ASSESSMENT OF PROGRESS AND STATUS OF DATA ASSIMILATION IN NUMERICAL WEATHER PREDICTION

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The International Workshop on Real-Time NWP Forecast System was hosted by the Korea Institute of Atmospheric Prediction Systems (KIAPS). The workshop focused on facilitating the advancement of operational data assimilation (DA) systems to improve real-time weather prediction, such as cutting-edge DA methodologies, the impact of observations in the operational numerical weather prediction (NWP) systems, and future directions of operational DA. Experts from various international operational centers were invited to share experiences in DA and to discuss how to further improve forecast performance. The workshop included 32 oral and 23 poster presentations, which covered the current status of real-time NWP, hybrid DA, satellite and radar DA, and ensemble DA, and the observation impact on overall forecast performance (a program of the workshop is available online at www.kiaps.org/eng/external/workshop_view.do?externalSeq=54).

INTERNATIONAL WORKSHOP ON REAL-TIME NWP FORECAST SYSTEM

What: Representatives from major operational centers and research institutes, including ECMWF, the Met Office, Météo-France, DWD, KMA, CMA, JMA, ECCC, NOAA/NCEP, NOAA/ESRL, NRL, NASA, and NCAR, gathered to discuss recent developments in real-time numerical weather prediction systems, especially data assimilation.
When: 31 May–2 June 2017
Where: Jeju-do, South Korea

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DOI:10.1175/BAMS-D-17-0266.1

In final form 1 December 2017

CURRENT STATUS OF NWP MODELS AND DA. The workshop began by demonstrating the current real-time NWP models and DA at the operational centers. Stephen English presented the European Centre for Medium-Range Weather Forecasts (ECMWF)'s strategy, which includes an Earth-system approach to deliver improvements for high-impact weather, regime change, and global-scale anomalies. The benefits of the ocean-coupled high-resolution model were emphasized, as was the continued importance of four-dimensional variational

DA (4DVar). The development and performance of ECMWF's ensemble of data assimilations using 25 reduced-resolution 4DVars was explained. William Bell (Met Office) described the recent progress with the Met Office NWP system, with particular focus on the assimilation of satellite data. He suggested that the forecast sensitivity to observation (FSO) metric might overestimate the value of humidity observations based on experience at the Met Office, where observation system experiments (OSEs) give lower impact than FSO for humidity observation. The Japan Meteorological Agency (JMA)'s NWP model and DA system were summarized by Yoichiro Ota (JMA). Its current operational global system is 4DVar, but they are facilitating new DA schemes, such as a hybrid 4DVar with a local ensemble transform Kalman filter (LETKF) and an all-sky assimilation of satellite radiances. Andrew Collard [National Oceanic and Atmospheric Administration (NOAA)/ National Centers for Environmental Prediction (NCEP)] presented recent changes in NCEP's NWP data assimilation configuration, including the introduction of four-dimensional ensemble–variational DA (4DEnVar). The background error covariances are 87.5% ensemble and only 12.5% static, which was the lowest-percentage static shown by any center at this meeting. Benjamin Ruston [Naval Research Laboratory (NRL)] spoke about the recent progress with the DA system at the U.S. Navy (NAVDAS). He noted that a major push at NRL now is for coupled data assimilation, particularly between atmosphere, ocean sea ice, and waves (with two-way coupling between each system). Song-You Hong (KIAPS) presented an overview of the KIAPS model development. The motivation for this model development is to create KMA's future NWP system. Environment and Climate Change Canada (ECCC) also uses 4DEnVar with an ensemble Kalman filter (EnKF) as its operational DA system (Mark Buehner, ECCC). They are using 256 ensemble members and use 50% static and 50% ensemble hybrid covariances in the 4DEnVar analysis. The concept of the German Weather Service [Deutscher Wetterdienst (DWD)]'s NWP model is an integrated system, including a nowcasting ensemble prediction system (EPS), Rapid Update Cycle (RUC) DA, and short-range NWP (Roland Potthast, DWD), where boundary conditions are provided by DWD's global Icosahedral Nonhydrostatic (ICON)-EPS model based on the hybrid LETKF plus EnVar DA.

The current global data assimilation in Météo-France is a hybrid DA with a deterministic 4DVar with 25 perturbed 4DVars. They have been developing a hybrid 4DEnVar (Gerald Desroziers, Météo-France). Wei Han [China Meteorological Administration (CMA)] presented the status of CMA's Global/Regional Assimilation Prediction System (GRAPES) and its DA system, and Seung-Woo Lee [Korea Meteorological Administration (KMA)] introduced current plans for the operational system at KMA.

HYBRID DATA ASSIMILATION. NOAA's 4DEnVar system was introduced by Jeffrey Whitaker (NOAA), who contrasted 4DEnVar with EnKF systems, pointing out that the main advantages of 4DEnVar are for the localization in model space, which means 4DEnVar handles nonlocalized observations, such as radiances, much better. He went on to claim that if an ensemble DA system had 1,000 members, there would be no need for any localization. Adam Clayton (Met Office) noted that the hybrid-4DEnVar system cannot yet match the performance of the 4DVar for accuracy of the Met Office's deterministic analysis; therefore, the Met Office is likely to remain with a hybrid 4DVar system for the next few years. The skill gap may be closed by the development of a localization scheme that can be advected in time with the flow. He also talked about a number of initiatives at the Met Office to gain a larger ensemble size at low cost. This includes data assimilations that are time lagged (using members from an older forecast as part of a lagged ensemble) and time shifted (taking perturbations of members for time slots before or after the analysis time). This has been shown to lead to very significant improvements in skill. Desroziers introduced the idea of Lagrangian advection of the localization to obtain better cross covariances between different times in 4DEnVar. In-Hyuk Kwon (KIAPS) introduced the data assimilation system and observation preprocessing system at KIAPS [KIAPS package for observation processing (KPOP)]. They also run a hybrid 4DEnVar, but with 70% static and only 30% LETKF ensemble system. The comparison between 4DEnVar and LETKF showed that the 4DEnVar is better for temperature and wind but that the LETKF is better for humidity, and he proposed partial recentering of humidity.

SATELLITE DATA ASSIMILATION. Bell presented the new variational bias correction (VarBC) system at the Met Office, focusing on those aspects unique to the Met Office implementation. Use of VarBC over a periodically updated set of coefficients showed a reduction of the analyzed biases for the Advanced Microwave Sounding Unit (AMSU)

channels 4 and 5. This suggested a possible interaction with the representation of surface errors. Examination of the performance of VarBC showed a strong latitudinal variation of the scan-dependent bias. Han introduced constrained VarBC (CVarBC). The CVarBC concept is where a constraint is applied to the change in bias corrections computed by VarBC. This has been successfully applied to both the upper-stratospheric AMSU-A channels and ozone (where observations with known biases are not corrected, so they can anchor the system). NCEP plans to add the Advanced Technology Microwave Sounder (ATMS) to NCEP's all-sky assimilation system. Note that unlike ECMWF's all-sky system, NCEP is interpolating cloud and rain fields to the observation location. It was pointed out that it is not desirable to interpolate cloud fields, because the interpolated fields can become physically inconsistent. Min-Jeong Kim (NASA) presented progress with all-sky microwave assimilation at NASA. The all-sky system is similar to that of ECMWF; it integrates a cloud index that combines satellite and model estimates (Geer and Bauer 2011) except that cloud variables are interpolated to observation locations, and the same cloud index is used in both the observation error model and a predictor for the bias correction model.

Ruston discussed some approaches to handling observation errors. He noted that considerable progress has been made in knowing how to progress from an initial diagnosis of correlated error, from a method such as the Desroziers approach, to an observation error covariance matrix that can be used as a conservative starting point in operational systems. The conditioning methods include symmetrization of the matrix; application of preconditioning, which reduces the condition number of the matrix; and a form of inflation of the variances, typically additive or multiplicative. Reasonable inflation magnitudes for the error variances generally result in values that do not exceed the variance of the fit of observation to the background and analysis.

ENSEMBLE DATA ASSIMILATION. Potthast introduced an ensemble approach to integrate nowcasting and RUC NWP systems. As a design of a convective-scale ensemble data assimilation (EDA) system, they are planning a nowcasting EPS with 5-min updates. The atmospheric probability will be distributed by many different perturbation techniques, including a global ensemble for the lateral boundary, high-resolution initial conditions from local area EDA with physical model perturbations.

Shu-Chih Yang (National Central University, Taiwan) presented radar assimilation with the Weather Research and Forecasting Model's local ensemble scheme (WRF-LETKF). The zenith total delay (ZTD) and radar work well together, with a combined impact greater than the sum of the parts. Seoleun Shin (KIAPS) presented the KIAPS-LETKF. After 80 DA cycles, the kinetic energy (KE) spectrum of ensemble mean at 500 hPa was compared to that of ECMWF interim reanalysis (ERA-Interim; Dee et al. 2011) at the same time to verify the correctness of the LETKF analysis. This sort of spectrum analysis is very powerful and should be encouraged. Soyoung Ha [National Center for Atmospheric Research (NCAR)] discussed the representation of model error in the ensemble system. The ensemble-mean error grows faster than the spread, as shown by Buizza et al. (2005), with a model error that is underdispersive. It was shown that the model error representation can improve ensemble forecasts deterministically and probabilistically.

The LETKF is used at JMA to generate the initial perturbations for its 50-member global EPS. It assimilates the same set of observations as JMA global DA except for hyperspectral infrared observations. The JMA found the ensemble to be overly dispersive at high levels. Some members exhibited unrealistically strong westerly equatorial jets at 0.25 hPa. This was attributed to excessive inflation and was resolved by limiting the multiplicative inflation above 0.85 hPa. New adaptive inflation methods with relaxation to prior spread (RTPS) or relaxation to prior perturbation (RTPP) have been tested and yielded a more robust and stable inflation scheme. While both methods successfully estimate the appropriate ensemble spread, the perturbations with RTPP tend to grow faster than those with RTPS.

OBSERVATION IMPACT. It is important to evaluate the effect of each observation to improve the performance of NWP. Hyun Mee Kim (Yonsei University, South Korea) compared the OSEs and the FSO for East Asia. A very detailed analysis of FSO by channel was presented. This was further examined by instrument and satellite. This suggested the most beneficial channel is AMSU channel 5; however, in some coastal areas assimilation of AMSU channel 5 led to an increase in forecast error. It was stressed that it is vital to look at the actual change in forecast error first to guide interpretation of FSO. Buehner noted the need for development of an EnVar FSO because not all observations are used in the EnKF.

This has been successfully compared with other techniques, including EnKF- and adjoint-based FSO. The EnVar technique, with a purely ensemble-based background error covariance, does not fully represent a hybrid system. The ensemble technique shows less impact from radiances, sondes, and GPS radio occultation (GPS-RO) than the adjoint technique. The near-surface observation impact is not propagated upward because of localization and is therefore underestimated.

It was noted by English that the importance of humidity observation in the all-sky assimilation is definitely growing, as shown by time series of FSO in ECMWF. The microwave "water vapor" observations have doubled in impact since 2012, which is due to use of water vapor sounders under "all sky" (Geer et al. 2017). This provides motivation to target investigations toward the assimilation of additional all-sky observations, including improvement in both the observation operator and the representation of the observation error covariances.

PLENARY DISCUSSION AND RECOMMENDATIONS. The workshop plenary session discussed issues in verification, bias correction, hybrid DA, and ensemble DA. This is summarized below.

Verification. We need to quantify the uncertainty of the verification metrics to establish the statistical significance of changes. We should verify against independent references when possible and recognize the dangers of verification against "own analysis." Traditional scores (e.g., 500-hPa geopotential height) are still useful, but we should take care in interpreting small changes in short tests. To measure the benefit from modifications of the DA method, or in observing system changes, examinations of the background and analysis fit (bias and standard deviation) to observations is a good indicator of the quality of the analysis. This is because, whereas in general experiments between 100 and 600 forecasts are needed to achieve statistical significance, a much smaller sample of background or analysis departures can provide robust results for the quality of the analysis. In particular, use of radio occultation observations provides information on the higher-vertical-resolution structure, whereas the radiances provide very accurate information but only about large-scale features in the vertical. To produce statistical significance in forecast scores requires very long periods of continuous cycling (Geer 2016). Often the changes of these scores will be small. Case studies can be approached as a way to illustrate and understand changes but only insofar as they are known to be representative of improvements found to be statistically significant in long experiments.

Bias correction. The perception is that bias correction in regional models continues to underperform that in the global systems. It is encouraged to consider using CVarBC with bias coefficients from the global system as a constraint in the regional system. Using bias corrections between systems typically leads to a degradation of observation fit, and a period of adjustment is required at a minimum. It is suggested that basic examination of 2D, 3D, and 4D structures of bias are needed to supplement the global statistics.

Hybrid data assimilation. Does the term *hybrid DA* convey a common understanding of methods? The answer seems to be no, though there was an attempt by Lorenc et al. (2015) to define a lexicon for the terminology. It was recommended that until a meaning becomes widely accepted in normal use (e.g., as 4DVar has now) care should be taken. Use of a few extra words can add clarity, for example, saying *hybrid covariances* when discussing methods such as the alpha control variable.

Ensemble data assimilation. Given finite resources there is a trade-off between the number of ensemble members and the resolution of each member. However, we do not know whether our current setups are close or far from the optimal trade-off. It is not a good idea to compromise the resolution of the members. The data volumes being read and written, archived, and communicated between processors is now very high. Therefore, efficient and innovative methods for input/out (I/O) are needed, such as parallel and asynchronous I/O, and dedicated I/O servers, alongside efforts to improve the scalability of core systems.

To advance the current state of the art for DA, workshop attendees agreed that it is important to share experiences learned in the field through further workshops.

ACKNOWLEDGMENTS. This work was carried out through the research and development project of global numerical weather prediction systems of the Korea Institute of Atmospheric Prediction Systems (KIAPS) funded by the Korea Meteorological Administration (KMA). The authors are grateful to Yoichiro Ota and Seoleun Shin for confirming the summary of their presentations. Benjamin Ruston is supported by the Navy Earth System Prediction Capability (U.S. DoD Program Element 0603207N).

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