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Coupled Data Assimilation for Integrated Earth System Analysis and Prediction: Goals, Challenges and Recommendations

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Coupled Data Assimilation for Integrated Earth System Analysis and Prediction: Goals, Challenges and Recommendations

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EXECUTIVE SUMMARY

Executive Summary

The purpose of this report is to identify fundamental issues for coupled data assimilation (CDA), such as gaps in science and limitations in forecasting systems, in order to provide guidance to the World Meteorological Organization (WMO) on how to facilitate more rapid progress internationally.

Coupled Earth system modelling provides the opportunity to extend skillful atmospheric forecasts beyond the traditional two-week barrier by extracting skill from low-frequency model components representing domains such as the land, ocean, ocean waves and sea ice. More generally, coupled models are needed to support seamless prediction systems that span timescales from weather, sub-seasonal to seasonal (S2S), multiyear, and decadal. Therefore, initialization methods are needed for coupled Earth system models. The field dedicated to developing the most effective and efficient initialization methods for such models is Data Assimilation (DA), which at a fundamental level in the context of coupled Earth system models can either be applied to each individual component (called Weakly Coupled Data Assimilation - WCDA) or to the coupled Earth system model as a whole (called Strongly Coupled Data Assimilation - SCDA). Using CDA, in which model forecasts and potentially the state estimation are performed jointly, each model component receives information from observations in other domains either directly using error covariance information known at the time of the analysis (SCDA), or indirectly through flux interactions at the model boundaries during the forecast (both WCDA and SCDA). Because the non-atmospheric domains are generally under-observed compared to the atmosphere, CDA provides a significant advantage over single-domain analyses and a great opportunity for improving our estimates of the Earth system state.

Next, we provide a synopsis of goals, challenges and recommendations to advance CDA:

Goals: (a) Extend predictive skill beyond the current capability of Numerical Weather Prediction (NWP) (e.g. as demonstrated by improving forecast skill scores); (b) produce physically consistent initial conditions for coupled numerical prediction systems and reanalyses (including consistent fluxes at the domain interfaces); (c) make best use of existing observations by allowing observations from each domain to influence and improve the full Earth system analysis; (d) identify critical weaknesses in coupled models and the Earth observing system; (e) generate full-field estimates of unobserved or sparsely observed variables; (f) develop a robust observation-based identification and understanding of mechanisms that determine the variability of weather and climate; (g) improve the estimation of the external forcings causing changes to climate; (h) transition successes from idealized CDA experiments to real-world applications.

Challenges: (a) Model resolution and parameterizations at the interfaces between interacting components of coupled Earth system models may be inadequate for estimating uncertainty or error covariances between domains; (b) current data assimilation methods may be insufficient to simultaneously analyse domains containing multiple spatiotemporal scales of interest; (c) there is no standardization of observation data formats or their delivery systems across domains; (d) the size and complexity of many large-scale coupled Earth system models makes it is difficult to investigate uncertainty due to sensitivities in model parameters and coupling parameters; (e) model errors lead to local biases that can transfer between the different Earth system components and lead to coupled model biases and long-term model drift; (f) information propagation across model components with different spatiotemporal scales is extremely complicated, and must be improved in current coupled modelling frameworks;

(g) there is insufficient knowledge on how to represent evolving errors in non-atmospheric components (e.g. in sea ice, land and ocean) on the timescales of NWP; (h) there are significant computational resource and data storage needs for coupled Earth system models, and existing numerical algorithms are not fully optimized for CDA.

Recommendations: (a) Standardize the observing network for all Earth system domains in order to meet the timeliness and quality control requirements of NWP; (b) identify gaps in the observing system that are essential for constraining CDA applications, including fluxes at the domain interfaces; (c) support international coordinated efforts to study and compare CDA approaches that are at a maturity level for use at operational prediction centers; (d) support the academic research community to explore fundamental aspects of CDA via simplified and intermediate complexity models; (e) develop CDA methods that can accommodate multiple spatiotemporal scales in support of the seamless prediction paradigm; (f) develop methods for CDA to identify, isolate, and elucidate model errors and biases that degrade forecast skill, which can then be used to directly improve coupled modelling; (g) promote improved representation of model uncertainty in the coupled forecast system using stochastic physics and other advanced methods; (h) perform research to increase knowledge on how to best represent evolving errors in non-atmospheric model components (e.g. sea ice, land and ocean) on the timescales of NWP; (i) facilitate collaboration with experts in computer and information science to modernize DA software and manage the technical aspects of CDA that qualify as big data applications.

SUMMARY REPORT AND RECOMMENDATIONS

Introduction

As operational Numerical Weather Prediction (NWP) centers around the world strive to extend the skillful range of their forecasts, it has become increasingly acknowledged that this will require the modelling and initialization of not only the atmosphere but also other domains of the Earth system. The climate and sub-seasonal-to-seasonal (S2S) prediction communities have already conducted significant effort in this area by coupling independent models to represent the complete Earth system *(*e.g. Meehl, 1995; Delworth et al., 2006; Saha et al., 2006; Koster et al., 2010; Dunne et al., 2012; Orsolini et al., 2013; Robertson et al., 2015; Kucharski et al., 2015; Guémas et al., 2016; White et al., 2017*)*. Such coupled models comprise two or more components including the atmosphere, ocean, land, sea ice, surface waves, atmospheric chemistry and aerosols, and ocean biogeochemistry.

The challenge now becomes bridging the developments in coupled modelling for climate and S2S timescales down to NWP timescales, while maintaining the skill of atmosphere-only NWP products and simultaneously extending this skill to the longer timescales (Brassington et al., 2015; Kinter et al., 2016*)*. This challenge is particularly relevant to operational centers adopting a 'seamless prediction' paradigm *(*Palmer et al., 2008; Hoskins, 2013*)* in which a single coupled forecast system is applicable to weather, S2S, and longer climate timescales. The ongoing transition to high-resolution and coupled modelling capabilities must be accompanied by a similar transformation and adaptation of the data assimilation (DA) procedures (e.g. Sun et al., 2014). The design of effective DA methods, able to simultaneously control all resolved scales, propagate net positive information across the climate system components, and create an initial state that minimizes coupled initialization shocks, is of primary importance for these coupled forecasts systems.

Coupled data assimilation (CDA) can be broadly categorized into two types: weakly coupled DA (WCDA) and strongly coupled DA (SCDA). WCDA indicates that the coupling occurs during the forecast by using a coupled forecast model. For WCDA, the state of the coupled model is differenced with observed values to produce the innovations, but the analysis is still computed independently for each domain. As a consequence, the direct impacts of observations on the analysis are limited to the domain in which the observations reside, while cross-domain impacts are produced as a secondary effect by the integration of the coupled model forecast. SCDA indicates that cross-domain error covariances are utilized when computing the analysis so that the entire Earth system is analysed as if it were a single system. The SCDA approach has the advantage of allowing all available observations at a given time to have instantaneous impact across all domains when forming the analysis (based on the timescales of the background error covariances and within the limits of any imposed localization length scales). SCDA thus drives the entire coupled system to be in relative agreement with all available observations while largely reducing initialization shocks that can be caused by WCDA, in which each component is analysed independently using a disjoint set of observations. As with WCDA, SCDA also allows past data to be propagated through the system and across component interfaces during the coupled forecast. In addition to these two approaches, there are many variations that have been explored in the research community spanning the spectrum between WCDA and SCDA that may be viable for different applications.

CDA has applications in prediction on many timescales, including NWP, S2S, multiyear, and decadal prediction. It is useful for prediction in high-impact weather scenarios (e.g. hurricane prediction), and in regional prediction (e.g. polar prediction, Jung et al., 2016). CDA also has applications in reanalysis, for example in the reconstruction of historical climate (e.g. Laloyaux et al., 2016a). We note that the overall goals of these broad application areas are somewhat different. For example, the former typically seeks to find initial conditions that lead to the most accurate forecast, while the latter seeks a state estimate or trajectory that most closely represents the true state or trajectory of the coupled system. These differing goals may lead to different solution approaches.

Benefits of Coupled DA

Expected benefits of coupled DA

Transitioning from WCDA to SCDA helps to reduce imbalances between domains caused when each is updated independently using disjoint information of the Earth system. These imbalances are often referred to as coupling "shocks" in the initialization of coupled systems. While the reduction or elimination of these shocks is expected with SCDA, there has been limited research supporting this claim. For example, it is unclear whether the current modelling of domain interfaces is sufficient to support the use of model-derived cross-domain error covariances in realistic applications.

Many surface observations, in particular those made from satellite platforms, are influenced not only by the ocean or land surface but also the atmosphere above. CDA provides the opportunity for an online computation using a consistent observation operator that includes the forecasted state of both the surface and the overlying atmosphere. For example, the computation of 'model equivalent' Sea Surface Temperature (SST) and Sea Surface Salinity (SSS) measurements should rely on radiative transfer models that include the corresponding modelled atmosphere directly above. As another example, gravity measurements made by the GRACE and GOCE satellites are influenced by the total integrated column of mass (with variability strongly dominated by water content), from the bottom of the ocean to the top of the atmosphere (TOA), or throughout the land surface to the TOA. It is expected that this more accurate computation of the model equivalent to the corresponding observation will lead to improved accuracy in CDA analyses.

Generally, the non-atmospheric domains are significantly under-observed compared to the atmosphere. Another key opportunity for CDA is to better constrain parts of the Earth system that are poorly constrained by a single-component DA system. For example, assimilation of sea-ice properties using SCDA may improve estimates of both oceanic and atmospheric states that are poorly constrained by independent atmospheric or oceanic DA systems because of a dearth of oceanic and atmospheric observations in the polar regions. Other opportunities include: (1) use of wave information to constrain transfer of energy among ocean, ocean waves, and the atmosphere; (2) use of cloud observations to constrain heat exchange in the ocean; (3) use of near surface observations to constrain poorly known land surface conditions for the atmosphere; (4) transport of marine aerosols into the atmosphere; (5) to add value to new Earth observations such as the Ice-Tethered Profilers (http://www.whoi.edu/page.do?pid=20756) measuring ocean temperature and salinity below sea ice or the European Space Agency (ESA) missions that provide Essential Climate Variables (ECV) covering components such as Soil Moisture and Ocean Salinity (SMOS); (6) use of observations at the air-sea interface from mooring arrays such as those planned in the Tropical Pacific Observing System (TPOS2020; Cravatte et al., 2016) to better constrain the ocean-atmosphere coupled system in the Tropics.

Sea-ice forecast errors can be dominated by errors in ocean SST, near surface currents, surface air temperature and winds, especially since these are poorly observed near ice *(*Buehner et al., 2013; Buehner et al., 2015; Smith et al., 2016*)*. In order to further constrain the sea-ice model, improvements must be made in estimates of winds, ocean currents, drag coefficients, ice strength, wave energy dissipation, and other parameters, though it is unclear which will have the largest impacts (e.g. Chevallier et al., 2016). Sea-ice concentration is generally well observed, though there are limitations in summer near land, from melt ponds and thin ice, and during high winds. Sea-ice drift is also fairly well observed by using sequential satellite images. However, coverage is insufficient for sea-ice thickness observations, which are important for air-sea interaction and long-term prediction. Simple CDA approaches help by allowing sea-ice observations to impose consistent SST for the ocean, and to correct winds and currents. Air temperature and winds can then be used for quality control of sea-ice observations. Linear/Gaussian approaches for CDA may not be adequate, particularly near the freezing points and at the creation of ridges, so it is expected that advances in nonlinear/non-Gaussian methods may provide new opportunities within a CDA environment.

DA is used with atmospheric chemistry models to improve air quality forecasts, construct reanalyses of three-dimensional chemical (including aerosol) concentrations and perform inverse modelling of input variables or model parameters such as emissions. Coupled chemistry meteorology models (CCMM) are atmospheric chemistry models that simulate meteorological processes and chemical transformations jointly. They offer the possibility to assimilate both meteorological and chemical data; however, because CCMMs are fairly recent, DA with these models has been limited and requires further investigation (Bocquet et al., 2015*,* and references therein). Even though the meteorological subpart of CCMMs is mildly affected by the chemical subpart (mostly through radiative feedback), it has been shown by Bocquet et al., (2015) that a corresponding CDA system could have very significant exchanges of information in between chemistry and meteorology, for example with the assimilation of chemical concentrations improving the estimation of wind fields. A major concern for CCMMs is the sparsity of chemical data, whereas the chemical part of CCMMs significantly increases the number of prognostic variables (in particular in presence of aerosols). This data deficiency could be alleviated by the new ESA sentinel space-born platforms. Moreover, the estimation and regularization of cross-domain covariances remains challenging, especially in presence of hundreds of species (or even more with size-resolved aerosols) that may further require localization not only in physical space but also in between species.

Early evidence for the benefits of coupled DA

To date, the number of studies documenting the degree of improvement in prediction and reanalysis applications is small but indicates great potential for CDA.

It is expected that by ensuring consistency between the analysed states of each coupled Earth system component, CDA systems will produce more balanced states and fluxes at the interfaces *(*Zhang et al., 2005, 2007; Sugiura et al., 2008; Zhang 2011*)*. Zhang et al., (2005) first used an ensemble Kalman filter to implement CDA to study impacts on ENSO forecasts. They found that the coherent surface fluxes and thermocline structure initialization is helpful in the initialization to enhance ENSO predictability. An ensemble coupled data assimilation (ECDA) system was developed using the Geophysical Fluid Dynamics Laboratory (GFDL) second generation coupled model (CM2) (Zhang et al., 2007) to produce seamless seasonal-interannual to decadal scale predictions. Based on the ECDA system, GFDL and collaborators conducted the following research activities, growing the body of evidence demonstrating the benefits of CDA: (1) improving the quasi-operational ENSO forecasts at GFDL (Zhang et. al, 2008); (2) providing balanced and coherent climate estimation good for decadal scale predictions *(*Yang et al., 2013); (3) identifying requirements of high-accuracy coupling covariance and challenges to implementing SCDA *(*Han et al., 2013); (4) developing the area of coupled model parameter estimation to reduce coupled model biases (e.g. Zhang 2011; Zhang et al., 2012).

Mulholland et al., (2015) found that forecasts at NWP timescales that were initialized by CDA reduce initialization shocks in lower atmospheric temperature relative to separate oceanic and atmospheric analyses, in some regions halving the RMSE on the first day of the forecast with sustained improvements for the duration of 10-day forecasts. As a cautionary note, improvements were found to be negligible when assessed using independent datasets over the limited period studied. More work is needed to realize the potential benefits of CDA at these scales.

For interannual to decadal timescales, Tardif et al., (2014, 2015) used a SCDA approach and found that assimilating time-averaged observations into an idealized low-order coupled system improved state estimates. Time-averaged atmospheric observations were particularly useful when there was an insufficient number of ocean observations. In recent research efforts reported during the 2016 CDA workshop in Toulouse (http://www.meteo.fr/cic/meetings/2016/CDAW2016/presentations/5_1.pdf), a multi-timescale extension of the DA method, where the long-timescale ocean states were constrained with atmospheric observations on 20-year timescales as well as monthly, provided more accurate analyses of fast and slow components of the system over the assimilation of non-averaged observations. A clear benefit of the SCDA approach was highlighted in a scenario using a poorly observed ocean.

Lu et al., (2015a/b) used what they called a Leading Averaged Coupled Covariance (LACC) CDA approach, attempting to address different time scales between model components. They focused on the effect of assimilating atmospheric surface temperature on the sea surface temperature (SST) in a coupled general circulation model (GCM). Lu et al., (2015a) used the LACC-SCDA method to reduce the analysis error of the oceanic variable by over 20% compared to WCDA and 10% compared to the pure SCDA (using simultaneous coupled covariance). It was noted that the LACC-SCDA method produced more notable improvements when using a system configuration with smaller ensemble size, bigger timescale difference, or larger model biases. Lu et al., (2015b) tested the LACC method with a coupled general circulation model (CGCM) in a perfect-model framework, adding the observational adjustments from the low-level atmosphere temperature to the SST. They found LACC-SCDA significantly reduced the global SST error compared to WCDA.

Sluka et al., (2016) took the CDA analysis further by applying innovations from multiple atmospheric variables to impact the full ocean column analysis. Sluka et al., (2016) indicated significant improvement (over 40%) by using SCDA versus WCDA with an intermediate-complexity coupled atmosphere-ocean model in an observing system simulation experiment (OSSE) using a perfect-model framework. The system used the SPEEDY/NEMO coupled model at coarse resolution with a 6-hour DA coupling interval. Improvements were present throughout the full ocean water column throughout most of the world ocean, at all latitudes except the Arctic. These improvements provided feedback to improve the atmospheric conditions in SCDA versus WCDA as well.

It has been shown that the atmosphere-ocean coupling is important for the analysis step to correctly estimate the initial conditions for tropical cyclones (Laloyaux et al., 2016b). Uncoupled hurricane models typically create too-deep TCs because there is no cold-wake in the SST field. As shown in Chen et al., (2010), model coupling is not only essential to the formation of cold water in the wake of TCs, it also affects the structure and symmetry of TCs. In the coupled case, mean sea level pressure (MSLP) forecast error is reduced (Mogensen et al., 2017).

In the European Centre for Medium-Range Weather Forecasts (ECMWF) CERA-20C (http://www.ecmwf.int/en/research/climate-reanalysis/cera-20c), the ocean and the atmosphere communicate every hour through the air–sea coupling at the outer-loop level of the variational method. Changes in the state of the atmosphere may directly impact the ocean properties and vice versa. The combination of CDA and additional improvements in the atmospheric DA corrected a spurious trend in the net heat fluxes received by the ocean, as identified in ORA-20C. On average, heat flux and ocean temperature increments in CERA-20C oscillate around 0 W/m2, suggesting a more balanced system state estimate. In addition, while in the ERA 20C there were no Tropical Instability Waves (TIW) or wind stress signals (the system was forced by monthly SSTs), the CERA-20C does produce TIWs in the ocean, with the atmosphere responding accordingly. This led to an improved correlation between SST and wind stress in CERA-20C. We note that the CFSR coupled reanalysis produced by NCEP also produced such TIWs (Wen et al., 2012).

Fujii et al., (2009; 2011) at the Japan Meteorological Agency/Meteorological Research Institute (JMA/MRI) compared a quasi-WCDA system (i.e. the ocean component alone is analysed) using Incremental Analysis Updates (IAU) with an analysis interval of 1 month versus an AMIP run forced by observed SST. Forcing the AMIP with observed SST did not lead to a more accurate analysis. Instead, precipitation was overestimated in the West Pacific, and underestimated in the Indian Ocean in winter. In summer, the position of the peak Intertropical Convergence Zone (ITCZ) was inaccurate in the AMIP, but modified by quasi-WCDA to be more accurate. With quasi-WCDA, precipitation corresponded to cyclonic structure, which did not occur in the AMIP run, and too-weak winds in the monsoon troughs were improved. In observed data, the correlations between SST and precipitation are not as strong as modelled in AMIP runs. Many of the improvements stemmed from the representation of the more realistic negative feedbacks between SST and precipitation in the coupled system, which reduced excessive rainfall over high SST regions. With quasi-WCDA, the false maximum over the western side of the Bay of Bengal disappeared and the contrast of the upper-troposphere velocity potential between the Pacific and Indian Ocean was intensified, resulting in enhancement of the Walker circulation and the monsoon trough in the western tropical Pacific.

Lin et al., (2016) indicated that the decadal shifts of East Asian summer monsoon were not recovered in simulations of an uncoupled atmospheric model, but correctly reproduced by a quasi-WCDA system (developed in IAP, China). A 7-day analysis cycle was used for the ocean DA. They confirmed that the decadal shifts were not correctly reproduced when the assimilation interval is one day or three days, which indicates that at least a loose constraint of

the ocean surface state is required to improve the atmospheric fields through reconstruction of the negative feedback between SST and precipitation.
Lea et al., (2015) showed implementation of WCDA and the use of assimilation outputs to diagnose coupled model errors (e.g. diurnal cycle of SST, issues with river outflows). They also demonstrated smaller average SST increments than in uncoupled DA, indicating a better-balanced analysis at the air-sea interface.

An excess latent heat flux seen in the JRA-55 is reduced in a WCDA system with a 10-day ocean, 6-hour atmosphere cycle recently developed in JMA/MRI. The WCDA also suppressed excess precipitation seen in the JRA-55. These improvements may have also been due to improvement in the bulk formulae. There was an improved (weakened) ITCZ as well.
There are indications that skilful ocean and sea-ice initialization requires CDA because ocean and sea ice are tightly interconnected thermodynamically and ocean observations under sea ice are lacking (Lisæter et al., 2003, Sakov et al., 2010, Massonnet et al., 2013). Flow dependent assimilation methods have been shown useful for representing the coupled error covariance between sea ice and ocean salinity that are non-stationary and anisotropic and crucial for preserving the ocean stratification (Lisæter et al., 2003, Sakov et al., 2010).

EnVar methods have been shown on a coupled chemistry meteorology low-order model to help build cross-domain error covariances, and perform nonlinear variational analysis without the development of the adjoint of the coupled system (Haussaire et al., 2016). Determining appropriate localization across domains and chemical species remains a challenge.

Detailed Recommendations

The following recommendations have been identified by the workshop participants through presentations, breakout discussions, and plenary session discussions, as important items that must be addressed for the successful development of CDA. The recommendations are separated into categories: "Research and Methodology", "Organizational Planning" and "Observing Missions".

Research and methodology

- Due to the computational costs of running large Earth system models, organized research efforts are needed among the international community to evaluate the benefits of (a) CDA versus independent DA for stand-alone modelling systems and (b) the benefits of WCDA versus SCDA on systems comparable to those used in operations. Further, Research efforts are needed to examine the benefits and trade-offs spanning the scale from WCDA to SCDA, as some centers may find larger costs are required to execute a full transition to SCDA.
- With the goal of seamless prediction, the international research community should develop and evaluate the impact of new methods for separating spatial and temporal scales in CDA (e.g. multiscale or multigrid DA). Investigation should be done on the impact of updating different model components at different timescales. This is a practice that is currently used to maintain stability in a few major CDA efforts, without rigorous theoretical justification.

- For the purpose of seamless prediction, the research community must demonstrate that CDA not only improves initial states but also improves forecasts at all time scales.
- Accordingly, the research community must identify the sources of first order errors that may prevent coupled forecast systems from clearly outperforming current operational NWP systems.
- As a specific focus, evaluations should be made to identify the degree to which coupled modelling and CDA can improve medium-range atmospheric forecasts. Such evaluations should identify the benefits versus tradeoffs for varying degrees of coupling for this timescale.
- The international research community must demonstrate the benefit of applying coupled observation operators within CDA systems, in comparison to current observation operator formulations, and in comparison to the assimilation of retrieval products still commonly used by many non-atmospheric DA applications.
- Some form of hybrid DA methods are likely to be necessary for CDA. From the variational perspective, complicated cross-domain covariances exist on multiple spatiotemporal scales and only the generation of real-time ensembles will adequately capture the dynamically varying error covariances. From the ensemble Kalman Filter (EnKF) perspective, the models are biased and a purely model-derived error covariance will overestimate the accuracy of the model and potentially ignore quality observations. Hybrid methods are maturing but still represent an emerging field in DA, and relatively little effort has been put into applying hybrid methods to CDA applications.
- Further advances are required to apply nonlinear/non-Gaussian methods to the domains of the coupled Earth system for which the linear/Gaussian assumptions are not well suited (e.g. sea ice or land), and to integrate these with the domains for which linear/Gaussian-based methods are adequate.
- The DA approaches for all domains must generate consistent analyses. It is common for WCDA to generate analyses for each domain that are inconsistent with one another, with the potential to create shocks at the interface when used to initialize the coupled model. A primary motivation for SCDA is to improve consistency and eliminate these shocks.
- CDA should be used whenever possible when applying DA to non-atmospheric domains. For example, low-resolution ocean models behave largely as forced-damped systems that respond linearly to the atmospheric forcing. Because the atmospheric models typically provide a majority of the resolved nonlinearities on short timescales, coupling the ocean to the atmosphere using CDA provides the opportunity for lower resolution ocean models to be treated more appropriately as nonlinear dynamical systems.
- As an international collaboration, assimilating near-interface observations with a focus on the temperature (e.g. SST, LST) at the interface between many model component combinations would serve as a useful coordinated exercise to start evaluating coupled error covariances in the context of different coupled models and resolutions. Subsequent investigations may expand to other important observation types near the domain interfaces.
- A first order challenge for CDA is determining how to address drift caused by biases in coupled models. Accurate estimates of the interfaces between domains should be used to characterize systematic errors in each of the components and the fluxes between those components. This requires also (a) improved modelling of the interfaces between domains and (b) improved observing of these interfaces.

- For reanalysis applications, a transition toward SCDA is recommended to make better use of the sparse historical observing network. Care must be taken to do this without also transferring biases (from both model and observations) between domains.
- Representations of surface fluxes must be improved, whether through improvements to the bulk formulae or improved resolution and modelling of the near surface boundary layers. A more sophisticated ‘surface interface model’ should be considered, to better match observed surface quantities and better resolve modelled surface fluxes.
- A better understanding of the impact of representing model error in CDA systems is necessary. This includes, for example, the impact of stochastic parameterizations, bias corrections, surface flux relaxations, and other frequently used tools used to correct model errors in DA systems.
- An improved understanding of the dynamical instabilities that dominate coupled systems is needed in order to develop CDA methods that target unstable modes.
- For any coupled modelling system configuration, the saturation time scales and amplitudes of each component should be quantified, and it should be evaluated how these affect the other (faster and slower) model components.
- Coherence between initial conditions of slow and fast modes relies on cross-domain error covariances. Research is needed to determine the appropriate characterization of these cross-domain error covariances, and also to develop observationally verifiable methods to estimate these quantities for the interfaces between atmos/ocean, ocean/sea ice, atmos/land, ocean/land, etc. While ensemble methods seem a straightforward strategy to estimate background error covariance, it is possible that deficiencies in the modelling of cross-domain interface dynamics may render large errors in these estimates. New methods and diagnostics are needed to evaluate the cross-domain error covariance derived from coupled model ensembles.
- The research community should investigate the time-varying nature of cross-domain error covariances in detail, showing how the cross-domain error covariance structure changes based on diurnal, seasonal, and longer timescales.
- Evaluate the impact of model resolution on cross-domain error covariances. For example, air-sea interaction plays an important role in Tropical Cyclone (TC) development - the ocean provides energy for the TC, the TC-induced cold wake acts as a negative feedback to prevent over-intensification. The TC air-sea coupling effect has more impact when there are ocean eddies present.
- Grid choice, choice of vertical coordinate, and choice of interpolation method to interface multiple domains can impact the accuracy of coupled models and CDA systems. Research is needed to understand the amount of error introduced due to these sources, and quantify how much that error degrades the coupled model forecast.
- The impacts of localizing coupling effects to the boundary layer must be quantified. As the focus of constructing cross-domain error covariance extends beyond the boundary layer to greater vertical scales, large ensemble investigations (e.g. Miyoshi et al., 2014) will be needed to ensure there is information in these distant correlations. For example, investigations should be made to determine whether some correlated processes (e.g. ocean mixed layer depth and cloud cover) benefit from consideration of larger scales in the vertical localization.
- Methods are needed to estimate appropriate length scales for localizing horizontal error covariance across domains. More abstract localization schemes should be explored given the nonhomogeneity of the contiguous domains.

- Methods are needed to estimate the temporal localization of the cross-domain error covariance and time-averaging of observations and background fields to evaluate both slow and fast modes of the coupled system.
- SCDA may be a necessity for the coupled ocean/sea-ice problem. For example, if too much sea ice is melted then the ocean stratification can be degraded, and this may have wider impacts on the overturning circulation. The impacts of WCDA versus SCDA should be quantified for the coupled ocean/sea-ice setting. Coupling between other Earth system domain pairs (e.g. atmos/chem, ocean/land, etc.) should be thoroughly investigated as well with dedicated research efforts.
- Develop methods to specify the minimum required quality standards for the different observation types to be useful in CDA, and quantify the benefits of increasing the quality of those observations.

Organizational planning

- The culture of many non-atmospheric observing efforts, which have been focused primarily on climate applications, are not set up in a way to transmit observational data rapidly to operational centers for use in NWP. A shift is required that will allow ocean, snow, sea ice, and other data to be used in near real-time NWP applications.
- Pathways must be established for major operational centers to ease the transition from WCDA systems pieced together from existing component systems to integrated SCDA systems with flexible capabilities to recover the component-wise DA as needed.
- A research-to-operations pipeline must be established to allow the academic research community the ability to (a) address scientific questions of interest to the operational centers and (b) facilitate the transfer of new methods and knowledge from the research community to the operational centers.
- There is a need for sustained working groups and regular workshops that will promote international exchange of information in this diverse community. Due to the highly interdisciplinary nature of CDA, it is recommended that CDA workshops have a significant training and tutorial sessions on coupled Earth system processes relevant to CDA. It is also highly encouraged that future CDA workshops encourage participation of experts in Earth system modelling and experts focusing on observations and process studies of exchange processes between Earth system domains.
- Reach out to the applied mathematics community that has experience in similar problems of stochastic filtering and state estimation in multiple scales systems (biology, machine learning, or communication networks).
- There is a need to actively increase DA community understanding of how emerging technologies (e.g. computer science, statistics, software, visualization, data science, big data, and data mining) map onto the objectives of CDA. Greater interaction with these external communities should be encouraged.
- The CDA community should begin reaching out to advertise open problems that may have technological solutions. It may be advantageous to selectively invite members of these communities to future CDA meetings.
- To collaborate with other fields and industries, the community should define specific “use-cases” that are representative of the questions in CDA that must be investigated within the next 5-10 years. Such use cases should be provided for: minimization

algorithms, visualization methods and tools, database design and accessibility for managing observations, NWP ‘forecast challenge’ that can be approached by specialists in each of these areas, general data scientists, and researchers in NWP.

- Establish common data sets/fields, such as observational innovations and air-sea fluxes, for a common time-period between CDA research groups for international intercomparisons.
- Guidance should be established for how to assess the impact of coupled NWP developments that take into account all state components. Guidance might include an indications of how the verification of coupled NWP systems should be carried out, such as the length of trials required to demonstrate impact of changes on an operational systems. It is recommended that a specific set of criteria be agreed upon and accepted for a baseline international ‘scorecard’ for NWP using CDA to provide a starting point for comparisons.
- A key challenge for the next 3-5 years is to validate methodology and software tools, and to establish best practices for CDA. In a 3-7 years timeframe, the community can begin to meaningfully address forecast and observation impact problems. To expedite research in the next 5 years, the community should establish avenues for exchanging tools such as algorithms, software, data, and diagnostics for CDA.
- CDA OSSEs should be a priority application for future observation network design, and to help plan and prioritize future observation campaigns.
- General trends in software design should be adopted for the development of future CDA tools, including: modularity of code, managing code complexity, efficient/optimal use of emerging hardware, etc.
- Databases/repositories storing observations across all domains with standardized data formats are recommended. Investigations are encouraged of commercial applications with big data support such as Google BigTable, or other open-source noSQL options.
- The development of standardized forward operators for the global observing network is encouraged. For CDA this applies in particular to forward operators dependent on multiple domains.
- Standardized output formats are recommended to support CDA diagnostics across domains.
- A common software infrastructure is recommended to simplify the application of the most common CDA methods to the most commonly used coupled modelling environments.

Observing missions

- Increase the observing effort of the cross-domain interfaces. This includes measurements of air-sea fluxes, ice-ocean fluxes, air-land fluxes, etc.
- Encourage field campaigns that plan for co-located observations spanning multiple domains. These are needed to constrain the coupled system, correct biases in observations, and estimate observation errors. As a general guiding principle for planning observing missions, DA typically benefits more from larger quantities of well-distributed data rather than a small quantity of specialized data.
- Increase collaboration between field campaigns, modellers, and the CDA community for conducting process studies that cross-domain boundaries.

- Regional field campaigns may be valuable for performing focused tests of CDA on a limited scale.
- Increase the observing effort for areas of the Earth system that are under-observed and underconstrained. As we shift from forced single-domain models to coupled Earth system models, the predominant impacts from biases in one domain can shift to another. In order to constrain these biases there must be a concerted effort to constrain long ignored regions, such as the deep ocean, sea ice, and the ocean under sea ice.
- Establish a mechanism for developing countries to securely contribute local observations to major global NWP operational forecasts. Further, establish a visiting scientist plan for providing expert training in DA and NWP to forecasters, researchers, and students from these countries.
- Dedicated field campaigns should be identified that can improve earth-system predictability through better formulation of either forecast, observation, or CDA methods due the insights derived from those campaigns. Examples of successful field campaigns in the past included studies of coupling in tropical cyclones, marginal ice zone, and the Madden-Julian oscillation (MJO).
- Establish a mechanism to contribute observations from temporary and/or experimental observing systems that focus on taking measurements across domains, or that complement an existing observing system in a different domain to be used for CDA studies.

COMPREHENSIVE WORKSHOP REVIEW

Workshop Description

The International workshop on Coupled Data Assimilation was held at the Centre International de Conférence, Météo France, Toulouse, France from 18 to 21 October 2016. It was sponsored by the World Meteorological Organization (WMO), Météo France, European Union, NOAA/ Climate Program Office (CPO) Modeling Analysis Prediction and Projections (MAPP) program. The workshop had representation from the European Centre for Medium-Range Weather Forecasts (ECMWF), the UK Met Office, the U.S. National Oceanographic and Atmospheric Administration (NOAA), the U.S. National Aeronautics and Space Administration (NASA), the U.S. Naval Research Laboratory (NRL), the Geophysical Fluid Dynamics Laboratory (GFDL), the Australian Bureau of Meteorology (BOM), the Japan Meteorological Agency (JMA), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Environment and Climate Change Canada (ECCC), Météo-France, and the academic community. A brief workshop summary is given by Penny and Hamill (2017), while this document provides a more thorough discussion of the proceedings.

Further information, including archived presentations, can be found at:
http://www.meteo.fr/cic/meetings/2016/CDAW2016/

The workshop participants including the Scientific and Local Organizing Committees are available in Annex A.

Role and Goals of WMO

The World Meteorological Organization (WMO) World Weather Research Programme (WWRP) "ensures the implementation of a research strategy towards the seamless prediction of the Earth system from minutes to months," (Brunet, Jones, and Ruti, 2015) as well as estimating forecast impacts for downstream end user needs and decisionmaking. The purpose of this workshop was to provide WMO with concrete actions to apply CDA in the context of the WWRP plan. The WMO working group on Data Assimilation (DAOS) recognizes CDA as one of the frontiers of DA research. From the perspective of the CDA community, the WMO can play a significant role in facilitating the coordination of efforts across multiple countries.
Further questions of interest to the DAOS working group include:

1) How can new and emerging data sources be considered for DA in the future, especially for data sparse regions like the African continents - the same needs exist (floods, etc.) but with fewer data?
2) How can this DA group contribute to field campaigns?
3) Are closer links needed with nowcasting and mesoscale research for high resolution modelling?
4) What can the DA community do to benefit all of the WMO members?
5) What DA guidelines should be provided for developed and developing countries?

Concepts and Terminology for Coupled Data Assimilation

The terms 'domain', 'component', 'sub-domain', 'sub-component', 'medium', and 'media' are all used somewhat interchangeably to refer to one part of the total coupled Earth system that may be isolated conceptually (e.g. atmosphere, ocean, sea ice, land, wave, aerosol, etc.). We generally refer to a 'domain' of the Earth system, or a 'component' of an Earth system model.

The existing methods for CDA exist on a spectrum (the list is not exhaustive):

- Quasi Weakly Coupled DA (Quasi-WCDA): assimilation is applied independently to each of a subset of components of the coupled model. The result may be used to initialize a coupled forecast.(Example: Quasi-CDA system at JMA - http://www.meteo.fr/cic/meetings/2016/CDAW2016/presentations/1_5.pdf)
- Weakly Coupled DA (WCDA): assimilation is applied to each of the components of the coupled model independently, while interaction between the components is provided by the coupled forecast system. (Example: NCEP's CFSv2 - Saha et al., 2010, http://www.meteo.fr/cic/meetings/2016/CDAW2016/presentations/1_4.pdf)
- Quasi Strongly Coupled DA (Quasi-SCDA): observations are assimilated from a subset of components of the coupled system. The observations are permitted to influence other components during the analysis phase, but the coupled system is not necessarily treated as a single integrated system at all stages of the process. (Example: ECMWF's CERA-20C, Laloyaux et al., 2016a -http://www.meteo.fr/cic/meetings/2016/CDAW2016/presentations/1_3.pdf)
- Strongly Coupled DA (SCDA): assimilation is applied to the full Earth system state simultaneously, treating the coupled system as one single integrated system. In most modern DA systems this would require a cross-domain error covariance matrix be defined. (Example: Sluka et al., 2016 approach applied to the CFSv2 - http://www.meteo.fr/cic/meetings/2016/CDAW2016/presentations/3_1.pdf)

This ‘bottom up’ approach to defining CDA is born out of the construction of CDA from existing DA systems for each separate domain of the coupled Earth system. The problem may also be considered from a ‘top down’ abstraction - all DA applied to a coupled model begins conceptually as SCDA which is then simplified using localization, either applied explicitly or applied implicitly by the decision to update only part of the total domain. As a frame of reference, NCEP currently initializes the Climate Forecast System (CFSv2) for seasonal prediction using WCDA. For the CFSv2 *(*Saha et al., 2014), each component is initialized with its own independent DA system: the atmosphere uses 3DVar (GDAS), the ocean uses 3DVar (GODAS), and sea ice uses nudging. Other centers have previously initialized each component of a coupled forecast system with analyses computed for each component independently.

A Summary of Coupled DA Efforts at Operational Centers

European Centre for Medium-Range Weather Forecasts (ECMWF)

ECMWF is currently testing a quasi-SCDA system called CERA which is based on a variational method with a common 24-hour assimilation window shared by the atmospheric and ocean components. The coupled model is introduced at the outer-loop level by coupling ECMWF’s Integrated Forecasting System (IFS) for the atmosphere, land and waves to the NEMO model for the ocean and to the LIM2 model for sea ice *(*Laloyaux et. al, 2016a). This means that air–sea interactions are taken into account when observation misfits are computed and when the increments are applied to the initial condition. In this context, ocean observations can have an immediate impact on the atmospheric analysis and atmospheric observations can have an immediate impact on the analysed state of the ocean. The increased complexity is intended to improve medium-range forecasts by extending prediction horizon *(*Mulholland et. al, 2015), making better use of observations *(*Laloyaux et. al, 2016b), and providing new applications. The system has implemented a relaxation scheme to constrain the SSTs.

ECMWF has completed the production of a new global twentieth century reanalysis which aims to reconstruct the past weather and climate of the Earth system including the atmosphere, ocean, land, waves and sea ice. This coupled climate reanalysis is based on the CERA system and is called CERA-20C. It assimilates only surface pressure and marine wind observations as well as ocean temperature and salinity profiles. The air–sea interface is relaxed towards the sea-surface temperature from the HadISST2 monthly product to avoid model drift while enabling the simulation of coupled processes. No data assimilation is performed in the land, wave, or sea-ice components.

ECMWF’s Roadmap to 2025, which summarizes the Centre’s new ten-year Strategy, highlights that, “As forecasts progress towards coupled modelling, interactions between the different components need to be fully taken into account, not only during the forecast but also for the definition of the initial conditions of the forecasts.” ECMWF data assimilation development plans are further detailed in Bonavita et al., (2017), including coupled assimilation for both reanalaysis and NWP applications. In this context, ECMWF is now producing CERA-SAT which is based on the CERA system at higher resolution with the full observing system (satellite, upper air, land, wave, sea ice). A proof-of-concept will be delivered over a recent period. In parallel, outer loop coupled ocean-atmosphere assimilation is being implemented and evaluated at ECMWF for NWP applications.

U.S. National Oceanographic and Atmospheric Administration (NOAA)/National Centers for Environmental Protection (NCEP)

The previous NCEP CFSv2 (Saha et al., 2014; Saha et al., 2010) used the 3DVar-GSI analysis scheme, assimilated satellite radiances with variational bias correction, for the ocean used the 3DVar-GODAS approach assimilating only temperature in a 1/2º model with 1/4º refinement at the equator, for land used the Noah land model with NASA LIS DA, and for sea ice applied nudging toward an offline sea-ice concentration analysis.

The new paradigm at NCEP is to have the prediction at all scales (weather, sub-seasonal, seasonal) be ensemble-based. As part of the strategy for the Next-Generation Global Prediction System (NGGPS), NCEP is developing a unified modelling framework that will use a NOAA Earth System Modeling System (NEMS) coupler to allow different Earth system component models to exchange fluxes. The interface software is based on the National Unified Operational Prediction Capability (NUOPC). The NGGPS system consists of atmosphere (FV3 dycore + GFS physics), ocean (MOM6/HYCOM), waves (WAVEWATCH III ®), land (NOAH), and sea-ice (CICE5/SIS2/KISS) component models. The design is flexible to allow for different components to be coupled together depending upon the prediction scales.

NCEP is currently upgrading its seasonal forecasting system to serve as a prototype for its coupled modelling framework. This system will include atmosphere, ocean, waves, aerosol, land and sea-ice components. The current plans for the seasonal forecast system leverage independent DA developments for each of the components, using Hybrid-EnVar for the atmosphere, and an EnKF for many of the other components (with plans to eventually extend to a hybrid framework for all components). The current expectation is to cycle at 6-hour intervals. An effort to standardize the DA software has been initiated by the Joint Center for Satellite Data Assimilation (JCSDA) under the title Joint Effort for Data Assimilation Integration (JEDI). NCEP is developing a community-based unified modelling framework to provide forecast guidance from weather to seasonal timescales by a target of 2022.

Japan Meteorological Agency/Meteorological Research Institute (JMA/MRI)

A prototype WCDA system was built in March 2016 in JMA/MRI. JMA/MRI had previous experience developing a quasi-WCDA system (only ocean observations assimilated into a coupled model). The new prototype system at JMA/MRI is designed to replace the ocean-only observation assimilation approach. A unique point of the system is using a 10-day ocean DA cycle that is much longer than the 6-hour atmospheric DA cycle. The coupled system uses an atmosphere component at T159L60, and an ocean component at 0.5º×1º (latitude × longitude). The atmosphere component is updated every 6-hours by 4D-VAR with a TL159L100 uncoupled inner-loop model, while the ocean component runs on a 10-day cycle using 3DVAR with IAU. This long DA cycle for the ocean component comes from the experience that reconstruction of the SST-precipitation negative feedback with a monthly DA cycle improves the atmospheric fields in the quasi-WCDA system (Fujii et al., 2009; 2011). Coupled reanalysis experiments have been performed for the period from November 2013 to December 2015. NWP experiments are also currently being conducted.

Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

JAMSTEC has developed a SCDA system using 4DVAR with fully coupled atmosphere-ocean adjoint model until 2007 (Sugiura et al., 2008). The coupled system uses an atmospheric component at T42L24 and an ocean component at 1º. The system is currently used for experimental seasonal and decadal predictions (Masuda et al., 2015; Mochizuki et al., 2016).

JAMSTEC is also exploring initialization of WCDA using LETKF, currently running experiments with a coupled model with an atmosphere component at T42L20 and an ocean component at 1.4º. Its expected applications are climate reanalysis, seamless climate prediction, and understanding mechanisms of natural variability on various timescales.

Australian Bureau of Meteorology (BOM)

BOM is focusing on sub-seasonal to multi-year prediction for its ACCESS-S2 system. The coupled model is based on the UK Met Office GC2 model with an atmospheric horizontal resolution of N216 and ocean horizontal resolution of ¼ degree. The relatively high resolution of the coupled model has led to some practical simplifications in the first version of the assimilation system used in ACCESS-2 to ensure the full system is ready by end of 2017 for a full coupled reanalysis from 1980-2017.

The WCDA scheme uses the Ensemble Optimal Interpolation (EnOI) version of the code developed by Sakov et al., (2012) to assimilate ocean temperature and salinity profiles into the NEMO ocean model each day. The surface temperature is strongly nudged (1-day timescale) to the Reynolds SST product. For the atmosphere, the atmospheric prognostic variables are replaced each day by the same values from ERA-interim. The sea ice and land surface fields are not assimilated but respond to forcing from the atmosphere and ocean during the model integration each day. This assimilation approach is applied to a central model run.

The EnOI uses 92 members standard (23x4) for each month, augmented 184. Observation error is estimated using an adaptive moderation of observations (Sakov et al., 2012). An ‘r-factor’ is used to inflate the observation error for the update of the ensemble anomaly. A ‘k-factor’ is a metric that ensure the updates remains within k-times the ensemble standard deviations. The r-factor is essentially used to hand-tune the relative importance of observations versus the model forecast. BOM currently starts estimating the observation error with the instrument error and hand-tunes the ‘r-factor’ from there.

A coupled model breeding method is used to produce an ensemble of perturbed atmosphere, land, sea ice, and ocean states about the central WCDA model run. The ocean fields and atmospheric fields are nudged each day to the central run, the magnitude of the nudging is such that: (a) for the atmosphere the zonal mean pressure spread is maintained at a pre-specific pseudo observed observation error level approximated as the difference between the NCEP and ERA-Interim reanalyses and (b) the ocean temperature and salinity difference at each gridpoint between two independent ocean reanalyses. Atmospheric perturbations produced a more reliable ensemble for sub-seasonal prediction than, for example, a lagged ensemble.

Several improvements are being developed for the following system, ACCESS-S3.
These include:

(a) Extending the assimilation scheme to a full EnKF as opposed to EnOI.

(b) SCDA by using the EnKF to assimilate both in situ temperature and salinity profiles and atmospheric variables from an existing reanalysis e.g. ERA-Int (assimilation of in situ atmospheric observations is not being considered). The EnKF error covariance matrix will be used to update all model variables including land surface and sea ice.

(c) Evaluating and potentially incorporating new observations, including: (a) altimeter sea level; (b) satellite based sea surface salinity; (c) sea-ice concentration; (d) assimilation of SST rather than nudging to an SST analysis.

UK Met Office

The UK Met Office has been focusing up to now on WCDA and its demonstration in an operational environment. Initial work to develop a global WCDA system was based on a coupled model comprising a ¼ degree ocean/sea-ice model and 60 km resolution atmosphere/land model, each with its own DA system. Early results from this WCDA system are reported in Lea et al., (2015) where a 13-month run of the WCDA system was compared to equivalent uncoupled atmosphere/land and ocean/sea-ice DA systems. Results were generally positive with similar innovation statistics from the WCDA as from the equivalent uncoupled runs. The average SST increments in the WCDA system were smaller than the ocean system, indicating a better ocean/atmosphere balance. However, some aspects of the coupled model used in the WCDA system needed improving, particularly in the diurnal cycle of SST which was over-amplified in the coupled model, in the river-runoff in certain regions, and in the assimilation of surface temperature data over lakes. Large differences were also seen over the Arctic. These aspects highlight the usefulness of WCDA for providing information about biases in the coupled model (as opposed to the individual component models).

Since the work of Lea et al., (2015), a technical implementation of an operational version of the WCDA system was developed while addressing some of the coupled model issues mentioned above. Particular attention was paid to dealing with ocean observations, which typically take longer to arrive than atmospheric observations, to make sure a high proportion of them can be assimilated within the WCDA system when running in near real-time. The system was implemented in 2016 in the operational suite at the Met Office to demonstrate the feasibility for coupled NWP (not yet providing products to customers), and the atmospheric resolution increased to 40 km.

Upcoming work includes the increase in atmospheric resolution of the aforementioned WCDA system to that of the operational global NWP forecasting system (about 10 km) and an assessment of whether the WCDA provides benefit over the existing uncoupled NWP system. If it is demonstrated that the WCDA system does provide improved forecast skill, it is planned to become the main operational global NWP system at the Met Office, and work to implement a coupled ensemble prediction system will follow.

U.S. National Aeronautics and Space Administration (NASA)/Global Modeling and Assimilation Office (GMAO)

NASA/GMAO is developing WCDA, with the background fields coming from a coupled Atmosphere/Ocean General Circulation Model (AOCGM). The choice of WCDA was due to latency of the ocean observations, slower timescales of the deep ocean, and direct assimilation of satellite radiances which are mostly influenced by the ocean surface. The latter point emphasizes that the surface fields must be correctly estimated in order to use radiance observations effectively.

The NASA DA plan is a coupling that transitioned from none, to semi-; and in future, to WCDA. The GEOS AGCM has transitioned from using a prescribed ocean surface to a prognostic SST, and in future will transition to a prognostic SST above an OGCM. The atmospheric analysis has transitioned from no analysis of SST to analysis of SST. Future development will also include the OGCM, such that it will resolve a diurnal cycle (including runoff) and the ocean analysis will transition from prescribed atmosphere excluding diurnal obs, to an analysed atmosphere that includes analysis of diurnal observations.

Analysis for diurnal varying SST is important, because SST diurnal warming can produce a bias from 0-4ºK. The background SST variability is dependent on a number of factors. Variability due to diurnal warming is high with low winds and low with high winds. Winds at 7 m/s lead to strong mixing, while 2.5 m/s winds degrade the relationship, and calm winds can create a sharp gradient near the surface.

The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) SST product is a foundation SST that excludes the diurnal signal. Until recently the skin temperature (T_s) was based on the SST fnd from OSTIA and the net heat flux at the surface was a diagnostic field. In the latest GMAO operational system, a prognostic model for T_s, an analysis for T_s, and a T_s analysis increment are all included, hence coupling T_s assimilation to assimilation of atmospheric quantities (u,v,t,q). Just as for SST retrievals, all in situ surface and satellite radiance observations contribute to the analysis of skin temperature.
The T_s model calculates a cool skin layer, with diurnal warming below that layer. The foundation depth is assumed given and cool skin depth is calculated empirically. The T_s analysis is conducted by first finding a temperature profile that fits vertical variation of observed temperature. Brightness temperature (T_b) and the Jacobian dT_b/dT_z are computed using the CRTM. An important note of warning is that the diurnal cycle is not restricted to only the top few meters. In fact, PIRATA measurements in the equatorial Atlantic show the diurnal cycle can penetrate as deep as 20-30m.

Results show a consistent impact due to resolving the diurnal cycle throughout all experiments. There is a lag for the impact of insolation on SST. The impact is a cooler daily average SST, but with warmer peaks in the mid-day. The T_s analysis is tightly coupled to the atmosphere, and gives neutral to positive improvement in forecast skill close to the surface (Akella et al., 2016).

The current MERRA-2 reanalysis includes a coupled analysis (weak coupling) of aerosols and atmospheric state (Gelaro et al., 2017). A future plan is to move to WCDA, and include analysis for SST and sea ice on top of an analysed ocean. A longer-term target is to analyse the continental shelves, ice shelves, ice sheets, etc. For future reanalyses, the GMAO is moving towards an Earth system approach, ultimately with CDA applied to atmosphere, ocean, land, ice, aerosols, and chemistry.

U.S. Naval Research Laboratory (NRL)

Initial operating capability for the global coupled model is planned for 2018, using an ocean at 1/25º for deterministic short-term forecasts, and a 1/12º ensemble for probabilistic long-term forecasts. The initial CDA implementation will take a WCDA approach with Hybrid-4DVar used for the atmosphere, NASA’s Land Information System (LIS) used for the Land Surface Model (LSM), 3DVar used for aerosols, no DA used for waves (due to the strongly forced nature of the system, though 2DVar is in research), 3DVar used for the ocean, and nudging to ice concentration analysis used for the sea ice. To allow for a reasonable handling of late arriving ocean observations without compromising the timeliness of the atmospheric 6-hour DA cycle, a new mixed DA window length will be tested. The approach will use four 6-hr DA windows are applied to assimilate atmospheric and quick arriving near surface observations. Both the atmosphere and ocean are analysed in each of these windows. The ocean-atmosphere analyses from preceding 6-hour DA windows are then used to construct a >24-hour first guess of the ocean that is already conditioned on atmospheric observations. This first guess will then be used to assimilate late arriving and relatively deep oceanic observations in order to correct deep and slowly varying aspects of the ocean.

The U.S. Navy plans to implement SCDA capabilities in the global system using the interface solver approach (Frolov et.al., 2016). In this approach, each component retains its own DA system but incorporates information about error cross-domain covariances using ensemble information. This is useful in cases where well-established DA systems exist for each domain, and cross-domain error correlations exist, but combining the systems is a technical challenge.

In addition to the global S2S system several regional CDA systems are currently in development. A coupled ocean/atmos 4DVar is being developed. The goal is to move away from separate analyses that can eventually lead to unbalanced coupled system states. In this fully coupled 4DVar system, the Tangent Linear Model (TLM) and adjoint can generate cross-domain error covariances - even if the initial cross-domain error covariances are set to zero. This enables information from atmospheric (oceanic) observations to correct the oceanic (atmospheric) state. In addition to the coupled regional 4DVAR system, NRL is investigating merits of a pure ensemble system.

In the future, the regional coupled 4DVar project might expand to the global ocean/wave scale. This means that HYCOM will be used as the forecast model, and corrections will be computed with the Navy Coastal Ocean Model (NCOM) 4DVar. The TLM and adjoint will be based on a hybrid background, but propagated with NCOM. 4DVar systems will be developed for WAVEWATCHIII®, including a TLM and adjoint, and will use the Earth System Modeling Framework (ESMF) coupling interfaces.

An ensemble-estimated TLM is being also developed by NRL called the Local Ensemble Tangent Linear Model (LETLM) as described by Frolov and Bishop (2016), Bishop et al., (2016) and Allen et al., (2017). This may allow for a straightforward construction of a TLM for a complex coupled model environment. The adjoint of the TLM can be used for forecast sensitivity studies, allowing the simulations to be run backwards in time, and can be used by more sophisticated data assimilation techniques such as 4DVar. The maintenance for an ensemble-based TLM is much simpler than traditional TLMs, thus allowing quick updates of the DA system after model upgrades.

National Center for Atmospheric Research (NCAR)

The Data Assimilation Research Testbed (DART) is a software implementation of various ensemble methods. DART comes with the EnKF, Ensemble Adjustment Kalman Filter (EAKF), Rank Histogram Kalman Filter (RHKF), quadratic ensemble filter, and a localized particle filter implementation. DART uses an observation-centric analysis; observations are processed serially, but the state-vector update due to each observation is computed in parallel (in contrast to LETKF, for example, which uses a gridpoint-centric analysis approach assimilating all observations simultaneously while processing the gridpoints in parallel). As with any assimilation method, one challenging area of implementation is in the prescription of how an observation will influence the state. In DART (as in most ensemble methods) this is done via the prescription of a localization scheme that limits the influence of an observation on physically distant state variables. Because DART is a modular system, new observation types and forward operators can be added with relative ease via a fixed set of required routines. A single module can implement observation operator functions that can make use of model state variables interpolated to any location. There are also several adaptive inflation algorithms available.

DART has been implemented with the POP (ocean), CAM (atmosphere), CICE (ice), and CLM (land) single component systems of the NCAR Community Earth System Model (CESM). In terms of CDA, NCAR has been working primarily with a WCDA system based on combining the CAMDART and POPDART systems. In this configuration, a coupled atmos/ocean model with a nominal 1-degree horizontal resolution is used with 30-member DART EAKF updates implemented separately for the ocean and atmosphere systems. The system assimilates in situ temperature and salinity profiles (XBTs, MBTs, CTDs, drifters) into the ocean state at 24-hour intervals, and assimilates radiosonde temperature, wind, and aircraft data at 6-hour intervals into the atmosphere. Initial tests of this configuration have been examined over 1970-1981, a time when observational coverage even in the atmosphere is mainly over the northern hemisphere. Evidenced by comparison to multiple data sources, results show that the system is able to constrain both atmosphere and upper ocean variables to reflect interannual variability and large-scale synoptic variability in the northern hemisphere.

Using the results of the WCDA system, work has been done examining the cross-domain ensemble error correlations (i.e. scaled error covariances) in the coupled system with the intent of better understanding how the oceanic and atmospheric data constraints may be useful in a SCDA framework. In general, significant ensemble error covariances between the atmosphere and ocean are restricted at this 1-degree resolution to being within the planetary boundary layer and mixed layer of the ocean, and are highest in the tropics. In the atmosphere, the summertime hemisphere tends to have higher correlations across the boundary than the wintertime hemisphere. Correlations are found to be spatially and temporally inhomogeneous, such that building an effective cross-component localization scheme is a challenging research topic. While there are general heuristics for reasonable localization radii in the ocean and atmosphere, there is no general guidance for how to localize across component boundaries.

Because DART has always treated model state vector data as a 1D array of individual points (only the model-dependent parts need to know about the connectivity) development of an SCDA version of the DART system was achieved through a relatively straightforward concatenation of the ocean and atmosphere state vectors. At this point a SCDA ocean/atmosphere system has been implemented and prototyped in a 6-month experiment. There were some initial technical implementation issues that required attention. For example, both localization and inflation schemes in DART have historically had component-specific parameter settings. Extension to multiple components thus required either that multiple components share one set of parameter settings or that the schemes be generalized. New definitions of observation types (e.g. temperature) to specify to which component they belong and rethinking how to generalize "vertical distance" given the different coordinate systems in the ocean and atmosphere also required attention. Work to make these types of issues more seamless within DART is ongoing.

Environment and Climate Change Canada (ECCC)

ECCC currently performs near real-time global coupled atmosphere-ocean-ice forecasts in "experimental mode" using the NEMO ocean model, CICE ice model and the GEM atmospheric model. The analyses for the ocean are obtained using a modified version of the Mercator data assimilation system (SAM2) with a daily assimilation cycle (assimilating only SST) combined with a weekly cycle (assimilating SST, altimeter data, Argo profiles and other in situ observations). This coupled forecast system will likely become operational, replacing the uncoupled atmospheric model forecasts, in the near future. Even without CDA, the initial conditions for each component are reasonably consistent with the others since they all use the same SST and sea-ice concentration analyses.

Work has recently begun to implement a WCDA approach for these global deterministic models in which the coupled background forecast is used for both the 4DEnVar atmospheric analysis and the daily SAM2 ocean analysis. The SST and sea-ice analysis systems are currently stand-alone systems that each use persistence of the previous analysis as the background state to perform either an Optimal Interpolation (for SST) or 3D-Var (for sea-ice concentration) analysis. Work will soon begin on migrating these analysis systems into the software framework of the atmospheric 4DEnVar. This is a preliminary step to facilitate future research on the estimation and impact of using cross-domain background error covariances in a context closer to SCDA.

Geophysical Fluid Dynamics Laboratory (GFDL)/NOAA

In 2005, GFDL/NOAA used a hybrid coupled model to implement the concept of coupled data assimilation in a WCDA framework and found that coherent coupled model initialization helps enhance the ENSO forecast skill (Zhang et. al, 2005). Encouraged by the results of hybrid coupled model data assimilation, two years later, the same group at GFDL developed their ensemble coupled data assimilation (ECDA) system with the GFDL second generation coupled model (CM2) (Zhang et. al, 2007). The GFDL ECDA system has been used to assess the importance of CDA in steady and balanced climate estimation (Zhang et. al, 2013) as well as decadal scale predictability (Yang et. al, 2013). The ECDA system will be further developed for complex Earth system models that have high-resolution and explicitly-resolving physics pursuing seamless weather-climate and eco-environment studies.

Review of Group Breakout Sessions

A series of breakout sessions were held to answer questions posed to the workshop participants. The breakout groups reported back during a daily plenary discussion at the close of each day. Some topics have general applicability to data assimilation, but all responses are focused on the implications specifically to CDA.

Methods for CDA

There is a need to build a body of evidence to demonstrate the benefits and drawbacks of various CDA methodologies. The field is still growing, in part due to the fact that experiments in CDA require a significant computational burden. From mathematical theorems, we know that if there is non-zero correlation between atmospheric and oceanic forecast errors then SCDA should provide more accurate analyses than WCDA or uncoupled DA. However, this statement only translates to applications provided the cross-domain error covariances are accurately specified. In practice, the accuracy of the cross-domain error covariances are dependent on modelling capabilities near the interface, which are dependent on complicated physical processes that are typically unresolved in global models. For operational centers to be persuaded to make the switch from uncoupled to WCDA or SCDA, a larger body of evidence is currently needed for simple-to-state tasks such as: (1) demonstrate that WCDA is more effective than uncoupled DA and (2) demonstrate that SCDA is more effective than WCDA.

Sluka et al., (2016) indicated benefits of strong coupling versus weak coupling using an intermediate complexity coupled atmosphere/ocean model (i.e. SPEEDY/NEMO). The perceived benefits presume quality estimates of co-variability, which are available in perfect model scenarios but unclear in real-world applications. The question remains whether the coupled models are reasonably estimating these quantities. If not, it must be determined why this is the case, and how the models can be improved to accurately reproduce a realistic cross-domain error covariance.

Many operational centers are not yet applying coupling in their DA efforts, so the most accessible starting point for CDA is to begin with WCDA using existing software (e.g. coupled forecasts in the outer loop of a 4DVar as done by ECMWF). There should be a focus on improving the less mature DA components, as these may unnecessarily degrade the quality of the coupled forecasts.

CDA approaches like the interface solver *(*Frolov et al., 2016*)* are attractive as a starting point for coupled approaches, particularly for variational DA methods. Simplified approaches could be attractive if it is found that 10% of the effort might achieve 90% of the effect of CDA. An interface solver and similar approaches could facilitate gradual steps towards SCDA by operational centers, e.g. starting first with WCDA, then to one-way strong coupling, then to two-way SCDA.

As SCDA research begins, many researchers are using different time windows for different state components. It is necessary for the research community to build a theoretical basis for the proper way to do this.

Sea-ice DA presents challenges in methods, observations, and timescales. Some inter-variable consistency is critical for sea-ice prediction. For example, a simple SST constraint is needed where sea ice is introduced. More sophisticated non-Gaussian methods may provide value, e.g. when SST is near the freezing point temperature.

More collaboration between universities and operational centers is needed. A significant challenge is the computational burden of large coupled models. Solutions must be developed to: (a) give universities access to full scale operational models, potentially on operational/dev machines (i.e. O2R) and (b) develop acceptable pathways for new discoveries on simple coupled models to be translated to operations (i.e. R2O). Demonstration of new methods and ideas in research labs and universities is a necessary precursor for acceptance and adoption in operational centers.

There is value seen in a unified database for all observations across state components, and possibly shared between organizations doing coupled DA research. The JCSDA has initiated an effort to develop such a database in the U.S. A modular software infrastructure separating observation processing, forward operators, solvers would facilitate co-experimentation, particularly as the best methods for CDA are not yet established. The ECMWF effort to develop the Object Oriented Prediction System (OOPS) is one example of such a software infrastructure. A nascent U.S. effort is the Joint Effort for Data Assimilation Integration (JEDI) led by the JCSDA.

Estimation of forecast error covariances

This session addressed several aspects of the forecast error covariance in the context of CDA. The forecast error covariance matrix plays a crucial role in encoding information about dynamical relationships, separated spatially and across state variables. In the atmosphere and to some extent in the ocean, modelling the forecast error covariance matrix is facilitated by knowledge of physical balances and of dominant forecast errors (e.g. due to baroclinic instabilities). Modelling the cross-domain forecast error covariance in an Earth system model is much more challenging because of the wide-range of timescales that span the relevant phenomena that produce forecast errors. Timescales of relevant phenomena range from minutes (such as convection) to centuries and beyond (such as the deep ocean circulation). Small forecast errors associated with convection might be negligible for synoptic weather prediction but can produce large biases in SST in longer time integrations. What is considered noise and what is considered signal may become conflated, and even small biases on short timescales can create large model drifts. Another practical issue in determining the forecast error covariance from ensemble-based estimates is to identify error growth rates and error saturation levels of each model component with coupling versus without. Uncoupled models are typically driven by external forcings, and in an ensemble setting such forcing fields can have a strong influence on the nature of the ensemble.

A detailed description of the topics discussed is given below.

Outstanding questions and challenges:

- Modelling model errors - Will stochastic perturbations, or model parameter perturbations be sufficient to represent model errors over a wide range of time scales? Is there value in using multi-model ensembles to represent model errors?
- Modelling the forecast error covariance matrix across distinct domains - Modelling the forecast error covariance at the interface of two or more Earth system components is complicated when there is a large contrast in the time and spatial scales of the evolution of their state variables. Optimal localization and inflation parameters may be inconsistent across domains and care must be taken to ensure they do not create new imbalances in the analyses used as initial conditions for subsequent forecasts.
- Knowledge of forecast error dynamics in CDA-initialized coupled models is limited. Beyond the typical (initial condition) error dynamics known in the atmosphere and the ocean, there is a need to increase understanding of errors in coupled models. Error dynamics strongly depend on the strength and type of the forcing. Error dynamics are also seasonally dependent and vary depending on climate regime changes. It is clear that saturation levels may also change. The sensitivity of coupled model error dynamics to uncertainties in atmosphere-ocean coupling also requires study.
- Moving from independent forecast error covariance matrices for each domain to a coupled forecast error covariance matrix for SCDA - The prescription of the forecast error covariance matrix is application dependent, e.g. for initializing NWP versus seasonal prediction. Timescales used for the construction of forecast error covariance matrices for different domains are likely to be different. The goals of a particular CDA application must be clear when defining the coupled forecast error covariance.
- Relevance and use of the coupled model’s climatological forecast error covariance matrix (B). Past work on generating the statistics of the climatological B matrix has focused primarily on independent components of the coupled system. Relatively little

work has been done on constructing cross-domain climatological error covariance for coupled Earth systems, identifying what timescales must be resolved, or what localization must be applied.

- There is a middle ground between using DA for the primary purpose of initializing models, or using DA for the primary purpose of forming an accurate estimate of the true state (which has traditionally been achieved by the application of Model Output Statistics (MOS) as a post-processing, and has recently be addressed with 'data fusion' methods in scenarios with high observational coverage). It was noted that the goal of estimating forecast error covariance may either be "true-to-model", in which only model-resolvable processes are allowed in the analysis, or "true-to-nature", attempting to resolve underrepresented processes (i.e. processes that can be resolvable by the model but may not be present without the use of DA, such as eddies in an ocean model using an eddy-permitting resolution). For the latter, for example, it would be insufficient to generate the forecast error covariance using a purely ensemble-based scheme.
- Missing authentic cross-domain observations - Estimating "true to nature" background error covariances from observations is complicated because observations are rarely co-located. More generally, the lack of observations in some domains produces large sampling errors in the computation of a cross-domain error covariance matrix.
- Regime-dependent B matrix - Assuming that it is possible to adequately characterize regime-dependent forecast error covariances (e.g. during different phases of ENSO), it is still a questions as to whether CDA can gain an advantage by accounting for these climatological modes.
- Static versus flow-dependent B - Is an inaccurate (never actually realized) but benign (low-impact/does not induce spurious features) static error covariance better or worse than an inaccurate and malignant (high-impact, induction of spurious features) but high-information content flow dependent covariance?
- Hybrid B in Earth system models - Hybrid methods are designed to balance the weaknesses of variational methods and ensemble-based methods to create more reliable and stable filters. Given the multiple spatiotemporal scales involved, it is unclear whether a traditionally constructed climatological forecast error covariance matrix can be incorporated into a hybrid system, as has been applied in atmospheric (Kleist 2012; Kleist et al., 2015) and oceanic (Penny et al., 2015) cases.
- Revision frequency of B matrix - Upgrading B requires a considerably amount of effort. Guidance should be given on how often the climatological forecast error covariance matrix should be revised. What forces control this decision? Is it too difficult, or is there too much user-resistance? How can it be determined whether there is enough new information to justify the work effort? Can this process be automated or put into the model development workflow? Should the climatological forecast error covariance matrix be recomputed every time model versions change, and/or when model configurations (e.g. resolution) change?

Recommendations

- There is a need to characterize forecast errors in fully coupled models. Understanding the growth rates of each model component with or without coupling and understanding the temporal variability of errors will be important to model the forecast error covariance.

- The limitations of the capabilities of the bulk flux formulae to adequately represent cross-domain forecast error covariance between the atmosphere and ocean must be assessed. Similar investigations are needed between other Earth system model components.
- Due to the numerous spatiotemporal scales present in the coupled Earth system, it may be advantageous to explore ideas for separating error covariance information from different time and space scales. For example, signals representing large versus local spatial scales can be separated in the forecast error covariance matrix. One could prescribe a set of error covariance matrices (as in a hybrid covariance DA method), or a set of gain matrices (as in the Hybrid-Gain method of Penny, 2014), and then estimate the optimal weights to combine these at any given time. This may also require separating observations into "large-scale" vs. "small-scale" signals as well as performed by Tardiff et al., (2014/2015).
- A more thorough treatment of the model forecast error covariance should be pursued. Corrections based on a more sophisticated understanding of model uncertainty (e.g. stochastic parameterizations, topography/bathymetry perturbations, surface flux/ boundary forcing ensembles) should be explored.

Model error and model bias

Both operational centers and their customers must to able to effectively quantify uncertainty to effectively use the forecast guidance. Improvements in observing systems, modelling, and DA have been effective over the past few decades at reducing initial condition uncertainty. Remaining uncertainty in state estimates may be represented using singular vector perturbations, bred vector perturbations, or general ensemble DA methods in NWP (Buizza et al., 2005). Another leading source of uncertainty occurs when approximations in model formulations lead to inaccuracies in the forecast. Broadly classified as 'model error', sources of these inaccuracies include approximations made in formulating model dynamics, approximations in the parameterization of subgrid-scale physics, compounding errors in numerical algorithms, specifics of the computing platform, and occasionally bugs in software.

Previous studies have used data assimilation techniques to assess model uncertainty. Annan et al., (2005) used an EnKF DA scheme where they included some model parameters as part of the control vector in the DA algorithm to estimate both optimal values for the parameters as well as uncertainty on these parameters. It is also possible that feedback from the model error terms could assist in quality control (e.g. do not reject observations when model error is high).

CDA provides an opportunity to improve estimates of coupling parameters in the models (Zhang, 2011). For example, the flux quantities can be corrected based on observations made from the corresponding domains that define the flux. As another example, parameters such as (ice) drag coefficients that are typically specified in advance can be made adaptive during CDA. This also opens the possibility for uncertainty quantification for parameter estimation of coupling parameters.

Work has begun in representing errors specifically in the subgrid-scale parameterizations by using stochastic parameterizations (Palmer et al., 2009; Berner et al., 2016). However, many other sources of model error remain largely unexamined. The transition to CDA compounds this problem, as the number of numerical algorithms, model parameters, and lines of code increase in kind, indicating that a more sophisticated strategy for model error estimation evaluation is necessary.

Relative to the atmosphere, the fully coupled Earth system has proportionally more regions of poor to non-existent observational coverage. The most poorly observed regions of the Earth system are more likely to accumulate bias, as we have no means to directly correct these areas and potentially insufficient modelling to indirectly correct them. There is a concern of the transfer of biases in coupled models given that the surface fluxes are inadequately observed. For example, an atmospheric bias in temperature could impact water mass formation in the ocean and create a long-term bias in ocean circulation. With insufficient deep ocean observing, such biases could persist for long periods before being identified. Identifying such biases early, at their source, is an important application of CDA in model evaluation. In addition, it should be noted that biases in a coupled model need not be constrained to the boundary layers - for example cloud cover has impacts on mixed layer depth in the ocean and upper ocean heat content.

Some centers are using assimilation of anomalies as a remedy to bias transfer, though it is unclear whether this is an appropriate long-term solution. A suggestion from the UK Met Office is to use 3D analysis increments as proxies to bias and model error terms for long forecasts. For ensemble-based methods, there is a danger that model bias can have a detrimental effect on ensemble spread (e.g. by reducing spread even where uncertainty is high).

Variational bias correction (varBC) is widely used for radiances, however the growing interest in ensemble methods for CDA may necessitate development of varBC equivalent in ensemble methods, such as that of Fertig et al., (2009). Ensembles have been used to provide prior estimates for leading model error and bias terms using a reliability budget estimate (Rodwell et al., 2015). In nonlinear forecasts performed at operational centers using ensemble data assimilation, the reliability of these forecasts are a key attribute to evaluate the ensemble performance. Analysing the analysis increments from the CDA in such an ensemble system as well as computing reliability budgets (Rodwell et al., 2015) to inform about model errors in a coupled system would be a useful diagnostic tool for model improvement and stochastic parameterization.

There is a need for more research in stochastic physics and parameterizations, which serve as a physically-based replacement to simple inflation techniques often applied in ensemble methods. There is limited research at this time studying the impact of stochastic physics on coupled models (for an example, see Vialard et al., 2005). More work is needed to investigate how the ocean responds to new stochastic parameterizations being developed for the atmosphere, where a primary focus has been on simply increasing spread in atmospheric ensemble forecasts. Little work has been done exploring stochastic parameterization in the non-atmospheric components themselves. Studies using stochastic perturbations for ocean mixing parameterization in idealized experiments (Mana and Zanna, 2014; Grooms et al., 2015; Jansen and Held, 2014; Brankart, 2013) and seasonal forecasts (Andrejczuk et al., 2016) show improvements in ensemble reliability both for atmospheric and ocean variables as well as improved ocean variability in the idealized models.

Experiments with model uncertainty in the land surface model represented using different stochastic methods were performed with the ECMWF seasonal forecasting system (Cloke et al., 2011; Macleod et al., 2016). These experiments show that improvements in ensemble forecast reliability of surface temperature can be achieved with better representation of model uncertainty in the land surface scheme. This can be extended further to CDA techniques where the uncertainty in coupled model components such as land and atmospheric boundary layer or convection scheme can be coupled in the cross-covariance matrices.

Stochastic sea-ice strength parameterization has been shown to influence and improve model mean climate variability of sea-ice distribution as well as improve forecast of sea-ice area on a seasonal timescale (Juricke et al., 2014a, b) in a coupled atmosphere-ocean-ice model. These representations of model uncertainty in sea-ice models can be combined with the representations of uncertainties in other model components in a CDA framework to incorporate appropriate uncertainty representation for the analysis.

It is acknowledged that there is uncertainty in the coupling terms in Earth system models. Previous studies have shown that representing model uncertainty with stochastic parameterization schemes in the air-sea fluxes can help improve modelling the upper ocean mixed layer (Williams, 2012*)* and similarly in atmospheric physics parameterizations can help improve modelling and forecasting of sub-seasonal to seasonal timescales in coupled systems (Subramanian et al., 2016). It would be advantageous to estimate the order of magnitude of errors in the coupler itself. There is a need to explore the use of stochastic parameterization for surface flux formulations to help improve the estimation of cross-domain flow-dependent covariances that account for model uncertainties in surface flux estimates.

Simple models for studying CDA

The world CDA research community must work on bridging the gap between simplified academic research studies and full-scale operational applications. This will require two-way communication between the interested parties, to ensure that simplified models are relevant to operational systems and that there are clear pathways for bringing these results into operational systems. NOAA's numerous testbeds (http://www.testbeds.noaa.gov/) provide an example framework for bridging the 'Research to Operations' (R2O) and 'Operations to Research' (O2R) gaps. In order to develop intermediate-complexity simplified models, perhaps based on current operational systems, a close cooperation between academic groups and operational centers is needed. It is recommended that a set of benchmark problems and datasets be developed that are suitable for the testing and evaluation of coupled models. In particular, it would be useful to design experiments in which the same data could be used on a hierarchy of models, e.g. to examine the assimilation of a single SST observation at a specific time and place. The set of experiments and the data to run them should be available from a central repository.

What kinds of simple models should be used to study and evaluate CDA? The widely-used Lorenz models (L63, L96) are good for training purposes, however it is unclear whether conclusions drawn from coupling such simple models can be reliably extended to more realistic coupled modelling environments. For research purposes, it would be advantageous to have a series of increasing complexity 1D, 2D, and simple 3D coupled models. The specific processes that are represented will depend on the research question being explored. Evaluation of new methods must be tested from a series of simple to more complex models, while providing the ability to quantify the impact on each individual component. Appropriately representative simplified models may also be useful for forecasting and for process understanding.

A range of complexity has been demonstrated in work done by Smith et al., (2015), Fowler and Lawless (2016), Tardif et al., (2014, 2015), Sluka et al., (2016). Examples of simplified coupled models include the L63 model coupled to a pycnocline ocean model (Han et al., 2013), the Peña and Kalnay (2004) coupled modified Lorenz system, a multi-layer Lorenz-96-type scheme by Bishop et al., (2017), the L96-T and L96-GRS coupled chemistry meteorology low-order models by Haussaire and Bocquet (2016), the Lorenz wave-mean-flow atmospheric model coupled to a Stommel-type box ocean model developed by Roebber (1995) as used by

Tardif et al., (2014, 2015) and low order models developed by Vannitsem et al., (2015). As a step up in complexity, a coupled 2-layer QG atmosphere with a 1-layer shallow water equation system was analysed by Vannitsem et al., (2015), De Cruz et al., (2016), and Vannitsem and Lucarini (2016). A 1-dimensional single-column model, based on the ECMWF atmospheric model and a mixed layer ocean model, was developed by Smith et al., (2015) and subsequently also used by Fowler and Lawless (2016). The SPEEDY/NEMO model (Kucharski et al., 2015), as used by Sluka et al., (2016) for SCDA is a more sophisticated coupled model that begins to approach the level of operational model complexity.

In order to aid the development and testing of new methodologies, it is useful to embed simplified models in software frameworks that allow different models to be tested using the same assimilation algorithms. Several such frameworks already exist, for example: the Data Assimilation Research Testbed (DART), the Object Oriented Prediction System (OOPS), the Parallel Data Assimilation Framework (PDAF) and Employing MPI for Researching Ensembles (EMPIRE). Thought must be given to the appropriate evaluation of CDA within simplified systems. This will depend on the question being asked, for example whether an experiment is designed to assess a new assimilation methodology or to study coupled processes. Input from the wider community is needed in order to ensure that the evaluation of CDA within simplified models is based on measures useful for the full-scale systems. It is important that any evaluation is not limited to the effect on only one component of the system, for example verifying only the atmospheric fields.

Coupled initialization and prediction

While there is general agreement that model quality is a first-order problem for CDA, a number of other challenges have been identified that deserve attention.

The background error covariance used in a cycled DA system may be more faithfully represented in a coupled system, either using WCDA or SCDA. Phenomena that would likely benefit from CDA include: precipitation/SST feedback effects, the MJO, the AMOC and NAO, Tropical Cyclones, ENSO, near surface atmosphere and land surface interactions, polar prediction (including sea-ice predictions). Enhancing land-atmosphere data assimilation coupling could allow surface moisture and snow observations to impact the atmosphere. A better representation of the land surface would also allow for better use of near-surface radiance channels from satellite observations.

It has been noted there is a degradation of coupled-prediction performance due to a lack of balance in the initialized variables (“shock”). For example, the ENSO problem, where an imbalance between the wind stress (surface pressure) and stratification (thermocline) will lead to systematic increments in the ocean and the generation of spurious vertical velocities. Another example is the sea-ice prediction problem - because the sea ice is in a sensitive equilibrium with ocean and atmosphere, imbalances can produce spurious melting or freezing. Yet another example is near-surface, near-shore ocean processes, where a lack of correction to the atmospheric fields will lead to a need to continuously re-update the ocean (due to loss of information if the system is highly slaved). It is anticipated that these types of problems can be improved with SCDA.

CDA can provide a means of improving the suboptimal use of observational data of the Earth system. Use of marine surface data to influence ocean (especially historically - pre-satellite) e.g. SST/surface pressure has a relatively long-record – CDA allows this to be used for initialization pre-1960 (e.g. for decadal prediction). Parameters for the boundary can be conceptualized as another "model state" and optimized (e.g. emission sources within a chemical transport model). It is also anticipated these problems can be improved with SCDA.

There are a number of challenges that must be overcome. First, when models are coupled in an Earth system model, biases may compound and drift from one model component to another. If these biases drift, or if modelling of the inter-component interface is poor, single model component assimilation may be more effective using high-quality boundary forcing data (even though these data introduce biases of their own).

The analysis that most closely agrees with observations does not necessarily lead to the most accurate prediction. Different methods may be better suited for initialization of forecast models and reanalysis, for example. CDA may in principle be designed to control error growth on instabilities related to low-frequency variability; those that produce longer-term forecast skill. The presence of such long-range modes arising from the coupling provides useful information for DA. In principle, by having an approximate estimate of their structure, CDA can help in reducing error along these modes and as a result can improve long-term prediction skill.

There are also a number of practical challenges specific to operational centers. The background errors may need to be re-characterized when moving from a single component background to a coupled background. Operational CDA may require building in new data-streams, assimilation systems, and standard operating procedures for the new components to support real-time prediction.

Investigation is necessary to determine the best methods to initialize decadal predictions, in which longer timescale signals are of greater interest and so there may be a need to filter out higher frequency signals. Because model drift is a challenging problem in climate model development, these models are often tuned to get a reasonably good mean climate and temporal variability. However, little attention is paid to the accuracy of the 'instantaneous second moment' - thus ensemble forecasts may not be sufficient for generating a reliable forecast error covariance matrix. A long reanalysis may be needed for drift correction and retrospective prediction verification. Another big challenge is the observational network changes on the same time and space scales as the signal in which we are interested. There is also an interest in using CDA to evaluate decadal scale variability.

Observing system

There is an overall need for greater observational coverage of the non-atmospheric components of the Earth system. For CDA, obvious needs are surface measurements - for example soil moisture, snow and improved fidelity of SSS. The continuity of missions already measuring surface quantities should be ensured, and expansion to all cross-domain interfaces is recommended. Flux measurements are important and should be increased. This includes not only air/sea and land/air fluxes, but also fluxes between other Earth system components such as sea ice/ocean, land/sea (e.g. river runoff, calving, etc.), and all other inter-component interfaces. Additional attention should be applied to the estimation of observation errors. In particular, there is a need for co-located observations (i.e. multiple observations made at the same lon/lat coordinate in both the atmosphere and underlying domain). Such co-located obs would help validate cross-covariance estimates between domains.

As the non-atmospheric components become integral to real-time NWP by their use in CDA, a faster and more organized delivery system will be necessary for observations of the non-atmospheric domains. This was noted particularly for ocean observations, but applies to all other domains as well. This need also includes notices of data dissemination changes that follow NWP operational data standards (e.g. an example of a short-notice change was the transition from Jason-2 to Jason-3 which gave only 13-days notice).

As one of the more under-observed components, there is a strong demand for more observations of sea ice in the polar regions. That includes, for example, sea-ice thickness, surface temperatures, surface snow, and ocean measurements under sea ice.

The predictive quantity of the wave models is the wave energy (wave spectra), but a limited number of sea surface wave measurements in wave spectral domain is collected. Observations for the calculation of the wave spectra are currently collected with in situ buoys and only one satellite. The number of the significant wave height observations (one of the integrated wave spectral properties) is higher, but still limited.

There is a need for observing systems that can better resolve the diurnal cycle. This is of particular interest to CDA because this has a large impact on the boundary layers and uncertainty in the state estimate in that boundary. Also, improved observing would lead to improvements in modelling the boundary layer interfaces and would consequently improve CDA.

Deep ocean observations are needed to help identify and diagnose the sources of long-term coupled model drift, particularly in climate and decadal prediction applications. It is well known amongst the ocean reanalysis community that deep ocean state estimates are quite poor due to the absence of data. This introduces a source of uncertainty and model drift in CDA applications.

Coupled observation operators

The application of DA to coupled systems opens the opportunity to utilize observation operators that require inputs from multiple domains. The most obvious of these are satellite measurements, which often compute integrated quantities within the satellite’s field of view from the plant surface to the height of the satellite orbit. Examples include radiance measurements impacted by surface emission and aerosols, gravity measurements impacted by total mass in the column from the top of the atmosphere to the bottom of the ocean or land hydrography, or satellite altimetry impacted by sea surface height and wave roughness. Many of the retrieved products that use these data depend on climatologies or model state estimates derived from inconsistent forecasting systems. CDA presents the possibility for a new age in observation operator accuracy by including up-to-date and consistent coupled forecast state estimates in every part of the observation operator computation.

The following observation types are some examples that were identified to have potential benefits from the use of coupled observation operators: sea surface temperature (atmos/ocean), scatterometer winds, altimeter sea surface height, ocean colour, gravity e.g. GRACE/GOCE (atmos/ocean, atmos/land, atmos/ice), SAR (ice/wave, ocean/wave), sea surface salinity (atmos/ocean), soil moisture (atmos/land), land surface temperature (atmos/land), snow cover (atmos/land, atmos/ice). To facilitate such coupled observation operators, radiative transfer models used to represent sea surface salinity and other surface fields must be improved. Instrument error estimates would ideally be provided for each. The uncertainty associated with the observation operator itself is also important information that should be provided. Coupled observation operators designed for radiance-based measurements magnify the need for coupled atmos/aerosol DA as aerosols play an important role in radiative transfer computations.

Sea/land/ice surface temperature
Discussion focused on temperature as an ideal starting point for addressing coupled observation operators and DA at the interface of many domains. Surface temperature experiences diurnal variability. CDA applied with models that represent this diurnal cycle requires that diurnal variability be represented in the observations as well.

The land surface models have a diurnal skin layer, which typically has a longer-term memory. However, the model representation is not realistic enough to what is seen in TIR observations. In general, the models generate realistic fluxes from their defined LST, but typically have long wave biases. There is a need for modellers to introduce LST that is more representative of a true skin layer in the land model. An alternative would be to introduce a diagnostic LST, either based on physical reasoning or a statistical regression. Models are beginning to be introduced that have dynamic vegetation, with separate surface temperatures for the canopy and soil, which should improve the realism of modelled LST. There are thermal sensors like MODIS, and microwave sensors that measure brightness temperature (more related to soil moisture). However, when assimilating MODIS LST, the measurement is not exactly surface or skin temperature. It can go through the canopy.

Sea-ice temperature retrievals: Sea ice has melt ponds that sit on top of sea ice. The models do not adequately resolve these features, though they may be parameterized (e.g. in CICE). This creates a notable bias in sea-ice temperature at the surface, particularly in the summer months.

In the ocean, diurnal variability is not restricted to the surface alone, though SST products are often averaged daily thus hiding this diurnal cycle altogether. While there is a clear diurnal cycle in the argo profiles down to 4 m, it has been observed (e.g. in the PIRATA moorings) that the diurnal variability can penetrate as deep as 20-30 m in the equatorial Atlantic (http://www.meteo.fr/cic/meetings/2016/CDAW2016/presentations/2_1.pdf).

“Do ocean and diurnal model need to be coupled?” The current generation of ALE ocean models (e.g. GFDL’s MOM6) can represent thin layers in the upper ocean and may prove useful in assimilating near surface temperature measurements. However, current efforts utilize additional Near Surface Sea Temperature (NSST) profile models to project ocean foundation temperature to an estimated ocean skin temperature (effectively acting as the ocean side a coupled observation operator) that can then be input into a radiative transfer model (completing the coupled observation operator).

It is critical to specify the definition of SST when assimilating SST measurements. The Group for High Resolution Sea Surface Temperature (GHRSST) gives a set of definitions for different types of SST (https://www.ghrsst.org/ghrsst-data-services/products/). Modern ocean general circulation models do not sufficiently resolve thermodynamics at the surface to be adequate for directly comparing to satellite observations of SST. Most ocean DA applications have typically either assimilated or relaxed to an SST product such as Reynolds OISST (Reynolds et al., 2007) or OSTIA (Donlon et al., 2011). In that case, certain ad hoc ‘tricks’ are needed for a successful analysis, such as artificially increasing the SST error estimates, because such processing of the observations induces additional correlations in the observation errors. With ensemble methods, for example, it is common to inflate observation error to account for representativeness errors and preserve the reliability of the system (Karspeck 2016, Wang et al., 2017). An alternative option is to include an overlying companion model of the SST between the top model level and the air-sea interface (currently being pursued, for example by S. Akella at NASA/GMAO and X. Li at NOAA/NCEP). By resolving most of the underlying processes that are measured by the observations (Radiometers- L1B Tb radiance measurements) and in situ obs, Akella found that additional processing was not required (Akella, Pers. Comm.). As a caveat, observation error can be correlated even without processing (e.g. wide-swath altimetry SWOT). For these reasons, most systems use "ad-hoc" method to estimate the observation error to not overly weight the observations in the analysis.

"Should we only assimilate T_b, retrievals, or a combination of the two?" In answering that question, we must resolve the difficulties with correlations in observation errors for both data types. Coupled observation operators must be developed until the direct assimilation of radiances (or other equivalent observed quantities) produces equivalent or better results than using precomputed retrieval products. The current representation of the diurnal cycle is insufficient in most coupled models in use today. Localization has often been a challenge in the vertical dimension, and this may require further effort to characterize the appropriate localization to be applied at the air-sea or land-air interface. Specification of observation errors requires more attention, as this can have a significant effect on analysis results. The assimilation of individual observations versus super-observations, also called 'super-obs' (i.e. statistically aggregated observational data), must be assessed. For example, the U.S. Navy constructs super-obs based on the Rossby radius of deformation and water type (temperature/salinity/density). Sea-ice temperature is difficult to characterize at global model resolutions and presents a challenge for CDA in the polar regions.

It is a common approach to manually tune observation errors to adjust data assimilation system performance. As system complexity and observing network size increases, this approach will likely prove inadequate and should be replaced by automated methods for accurate estimation of observation errors. For ensemble methods, the localization radius is highly dependent on ensemble size (Sakov et al., 2008; Miyoshi et al., 2014), observational coverage, and model resolution. There are latitudinal dependencies as well (Zhang et al., 2005; Wang et al., 2017). We note that different localization scales can be applied to different observation types. For example, it is possible to apply a different radius to SST observations versus in situ profiles.

"What are the next big challenges for surface observations?" At present, it appears the primary challenge is reconciling that the dynamics at the surface require more fidelity than the general circulation models can provide. Current efforts are creating simple extensions from the surface layers of the model to the observed quantities. However, in the future, more sophisticated 'surface interface models' may be needed to provide a more accurate representation of observed surface quantities as well as a more accurate modelling of surface fluxes.

Software and hardware issues

General trends in software design are encouraged for the development of future CDA tools, including: modularity of code, managing code complexity and efficient/optimal use of emerging hardware. Trends in hardware include accelerators, many-core processors, reduced memory bandwidth, NV RAM (nonvolatile RAM)/"burst" memory/arrays of SSDs.

Active management (i.e. minimization) of communication within the CDA system and with the coupled model is encouraged. This includes a reduction of ‘transposes’. A common bottleneck in DA applications (especially ensemble-based methods) is input and output (I/O); implementation strategies that minimize I/O are preferable.

There is a need to actively increase DA community understanding of how emerging technologies (e.g. computer science, statistics, software, visualization, data science, big data, and data mining) map onto the objectives of CDA. Greater interaction with these external communities should be encouraged, in particular communicating the needs of CDA to these communities. The CDA community should begin reaching out to advertise open problems that may have technological solutions. Common data formats and APIs should be established and made available to these communities. It may be advantageous to selectively invite members of these communities to future CDA meetings.

Much of the existing DA code may need to be refactored to make use of new hardware. Due to the legacy constraints of many existing centers that has led to the adoption of WCDA techniques, this may actually provide an opportunity to build versatile and appropriate CDA software that can perform a spectrum of WCDA to SCDA methods. Such a refactoring further provides an opportunity for an international standardization of modular software for CDA that promotes intercomparison of results, increases efficiency of scientific research, and promotes R2O and O2R. Given these recommendations, it is important to find as models existing efforts that have been successful in establishing a common framework and staying up-to-date with new software and hardware developments. Feedback is encouraged to High Performance Computing (HPC) infrastructure designers.

The priorities in such an international collaboration for software standardization are:

1) Databases/repositories storing observations and observational innovations across all domains with standardized data formats. Investigation of commercial big-data supporting applications such as Google BigTable, or other open-source noSQL options may be useful.
2) Development of standardized forward operators for key observation types. In particular, for CDA this applies to operators dependent on multiple domains. Such standardization is especially valuable for complex operators (e.g. Radiative Transfer Models for radiance assimilation).
3) Standardized output formats to support CDA diagnostics. This would support both tools that could be run integrated within models and CDA systems, as well as tools that might be run offline.
4) A common infrastructure to apply the most common CDA methods (e.g. either pointwise local or simultaneous global solutions). Flexibility is encouraged to avoid preventing new solution methods from being viable on such a platform.

The CDA community must define specific “use-cases” that are representative of the work we expect to be doing in the next 5-10 years. This might include an EnKF CDA use case (limited by communication, ensemble simulation), as well as a variational CDA case (limited by running the adjoint, performing a global minimization), and hybrid use cases. Different constraints may be applicable for real-time operational forecasts versus offline reanalyses. To collaborate with other fields and industries, use cases should be provided for minimization algorithms, visualization methods and tools, database design and accessibility for managing observations, and a NWP ‘forecast challenge’ that can be approached by both data scientists and NWP.

As ensembles are likely to be used for the construction of the background error covariance any of the CDA solution methods, the potential for 'intrinsic ensemble models' (i.e. adding a 5th ensemble dimension to the model) may provide opportunity for optimization. This would require a refactoring of many models, so would require a clear demonstration as to the benefits of such an approach. It is likely that there would at least be potential savings in shared 'meta-data' across all members (e.g. grid data), reduced overhead costs for initializing the model, and potential coordination between model and DA parallelization schemes. This could lead to a transformative change for ensemble modelling (prediction/simulation/ projection) and should be explored, if cautiously.

Coupled land/atmosphere perspectives

(P. Rosnay, C. Draper, J-F. Mahfouf)

For several decades, most NWP centers have been running weakly coupled land and atmosphere data assimilation, using coupled model for the background forecast, assimilating low-level atmospheric observations to update the land surface soil moisture and temperatures, while also often running a separate snow (cover and depth) analysis. The use of screen-level observations has been very successful in improving low-level atmospheric forecasts in regions that are well observed, however its impact on the land surface states is more mixed.

Future developments will be focused on enhancing the coupling between land and atmospheric DA, and assimilating more remotely sensed land surface observations. Based on current capabilities, stronger coupling of land and atmosphere DA will most easily be obtained through ensemble approaches. Some of the significant remaining challenges include estimating model error covariances across the land/atmosphere interface (through ensemble methods, or otherwise), differences in horizontal resolution between the (courser) atmospheric DA, the (even coarser) ensembles in atmospheric hybrid systems, and (full resolution) land DA, and the potential for unknown, and often large, land surface biases to be passed to the atmosphere.

Development should focus on improving both the land and atmosphere through CDA, rather than updating one at the possible expense of the other. This can be achieved by assimilating observations informative of both atmosphere and surface states, assimilating a range of observation types selected to constrain different aspects of the model physics (moisture/energy), development of diagnostics targeting CDA, and strong support from model development. The CDA could itself provide a breakthrough in diagnosing land surface biases (and split random and systematic errors in the observations and forecast).

The development of modular platforms, such as EMPIRE, OOPS, and JEDI is a key component of CDA developments. These platforms will support research activities required to explore the diversity of coupling strengths ranging from WCDA to SCDA. Likewise, the introduction of common data formats, observations databases, and I/O for each of the land and atmosphere components will speed development of coupled land/atmosphere DA and enable operational implementation for NWP applications.

In terms of the network of observations for assimilation, continuity beyond SMOS and SMAP, of L-band missions for sensing soil moisture is particularly important, and the follow-on L-band missions should provide data in near real-time. Additionally, there is an urgent need for remotely sensed snow mass missions, as this is a major gap with the current observing systems. From an evaluation perspective, there is need for more in situ and global gridded observations (snow, soil moisture, fluxes), and development of methods for up-scaling in situ observations to model scales. For evaluation of CDA, the development of coupled diagnostics, and associated observations, is required.

Coupled DA for reanalysis

What are the challenges and priorities from a reanalysis perspective?

The ERA-CLIM2 project has a number of key activities: rescue observations, R&D, reanalysis production, and reanalysis assessment. Within the ERA-CLIM2 project, there have been identified apparent coupled model biases. Fewer data are available to constrain the system in the early period. There are drifts and jumps in the stratosphere, deep ocean and sea ice. A challenge for SCDA is identifying whether it will only have a positive impact, or whether it could potentially transfer biases from one part of the system to another.

Research is needed to improve the coupled Earth system models. A related concern is a need for dedicated bias correction schemes as there are fewer constraints in the coupled system to compensate for biases in individual components. This leads to a recommendation to encourage intercomparisons of biases and drifts in different coupled reanalyses.

Changes in the observing system over time are a notable challenge. Current approaches to assimilate only surface pressure (atmos) and SST (ocean) are meant to address this, but better ways should be explored that allow more observation data to be used as they become available. Quality control is needed, especially with sparse observation data, or a sudden newly observed area or variable type.

There is a need for flexibility in the representation of multiple spatial scales in the background error covariances. Better assimilation at the air-sea interface is needed, particularly to separate coupled interactions from biases. ECMWF currently uses nudging to SST. Weights must be specified, and this parameter is not easy to tune. They would like to shift from nudging to SST assimilation as the UK Met Office is attempting.

Spin up and initialization of multiple streams is a challenge in coupled systems due to the many timescales present in the different components of the system. Ocean and sea-ice initialization at the start of the century (where data is very sparse) and also at the beginning of each stream is a challenge, both in determining the state itself as well as the uncertainty. Assessment is difficult because of the multiple components. Visualization and standardized diagnostics are needed. CDA should provide feedback on coupled model biases (e.g. estimated via analysis increments).

A coupled reanalysis ensemble may be needed for flow-dependent covariance estimation and uncertainty estimation. Spurious climate signals and trends are exacerbated by model and observation bias. Novel observation types should be considered. These might include tracer observations, bottom pressure, tide gauges, and various climate proxy data such as tree ring widths and isotope ratios from corals and ice cores.

There are ongoing efforts using data assimilation for the generation of paleoclimate reanalyses. This type of paleoclimate data assimilation provides an alternative to regression models or Bayesian hierarchical models. Hakim et al., (2016) use an offline CDA analysis that uses a coupled atmosphere/ocean in combination with proxy system models (e.g. Dendro model, Coral model, Ice core model) as observation operators to compare to proxy observations.

Conclusion

This whitepaper provides a summary of the goals, challenges, and recommendations that arose out of interactions at the international workshop on coupled data assimilation held in Toulouse, France, 2016 (http://www.meteo.fr/cic/meetings/2016/CDAW2016/). Further input has been solicited from workshop participants and external reviewers to ensure the accuracy and relevance of the material presented here. However, it is acknowledged that CDA is a growing and rapidly evolving area of research. It is expected that given the momentum of current research efforts some of the questions raised in this workshop will be answered within only a few years, while some will require modest increases in exploratory research, and others may require larger institutional investments. In the long term, it is generally believed that CDA will provide significant improvements to Earth system monitoring and operational NWP. We look forward to the developments on the horizon.

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World Weather Research Programme (WWRP)
Report Series

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Verification of Environmental Prediction in Polar Regions: Recommendations for the Year of Polar Prediction, (WWRP 2017-1).

Ninth Session of the Scientific Steering Committee (SSC) for the World Weather Research Programme (WWRP), 24-27 October 2016, Geneva, Switzerland, (WWRP 2017-2).

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