WWRP 2019 - 1

Seventh International WMO Data Assimilation Symposium

Florianópolis, Brazil, 11–15 September 2017

WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

WWRP WORLD WEATHER RESEARCH PROGRAMME

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INTRODUCTION

The 7th International WMO Symposium on Data Assimilation was held in Florianóopolis, Brazil from 11 to 15 September 2017 (http://www.cptec.inpe.br/das2017/). A new format was chosen for the Symposium, which promoted the participation of early-career scientists from all over the world fostering the presentation of new frontiers in methodology and the use of observations from convective to synoptic scales, and for a wide spectrum of applications in atmospheric, oceanic and Earth system science. A total of 204 scientists from more than 20 countries participated with 76 oral presentations and 128 posters. 25 students were financially supported by WMO (World Meteorological Organization), EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites), ESA (European Space Agency), Vaisala, and the Brazilian organizations CPTEC (Centro de Previsão de Tempo e Estudos Climáticos), INPE (Instituto Nacional de Pesquisas Espaciais), CGPDI (Technical Cooperation between Developing Countries), JRC (Japan Radio Company), Floripa Convention and Visitor's Bureau, Hobeco, SimTech, EEC (Enterprise Electronics Corporation) and Simepar. 42% of the presentations were given by women (compared with less than 10% in the 2013 Symposium), and half of the presenters were early-career scientists. All of the presentations were of equal length of 20' (17' for presentations and 3' for questions). Every day, two different groups of chairpersons were selected to enable a combination of early-career and established scientists to work together to introduce the presenter, trigger questions and organize, motivate and summarize the discussion sessions at the end of each day. The Symposium reflected the main challenges and the future perspectives in data assimilation. The wide-ranging audience attending from universities, research and operational centers delivered a dynamic and innovative Symposium.

KEY TOPICS

The state of the art of data assimilation for weather and climate prediction was presented. The aim of the Symposium was to gather a worldwide representation of well-established scientists as well as early-career scientists to create opportunities of discussion, to establish common areas of interest and future mutual collaborations to advance work on data assimilation methodology.

The data assimilation topics included advancing assimilation methodologies, in particular ensemble data assimilation methods; the evaluation of model and assimilation system performance, the assessment of observational impact and diagnostic tools used. Coupled-state estimation for atmosphere-ocean, atmosphere-land, atmosphere-chemistry was an interesting innovation of the Symposium presentations together with convective-scale data assimilation methodology and ocean data assimilation. In summary, the DA themes discussed were:

- Global and regional atmospheric DA
- Global and regional ocean DA
- Atmospheric assimilation coupled with ocean, land and chemical constituents
- Convective-scale DA
- Assimilation of space-based remote sensing, ground-based remote sensing and in situ observations
- Methodology
- Assimilation system performance diagnostics.

HIGHLIGHTS

Methodology

Ensemble and hybrid algorithms are the established methodologies used in operational centers for Numerical Weather Prediction (NWP): EnKF (Ensemble Kalman Filter), EnVar (Ensemble Variational), Hybrid 4DVar, and Hybrid 4DEnVar. Currently, 4D hybrids are the state of the art for global atmospheric NWP, but the evidence so far is that Hybrid 4DVar performs better than Hybrid 4DEnVar (e.g. 2% lower error at UK-Met office) but it is computationally more expensive. From the results shown at the Symposium, Hybrid 4DVar still has utility and longevity even in a non-linear, non-Gaussian context. The point is that this gap between the two approaches may be closed with modelling advancements such as evolving localization and climatological error covariances. For example, it should be investigated whether a 1000-member size ensemble, which would allow neglecting vertical and (possibly) horizontal localization, is affordable for operational forecast centers in the near future. Other questions are arising from next-generation computing in terms of the choice of algorithms and parallelization. A typical example is the scalability of EnVar versus the scalability of weak constraint (long window) 4DVar.

Data assimilation (DA) methods have their use, advantages and disadvantages, it is therefore important to keep in mind that their full potential is mostly hindered by computational and operational constraints, which still limit the possibility to fully exploit systems as weak constraints 4DVar or thousands-member ensemble system.

The initial state estimation problem is further complicated by the necessity to develop an initial condition for Earth system models, which couple the atmosphere with the ocean, the land, the cryosphere and the chemical constituents. The implications of moving toward a fully coupled system in terms of algorithmic choices are not yet well understood and will be an area of active research in the coming years.

In contrast, research institutes and universities are moving away from traditional models and DA approaches, towards methodologies like particle filters, synchronization, neural networks (NN) and nudging-based observers for joint state-parameter estimation. The idea is that for high-dimensional, non-linear and non-Gaussian systems with increasingly non-linear observation operators, these new methodologies could lead to a more efficient and complete state estimation. There was an extensive discussion about the effectiveness and efficiency of NNs within or instead of certain components of models and assimilation schemes. Two points were the focus of discussions: 1) how NNs would perform in cases of extreme weather events; and 2) whether NNs are really cost-effective as they require the need to be trained and re-trained when models change, new observations become available, or extreme events occur that were not originally part of the training dataset. The exploitation of artificial intelligence for components of data assimilation systems is likely to emerge as an area of active research in the coming years.

Regarding particle filter methods, in the last few years many developments have been accomplished either in a simplified or more complex model system at different centers. The results are encouraging. In particular, a potential choice in the particle filter approach is the use of a density function from the synchronization theory that synchronies the model with the true evolution of the system using the one-way coupling via the observations. In practice, such a density function would damp the growth of instabilities transversal to the synchronization manifold and would increase therefore the particle filter performance in high dimensional systems. When only part of the system is observed, synchronization can be achieved via a time embedding, similar to a smoother in data assimilation

Finally, the nudging-based observers is a back and forth nudging algorithm, which consists of solving iteratively the forward nudging equation and the model system backwards in time with a feedback term stabilizing the backward solution, given the fact that this problem is usually ill-posed for irreversible geophysical systems. The initial condition of this backward resolution is the final state obtained by the forward nudging method. These forward and backward resolutions are repeated until convergence, providing an estimate of the initial state of the system. Several improvements of the nudging-based system are under investigation: it has been proved in simplified models or in combination with EnKF system that it is possible to correct non-observed variables with simple nudging feedbacks to observed variables.

There are alternative strategies being explored to deal with non-Gaussianity while using some of the more traditional EnKF and variational infrastructure, such as Gaussian transformation/anamorphosis and the Gamma, Inverse Gamma, and Gaussian (GIGG) EnKF. In particular, some of these techniques have demonstrated their usefulness in applications such as precipitation assimilation. Within the context of all of these techniques for dealing with nonlinearity and non-Gaussianity, different skill measures other than the standard RMSE (Root Mean Square Error) for example, should be investigated, as they may be more appropriate for assessing the effectiveness of non-linear DA schemes such as particle filters when compared to traditional linearly based variational, ensemble and hybrid schemes.

Convective scales

Data assimilation at convective scales needs to capture fast changing processes and scales of motion that are resolved only by high resolution models. Convection develops quickly resulting in different error-covariance structures, which depends on whether convection is present or not. Rapid updates of the system are essential to capture the system's evolution but they can cause problems related to balance and noise. Observations related to convection (environment, clouds and precipitation) require high spatial resolution (1-10 km) and high temporal resolution (5-15 min). Existing observations, i.e. from weather radars (reflectivity and radial winds), wind profilers (radar & Doppler lidar), ceilometers, passive temperature and humidity profilers (microwave and infrared), visibility sensors, GNSS (Global Navigation Satellite System) (ZTD (Zenith Total Delay)), cloud and lighting detection sensors and soil moisture networks etc. are important for prediction at these scales, but are difficult to assimilate with ensemble systems due to the current representation of background errors (e.g. location error), which is non-Gaussian. This highlights the potential improvement that can be obtained with the development of non-linear data assimilation schemes for convective-scale DA. Moreover, the predictability of convective storms lasts only a couple of hours although it has been shown that extended predictability can be obtained under certain situations such as in the presence of complex terrain. Like for the aforementioned global NWP problem, ensemble and hybrid methods are the current state-of-the-science for convective-scale data assimilation.

Coupled DA

Different coupled assimilation systems were presented. It was encouraging to see developments on fully coupled ocean-atmosphere DA using a 4DVar system for short-term regional forecasting. The system provides a fully balanced analysis that accounts for all combined observations in both primary fluids. On the land-atmosphere coupled DA, both ensemble (e.g. ETKF (Ensemble Transform Kalman Filter)) and particle filter methodologies (e.g. Equivalent Weight Particle Filter, (EWPF)) have been used for atmospheric DA. In particular, these methods are implemented and available in the EMPIRE (Employing Message Passing Interface for Researching Ensembles) data assimilation system to which the JULES (Joint UK Land Environment Simulator) land surface model has been coupled using MPI (Message Passing Interface) calls. Preliminary results show that a particle filter can better predict the state variables, likely because the filter is addressing the non-linearity of the problem. This coupled system is meant to improve African crop forecasting.

Atmospheric constituents

The impact of assimilated observations of constituents like reactive gases, aerosols and greenhouse gases (GHGs) on NWP was presented. Benefits of assimilating atmospheric constituents are found on the forecasting of extreme events and on the water cycle. Constituent DA also has operational applications for air quality forecasting, emergency response and climate monitoring and adaptation. For example, the Copernicus Atmosphere Monitoring Service (CAMS) comprises of a global system and a selection of 7 regional ones covering Europe and provides analyses and forecasts of atmospheric constituents. CAMS is also producing reanalysis products of atmospheric constituents (2003 onward). In the meantime, the MERRA (Modern Era Retrospective analysis for Research and Applications) reanalysis is currently being produced by the NASA (National Aeronautics and Space Administration)/GMAO (Global Modeling and Assimilation Office) data assimilation system (GEOS-5 (Goddard Earth Observing System Model, Version 5)) where the aerosol assimilation is being adapted to hybrid-DA systems. Atmospheric constituent simulations need good estimates of surface sources (like emissions) together with the initial condition. Consequently, there are plans to include emissions for CO2, CO, CH4, NO2 in the control vector. The need for coupling of weather and tracer transport for GHG was successfully explored. The impact of GHG assimilation on weather forecasts has been investigated and the assimilation of IASI (Infrared Atmospheric Sounding Interferometer) CO2 and CH4 was found to improve stratospheric winds. With a coupled meteorological and tracer transport model, the uncertainty in the wind analyses was shown to place limits on the spatial scales of the constituents that can be resolved. The implications are that the inverse problems for GHG with offline transport models have spatial limitations on the ability to pinpoint upstream sources and sinks. The EnKF has been applied to model volcanic ash dispersion. In terms of observations, the constituent observing network is incomplete. For example, only a few of the hundreds of species needed for tropospheric chemistry modelling are actually observed. Moreover, so far only satellite retrievals of constituents have been assimilated e.g. by CAMS because the radiative transfer model observation operator is too expensive to be directly executed in a DA system like 4D-Var. Also because of the coupling of the constituents with the meteorological variables, the quality of the radiances assimilation depends very much on their respective accuracies, which are not necessarily well known for the constituents.

Observations

Regarding the assimilation of satellite observations (radiances), the general trend is to move to All-Sky (e.g. including cloudy and precipitating fields of view) assimilation for other than microwave electromagnetic wavelengths (e.g. infrared). The positive impacts obtained from profiling satellite sensor led to recommend the continuity of active satellite profiling observations (as lidar and radar) beyond EarthCARE and GPM (Global Precipitation Mission).

Regarding the assimilation of correlated observations, so far, only inter-channel (satellite radiances) and inter-scan (radar winds) correlations have been successfully taken into account in the DA-process, but addressing correlated observation errors was an interesting aspect of the Symposium. It is envisaged that the knowledge and techniques acquired for modelling the background error covariance matrix could be used to address observation error correlation in DA.

Assimilation performance diagnostic

Well-designed, properly validated, and carefully conducted Observation System Simulation Experiments (OSSEs) can be invaluable for estimating and understanding impacts of proposed observing systems and new data assimilation methodologies. Although significant imperfections and limitations should be expected, OSSEs complement and provide both qualitative and quantitative characterizations of different components of the Earth observing system. Clearly, OSSEs require extensive validation of all components before being applied.

Observing System Experiments (OSE) and Forecast Sensitivity to Observations Impact (FSOI) are the established tools to assess the impact of various observing systems in the forecast. Comparisons of adjoint- and ensemble-based FSOI techniques highlight potential inconsistencies with the ensemble FSOI diagnostic tool. Additional hybrid variants of the FSOI technique are being explored at ECCC and NASA GMAO. Furthermore, quantitative and qualitative observation impact differences can emerge if a different objective function is used in the FSOI. In particular, if the objective function is based on observations the observation impact is on average a few percent larger than when a model-dependent objective function is used (e.g. energy norm). This is because a model-dependent objective function is not able to disentangle the degradation due to systematic model error from the degradation due to the observation quality.

CONCLUSION AND FUTURE POINTS

As global assimilation continues to increase spatial resolution and temporal frequency, the assimilation systems are inheriting problems traditionally encountered with regional convective-scale applications. Can we continue to find ways to extract more information from ensembles in cost effective ways from time lagging and shifting and scale-dependent localization? As complexity increases, the parameter space increases. There is a need to continue efforts to quantify and automate flow-dependent parameter estimates such as hybrid weights and localization.

The continuing need for performing massive numbers of parallel computations highlights the need for DA systems to be modular, flexible, generic and scalable (emerging technologies). The new JCSDA initiative JEDI (Joint Effort for DA Integration) aims to develop a unified DA system for all models from toys to Earth system models, with unified forward operators and for users from research to operations. It aims to improve the cooperation between universities and operational centers resulting in a better exploitation of university resources for addressing operational problems. JEDI will take advantage of new architectures, fast computers, and new ways of working together (i.e. in large distributed teams). DA systems are broken down into building blocks (observation operators, state vectors, covariance matrices, models, etc.) and modern software engineering is used to manipulate these. This approach should naturally facilitate coupled DA development. Modular components must include tests that can be automatically run when new components or features are added, so that the new code does not "break" previously working codes. The PDAF (Parallel DA framework) is also a unified framework that aims to improve generality and flexibility of DA systems in the context of high-dimensional models using massively parallel computer architectures. It supports various models for ensemble DA and various computer platforms from laptops to supercomputers. Unlike JEDI, PDAF uses Fortran 2003 without object orientation to keep the code close to current models. The PDAF also permits coupled DA. It is an open-source community software that is freely available online (http://pdaf.awi.de).

Ensemble-based (including hybrid) DA continues to be a popular, successful algorithmic choice for many applications. However, there has been insufficient research on model error and its representation. The stochastic perturbation methods that have been leveraged from research in the ensemble prediction community have not been sufficiently innovated for optimized use within the context of short-term forecast, background/model error representation, and the data assimilation problem. A significant investment needs to be made in further exploring the estimation and representation of the model error component of the system error in order to maximize the benefit of the exploitation of ensemble-based information in the assimilation process.

There will continue to be developments across a broad range of DA algorithmic solvers including variational, ensemble, hybrid, and non-Gaussian/non-linear schemes. As the spectrum of applications for data assimilation continues to broaden, the advancements across a variety of these schemes will continue to advance data assimilation science and understanding.

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