these longer-range outlooks so far being mostly restricted to the Atlantic basin.

5.2.5 Recommendation

Seasonal forecasts are now issued for every TC basin around the globe. While these forecasts have documented skill for most basins, the focus has shifted towards applying new techniques to the seasonal prediction problem. Several groups submitting forecasts to http://www.seasonalhurricanepredictions.org are using machine learning techniques to develop seasonal forecasts. Other groups have moved beyond basinwide TC forecasts to issuing regionally-based predictions.

There remains room for improvement for seasonal prediction, however. As new historical datasets come online with longer periods of more reliable upper-level data including ensemble uncertainty back to the 1950s (e.g. ERA5, JRA-55), statistical models for TC activity can likely be improved. In addition, historical reanalysis of Atlantic hurricane seasons continues, which should help provide an improved calibration target for observed TC activity for seasonal TC forecasts for that basin. Other groups are conducting reanalysis of historical TC activity for other TC basins as well. The combination of improved historical TC records and more reliable reanalysis records should improve statistical forecasts considerably. As dynamical models improve their skill at being able to predict large-scale oscillations such as ENSO, especially during the boreal spring when the springtime predictability barrier is evident, this should also improve skill for hybrid statistical/dynamical seasonal TC forecasts for Northern Hemisphere basins. Global and regional climate models also continue to show steady improvement in skill at being able to predict TC seasons using various dynamical approaches.
Over the next several years, we recommend that new historical reanalysis products be evaluated to improve the skill of statistical models. We also encourage seasonal forecast groups to consider using new techniques for statistical modelling including various machine learning approaches. We suggest that additional efforts be spent on improving seasonal forecast skill for seasons where ENSO-neutral conditions predominate. We also recommend using statistical, statistical/dynamical and dynamical approaches to provide additional value beyond basinwide TC forecasts by considering regionally-based and landfall predictions. Finally, we recommend that additional research be conducted on the potential for multi-annual predictions.

References


TOPIC 7.3 - TROPICAL CYCLONE PREDICTION ON SUBSEASONAL TIMESCALES AND THE S2S DATABASE

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Abstract
In this report we discuss the progress in tropical cyclone (TC) subseasonal variability and forecasting during the last few years. There has been a large effort in the scientific community in understanding the sources of predictability at subseasonal time-scales. Besides the well-known modulation of TC activity by the Madden-Julian Oscillation (MJO), other modes of variability affect TCs at these time-scales, in particular various equatorial waves. There has been significant progress in the ability of models in simulating the MJO and its modulation of TC activity. Community efforts have created multi-model ensemble data sets, such as the S2S (Subseasonal to Seasonal) dataset and TIGGE (The International Grand Global Ensemble), which have made possible the skill analysis of forecasts of the MJO and TCs on subseasonal time-scales in multiple forecasting systems. While there is positive skill in some cases, there is strong dependence on the ensemble system considered, the basin examined, and whether the storms have extra-tropical influences or not. Furthermore, the definition of skillful differs among studies. For instance, while some studies consider a model skillful for forecasting the basin based on seasonal time-scale performance, others require forecasts of subseasonal anomalies. Modelling centers are currently issuing subseasonal TC forecasts using various techniques (statistical, statistical-dynamical and dynamical). There is also a strong interest in the private sector for forecasts with 3-4 weeks lead time and they are investing in this type of product.

7.3.0 Introduction
The modulation of tropical cyclone (TC) activity on intraseasonal time-scales by various subseasonal modes of variability has been well established. Li et al. (2018) highlighted a manuscript in the Chinese literature (Xie et al., 1963), which first documented a relationship between an oscillatory signal of the 700 hPa zonal winds at stations in Southeast Asia with a 40-50-day period and the occurrence of typhoons. This oscillation was a few years later described in detail in the classic paper by Madden and Julian (1972). Nakazawa (1988) and Liebmann et al. (1994) noticed a match between the enhanced convective phase of the Madden-Julian Oscillation (MJO) and an increase in TC activity over the western North Pacific.
Since these early studies, there has been a large body of research on the modulation of global TC activity by various intraseasonal modes. For instance, Schreck et al. (2012) examined cases where the genesis of TCs in the deep tropics can be attributed to enhanced convection due to precursor waves, such as equatorial Rossby waves, mixed gravity Rossby waves, Kelvin waves and easterly waves (tropical depression-like waves). The MJO also affects TC genesis by modulating these high-frequency waves, in particular Kelvin waves. The progress in models in forecasting the MJO and coupled equatorial waves has opened the possibility of skillful TC forecasts on subseasonal time-scales. In the last few years, collaborative multi-institutional projects have allowed the scientific community to explore to what extent the current generation of weather forecasting models have skill in forecasting TCs beyond the current operational 5-day forecasts. In this report we summarize the progress in understanding the modulation of TCs by subseasonal modes of variability, the current state-of-the-art in simulating TCs on these time-scales, and operational subseasonal TC forecasts.

7.3.1 Subseasonal variability of tropical cyclone activity

7.3.1.1 Modulation of TCs by subseasonal modes of variability

Klotzbach and Oliver (2015a) used a long-period MJO index since 1905 based on sea level pressure data from the 20th Century Reanalysis to examine long-term relationships between Atlantic TCs and the MJO. They showed that when the MJO was enhancing convection over Africa and the western Indian Ocean, Atlantic TC activity tended to be enhanced due primarily to reductions in vertical wind shear. They also examined the joint relationships between the Atlantic Multidecadal Oscillation (AMO) and the MJO as well as El Niño-Southern Oscillation (ENSO) and the MJO. When El Niño events or a negative AMO were present, favourable phases of the MJO were not enough to enhance TC activity above climatological levels, while La Niña events or a positive AMO could combine with conducive phases of the MJO to lead to hyperactive periods for Atlantic TCs. Klotzbach and Oliver (2015b) used the same long-period MJO dataset to examine the long-term relationship between the MJO and global TC activity. They documented that the previously-discussed MJO-TC relationships for individual TC basins using the Wheeler-Hendon MJO index since 1974 showed similar relationships prior to that time. Broadly speaking, TC activity was enhanced in individual ocean basins during and immediately after the convective maximum of the MJO traversed that basin. As was found in the Atlantic basin, the MJO could either constructively combine or interfere with ENSO’s impacts on TC activity on subseasonal timescales.

The MJO has been shown to modulate the occurrence of multiple TC events (MTCEs) over the western North Pacific (WNP), which are defined as two or more TCs simultaneously occurring in the WNP (He et al., 2013; Schenkel 2016; You et al., 2018). When convection associated with the MJO is enhanced east of the Indonesian Islands and over the WNP, MTCEs occur more frequently over the WNP than in other regions (He et al., 2013). Most recently, You et al. (2018) showed that more than 60% of MTCEs occur in the convective enhanced phase of MJO, whereas only ~18% of MTCEs appear in the suppressed phase of the MJO. The QBWO (Quasi-biweekly Oscillation) has also been documented to have an important influence on MTCE occurrence (Jin et al., 2016; You et al., 2018). Generally speaking, the convectively active phase of the QBWO is more favourable for MTCE occurrence than its inactive phase. MTCE occurrence is further modulated by different combinations of the MJO and the QBWO phases. You et al. (2018) found that the most frequent MTCEs occur in the combined enhanced convective phases of the MJO and the QBWO, while the least occur in their combined dry phases.
Chen et al. (2018) evaluated the influence of the MJO, ENSO and equatorial Rossby Waves (ERW) on TC genesis, by analysing the percentage of tropical disturbances that developed into TCs in the western North Pacific. They showed that in the convectively enhanced (suppressed) phase of the MJO, El Niño (La Niña) and positive (negative) vorticity ERWs cause the percentage of developing TCs to significantly increase (decrease) compared with the climatology.

Convectively coupled atmospheric Kelvin waves are emerging as another potential modulator of TCs on subseasonal scales. These waves have synoptic-scale wavelengths of 3000–7000 km and rapid eastward phase speeds of 10–20 m s$^{-1}$. However, their lifespan extends into the subseasonal range. A single wave can circumnavigate the globe over the course of a month. Ventrice et al. (2012a) and Schreck (2015) showed that tropical cyclogenesis is generally inhibited during the two-to-three days before the arrival of the convective phase of a Kelvin wave and then enhanced two-to-three days after its convective phase. The schematic below illustrates the primary impacts. The Kelvin wave’s convection may enhance potential vorticity within the protovortices, even if cyclogenesis occurs later (Fang and Zhang 2016). At 850-hPa, equatorial westerlies enhance the cyclonic vorticity for the storm. These persist longer than the period of the Kelvin wave because Kelvin waves are often embedded within the MJO as the leading edge and with the strongest portion of the convection. In addition, the westward tilt with height of Kelvin waves means that it takes a few days for these westerlies to build from the surface to the middle-troposphere which is necessary for TC genesis (Schreck 2016).

![Figure 1. Schematic adapted from Schreck (2015) of impacts of Kelvin waves on tropical cyclogenesis. Relationships are shown in latitude–time at (a) 200 hPa and (b) 850 hPa, while (c) shows time–longitude interactions between the Kelvin wave, MJO, and parent easterly wave.](image)
### 7.3.1.2 Impacts of extratropical Rossby wave breaking on Atlantic tropical cyclones

Studies on the extratropical impacts on TC formation date back to the 1970s. Sadler (1976, 1978) showed that the tropical upper-level trough, which often has extratropical origin (Palmén and Newton 1969), can lead to TC formation over the western North Pacific. Similar mechanisms also exist over the North Atlantic, where upper-level troughs or potential vorticity streamers may induce tropical cyclogenesis (Galarneau et al. 2015; Bentley et al. 2017). In particular, the transition of a subtropical cyclone to a TC was termed as tropical transition by Davis and Bosart (2003, 2004), who noticed that the upper-level troughs involved in the tropical transition processes resemble anticyclonic Rossby wave breaking (RWB). Although RWB can occasionally induce TC formation, Zhang et al. (2016, 2017) showed that the overall impacts of RWB on Atlantic TC activity are negative. This is because active RWB can induce frequent equatorward intrusions of dry and cold air and enhance vertical wind shear and mid-to upper-tropospheric dryness over the tropical and subtropical Atlantic. The correlations between a RWB index and Atlantic TC indices (hurricane counts or accumulated cyclone energy) are negative (~ -0.7 during 1979-2013) and exceed those for ENSO.

Similar impacts were found on the subseasonal time scales. Li et al. (2018) showed that active anticyclonic RWB episodes over the western Atlantic are associated with a wave train spanning from the North Pacific to the North Atlantic and significant anomalies in sea level pressure, vertical wind shear, tropospheric humidity, and precipitation over the North Atlantic (Li et al., 2018; Zhang et al., 2017). Consistent with the large-scale circulation anomalies, TC activity is reduced significantly during active episodes of RWB (Fig. 2). Li et al. (2018) also examined the impacts of RWB on predictability of tropical cyclogenesis using the Global Ensemble Forecast System (GEFS) Reforecast, version 2. Lower predictability of tropical cyclogenesis was found during active RWB episodes than at other times, and it was linked to the lower predictability of environmental variables, such as vertical wind shear, moisture, and low-level vorticity. These variables show a larger ensemble spread during the episodes of active RWB. Wang et al. (2018) examined the dependence of tropical cyclogenesis predictability on different synoptic flow regimes using the concept of tropical cyclogenesis pathways (McTaggart-Cowan et al., 2013), and found that the strong and weak tropical transition pathways, which are subject to strong extratropical influence, are associated with lower predictability than the other pathways. Although the extratropical atmosphere has lower intrinsic predictability than the tropical atmosphere with a forecast lead-time beyond several days (e.g. Davis et al., 2016; Palmer 1996), a better representation of the tropical-extratropical interaction may help to improve the practical predictability of tropical cyclogenesis in numerical models.

![Figure 2. Mean TC track density function for (a) climatology and (b) during active anticyclonic Rossby wave breaking (AWB) episodes, and (c) TC track density anomalies (only regions above the 95% confidence level shaded). The black dashed box highlights the Atlantic Main Development Region. (Li et al., 2018).](image-url)
7.3.2 Simulation of subseasonal TC activity

7.3.2.1 Hindcasts of TC activity in the S2S dataset

To bridge the gap between medium-range weather forecasts and seasonal forecasts, in 2013 the World Weather Research program (WWRP) and the World Climate Research program (WCRP) jointly launched a 5-year research initiative called the Subseasonal to Seasonal prediction project (S2S). Its goal is to improve forecast skill and understanding of the sources of subseasonal to seasonal predictability, and to promote its uptake by operational centres and use by the applications communities (www.s2sprediction.net). To achieve these goals, an extensive database has been established, containing subseasonal (up to 60 days) near real-time forecasts (3 weeks behind real-time) and reforecasts (sometimes known as hindcasts) from 11 centers (Vitart et al., 2017). The S2S database, available to the research community since May 2015, contains daily data of about 80 variables. A TC tracker (see Vitart and Robertson 2018 for details) has been applied to all of the S2S real-time forecasts and reforecasts and the TC tracks, as well as MJO indices, and is publicly available from the ftp site s2sidx@acquisition.ecmwf.int. Using these MJO indices and TC tracks, Vitart and Robertson (2018) showed that eight S2S models display more (less) TC activity over the South Indian Ocean and less (more) TC activity over the South Pacific and near the Maritime Continent when there is an MJO in phase 2 or 3 (6 or 7) in the model (their Figure 2) during the boreal winter, which is consistent with observational studies and with previous modelling studies. This result suggests that the S2S models are capable of reproducing the modulation of TCs in the Southern Hemisphere by the MJO, even if the model resolution is very coarse. The BoM model, for example, has a resolution of ~200 km.

Yamaguchi et al. (2016) investigated the performance of operational global ensembles in predicting the number of TCs generated for a month in the western North Pacific basin using the S2S database. The model climatology of the number of TC genesis events over 4 weeks from initial times of the predictions was assessed with the reforecast dataset from the global BoM, ECMWF, JMA, and NCEP ensembles and then compared to the best track data. The ECMWF is found to simulate well the seasonal variability of TC genesis. JMA underestimates the number of TC genesis events even with a lower wind threshold applied. The BoM tends to overestimate (underestimate) the number of TCs during the early and late (peak) TC season. NCEP simulates the seasonal variability realistically but over- and under-estimates TC frequency if a constant threshold value is used throughout the year.

Lee et al. (2018) evaluated the subseasonal probabilistic prediction of TC genesis using the S2S dataset. Forecasts for basin-wide TC occurrence and weekly time-scales were considered, and the forecast skill was evaluated using the Brier skill score relative to a seasonal monthly varying climatology. Most models have skill for week 1, when the model initialization is important. Among the models evaluated, the ECMWF has the best performance, followed by the BoM. Both systems have skill for several TC basins at week 2. There is a relationship between the models’ skill scores and their ability in accurately representing the MJO, as well as the modulation of TC activity by the MJO (shown in Fig. 3) and the models’ TC climatology. All of these factors are basin dependent.
7.3.2.2 Hindcasts of TC activity in TIGGE

Yamaguchi et al. (2015) evaluated the skill of TC activity (genesis and subsequent track) forecasts from operational global medium-range ensembles as well as the relative benefits of a Multicenter Grand Ensemble (MCGE) with respect to a single model ensemble using the International Grand Global Ensemble (TIGGE, Swinbank et al., 2016). The global ECMWF, JMA, NCEP, and UKMO ensembles were analyzed in seven TC basins. The Brier skill score (BSS) was calculated within a 3-day time window over a forecast length of 2 weeks to examine the skill from short- to medium-range time scales (0–14 days). In most of the TC basins verified, these operational global medium-range ensembles were capable of providing skillful guidance of TC activity forecasts with a forecast lead time extending to week 2. The MCGE has more skill (larger BSS) than the best single-model ensemble (ECMWF). The reliability of these forecasts is improved in the MCGEs compared to the individual ensembles. Both the BSS and the reliability are sensitive to the choice of threshold wind values that are used to define model TCs.

![Candy plot for the MJO–TC relationship in the observations and from two S2S models from week 2 forecasts. The colour of each candy indicates the PDF (%) in the corresponding MJO phase in the basin. The sum of the circles across the MJO phases in each basin is 100%. The black circle at the edge indicates that the value is above the 90th percentile while the cross symbol (x) at the center means the value is below the 10th percentile. Figure adapted from Lee et al. (2018).](image)

7.3.2.3 Simulations and Hindcasts of TC activity in individual models

In a sequence of papers, the skill and predictability of the Geophysical Fluid Dynamics Laboratory (GFDL) coupled system at 50-km resolution for MJO and tropical cyclogenesis was examined. First, Xiang et al. (2015a) showed that the MJO prediction skill in this system can reach out to 27 days, with a potential predictability of 42 days. The MJO forecast skill is dependent on the amplitude and phase of the MJO events. The predictability of this system in forecasting two case studies (Hurricane Sandy and Super Typhoon Haiyan) was examined in Xiang et al. (2015b), showing that the genesis of these events had a maximum prediction lead
time of 11 days, while the landfall location was predicted one week ahead for Sandy and two weeks ahead for Haiyan. Jiang et al. (2018) found limited skill in predicting intraseasonal cyclogenesis with more than 1-week lead time as well as a high false alarm rate. Higher skill was found for TCs forming during strong MJO periods. In the case of the North Atlantic, higher predictability is evident along a tropical belt from the West African coast to the Caribbean Sea, while in the extratropical North Atlantic the predictive skill is poor.

Kim et al. (2014) analysed the modulation of western North Pacific TCs by the MJO in the NASA Goddard Earth Observation System version 5 (GEOS-5) model. While the MJO in the model is weaker and propagates faster than observations, the system reproduces the modulation of the TCs in the basin, with higher TC activity occurring in the active phase of the MJO. The North Atlantic TC modulation by the MJO in the NOAA Climate Forecast System (CFS) version 2 was analyzed in Barnston et al. (2015). The CFS shows useful skill in predicting the MJO phase and amplitude out to 3 weeks. In spite of the too slow MJO propagation, the CFS still shows usable skill in predicting weekly variations of TC activity out to 10-14 days.

7.3.3 Subseasonal forecasts of tropical cyclones: description, skill and verification

As numerical guidance for TC prediction has improved in quality, the lead times at which predictions are useful have begun to extend into the subseasonal range. NWP models and ensemble prediction systems can provide guidance at the 1-2 week range or possibly even longer. A recent review of this topic can be found in Sobel et al. (2018). Historically, and to some extent still, TC forecasting – as practiced by national meteorological services – begins in earnest at the moment when a TC forms. Many forecast agencies predict genesis, typically at lead times up to 5 days or less. They generally do not, however, forecast the subsequent track and intensity at that time, but only do so after genesis has occurred. The typical maximum forecast lead time after genesis has occurred is 5 days. Ensemble systems, on the other hand, need not draw a sharp distinction between the pre- and post-genesis periods, and several ensemble systems generate forecast products which extend from before the moment of genesis to after it. A “strike probability” map is typical (e.g. Vitart et al., 2011). Such products are generally produced by numerical prediction centers, which are often distinct from actual forecast offices. So, for example, the ECMWF and other centers produce strike probability maps out to 10 or 15 days. Forecast centers such as the US National Hurricane Center (NHC) examine this guidance in producing their forecasts, but NHC forecasts do not extend beyond 5 days, and in general do not begin before genesis. Recently, however, NHC has begun issuing forecasts for “potential tropical cyclones” in instances where genesis is predicted and the system is then expected to pose a danger to life and property soon (48 hours) afterwards.

Belanger et al. (2010, 2012) quantify skill at these lead times for the Atlantic and North Indian Ocean basins. Webster (2008, 2012, 2013) argues that ensemble systems should be used to make probabilistic TC forecasts as far in advance as 10-15 days, both in general and in the North Indian Ocean basin in particular. Current practice in most regions, however, is to make forecasts that are largely deterministic, and do not extend to such large lead times. Five days is a typical maximum lead time (Webster 2012; Sobel et al. 2018). The reason for this appears to be that the skill at longer lead times, though arguably usable for some kinds of decision-making, is small, so that forecasters are concerned about false alarms, and a resulting loss of public confidence. It appears that research into forecast communication, as well as the optimal use of long-range, low-skill forecasts by key decision makers (e.g. government agencies
tasked with disaster preparedness) could be valuable in deriving the maximum societal benefit from existing numerical guidance.

### 7.3.3.1 Skill of models to predict the MJO/Boreal Summer Intra-Seasonal Oscillation

Ensemble prediction systems (EPS) have shown remarkable improvements in MJO forecast skill in recent years (e.g. Vitart, 2014; Wang et al., 2014; Marshall et al., 2017; MacLachlan 2015). Neena et al. (2014) assessed the skill of several dynamical model re-forecasts from the Intra-Seasonal Variability Hindcast Experiment (ISVHE). They found skill for 1 to 4 weeks in the boreal winter, with the majority of the models having skill for 2-3 weeks. More recently, Vitart (2017) found that the S2S Project hindcasts have significant RMM (Real-time Multivariate MJO index) prediction skill scores varying widely between 10 to 32 days, which represents an overall improvement over the ISVHE models. In addition, studies have shown the MJO prediction skill in various models. About 4-weeks of RMM skill have been demonstrated in the GFDL (Xiang et al. 2015) and NICAM models (Miyakawa et al. 2014) in boreal winter, with about 3-weeks skill for the UKMO GloSea5 (MacLachlan et al., 2015), BCC (Liu et al., 2017), and FIM-iHYCOM (Green et al. 2017) models in all seasons. Atmosphere-only models, such as GEFS (Hamill and Kiladis 2014) and BCC (Wu et al., 2016) have about two weeks of skill (see Kim et al. 2018 for a more extensive review on the prediction of the MJO). The Boreal Summer intra-seasonal Oscillation (BSISO), which is characterized by a northward propagation in addition to the MJO eastward propagation, is also an important source of predictability for Northern Hemisphere TC activity. Jie et al. (2017) assessed the skill of the re-forecasts from 10 models of the S2S database to predict the BSISO, using a BSISO index developed by Lee et al. (2013). They found that the operational models from the S2S database can predict the BSISO1 (eastward propagation) and BSISO2 (northward propagation) events up to 24.5 and 14 days in advance respectively, although the models tend to underestimate the amplitude of BSISO as the lead time increases.

### 7.3.3.2 CSU Forecasts

The Colorado State University (CSU) has issued two-week forecasts of Atlantic hurricane activity during the peak months of the season (August-October) since 2009. These forecasts predict Accumulated Cyclone Energy (ACE) in the upper, middle, or lower tercile for the next two-week period using a combination of: 1) current storm activity, 2) NHC Tropical Weather Outlooks, 3) forecast output from global numerical weather prediction models, 4) the current and projected state of the MJO and 5) the current seasonal Atlantic hurricane forecast. Six two-week forecasts are issued for each hurricane season, and these predictions have generally shown skill above a persistence forecast from the prior two weeks. For example, five of the six two-week forecasts in 2017 and in 2018 verified in the correct tercile.

### 7.3.3.3 ECMWF Forecasts

The European Centre for Medium-Range Weather Forecasts (ECMWF) has issued week 1-4 forecasts of TC activity for each TC region since 2010. The TC forecast products include: (i) predicted number of tropical storms/hurricane or ACE over a TC basin for a weekly period (calendar week 1 to 4). (ii) TC strike probability map: the probability of a tropical depression/storm/intense storm (hurricane intensity) passing within 300 km. TC strike probability anomaly maps are also available (anomalies relative to model climatology). The forecasts are issued twice a week, but are not available publicly. The skill of the weekly TC
strike probabilities has been assessed in Vitart et al. (2010) over the Southern Hemisphere. A more recent assessment confirms that these forecasts are more skillful than weekly observed climatology and persistence for week 1 and 2 over all TC basins and beyond week 3 for some TC basins.

7.3.3.4 Evaluation of the ECMWF forecasts

Elsberry, et al. (2010) combined the ECMWF 32-day forecast ensemble member vortices with similar tracks into “ensemble storm” tracks with a weighted-mean vector motion technique in which the weighting factor was inversely proportional to the distance from the endpoint of the previous 12-h motion vector. A sample of 30 weekly forecasts for 2008 were compared with the Joint Typhoon Warning Center (JTWC) tracks, and demonstrated that the formations and tracks of five typhoons and four strong tropical storms were consistently predicted during weeks 1 through 4. Elsberry et al. (2011) made a similar evaluation during the 2009 western North Pacific season and found that 12 typhoons were successfully predicted. Many of the deficient track predictions involved unusual and rapidly changing tracks that are likely not predictable on extended-range (5-30 days) timescales.

Tsai et al. (2013) developed an objective track analog verification technique in which ensemble storms within specified time and space differences of the JTWC tracks are first extracted as potential analogs, and four metrics of shortest distance, average distance, distance at formation time, and distance at ending time are calculated. An objective quality measure called LikeliHood Values (LHV) that assesses the overall track similarity between the potential analogs and the JTWC storm is calculated in terms of membership functions for the four track metrics. The performance in the Atlantic in terms of the LHV for ensemble storm tracks that matched an observed storm was done in Elsberry et al. (2014). Four hurricanes and one tropical storm were successfully forecast in three of the four weeks. Two hurricanes and three tropical storms were not predicted by the ECMWF 32-day ensemble, even in Week-1. Four of these storms began in the central Atlantic with strong mid-latitude influences. Because the dynamics of those tropical events are strongly affected by baroclinic processes during the interaction of the eastward-moving midlatitude troughs with the westward-moving pre-TC seedlings, and such interactions are inherently difficult to predict, predictability of a considerable fraction of Atlantic TC events (formation plus track) is quite limited compared to western North Pacific events.

Similar evaluations were carried out for the seasonal (seven-month) ECMWF ensemble forecasts. Although some useful predictions were made for African easterly wave-type storms, limited or no skill was found for the baroclinic-affected formations (Elsberry and Tsai 2016). The performance for the western North Pacific was far superior in that nearly all of the JTWC storms could be matched with an ECMWF ensemble storm track. Only two of the 17 storms evaluated were predicted for all four weeks, but eight of the other storms were predicted in three of the four weeks. However, one early season tropical storm, one baroclinically influenced tropical storm, and one late season tropical depression were not forecast in any of the four weeks. Thus, Elsberry and Tsai (2016) concluded that the performance of the ECMWF ensemble performance in the western North Pacific was very encouraging, and propose that even the distribution of numbers among the three basic track types (westward, northwestward, and recurving) of TC events may be predictable with an appropriate calibration procedure.
7.3.3.5  **Australian Bureau of Meteorology forecasts**

The Australian Bureau of Meteorology (BoM) produced trial subseasonal tropical cyclone products during the 2017-18 Southern Hemisphere cyclone season, which were made available to internal forecasters. These products aimed to match those provided twice weekly by ECMWF using output from the new BoM seasonal forecasting system: ACCESS-S1 (Hudson et al., 2017), which became operational in early 2018. The ACCESS-S system is based on the UKMO GloSea5 (MacLachlan et al., 2015), and shows significant skill for predictions of the MJO out to 30 days and changes in the spatial distribution of TC tracks with the phase of the MJO out to 5 weeks ahead (Camp et al., 2018). The trial forecasts showed performance similar to the ECMWF forecasts and provided guidance out to three weeks ahead for major cyclone events, including Cyclone Gita in the South Pacific and Cyclone Hilda which later made landfall in North West Australia (Gregory et al., 2018, in review). These forecasts were developed in collaboration with the UKMO.

7.3.3.6  **China Meteorological Administration forecasts**

Since the mid-1990s, the China Meteorological Administration (CMA) has been issuing monthly TC forecasts for the number of tropical storm formations over the WNP and the number of TCs making landfall in China. The forecasts are issued monthly from June to August each year based on projection-pursuit diagnostic analyses. The diagnostic analyses use the relationship of TC activity with ENSO, the MJO, and the local thermodynamic and dynamic conditions. In 2017, the hybrid statistical-dynamical approach was developed based on the relationships between the observed monthly TC activity and the large-scale environmental variables from the NCEP CFSv2 forecast system. In addition to numbers of tropical storm formations over the WNP and landfalling TCs in China, the forecasts also include the basin-wide Accumulated Cyclone Energy (ACE). The statistical-dynamical forecasts are probabilistic with three terciles and deterministic with a median. The forecasts provide skillful forecasts for monthly TC number and ACE, with correlation coefficient 0.23 and 0.58 and probabilities of detection of 65% and 78%, respectively. Since 2013, CMA has also been issuing subseasonal forecasts for active, normal and inactive periods of multiple TC events over the WNP (Gao et al., 2011). The forecasts are produced by analyzing the relationship of multiple TC events with the MJO, as well as with subseasonal variability of the monsoon trough and subtropical high over the WNP based on the CFSv2 45-day forecasts. The forecasts are produced once a week and cover the next 30 days from July through September each year. Preliminary verification shows that the 30-day forecasts have good skill for long duration but no skill for short duration. An ongoing effort is to develop an experimental prediction for TC activity in Week 1 to Week 4 periods using the subseasonal forecast model developed by the National Climate Center of China (DERF2.0). Weekly TC activity in DERF2.0 forecasts uses the TC detection and tracking method of Camargo and Zebiak (2002). These forecasts are going to be released operationally in about two years.

7.3.3.7  **Sub-Seasonal Prediction of Tropical Cyclones in the Private Sector**

There is growing interest in the subseasonal prediction of TC activity in all facets of business. A threatening TC can alter the decision tree making process of a business, which can then play a direct outcome on the economic performance of that company for a given year. Some companies need 3-4 weeks warning in order for decisions to be made with regards to preparation and or mitigation of a TC. Thus, there is a need for skillful predictions of TC activity across all basins for which a company has assets. There is currently a lack of model
guidance data that quantifies the TC activity of a particular basin at intraseasonal lead-times. Many forecasters in the private sector will use concepts discovered in research/academia when drawing their Week 3-4 forecasts of TC activity. The MJO (Maloney and Hartmann 2000; Mo 2000; Roundy and Paul 2006; Maloney and Shaman 2008; Klotzbach 2010; Ventrice et. al., 2011) and or convectively coupled atmospheric Kelvin waves (CCKWs; Ventrice et al., 2012a,b; Schreck 2015) are often tracked through the use of observational reanalysis and weather model prediction ensemble systems to derive a Week 3-4 outlook of whether TC activity across a particular basin will be active versus inactive. In addition to these advanced forecasting techniques, the ECMWF monthly model is also utilized for the prediction of TC activity across a basin of interest. Some companies will go a step further, and provide above or below TC activity predictions at the Week 3-4 lead using the ECMWF monthly reforecast, in which the frequency of TCs in the live run relative to the model climate is computed.

7.3.4  Conclusions and Future Work

Considerable progress has been made by the scientific community during the last four years in understanding the sources of predictability and the modulation of TC activity at subseasonal time-scales. There has been significant progress in the ability of models in simulating the MJO and its modulation of TC activity. Community efforts have created multi-model ensemble data sets, such as the S2S (Subseasonal to Seasonal) dataset and TIGGE (The International Grand Global Ensemble), which have made possible the skill analysis of forecasts of the MJO and TCs on subseasonal time-scales in multiple forecasting systems. While there is positive skill in some cases, there is strong dependence on the ensemble system considered, the basin examined, and whether the TC activity has been influenced by the extratropical circulations or not. Furthermore, the definition of skill differs among different authors, as some studies consider a model skillful for forecasting the basin on a seasonal time-scale, while others require forecasts of subseasonal anomalies. Various modeling centers are issuing subseasonal TC forecasts using statistical, statistical-dynamical, or dynamical techniques. Some outputs of the subseasonal TC forecasts are spatially dependent which makes comparison among groups using different verification measures a challenge. There is a growing need for skillful subseasonal forecasts of TC activity in the private sector since certain parts of the private sector require significant lead time to prepare for a TC impact.
7.3.5 Recommendations

1. WMO should encourage and facilitate the scientific community investments in modelling and observational efforts that could potentially improve the subseasonal TC forecasts, both for forecasts of basin-wide activity and for skillful regional predictions.

2. Researcher community focus should be on verification studies as to how well subseasonal single models and multi-models perform in predicting TC activity during weeks 3-4, whether calibration techniques are needed, and development of specific consistent metrics for verification with comprehensive measures for skill of subseasonal TC forecasts.

3. Researcher community should actively explore a better understanding and prediction of tropical-extratropical interactions to contribute to improved subseasonal TC predictions.
as well as their downstream impacts on high-impact weather events on subseasonal timescales.

4. WMO should encourage and facilitate a “Severe Weather Forecasting Demonstration Project” focused on subseasonal TC forecasts, especially in the western North Pacific where the Madden-Julian Oscillation is known to modulate TC formation and activity, and collaborate with both the meteorological and hydrological services to advance the interpretation and appropriate usage of such subseasonal predictions.

Acronyms

ACE: Accumulated Cyclone Energy
ACCESS-S: Australian Community Climate and Earth System Simulator – Seasonal
AMO: Atlantic Multidecadal Oscillation
BCC: Beijing Climate Center
BoM: Australian Bureau of Meteorology
BSISO: Boreal Summer Intra-Seasonal Oscillation
BSS: Brier Skill Score
CCKWs: Convectively Coupled Kelvin Waves
CFS: Climate Forecast System
CFSv2: Climate Forecast System version 2
CMA: China Meteorological Administration
CSU: Colorado State University
DERF2.0: Dynamic Extended-Range Forecast Operational System Version 2
ECMWF: European Centre for Medium-Range Weather Forecasts
ENSO: El Niño-Southern Oscillation
EPS: Ensemble Prediction Systems
ERW: Equatorial Rossby Waves
FIM-IHYCOM: Flow-Flowing Icosahedral Model – Icosahedral Hybrid Coordinate Ocean Model
GEFS: Global Ensemble Forecast System
GEOS-5: NASA Goddard Earth Observatory System version 5
GFDL: Geophysical Fluid Dynamics Laboratory
GloSea5: Global seasonal forecasting system version 5
ISVHE: Intral-Seasonal Variability Hindcast Experiment
JMA: Japan Meteorological Agency
JTWC: Joint Typhoon Warning Center
LHV: Likelihood Values
MCGE: Multicenter Grand Ensemble
MJO: Madden-Julian Oscillation
MTCE: Multiple tropical cyclone events
NASA: National Aeronautics and Space Administration
NICAM: Nonhydrostatic Icosahedral Atmospheric Model
NCEP: National Centers for Environmental Prediction
NHC: National Hurricane Center
NOAA: National Oceanic and Atmospheric Administration
QBWO: Quasi-biweekly Oscillation
RMM: Real-time Multivariate MJO Index
RWB: Rossby Wave breaking
S2S: Subseasonal to seasonal
TC: tropical cyclone
TIGGE: The International Grand Global Ensemble
UKMO: United Kingdom Meteorological Office
US: United States of America
WNP: western North Pacific
WCRP: World Climate Research Program
WWRP: World Weather Research Program

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# 9th International Workshop on Tropical Cyclones

## PROGRAMME

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9th International Workshop on Tropical Cyclones

RECOMMENDATIONS

1. Study how nonlinear interactions of environmental factors, and their multiscale nature, affect genesis, including multiple genesis events and baroclinically-influenced genesis. [RESEARCH]
2. Continue research studies to improve the understanding of the conditions, precursors, and processes leading to TC intensity change, taking into account its multiscale nature. Special focus should be given to rapid intensification, including onset, duration, and potential intensification rate. [RESEARCH]
3. Continue research on the interactions and processes that impact TC track, including structural changes [RESEARCH]
4. Continue research on Secondary Eyewall Formation (SEF)/ Eyewall Replacement Cycles (ERC) and associated structure and intensity changes, to guide operational forecasters on the likelihood of SEF/ERC, what wind field changes may occur, and whether the ERC will complete. [RESEARCH]
5. Develop a definition of Extratropical Transition (ET) that builds on cyclone phase space, but that takes into account different pathways to ET [RESEARCH]
6. Continue efforts to develop, improve, document, and maintain climate-quality datasets including periodic reanalysis of tropical cyclones and impact-relevant TC metrics across all ocean basins, reanalysis of large-scale atmosphere/ocean fields (e.g., ERA-5, JRA-55, etc), and error characteristics. Consider dynamically-consistent reanalysis using high resolution models and improve tropical cyclone representation in reanalysis and global climate models. [RESEARCH]
7. Encourage peer-reviewed attribution studies (or at least real-time attribution studies based on established peer-reviewed methods), as opposed to “real-time” attribution studies using un-reviewed methods. Trend attribution studies should include an expression of uncertainties and provide open access to data used. [RESEARCH]
8. Improve our understanding of the relationship between climate and TCs based on observations, theories, and climate models and including ocean coupling as a TC-relevant environmental condition. [RESEARCH]
9. More research on variabilities of various timescales that are important for subseasonal TC activity and forecasting is recommended. [RESEARCH]
10. Additional efforts should be spent to improve region-specific forecasts and actionable information on tropical cyclones and associated landfall and user-relevant parameters on all time scales. [RESEARCH]
11. Expand the evaluation of the skill of climate models in representing TC activity from monthly to climate change timescales, using standardized verification techniques to allow comparison of different methodologies. Involve WMO verification groups in TC sub-seasonal verification and encourage the sharing of verification codes through public repositories. [RESEARCH]
12. Develop new aircraft, unmanned, tethered and ground-based observations of ocean and atmospheric fields and, when possible, provide real-time or near real-time, high quality, high-resolution observations in both space and time. [RESEARCH]

13. Improve targeted observations including airborne and space-borne measurements, such as those from new high-resolution satellite AMVs. Emphasis should be placed on weak systems, regions commonly with large forecast errors, and regions typically without airborne measurements [RESEARCH]

14. Develop an international community-based platform to support expanded research and development efforts on new intensity prediction methods to facilitate the real-time exchange of forecast model data, observational data, and the data inputs that are needed to drive intensity prediction techniques, and to facilitate consistent verification according to identified community standards [INTEGRATED RESEARCH AND OPERATIONS]

15. Implement new strategies to observe the TC inner-core and environment with high spatial and temporal resolution from the upper ocean (including pre-and post-storm) to the lower stratosphere. In particular, WMO requests the European Union’s Earth Observation Programme (the space component of Copernicus) to prioritize access to C-Band SAR data collection from Sentinel-1A and 1B satellites in Wide swath mode over global tropical cyclones for the purpose of wind speed estimates (including RMW) for operational (and other) uses, provided that there is no additional cost. This would include the set up of an internationally coordinated framework for targeting SAR acquisitions on TCs. [RESEARCH, WMO]

16. Routinely analyze Radii of Maximum Winds (RMW) and 34-kt winds (R34) and include these as best-tracked parameters in post-season best track databases for all basins. Standardized methods should be developed to guide the evaluation of these parameters and their error estimation. [INTEGRATED RESEARCH AND OPERATIONS]

17. Expand verification beyond current WMO guidelines to identify difficult cases of TC genesis, track, intensity, structure, and impacts. Such cases, as well as the metadata explaining why they were difficult cases, should be collated and stored on a community-based database for subsequent research by, e.g., involving the research group on forecast verification. [INTEGRATED RESEARCH AND OPERATIONS]

18. Explore the capability of issuing pre-genesis track, intensity, and size forecasts with watches and warnings as required for disturbances with a high probability of genesis, in particular near land. [OPERATIONS]

19. Consider working toward replacing static cones of uncertainty with dynamic types, which can be ensemble-based or hybrid statistical and dynamical techniques. [OPERATIONS]

20. Include social science aspects and knowledge of ensemble and uncertainty as (mandatory/desirable) components of basic meteorological training under WMO, e.g., Basic Instruction Package for Meteorologists (BIP-M), taking into account latest scientific advances and the forecasters’ continually evolving role. [OPERATIONS]

21. Encourage access to forecast data (deterministic and ensemble; global/regional) and international data sets, particularly TIGGE, to facilitate research and operational use of ensemble forecasts. WMO should promote such sharing of data and code more widely across all topics covered in IWTC-9, e.g., by providing links to data sets from different sources. [INTEGRATED RESEARCH AND OPERATIONS , WMO]

22. Explore the possibility of standardizing the definition of TC genesis and how genesis is tracked, independent of basin and model configuration, to be used for forecast and verification purposes. [INTEGRATED RESEARCH AND OPERATIONS]
Explore the possibility of a consistent definition of SEF/ERC onset, including confidence levels, that is useful for both the research and operational community, and use it to develop a database for use by the research community [INTEGRATED RESEARCH AND OPERATIONS]

Advance intensity forecast guidance, visualization and integration into operational centers, including diagnostics (especially vertical wind shear), dynamic models, statistical-dynamical techniques, machine learning approaches, and ensembles to promote probabilistic intensity output. [INTEGRATED RESEARCH AND OPERATIONS]

Establish an objective database of developing and non-developing disturbances. Include storm characteristics such as center location, Dvorak (CI) number, and Invest designation, when applicable. [INTEGRATED RESEARCH AND OPERATIONS]

Support efforts to make current and future research and developmental satellite data and products available in real-time or near real-time and aggregate the products on a web site. Upon successful demonstration of capability from research missions, efforts should be made to transition these capabilities to operations by operational entities and provide appropriate training. [INTEGRATED RESEARCH AND OPERATIONS]

Coordinate researchers, operational forecasters and social scientists to jointly work together to design early warning systems using impact-based parameters with users in mind taking into consideration the decision-making processes, cascading TC impacts, forecast uncertainties, and varying capacity to respond. Special emphasis should be placed on maximizing the use of social media in a responsible manner, as a platform to engage communities. [INTEGRATED RESEARCH AND OPERATIONS, WMO]

Coordinate the transfer of all forecast (including probabilistic) tools and guidance to all TC forecast agencies. [WMO]

Coordinate an intercomparison project on different diagnostic techniques, such as ensemble sensitivities, to better understand large errors associated with forecast busts from existing databases such as the TIGGE and WGNE collection of model forecasts on ensemble sensitivity experiments. [WMO]

Assist with multi-region and multi-center coordination of TC reconnaissance efforts and promote the real-time sharing and exchange of aircraft/UAV –based observational data in a standardized format to encourage easy use for modeling centers and forecasters. (WMO)

Promote the real-time sharing of airborne and land-based observations (WMO).

Encourage the growing number of research and operational programs that are providing validation data for radar-derived, aircraft-derived and satellite-derived surface wind speeds/vectors outside the Atlantic basin. These efforts would include support for validation and development needed for assimilation into NWP. (WMO)

Encourage and support another International Workshop on Satellite Analysis of Tropical Cyclones (IWSATC) in the near future, expanding the role to better reach underdeveloped TC-prone countries to provide information on the satellite sensors, data availability, data accessibility, and platforms and to develop training for how to use the products/applications. (WMO)

Encourage sharing of and facilitate the training of advances in observing and modeling subseasonal TC basin-wide activity. (WMO)

Encourage the opportunity for major interdisciplinary research activity in the Asian Region aimed at improving the information available to typhoon forecasters and providing the research needed to enhance the communication and utility of typhoon warnings. This should be a pilot project for the seamless Global Data Processing and
Forecasting System co-designed between WWRP and any interested regional body/ies in the Asian region to ensure a strong linkage between research and operational forecasting. The WWRP focal point of the activity would be its HIWeather project with significant contributions from all WWRP Working Groups and from WGNE. IWTC-9 recommends that interested parties meet early 2019 to discuss the development of such an activity. [INTEGRATED RESEARCH AND OPERATIONS, WMO]
World Weather Research Programme (WWRP)
Report Series

Sixth WMO International Workshop on Tropical Cyclones (IWTC-VI), San Jose, Costa Rica, 21-30 November 2006 (WMO TD No. 1383) (WWRP 2007-1).


WMO International Training Workshop on Tropical Cyclone Disaster Reduction (Guangzhou, China, 26 - 31 March 2007) (WMO TD No. 1392) (WWRP 2007-3).


Expert Meeting to Evaluate Skill of Tropical Cyclone Seasonal Forecasts (Boulder, Colorado, USA, 24-25 April 2008) (WMO TD No. 1455) (WWRP 2008-4).

Recommendations for the Verification and Intercomparison of QPFS and PQPFS from Operational NWP Models – Revision 2 - October 2008 (WMO TD No. 1485) (WWRP 2009-1).


4th WMO International Verification Methods Workshop, Helsinki, Finland, 8-10 June 2009 (WMO TD No. 1540) (WWRP 2010-1).

1st WMO International Conference on Indian Ocean Tropical Cyclones and Climate Change, Muscat, Sultanate of Oman, 8-11 March 2009 (WMO TD No. 1541) (WWRP 2010-2).

Training Workshop on Tropical Cyclone Forecasting WMO Typhoon Landfall Forecast Demonstration Project, Shanghai, China, 24-28 May 2010 (WMO TD No. 1547) (WWRP 2010-3) (CD only).

2nd WMO International Workshop on Tropical Cyclone Landfall Processes (IWTCPL-II), Shanghai, China, 19-23 October 2009 (WMO TD No. 1548) (WWRP 2010-4).

5th WMO Symposium on Data Assimilation, Melbourne, Australia, 5-9 October 2009 (WMO TD No. 1549) (WWRP 2010-5).
7th International Workshop on Tropical Cyclones (IWTC-VII), Saint-Gilles-Les-Bains, La Réunion, France, 15-20 November 2010 (WMO TD No. 1561) (WWRP 2011-1).


Recommended Methods for Evaluating Cloud and Related Parameters (WWRP 2012-1).


Second WMO/WWRP Monsoon Heavy Rainfall Workshop, Petaling Jaya, Malaysia, 10-12 December 2012 (WWRP 2013-1).

International Workshop on Unusual Behaviour of Tropical Cyclones, Haikou, Hainan, China, 5-9 November 2012 (WWRP 2013-2).

Abstracts of Papers for the Fifth WMO International Workshop on Monsoons (IWM-V), Macao, China, 28-31 October 2013, Hong Kong, China, 1 November 2013 (WWRP 2013-3).

Second International Conference on Indian Ocean Tropical Cyclones and Climate Change (IOTCCC-II), New Delhi, India, 14-17 February 2012 (WWRP 2013-4).

WMO/WWRP International Workshop on Rapid Changes in Tropical Cyclone Intensity and Track, Xiamen, China, 18-20 October 2011 (WWRP 2013-5).

5th International Verification Methods Workshop, Melbourne, Australia, 5-7 December 2011 (WWRP 2013-6).

Verification Methods for Tropical Cyclone Forecasts (WWRP 2013-7).


Joint Meeting of the THORPEX International Core Steering Committee (ICSC) and the World Weather Research Programme (WWRP) Joint Scientific Committee (JSC), (Geneva, Switzerland, 17 July 2013) (WWRP 2014-2).

Workshop on Communicating Risk and Uncertainty, Melbourne, Australia, 26-27 July 2012 (WWRP 2014-3).


6th International Verification Methods Workshop, New Delhi, India, 13-19 March 2014 (WWRP 2014-6).

Proceedings of the 5th International Workshop on Monsoons, Macao, China, 28-31 October 2013, Hong Kong, China, 1 November 2013 (WWRP 2015-1).


8th International Workshop on Tropical Cyclones (IWTC-VIII), Jeju, Republic of Korea. 2-6 and 10 December 2014 (WWRP 2015-3).


3rd International Workshop on Monsoon Heavy Rainfall (MHR-3), New Delhi, 22-24 September 2015 (WWRP 2015-6).


Verification of Environmental Prediction in Polar Regions: Recommendations for the Year of Polar Prediction, (WWRP 2017-1).


7th International Verification Methods Workshop (IVMW-7), Berlin, Germany, 3-11 May 2017 (WWRP 2018-5).
6th International Workshop on Monsoons (IWM-6), Singapore, 13-17 November 2017 (WWRP 2018-6).

4th International Workshop on Tropical Cyclone Landfall Processes (IWTCLP-4), Macao, China, 5-7 December 2017 (WWRP 2018-7).

Design, Validation and Application of Observing System Simulation Experiments (OSSEs) for WMO/WWRP Projects (WWRP 2018-8).

Seventh International WMO Data Assimilation Symposium, Florianópolis, Brazil, 11-15 September 2017 (WWRP 2019-1).


