RMetS special interest group meeting: high resolution data assimilation

Article

Accepted Version

Browne, P. A., Charlton-Perez, C. and Dance, S. L. (2014) RMetS special interest group meeting: high resolution data assimilation. Atmospheric Science Letters, 15 (4). pp. 354-357. ISSN 1530-261X doi: https://doi.org/10.1002/asl2.512 Available at http://centaur.reading.ac.uk/37056/

RMetS Special Interest Group Meeting: High resolution data assimilation

PA Browne[1,*], C Charlton-Perez[2], and SL Dance[1]

[1]School of Mathematical and Physical Sciences, University of Reading, Reading. RG6 6BB United Kingdom
[2]MetOffice@Reading, Meteorology Building, University of Reading, Reading. RG6 7BE United Kingdom
[*]Correspondence to p.browne@reading.ac.uk

Friday 19 April 2013

Data assimilation (DA) systems are evolving to meet the demands of convection-permitting models in the field of weather forecasting. A special interest group meeting of the Royal Meteorological Society brought together UK researchers looking at different aspects of the data assimilation problem at high resolution, from theory to applications, and researchers creating our future high resolution observational networks. The meeting was chaired by Dr Sarah Dance of the University of Reading and Dr Cristina Charlton-Perez from the MetOffice@Reading.

The purpose of the meeting was to help define the current state of high resolution data assimilation in the UK. The workshop assembled three main types of scientist: observational network specialists, operational numerical weather prediction researchers and those developing the fundamental mathematical theory behind data assimilation and the underlying models. These three working areas are intrinsically linked; therefore, a holistic view must be taken when discussing the potential to make advances in high resolution data assimilation.

1 Background

In 2003, a workshop was convened to assess the feasibility of a mesoscale nowcasting system [Dabberdt et al., 2005]. At that meeting the scientific challenges facing high resolution precipitation forecasting were identified as improving the simulation of convective processes within numerical models, improving knowledge of convective downdrafts and gusts from individual storms and improving the understanding of the initialisation of convection [Wilson and Roberts, 2006]. On the lack of high resolution three-dimensional observations of state variables above the boundary layer, they noted there was “currently no observational capability to fill this gap” [Dabberdt et al., 2005].

Around the same time, review articles were released summarising the state of high resolution DA [Dance, 2004; Sun, 2005; Park and Županski, 2003]. In all references the main problem addressed is the forecasting of precipitation at fine space and time discretisations.

2 Current state of data assimilation and forecasting at high resolutions

At the present time, pressing issues with DA methods related to both the high spatial and time resolution in the forecasting system are no longer limited to precipitation forecasting. Issues discussed at this meeting could be grouped into the following themes:

- lateral boundary conditions for nested models,
- nonlinearity of the models,
- scale disparities,
- background, model and observational errors and
- computational demands of DA at scales relevant to precipitation forecasting.

Ad hoc networks of devices such as smart phones and vehicles have exploded in size and functionality. These networks are currently being considered for their feasibility to provide information to assimilate into meteorological models [Mahoney and O’Sullivan, 2013]. These networks have the potential to provide surface measurements at the resolutions required by future high resolution data assimilation systems, however they will still lack the three-dimensional structure desired to fill the aforementioned observation gap.

Numerical weather prediction has benefited greatly from an increase in available computational power. This has allowed the models to grow rapidly in complexity and resolution, producing much more realistic simulations. Likewise the number, type and quality of observations have increased, thanks to the expansion of radar networks and increases in the number and quality of satellite data products. However, the data assimilation techniques to combine these two areas of science in order to initialise a forecast are not yet capable of utilising all the modern advances in modelling and observation. As an example, only around 5% of scatterometer data are assimilated into both global and limited area models at the MetOffice, whereas in the global model only 24% of AMDARS data is assimilated which increases to 68% in the high resolution model [personal communication, MetOffice]. The reasons for the number of observations utilised in models of different resolution are complicated and vary greatly by observation type. In some cases it is due to the resolution of the observations, their temporal and physical spacing or the quality control procedures used. Hence impact studies of potential new observations are proving necessary to quantify the benefits of additions to observing networks [Eyre and Weston, 2013; Simonin et al., 2013a].

In the summer of 2012 during the London Olympic Games, the MetOffice demonstrated its numerical weather prediction (NWP) based nowcasting system using 4D-Var [Golding et al., 2013; Simonin et al., 2013b]. Nowcasts are very short-range, high resolution forecasts used to give a prompt, quantitative forecast of hazardous weather and precipitation. This was an advance on previous nowcasting systems which used extrapolation and heuristic techniques, and is described in Sun et al. [2013].

3 Scientific presentations

Dr Ali Rudd of the University of Reading began the presentations by talking on the subject of model errors in high resolution, hence convection-permitting, numerical weather prediction models. A random parameter perturbed physics scheme has been used to represent the uncertainties due to model error in a convective-scale research ensemble prediction system (1.5km-EPS). As a test case, they used a DIAMET [DIAMET, 2013] flight campaign case, during which measurements were made of a frontal wave with structures not captured by the Met Office UKV (1.5km) operational model forecast or the 1.5km-EPS control forecast. The random parameters scheme had the effect of changing the spread of the ensemble, but did not improve the forecast skill in capturing the banding observed (by radar) in the rainfall [Baker et al., 2014]. It is vital to understand these changes in ensemble spread in order to tune an ensemble data assimilation system such as the ensemble transform Kalman filter that was used.

Prof Rob Scheichl of the University of Bath spoke on multilevel approaches from numerical analysis which show great potential in the next generation of data assimilation applications. These included geometric multigrid methods for the fast solution of a linear system [Buckeridge and Scheichl, 2010] where the matrix in question is the background error covariance matrix from variational data assimilation. Techniques from multilevel methods for the efficient solution of stochastic PDEs were presented [Teckentrup et al., 2013] because they promise to improve the efficiency of particle filters.

Prof Slobodan Djordjevic of the University of Exeter spoke on high resolution modelling of urban flooding events [Chen et al., 2012a,b]. With satellite imagery used to generate a topological network of the area in question, a multi-layered approach to calculation of flood extents was shown to be close to a much more computationally expensive high resolution model. Case studies shown included flooding events on the Isle of Wight and in Dhaka, Bangladesh. These computational techniques can be used to inform drainage system re-design, emergency flooding evacuation plans and the health impacts of pollution. The feasibility of creating a real-time flood warning system in which satellite and in-situ observations would be assimilated into such models was discussed.

Dr Lee Hawkness-Smith from the MetOffice@Reading Data Assimilation Group presented work on the assimilation of radar reflectivity in high resolution numerical weather prediction [Hawkness-Smith and Ballard, 2013]. Reflectivities were assimilated using 4D-Var into the Met Office Nowcasting Demonstration Project model, an NWP-based nowcasting research system.

Dr John Lees-Miller of the University of Bristol spoke on extracting information from wireless networks for traffic modelling [Lees-Miller et al., 2013]. Making use of Bluetooth devices found in mobile phones and those increasingly built into motor vehicles, observations of traffic densities and speeds were used to build a hidden Markov model for traffic flow. These novel observations brought with them a number of challenges, including privacy considerations, missed detections and difficulties in discerning what is being measured; for example, is the device which is detected actually in a car or on a bicycle? One application of the model is measuring whether traffic policy changes have made an impact on the dynamics of the road network. The use of such observations as described by Dr Lees-Miller shows promise as a way in which to provide high resolution surface observations for use in NWP models.

Dr Barbara Brooks from the University of Leeds was the final speaker of the meeting and presented work on improving NWP forecasts by the use of remotely controlled aircraft measurements [Jonassen et al., 2012]. Unmanned aerial systems (UASs) are being developed to reduce costs and increase both spatial and temporal resolution of the observation network in areas that are currently under-observed. The main application of a particular UAS was to act as a reusable radiosonde. A range of available UASs was described in order to highlight the wide range of measurements that can be made using these modern, reusable devices.

4 Discussion

A well-attended discussion session followed the presentations to consider the future of high resolution data assimilation. Techniques to adaptively improve the representation of background error covariances are already being employed in high resolution DA systems [Piccolo and Cullen, 2012; Browne et al., 2014]. These methods go some way to addressing scale disparities in nested models, particularly those disparities which can impact the simulation of boundary layer dynamics. However, it was generally agreed that due to the nested nature of high resolution meteorological data assimilation systems, a considerable amount of the larger forecast errors on the high resolution grid come from large-scale or synoptic uncertainties. During the discussion, a number of open research questions emerged as the most pressing to be considered:

- Errors in the boundary conditions for the high resolution model exist due to intrinsic errors in the synoptic scale model and to the process of taking the coarse data down to a fine scale. Should the high resolution data assimilation system be tailored to incorporate these uncertainties in the boundary conditions?

- A recent study [Baxter et al., 2011] has shown that large scale meteorological features may not be sufficiently well represented in a limited area domain, thus posing difficulties for DA in the smaller domain. What scales should one analyse in high resolution DA (just the small scale or also the large scales)?

- In a future where NWP uses correlated observation errors, how do the scales implicit in the background and observation error correlations interact?

The future of observational networks were discussed, specifically the networks which are not being designed or run specifically for meteorological applications. For example, important meteorological data is being extracted from existing networks such as AMDAR [AMDAR, 2013] and mode-S data [de Haan, 2011; de Haan and Stoffelen, 2012; Strajnar, 2012] from air traffic, humidity measurements from global positioning systems [de Haan, 2013] and road traffic data [Mahoney and O'Sullivan, 2013]. Increasingly, cheap sensors found in mobile phones are being adapted for use in all kinds of observational networks. If such sensors prove to be the most important part of a meteorological observational network then the agencies which rely on them will come under increasing pressure to control them in order to have confidence in their resilience.

- How will operational centres ensure the security of new ad-hoc networks of observations?

Making full use of all of the available meteorological observations will still be limited by the amount of computational power available to operational centres. In the next generation of data assimilation systems more value may be gained by incorporating information such as error structures in observations [Stewart et al., 2008, 2013b; Weston, 2011; Stewart et al., 2013a; Bormann and Bauer, 2010] instead of simply increasing the number of observations.

- What gains could be made in forecasting by including observational error structures in the data assimilation process compared with simply increasing the number of observations?

In order to seek the greatest improvement of forecast skill in all applications of atmospheric science, data assimilation must be heavily invested in. Only in doing so will the gap between modern models of atmospheric dynamics and high resolution observations be bridged in a rigorous way. Whilst the use of development systems or *test-beds* were strongly encouraged a decade ago [Dabberdt et al., 2005], the ability for researchers to test their advances using operational systems and access any impact of new types of observations remains rather limited. Systems like the Data Assimilation Research Testbed (DART) [Anderson et al., 2009], OpenDA [OpenDA, 2013] and the Parallel Data Assimilation

Framework (PDAF) [Nerger and Hiller, 2012] have the ability to test well developed DA methods on new models in various areas of science, but they do not easily lend themselves to testing novel DA methods with operational atmospheric science models. Adoption of functionality such as EMPIRE [Browne and Wilson, 2014] in operational forecast models would allow rapid testing and prototyping of academic concepts and theories in the most realistic settings.

The need for a flexible data assimilation system that can be accessed by researchers in academia and industry who are not in the operational centres remains an imperative goal that if created will benefit the whole atmospheric science community.

References

AMDAR (2013). The World Meterological Organisation Aircraft Meteorological DAta Relay Observing System. http://www.wmo.int/pages/prog/www/GOS/ABO/AMDAR/.

Anderson, J., Hoar, T., Raeder, K., Liu, H., Collins, N., Torn, R., and Avellano, A. (2009). The Data Assimilation Research Testbed: A Community Facility. *Bulletin of the American Meteorological Society*, 90(9):1283–1296.

Baker, L. H., Rudd, a. C., Migliorini, S., and Bannister, R. N. (2014). Representation of model error in a convective-scale ensemble prediction system. *Nonlinear Processes in Geophysics*, 21(1):19–39.

Baxter, G., Dance, S., Lawless, A., and Nichols, N. (2011). Four-dimensional variational data assimilation for high resolution nested models. *Computers & Fluids*, 46(1):137–141.

Bormann, N. and Bauer, P. (2010). Estimates of spatial and interchannel observation-error characteristics for current sounder radiances for numerical weather prediction. I: Methods and application to ATOVS data. *Quarterly Journal of the Royal Meteorological Society*, 136(649):1036–1050.

Browne, P., Budd, C., Piccolo, C., and Cullen, M. (2014). Fast three dimensional r-adaptive mesh redistribution. *Journal of Computational Physics*. Under Review.

Browne, P. and Wilson, S. (2014). A simple framework for integrating a complex model into an ensemble data assimilation system using MPI. *Environmental Modelling and Software*. Under Review.

Buckeridge, S. and Scheichl, R. (2010). Parallel geometric multigrid for global weather prediction. *Numerical Linear Algebra with Applications*, 17:325–342.

Chen, A. S., Evans, B., Djordjević, S., and Savić, D. a. (2012a). A coarse-grid approach to representing building blockage effects in 2D urban flood modelling. *Journal of Hydrology*, 426-427:1–16.

Chen, A. S., Evans, B., Djordjević, S., and Savić, D. a. (2012b). Multi-layered coarse grid modelling in 2D urban flood simulations. *Journal of Hydrology*, 470-471:1–11.

Dabberdt, W. F., Schlatter, T. W., Carr, F. H., Joe Friday, E. W., Jorgensen, D., Koch, S., Pirone, M., Ralph, F. M., Sun, J., Welsh, P., Wilson, J. W., and Zou, X. (2005). Multifunctional Mesoscale Observing Networks. *Bulletin of the American Meteorological Society*, 86(7):961–982.

Dance, S. (2004). Issues in high resolution limited area data assimilation for quantitative precipitation forecasting. *Physica D: Nonlinear Phenomena*, 196(1-2):1–27.

de Haan, S. (2011). High-resolution wind and temperature observations from aircraft tracked by Mode-S air traffic control radar. *Journal of Geophysical Research*, 116(D10):D10111.

de Haan, S. (2013). Assimilation of GNSS ZTD and radar radial velocity for the benefit of very-short-range regional weather forecasts. *Quarterly Journal of the Royal Meteorological Society*.

de Haan, S. and Stoffelen, A. (2012). Assimilation of High-Resolution Mode-S Wind and Temperature Observations in a Regional NWP Model for Nowcasting Applications. *Weather and Forecasting*, 27(4):918–937.

DIAMET (2013). DIAbatic influences on Mesoscale structures in ExTratropical storms. http://www.ncas.ac.uk/index.php/en/diamet-introduction.

Eyre, J. and Weston, P. (2013). The impact of the temporal spacing of observations on analysis errors. Technical Report 573, Met Office Forecasting Research.

Golding, B. W., Ballard, S. P., Mylne, K., Roberts, N., Saulter, A., Wilson, C., Agnew, P., andJ. Trice, L. S. D., Jones, C., Simonin, D., Li, Z., Pierce, C., Bennett, A., Weeks, M., and Moseley, S. (2013). Forecasting capabilities for the London 2012 Olympics. *Bulletin of the American Meteorological Society*. Under review.

Hawkness-Smith, L. D. and Ballard, S. P. (2013). Assimilation of radar reflectivity data in the Met Office convective-scale forecast system. In *36th Conference on Radar Meteorology*, Breckenridge, CO, USA. American Meteorological Society.

Jonassen, M. O., Ólafsson, H., Ágústsson, H., Rögnvaldsson, O., and Reuder, J. (2012). Improving High-Resolution Numerical Weather Simulations by Assimilating Data from an Unmanned Aerial System. *Monthly Weather Review*, 140(11):3734–3756.

Lees-Miller, J. D., Wilson, R. E., and Box, S. (2013). Hidden Markov Models for Vehicle Tracking with Bluetooth. In *TRB 92nd Annual Meeting Compendium of Papers*.

Mahoney, W. P. and O'Sullivan, J. M. (2013). Realizing the Potential of Vehicle-Based Observations. *Bulletin of the American Meteorological Society*, 94(7):1007–1018.

Nerger, L. and Hiller, W. (2012). Software for ensemble-based data assimilation systems - Implementation strategies and scalability. *Computers & Geosciences*, 55:110–118.

OpenDA (2013). The OpenDA data-assimilation toolbox. http://www.openda.org.

Park, S. K. and Županski, D. (2003). Four-dimensional variational data assimilation for mesoscale and storm-scale applications. *Meteorology and Atmospheric Physics*, 82(1-4):173–208.

Piccolo, C. and Cullen, M. (2012). A new implementation of the adaptive mesh transform in the Met Office 3D-Var System. *Quarterly Journal of the Royal Meteorological Society*, 138(667):1560–1570.

Simonin, D., Ballard, S., and Li, Z. (2013a). Convective-scale Doppler radar radial wind assimilation using a 1.5km resolution version of the Met Office Unified Model and 3D-Variational Data Assimilation System for Nowcasting. *Quarterly Journal of the Royal Meteorological Society*. Under review.

Simonin, D., Li, Z., Ballard, S., and Caron, J.-F. (2013b). Performance of 4DVar NWP-based Nowcasting at the Met Office for Summer 2012. *Quarterly Journal of the Royal Meteorological Society*. In preparation.

Stewart, L. M., Dance, S. L., and Nichols, N. K. (2008). Correlated observation errors in data assimilation. *International Journal for Numerical Methods in Fluids*, 56(8):1521–1527.

Stewart, L. M., Dance, S. L., and Nichols, N. K. (2013a). Data assimilation with correlated observation errors : experiments with a 1-D shallow water model. *Tellus A*, 65:1–14.

Stewart, L. M., Dance, S. L., Nichols, N. K., Eyre, J. R., and Cameron, J. (2013b). Estimating interchannel observation-error correlations for IASI radiance data in the Met Office system. *Quarterly Journal of the Royal Meteorological Society*.

Strajnar, B. (2012). Validation of Mode-S Meteorological Routine Air Report aircraft observations. *Journal of Geophysical Research*, 117(D23):D23110.

Sun, J. (2005). Convective-scale assimilation of radar data: Progress and challenges. *Quarterly Journal of the Royal Meteorological Society*, 131(613):3439–3463.

Sun, J., Xue, M., Wilson, J. W., Zawadzki, I., Ballard, S. P., Onvlee-Hooimeyer, J., Joe, P., Barker, D., Li, P.-W., Golding, B., Xu, M., and Pinto, J. (2013). Use of NWP for Nowcasting Convective Precipitation: Recent Progress and Challenges. *Bulletin of the American Meteorological Society*.

Teckentrup, A. L., Scheichl, R., Giles, M. B., and Ullmann, E. (2013). Further analysis of multilevel Monte Carlo methods for elliptic PDEs with random coefficients. *Numerische Mathematik*, pages 24–29.

Weston, P. (2011). Progress towards the Implementation of Correlated Observation Errors in 4D-Var. Technical Report 560, Met Office Forecasting.

Wilson, J. W. and Roberts, R. D. (2006). Summary of Convective Storm Initiation and Evolution during IHOP : Observational and Modeling Perspective. *Monthly Weather Review*, 134:23–47.