Foreword

The accuracy of modern weather forecasting systems continues to improve; accurate forecasts of mid-latitude storms and tropical cyclones up to 7 days ahead are now common. Key contributions to this achievement are the advances made in data assimilation, coupled with increased computer power, better weather prediction systems, and more extensive observing systems. Experiments with reanalyses have shown that data assimilation systems (and the improved forecast models they use for the first guess) are a primary source of the improved forecast accuracy.

Data assimilation systems continue to evolve, and they are being used in a wider variety of contexts. This symposium on data assimilation, organised under the auspices of the WMO World Weather Research Programme (WWRP), aimed to bring together the world experts to review progress and define the state of the art. It also attracted many young scientists to learn more about the science of data assimilation, an important investment for the future of this subject. Data assimilation techniques are now used for a range of geophysical state estimation problems (e.g. land surface, ocean, atmospheric constituents) and are applied to the atmosphere on scales from global to convective. Coupling between the state components (e.g. ocean and atmosphere) has also become an important area of research.

WMO-sponsored Symposia on Data Assimilation have been held previously in Clermont-Ferrand, France in 1990, followed by Tokyo, Japan (1995), Quebec City, Canada (1999), Prague, Czech Republic (2005), Melbourne, Australia (2009) and now Washington DC, USA (2013). They have showcased the latest developments and provided a forum for discussing the key issues to be addressed in the next few years. About 300 attended this meeting in spite of the coincident United States government shutdown. There were 74 oral presentations and 227 posters displayed. The presentations at this meeting showed that despite the rapid improvement in assimilation systems, further development is still needed to bridge the gap between current and desired levels of performance. The variety of presentations on new techniques, novel combinations of established techniques, and enhanced use of existing and planned observing systems highlights the dynamism within data assimilation theory and application.

The symposium was divided into several themes, listed below, and the main conclusions and issues for each theme are briefly summarized here. These were taken from the plenary session on the final day of the symposium. More details on the themes are given in the papers submitted to this special issue.

Methodology

A variety of methods were discussed in this session. Operational system development has primarily been oriented around advanced methods that work efficiently on massively parallel computers: this will be imperative given expected computer developments. A range of advanced algorithms were presented, including weak-constraint 4D-Var, 4D-Ensemble-Var, and Ensemble Kalman Filters (EnKF). There was no consensus on the best approach, but at this symposium there was more emphasis on the development of ensemble data assimilation methods and hybrid methods than on the traditional 4D-variational methodology, which has dominated over the past decade. At least one operational centre is moving away from 4D-Var to a 4D hybrid ensemble Var system. Methods such as iterated EnKFs and particle-filter approaches are being examined as possible methods that could be applied to future systems.

Assimilation of Atmospheric Constituents
This is a growing area of activity, with several atmospheric models incorporating chemical and aerosol capabilities. The assimilation of aerosol optical depth products (at 0.55μm wavelength) using MODIS measurements is now operational at several NWP centres. Assimilation of satellite ozone concentration measurements in atmospheric models continues to be an area of research. There is concern over the lack of continuity of limb sounders for stratospheric composition measurements in the future.

Atmospheric Data Assimilation
For this symposium there were fewer talks comparing EnKF with 4D-Var but more on investigating which combination of ensemble and variational methods worked best. ECMWF are planning to work on hybrid, long-window, weak-constraint 4D-Var ensembles and appear to have solved their scalability issues. Environment Canada is retiring 4D-Var in favour of a 4D hybrid ensemble Var system. There was an increasing emphasis on convective scale models, where the EnKF methodology is mainly being pursued.

Reanalyses
There are continuing efforts at several centres in maintaining and improving atmospheric and ocean reanalyses, many applying EnKF techniques that produce ensembles of analyses. These reanalyses are increasingly important for climate services and for reforecast initialization (reforecasts are used to facilitate statistical post-processing). The Japanese 55-year reanalysis was just completed. The US/NOAA EnKF-based 20^{th}-Century reanalysis (actually from 1850 onward) is now available; this data set uses only surface pressure observations. ECMWF has continued running "ERA-Interim" with future reanalyses planned. There are also several regional reanalyses activities underway, but no results were presented in the oral sessions.

Convective Scale Data Assimilation
All methods developed for global models are being applied to the convective scale data assimilation (i.e. 4D-Var, EnKF and hybrid schemes) down to 1 km. Due to the small, quickly evolving processes that are now resolved in many numerical models, data assimilation systems have to estimate the model state down to much smaller scales of motion. Analysis accuracy at the convective scales may be able to be improved by incorporating methods that permit non-Gaussian background-error statistics which are much more common due to more rapid relative onset of nonlinear processes at the smaller scales. Also, when dealing with smaller-scale features, involving for example clouds or precipitation, displacement errors play an important role. Initialization procedures that ameliorate the "spin-up" problem are of particular interest to convective scales and the short-term forecast problem. Balance constraints (hydrostatic or geostrophic) may be inappropriate to include in the construction of the background-error covariance at convective scales. There is also work on assimilating many new novel observation types (e.g. radar reflectivity) in rapid update mode (sub-hourly). Multi-scale data assimilation and verification is an area being investigated

taking into account predictability. This topic is receiving increasing attention as convective scale models are increasingly an important operational tool for nowcasting to short range (~48 hrs) local area forecasts.

Ocean Data Assimilation

Ocean data assimilation presents some different challenges, including a comparative paucity of data and a system that includes very slow-timescale dynamics (El Nino-Southern Oscillation) and much faster dynamics (eddies along boundary currents). Several ocean reanalyses are now being produced or developed, including both weakly coupled (background ocean and atmospheric states from a coupled model, with separate ocean and atmospheric analyses) and strongly coupled (joint state estimations, with cross-covariances accounted for).

Land-surface Data Assimilation

Several new satellite missions dedicated to land surface measurements have been launched and are providing useful measurements, and more are planned. Soil moisture analysis uses satellite data and/or in situ SYNOP observations of screen-level parameters. It is done regularly in support of operational weather and climate prediction systems and has improved the representation of near-surface temperatures. Measurements of fractional snow cover and in-situ snow depth are also being assimilated in many operational centres. Skin temperature from satellite measurements over land is a more challenging variable to assimilate, but efforts are now underway at several centres to achieve this. Finally, as with the ocean, data assimilation systems with enhanced coupling between the land surface and the atmosphere are being investigated.

Coupled Data Assimilation

There is an increasing trend towards assimilation of observations in coupled systems. Many talks and posters at this symposium demonstrated weakly coupled models and assimilation systems and their benefits. Strong coupling (e.g. simultaneous cycled assimilation and forecasting of ozone concentrations and the upper stratospheric temperatures) is more challenging and not always beneficial in current systems. The applicability and accuracy of the estimates of cross-covariances between the atmosphere and land/ocean for coupled data assimilation is an area of active investigation.

Assimilation of Satellite, In-situ and Radar Observations

Several studies showed improved estimation of the initial state and improved regional-scale forecasts using the EnKF to assimilate radar reflectivity. The use of improved satellite-derived Atmospheric Motion Vectors is increasing resulting in higher impacts at some centres. Exploiting the data from the advanced infrared sounders is becoming more sophisticated. It has been shown that it is important to allow for the cross-correlation between channels especially for low noise instruments such as the new high-resolution infrared sounder, CrIS, on the Suomi-NPP satellite.

Data Assimilation Diagnostics

Understanding the impact of observations on the analyses and forecasts continues to be an important area of research and a useful diagnostic of the data assimilation system. The traditional Observing System Experiment where data are denied or added to a baseline system continues to have merit, especially for the longer forecast ranges.

The forecast sensitivity to observations (FSO) tool is providing useful information for the short-range impacts. The applicability of Observing System Simulation Experiments (OSSEs) was also discussed, whereby a nature run of a forecast model (usually different from the assimilating model) is used to create a synthetic true state, and then simulated new and existing observations are generated from the synthetic true state, assimilated, and assimilation and forecast accuracy against the synthetic truth is assessed. There are also objective diagnostics for tuning observation errors and spatial/inter-channel correlations. Similarly, diagnostics for tuning covariance localization and optimal/adaptive ensemble inflation for EnKFs have been developed.

All the abstracts, slides and, for most sessions, webinar recordings from the symposium are available on the symposium web site at: http://das6.cscamm.umd.edu/. This is a valuable resource for the data assimilation research community.

The next data assimilation symposium will be planned for 2017. In the interim, the WWRP-sponsored Data Assimilation and Observing Systems working group will continue to review global progress in data assimilation and observations at its annual meetings.

Finally we would like to take this opportunity to thank the local organizing committee, led by Daryl Kleist and Kayo Ide, who (because of the US government shutdown) had to relocate the symposium at short notice from NCEP to the University of Maryland and cope with many last-minute changes to the programme.

International Scientific Organizing Committee.
Roger Saunders and Tom Hamill (co-chairs)
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