## World Meteorological Organization

# International Workshop on Satellite Analysis of Tropical Cyclones II (IWSATC-II)

## Report and Recommendations

**Prepared by Andrew Burton and Christopher Velden (Co-Chairs)**

**HONOLULU, HAWAII, USA**

**(17 - 19 February 2016)**

## FINAL REPORT

World Meteorological Organization
Weather • Climate • Water

# Contents

# 1. Introduction

Tropical cyclones (TCs) are a global extreme weather hazard. In the absence of penetrating reconnaissance aircraft observations, the analysis of TC position, intensity and size (radius to gale, storm and hurricane force winds) are mainly determined by satellite based remote sensing methods. The most notable method to estimate intensity is the Dvorak technique, which has been the predominant systematic procedure for TC analysis for over forty years, and forms the basis of much of the global best track record (Dvorak, 1984; Velden et al. 2006). Verification against reconnaissance aircraft observations has proven the technique to be generally reliable in delivering a useful level of skill in TC analysis (Guard, 1988; Mayfield et al. 1988; Brown and Franklin, 2002). However, a number of authors have also noted the shortcomings of the technique including known biases related to translation speed, latitude, size and intensity trends (Brown and Franklin, 2004; Kossin and Velden, 2004; Knaff et al. 2010). In addition to these limitations, Velden et al. (2006) documented common misapplications of the Dvorak technique, and a number of regional modifications that have occurred over the many years of its use. The ramifications of this are twofold: 1) Multiple agencies issuing TC intensity warnings in a common basin may not agree, thereby causing emergency management and public confusion, and 2) Historical TC archives may acquire regional intensity biases, making global TC climate trend studies a challenge.

Recognition of these issues amongst the global TC community led to the first World Meteorological Organisation (WMO) International Workshop on the Satellite Analysis of Tropical Cyclones (IWSATC-I), which was held in April 2011 in Honolulu, Hawaii, USA. As noted in the meeting summary paper (Velden et al. 2012), IWSATC-I was held in conjunction with the second workshop of the International Best Track Archive for Climate Stewardship (IBTrACS). IBTrACS is a WMO supported initiative of the World Data Center for Meteorology which is maintained by the National Oceanic and Atmospheric Administration National Centers for Environmental Information (NOAA/NCEI). The organisers of the IWSATC and IBTrACS workshops envisaged a cross linkage between the two to support the improvement of the global tropical cyclone record.

The main purpose of IWSATC-I was to increase the accuracy and reliability of satellite analyses of TCs by sharing the latest knowledge and techniques developed by the TC research community with operational forecasters of the major warning centers.

The specific objectives of IWSATC-I were to:

a) Describe the latest operational procedures of satellite analysis of TCs (including the use of the Dvorak technique) in the participating TC warning centers;
b) Identify the differences in the procedures between the centers and their relevance to final TC intensity estimates and resulting Best Track data;
c) Share recent developments in the satellite analysis of TCs, particularly new objective methods;
d) Make recommendations on 1) how operational forecast centers in common TC basins can better reconcile Dvorak technique procedural differences to derive more consistent TC estimates for real- time warnings, and among all TC basins for improved continuity in Best Tracks, and 2) how operational centers can optimally blend the emerging objective guidance methods with existing subjective methods in order to improve the overall satellite analysis of TCs as it relates to both operational warnings and the Best Track data.

IWSATC-I documented significant regional differences in the application of the Dvorak technique and introduced operational warning centres to new developments in objective satellite analysis techniques. For further details of the proceedings and outcomes of IWSATC-I the reader is referred to Velden et al 2012.

Through the ongoing support of WMO, a second workshop (IWSATC-II) was held in conjunction with the third IBTrACS workshop in February 2016 in Honolulu, Hawaii, USA. The primary objectives of IWSATC-II were to update operational analysis practices at TC Regional Specialised Meteorological Centres (RSMCs) / Tropical Cyclone Warning Centres (TCWCs) in the 5 years since IWSATC-I, and to explore greater use of emerging objective satellite-based aids.

The specific aims of IWSATC-II were to:

1. Describe the operational TC analysis procedures and any changes that may have been made since IWSATC-I by the participating RSMCs/TCWCs;
2. Identify the continuing differences in procedures between these centres and their potential relevance to operational TC warnings and Best Tracks;
3. Share the recent developments in TC satellite analysis using automated and objective methodologies;
4. Make recommendations on how RSMCs/TCWCs can optimally blend the available objective guidance with subjective methodologies to improve satellite analysis of TCs for both operational warnings and Best Track purposes.

A list of participating countries and organisations is given below:

| COUNTRY | PARTICIPANT |
|---|---|
| AUSTRALIA | Australian Bureau of Meteorology (BoM) |
| AUSTRALIA | University of New South Wales (UNSW) |
| CHINA | China Meteorological Administration (CMA) |
| FRANCE | Regional Specialized Meteorological Center (RSMC) La Réunion<br>METEO-FRANCE |
| HONG KONG, China | Hong Kong Observatory |
| INDIA | India Meteorological Department |
| JAPAN | Japan Meteorological Agency (JMA) |

| | |
|---|---|
| REPUBLIC OF KOREA | National Meteorological Satellite Center (NMSC)<br>Korean Meteorological Administration (KMA) |
| NEW ZEALAND | Met Service (NZMS) |
| USA | NOAA/National Climatic Data Center |
| USA | RSMC Miami / National Hurricane Center (NHC) |
| USA | Naval Research Laboratory (NRL) |
| USA | University of Wisconsin- Madison/CIMSS |
| USA | RSMC Honolulu / Central Pacific Hurricane Center (CPHC) |
| USA | U. S. Joint Typhoon Warning Center (JTWC) |
| WMO | World Meteorological Organization |

In this report, we summarize the reported changes in TC satellite analysis techniques since IWSATC-I (2011) and highlight the continued development of existing objective analysis methods as well as the emergence of new algorithms.

## 2. Developments in operational analysis

A representative from each TC operational centre presented a summary of the changes in operational practices since IWSATC-I in 2011. The following paragraphs summarize some of the more significant changes in satellite analysis practices that were reported.

The Korean Meteorological Administration (KMA) was not represented at IWSATC-I and hence the presentation on behalf of KMA provided a complete summary of both historical and current operational practice. KMA first introduced the subjective Dvorak technique into operations in 2002, however they stopped using it in 2009 and did not reintroduce it until 2015. In 2005 during the period when they were not employing the subjective Dvorak technique they introduced the Advanced Objective Dvorak Technique, the forerunner to the Advanced Dvorak Technique (ADT, Olander and Velden, 2007). In 2011, they upgraded to the ADT and continued to use the algorithm in “semi-manual” mode. When they reintroduced the Dvorak technique in 2015, they also began running ADT in automatic mode (i.e. without manually entering in centre positions or subjectively determining the scene type).

Amongst the delegates from agencies that were represented at IWSATC-I, a number reported changes to operational analysis procedures that were significantly influenced by the IWSATC-I proceedings and recommendations.

The China Meteorological Administration (CMA) reported that in 2012 as a result of IWSATC-I, they introduced the classical Dvorak technique, replacing the previously employed "simplified Dvorak technique" (see Velden et al. 2012 for further details). With assistance from the Cooperative Institute for Meteorological Satellite Studies (CIMSS), CMA has also developed and implemented an objective tropical cyclone intensity estimation method similar in nature to the ADT. Two additional objective aids have also been developed by CMA within the last five years. The first of these is an intensity estimation technique based on the statistical relationship between TC intensity and its inner-core convection, plus the persistence of TC intensity. The algorithm describes the inner core convection using several parameters retrievable from infrared (IR) satellite images, including the number of convective cores, their distance from the center and their brightness temperature (Lu and Yu, 2013). Additionally, CMA has developed a mathematical morphology-based algorithm for TC center location. In post analysis (best track analysis) each of these objective aids is used in conjunction with the operational subjective Dvorak estimates and subjective interpretation of passive microwave imagery. Subjective Dvorak estimates are not completed as part of the best track process, instead the real-time estimates are used as an important reference.

The delegate representing Meteo France Regional Specialised Meteorological Centre (RSMC) La Réunion reported that as a result of recommendations made at IWSATC-I they began separately storing Dvorak Current Intensity (CI) estimates and no longer require that the final operational intensity estimate be consistent with the CI number. This change in procedures allows the "pure" Dvorak estimate to be stored in the database for verification purposes while allowing the final operational intensity estimate to be adjusted according to other guidance and observations (e.g., a scatterometer pass) to obtain the optimal intensity estimate.

Of course, not all changes in operational methods in the last five years can be directly related to IWSATC-I.

Use of the Courtney-Knaff-Zehr (CKZ) pressure wind relationship (Knaff and Zehr, 2007; Courtney et al. 2009) has become more widespread with two agencies reporting that they have implemented it since IWSATC-I, including RSMC La Réunion (2011), and the Central Pacific Hurricane Center (CPHC, 2014).

The Japan Meteorological Agency (JMA) reported that they have replaced the operational use of the subjective Dvorak technique with a semi-objective Dvorak-based technique: Cloud Grid Information Objective Dvorak Analysis (CLOUD) (JMA-1). CLOUD was developed by RSMC Tokyo and introduced into operations in 2013 in recognition of the dependency of the Dvorak technique on the skill of the analyst. CLOUD requires a manually determined center position and cloud pattern, but enables new TC analysts to obtain reliable Dvorak-based intensity estimates without the higher levels of training and experience associated with the Dvorak technique. JMA continues to employ the subjective Dvorak technique for best track analysis to maintain Dvorak skills and ensure consistency and quality of the best track data.

While most agencies cease Dvorak analysis once a TC makes landfall, the Hong Kong Observatory (HKO) has made modifications to the Dvorak weakening rules to produce better post-landfall Dvorak intensity estimates. HKO also reported that they have adopted the 0.93 conversion factor for converting from 1-min to 10-min maximum sustained winds that was recommended by Harper et al (2010).

There was some discussion amongst delegates regarding this change and the possible impacts on the historical record. The Australian Bureau of Meteorology and RSMC La Réunion reported that they had not yet implemented the Harper et al. recommendation due to concerns about introducing another source of inhomogeneity in the global best track record. Most agencies round maximum wind estimates to the nearest 5 knots. When rounding is factored in, the adoption of a 0.93 conversion factor results in a Dvorak CI of 2.5 (T2.5) being assigned gale force winds. This creates potential for a small quantum shift in the number of TCs being recorded in the best track records. If all systems that had reached a maximum intensity of T2.5 were previously recorded in the database despite (at the time) not reaching TC intensity, and if the Dvorak estimates were also recorded then it would be a simple matter to reclassify the existing records and ensure homogeneity. Unfortunately, some agencies only recorded systems that reached TC intensity, as defined at the time, and many did not record the Dvorak metrics that determined the final intensity estimate. For these agencies it is difficult to introduce the new conversion factor without having a negative impact on the historical record.

A general increase in the use of objective analysis aids was evident across operational centers. A common theme that emerged from delegates' presentations was the difficulty in blending the available intensity estimates in an optimal manner. The emergence of new objective analysis methods has created a challenge for operational analysts to understand the relative strengths and weaknesses of the various objective aids in different synoptic situations in order to consistently add value to the final intensity estimate.

A major recommendation from IWSATC-I was to expand training material focused on helping TC forecasters make optimal use of the available satellite-based intensity estimates and establishing guidelines for the improvement of satellite TC analyses. The release of a training module (University Corporation for Atmospheric Research (UCAR), 2016) specifically targeting this aspect of the TC warning process has gone a long way toward meeting these objectives. Exercises held during IWSATC-II enabled delegates to discuss and compare different methods for blending guidance inputs to arrive at a final operational intensity estimate. The opportunity to discuss details of objective satellite analysis algorithms with the developers of the algorithm provided delegates with better understanding of the strengths and limitations of each technique. Delegates reported that this knowledge gave them greater confidence in using the objective algorithms as part of the analysis process rather than relying primarily on the more familiar subjective Dvorak estimates.

Delegates agreed that a future IWSATC should include a "train-the-trainer" session to continue to encourage and facilitate incorporation of objective algorithms in the satellite analysis process.

IWSATC-I was successful in recording regional differences in satellite analysis of TCs and resulted in some changes that will lead to greater uniformity in the global TC record. However most of the regional differences in the application of the Dvorak technique that were noted at IWSATC-I still exist. Many of the differences are minor and are not expected to have a significant effect on the homogeneity of the global record. We note below several of the more significant differences that remain.

The India Meteorology Department IMD continue to give preference to VIS analyses over EIR despite the explicit recommendation of Dvorak (1984).

Meteo France continues to punctually employ microwave imagery when determining the extent of curved bands in the Curved Band scene type of the Dvorak technique. Combined with a strict interpretation of the rules governing breaks in curved bands this practice may result in a (marginal) low intensity bias compared with other warning agencies.

The Australian Bureau of Meteorology continues to use a TC definition that requires gale force winds to wrap more than half way around the center and be maintained for more than six hours. This definition is stricter than that employed by most agencies and over time will lead to a slightly lower number of TCs being recorded in the best track records than what would be recorded by other agencies.

# 3. Developments in objective satellite analysis aids

Following the operational center presentations, the workshop focused on new developments in TC satellite analysis from the research community.

The delegate from CMA reported on a number of ongoing developments in relation to objective satellite-based TC analysis algorithms. With assistance from CIMSS, CMA has developed an objective intensity estimation technique similar to the ADT. The algorithm is run in semi-automated mode, requiring the analyst to provide the center position to the algorithm. They are currently developing an automated center-fixing algorithm that incorporates spiral centering and ring fitting algorithms in the style of the CIMSS ARCHER application (see below). Ellipse-fitting and inflection point algorithms are also being developed to improve the accuracy of the objectively determined center fixes.

CMA is also working on a number of projects designed to maximize the benefits from their national meteorological satellite constellation: 1) Using the microwave imager (MWRI) onboard FY-3B/C, a method has been developed to estimate TC intensity. 2) CMA has also developed a method to merge data from FY-2G and ASCAT in order to analyze TC structure. 3) Based on FY-2E, a TC precipitation estimation product has been developed.

A new method to estimate TC intensity from IR was introduced by Dr. Liz Ritchie (UNSW). This near-real-time objective technique quantifies the level of organization or axisymmetry of the infrared cloud signature of a TC as an indirect measurement of its maximum wind speed. The method is referred to as the deviation-angle variance (DAV), and has been tested in several TC basins. In addition to intensity, the method produces estimates of TC structure such as surface wind radii.

KMA has developed an algorithm to retrieve sea surface wind speed (SSW) under rain-free and rain conditions using the low frequency bands (6.9 GHz and 10.7 GHz) of passive microwave satellite observations such as GCOM-W/AMSR-2 and GPM/GMI. Wind speed is the main factor responsible for the increase in ocean thermal emission because sea surface emissivity strongly depends on surface roughness. An alternative approach to estimate the SSW as a function of surface roughness is developed in KMA. The surface roughness is computed using the approximation and characteristics of the polarization ratio (Hong and Shin, 2013). Using the retrieved SSW of GCOM-W/AMSR2, GPM/GMI and received L2 of METOP/ASCAT from EUMETSAT. Radii of gale and storm of TC have been estimated since 2015.

JMA has been actively working on several objective satellite algorithms designed to estimate TC intensity: 1) Objective Dvorak analysis called CLOUD went into operations during the 2013 TC season to improve objectivity and efficiency of Dvorak analyses (JMA-1, 2016). 2) Methods using microwave sounder data from AMSU-A and ATMS were developed and have been operational since 2013 and 2016 respectively. 3) A maximum sustained wind (MSW) estimation method using microwave imager data from TMI went operational from 2013 until TMI's operation was terminated in 2015. JMA also developed a similar SSMIS-based MSW estimation method in 2015. 4) A weighted consensus method using Dvorak and AMSU central pressure estimates was developed in 2016 (JMA-2, 2016). All of these TC intensity estimates, other than the MSW estimation using microwave imager data, are available to the Typhoon Committee Member countries starting with the 2016 TC Season.

Several presentations were given by CIMSS (University of Wisconsin) researchers on evolving objective methods.

A summary of the Advanced Dvorak Technique (ADT) focused on upgrades to the algorithm since the first IWSATC, including the implementation of an inline passive microwave eye structure and intensity estimation routine. Current and planned upgrades include enhancements to allow the algorithm to be utilized on subtropical and extratropical systems.

Major upgrades were introduced to the Automated Rotational Center Hurricane Eye Retrieval (ARCHER) algorithm that allows for a robust application of TC center-fixing and characterization in real-time operations. The specific new features include: 1) Calibrated adaptation to observations in 37 GHz, 85-92 GHz, IR window, Shortwave IR, Visible, and scatterometer; 2) Corresponding output of the center-fix expected error; 3) A TC track display that assimilates the wide variety of center-fix information into a clear depiction of TC evolution in real-time; and 4) Diagnostic measurements of secondary eyewall formation, to serve as an early notification of an imminent eyewall replacement cycle. A thorough validation of the algorithm includes absolute accuracy relative to the NHC Best Track during aircraft reconnaissance flights, and also relative to operational analyst center-fixes.

The status of the CIMSS and CIRA microwave sounder intensity and structure algorithms was presented. Changes in the CIMSS intensity algorithms since the previous IWSATC workshop include addressing the loss of AMSU-B on NOAA-15, updating limb corrections for all the NOAA satellites, adding Metop-B to the AMSU intensity algorithm, the use of ARCHER-based eye size estimates as the primary source for AMSU bias corrections, and development of the SSMIS and S-NPP ATMS sounder intensity algorithms. The primary change for the CIRA algorithm since 2011 is the use of the MIRS temperature retrieval system for the AMSU-based intensity and structure algorithm. CIRA has also developed an S-NPP ATMS algorithm which uses the MIRS retrievals. Recent field campaigns by NASA (HS3) and the US Navy (TCI) have provided unprecedented detail of TC warm core structure using high-altitude dropsondes at high vertical and horizontal resolution. A brief summary of some initial results from this analysis showed how this data can be used to calibrate/evaluate the satellite-based warm core observations.

The latest upgrades and performance of the CIMSS SATCON (satellite consensus) algorithm were also presented. Updates to the algorithm since 2011 include interpolation of the sounder members to improve the number of matches to the ADT and to create a more smooth transition temporally. The addition of 2-standard-deviation-error bounds to the plot of SATCON estimates now act as a guide to warning agencies when the best track significantly falls outside of these bounds. A pressure-wind estimate of Vmax is derived from the SATCON pressure anomaly estimate that provides 25% of the final SATCON Vmax estimate with the remaining 75% coming from the weighted Vmax estimate based on the available objective members (ADT, AMSU and SSMIS). The loss of SSMIS sounders on F-19, F18 and F-16 in 2015 required the development of a time-weighting scheme since F-17 estimates may only be available once per day. An analysis of the error distributions for the 1999-2012 SATCON estimates sample indicate an improved error distribution of Vmax errors compared to the DT with a near zero bias compared to the DT too weak bias. Analysis of a homogenous sample of cases from 2006-2012 indicate that SATCON outperforms all objective members with an RMSE of 8.3 knots for Vmax compared to 9.2 knots for the DT (N=275). Future work will focus on including the S-NPP sounder estimates, evaluation of the DAV technique for inclusion in SATCON, and exploring a Bayesian approach to SATCON intensity estimation.

There still exists the challenge of adequate calibration and validation of the satellite-based algorithms in regions lacking in situ TC observations. This will lead to difficulty in resolving regional differences in TC analysis without regional validation data. However, from the promising multispectral methods being developed by the TC research community to estimate TC position, intensity and structure, the possibility of fully objective best track estimates seems to be emerging.

# 4. Recommendations

1 Noting the importance of satellite data for tropical cyclone disaster risk reduction, IWSATC-II recommends that the WMO Space Program make every possible effort to ensure that the current observing system is maintained (e.g., microwave imagers/sounders) and new data streams are encouraged. For example, the developments in microsats/CubeSats and the possible future commercialisation of some satellite data streams may impact future tropical cyclone monitoring capabilities.

2 Given the progress and achievements of the first two workshops, both the operational and research TC communities encourage the continued sponsorship by WMO for regular (2-4 years) IWSATC workshops (incorporating IBTrACS). This will facilitate the essential exchange of operational needs and research advances to meet them. It is further recommended that the next workshop include a "train-the-trainer" day to facilitate widespread adoption, optimal employment and consistent application of new operational techniques.

3. Innovative satellite-based methods that are showing promise for TC analysis need to be integrated into the forecast process of each RSMC/TCWC for optimal employment. Therefore, the IWSATC-II recommends that WMO helps to identify resources for providing algorithm transition into operational center environments.

4. Noting the ongoing need for satellite validation datasets (reports during TC passage from local islands. buoys, ships, etc.), IWSATC-II recommends that WMO, through the Regional Associations, encourage RSMCs/TCWCs to share all available datasets with the TC research community.

5. Satellite observations of TCs are a primary contributor to global Best Tracks and reanalyses. Therefore the IWSATC-II recommends that the satellite TC community continue to work closely with IBTrACS towards the goal of a global, unified Best Track record.

6. The IWSATC-II community re-emphasizes and strongly supports a recommendation from IWTC-VIII:

"Recognizing the value and importance of the NRL Tropical Cyclone site [http://www.nrlmry.navy.mil/TC.html] for both real-time operational use and as a resource for researchers, the IWTC expresses concern that continuing development and availability of this resource may cease. Reflecting on the exceptional value that operational centers in particular place on this web site as a unique and effective means of providing global access to the full suite of microwave imagery, the IWTC community recommends that WMO send a letter of commendation to the development team at NRL-MRY in recognition of the significant contribution they make to global disaster risk reduction." IWSATC-II also encourages WMO to request in this letter the continued support of this resource by NRL-MRY sponsors.

7. The IWSATC-II endorses the following recommendation from the IWTC-VIII. That satellite techniques be developed and calibrated for atypical TC structures, such as those that are problematic for the traditional Dvorak technique. Note: this encompasses the entire range of TC structures with specific focus on those atypical ones that have been problematic for forecasters in the past (e.g., subtropical and extratropically transitioning cyclones, monsoon gyres, as well as TCs making landfall).

8. The IWSATC-II recommends the development of a living document that provides details of the various satellite-based observations and techniques used in operational centers. The document should provide information about the observation or technique and any known strengths and weaknesses that would be useful to a forecaster in an operational setting. The document should be updated on an "as needed" basis by individuals identified as the responsible person for that particular observation or technique and should be made available on the WMO TCP web site and the Tropical Cyclone Forecaster Website hosted by Hong Kong Observatory.

# 5. References


Brown, D. P., and J. L. Franklin, 2002: Accuracy of pressure–wind relationships and Dvorak satellite intensity estimates for tropical cyclones determined from recent reconnaissance-based "best track" data. Preprints, *25th Conf. on Hurricanes and Tropical Meteorology*, San Diego, CA, Amer. Meteor. Soc., 458–459.

Brown, D.B. and J.L. Franklin, 2004: Dvorak TC wind speed biases determined from reconnaissance-based best track data (1997-2003). *26th Conf. on Hurricanes and Tropical Meteorology,* Miami, FL, Amer. Met. Soc., 86-87.

Courtney, J, and J.A. Knaff, 2009: Adapting the Knaff and Zehr wind-pressure relationship for operational use in Tropical Cyclone Warning Centres, *Australian Meteor. and Ocean. J.*, **58**, 167-179

Guard, C. P. 1988: Tropical Cyclone Studies: Part 3 – Results of a tropical cyclone accuracy study using polar orbiting satellite data. Federal Coordinator for Meteorological Services and Supporting Research, FCM-R11-1988, 3-1 – 3-36.

Dvorak, V.F., 1984: Tropical cyclone intensity analysis using satellite data. *NOAA Tech. Rep.* NESDIS 11, NOAA, Washington, DC, 47 pp.

Harper, B.A., J. D. Kepert, and J. D. Ginger, 2010: Guidelines for converting between various wind averaging periods in tropical cyclone conditions. World Meteor. Org., *TCP Sub-Project Report*, WMO/TD-No. 1555.

S. Hong and I. Shin, 2013: Wind Speed Retrieval Based on Sea Surface Roughness Measurements from Spaceborne Microwave Radiometers. J. Appl. Meteorol. Climator. vol. 52, no. 2, 507-516.

JMA-1, 2016: http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/techrev/text15.pdf

JMA-2, 2016: http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/techrev/text18-1.pdf

Knaff, J.A., D.P. Brown, J.Courtney, G.M. Gallina, J.L. Beven II, 2010: An Evaluation of Dvorak Technique-Based Tropical Cyclone Intensity Estimates. *Wea. Forecasting*, **25**, 1362-1379.

Knaff, J.A., and R.M. Zehr, 2007: Reexamination of Tropical Cyclone Wind-Pressure Relationships. *Wea. Forecasting*, **22**, 71-88.

Kossin, J. P., and C. S. Velden, 2004: A pronounced bias in tropical cyclone minimum sea-level pressure estimation based on the Dvorak technique. *Mon. Wea. Rev*., **132**, 165–173.

Lu, X., and H. Yu, 2013: An Objective Tropical Cyclone Intensity Estimation Model Based on Digital IR Satellite Images, *Tropical Cyclone Research and Review*, **2**, 233-241.

Mayfield M., C. J. McAdie, and A. C. Pike, 1988: Tropical cyclone studies Part 2 – A preliminary evaluation of the dispersion of tropical cyclone position and intensity estimates determined from satellite imagery. Federal Coordinator for Meteorological Services and Supporting Research, FCM-R11-1988, 2-1 – 2-17.

Olander, T., and C. Velden, 2007: The Advanced Dvorak Technique: Continued development of an objective scheme to estimate tropical cyclone intensity using geostationary infrared satellite imagery. *Wea. Forecasting*, 22, 287-298.

UCAR, 2014: *Tropical Cyclone Intensity Analysis*, viewed 14 June 2016, https://www.meted.ucar.edu/training_module.php?id=1083

Velden, C.S., A.D. Burton, and K. Kuroiwa, 2012: The first International Workshop on Satellite Analysis of Tropical Cyclones: Summary of Current Operational Methods to Estimate Intensity, Trop. *Cycl. Res. Rev*., **1**, 469-481.

Velden, C.S., and many co-authors, 2006: The Dvorak tropical cyclone intensity estimation technique: A satellite-based method that has endured for over 30 years. *Bull. Amer. Meteor. Soc.*, **87**, 1195-1210.