Summary of Ljubljana workshop on “Mesoscale data assimilation and the role of winds in limited-area models for NWP in Europe”

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1 Background

Over the past two decades, limited area models (LAMs) for numerical weather prediction (NWP) have become operational in practically every country across Europe. Clustered around the four major development centres: the UK MetOffice, Meteo-France, Deutsche Wetterdienst and the HIRLAM group, the European LAMs initially focused mainly on the downscaling of global analyses and forecasts produced by their own global NWP systems or by the ECMWF. In the new millennium, developments have become better focused on advanced methods for mesoscale data assimilation (DA), first using the 3D-Var, followed by the 4D-Var, the ensemble Kalman filter and, most recently, hybrid methods. Over the same period, the ECMWF model and other global models have steadily increased their horizontal grids that are now approaching 10 km.

Mesoscale data assimilation (MDA) is expected to provide initial conditions for km-scale forecasts that outperform the global model forecasts on the short range (few hours to 1-day). In this range of spatio-temporal scales, MDA affects processes with timescales of hours in contrast to the processes with timescales of days addressed by global models. A lack of frequent and accurate high-resolution observations, especially wind observations, makes the challenge of MDA only greater.

The workshop on “Wind profiles and mesoscale data assimilation” at the Faculty of mathematics and physics, University of Ljubljana, addressed the potential impact of the forthcoming wind profile measurements by the ESA’s ADM-Aeolus satellite in mesoscale models. The participants discussed the modelling of the background-error covariances for MDA in a couple of presentations based on hybrid MDA methods. Sensitivity studies with several new wind observations (e.g. Mode-S) showed mixed results in spite of the observation high quality. The potential of the line-of-sight ADM-Aeolus measurements in mesoscale observing system simulation experiments (OSSE) suggested that improvements in the analysis of the amplitude and location of the baroclinic development in the northern Atlantic will be possible thanks to the ADM-Aeolus wind profiles. The workshop presentations are available at http://meteo.fmf.uni-lj.si/en/workshop.

In the following, we summarize the workshop discussion of challenges and recommendations for further research in the mesoscale NWP and DA communities.

2 Challenges in mesoscale NWP modelling

Representation of mesoscale dynamics

Observations and numerical model simulations provide increasing evidence that at scales around 500 km atmospheric dynamics becomes predominantly unbalanced, i.e., that the divergent component of circulation becomes comparable to the rotational component. In other words, flow variability is produced to a larger extent by the internal inertio-gravity and gravity waves than by the Rossby waves. Consequently, the energy spectrum becomes shallower (changing from a slope of -3 to -5/3). So far, the mesoscale NWP models have not been applying the criterion of a -5/3 slope of the energy spectrum as a strong constraint in their model validation.

A recent decomposition of the mesoscale energy spectra in the ALADIN model into rotational and divergent components showed that divergent energy, used as a synonym for inertio-gravity waves in the mid-latitudes, comprises about 50% of kinetic energy in the free troposphere [1]. In the stratosphere this percentage increases and the energy spectra become shallower. A similar shallowing of the spectra takes place close to the surface in relation to the strong orography forcing. In the free troposphere, the slope of the kinetic energy spectrum in mesoscale NWP models may significantly deviate from the expected -5/3. Furthermore, some methods for the computation of spectra in limited-area domains produce somewhat biased slopes at the shortest range of scales [2]. Several studies also showed that the slope can be greatly altered by the applied numerical diffusion [3].

Research practice in NWP is to tune mesoscale NWP models to produce optimal forecasts regardless of the slope of the spectrum. An established efficient method to smooth apparently noisy forecasts is the horizontal diffusion [3]. The spatial characteristics of LAMs can be verified by covariance methods on collocated model and observation fields [4].

An inter-comparison exercise with the European operational mesoscale NWP models regarding their ability to produce the -5/3 spectrum would help address this issue in a systematic manner.

Lateral boundary conditions and scale interactions

The need for a large domain for mesoscale models has been well recognized in the NWP community. At the same time, domains applied in practice are a compromise between the applied grid density and available computer resources to frequently provide updated forecasts in real time. The grid issue is usually considered only with regard to the horizontal. Thus, the mesoscale NWP models applied in Europe may have a smaller number of vertical levels in the troposphere than the ECMWF model.

Some domain dimensions, currently used with a horizontal grid distance of around 2 km, are such that the impact of lateral boundaries (LBs) reaches the centre of the domain within 24 hours, especially in the upper troposphere. Traditionally, the forecast-error growth in mesoscale models focused on the growth of errors in small scales and their upscale cascades. However, it is now understood that the errors grow from the start of the forecast on all scales [5]. Furthermore, there is also a downscale cascade of the initial-state error from the synoptic scales to smaller scales [6]. The errors cascading downscale and the errors growing in the small scales interact from the start of the forecast across all scales represented by a mesoscale model.

We consider it crucial to push for a more intense research on the scale-dependent growth of forecast errors in a mesoscale model and the interaction with the errors in LBs, especially on larger meso scales.

3 Mesoscale data assimilation

Identification of the forecast errors

It is recognized that spatio-temporal error structures that are only partially observed may cause rather artificial analysis updates (in the engineering community commonly referred to as aliasing) [7]. Should thus MDA be restricted to analyse only those spatial and temporal scales that are well resolved by the density of the observation network? Does this imply that due to lack of frequent high-resolution observations background error covariances with broad structure functions should be employed, relying on the model itself to constrain the small scales accordingly?

Structure functions produced by the ensembles of high-resolution simulations are characterized by sharp spatial gradients [8]. However, can we rely on the ability of currently applied ensemble generation techniques to realistically simulate processes with a short length of life (order of an hour)? Are the currently applied hybrid ensemble methods and/or methods copied from the global NWP model (perturbed observations) capable to realistically simulate flow-dependent forecast errors on scales around 10 km? What information on error propagation do we get from ensemble simulations?

Are these simulations at short forecast ranges affected by artifacts of ensemble generation approaches and do they to a large extent reflect the adjustment processes or are they provoked by noise and imbalances?

Provided that the mesoscale ensemble reliably simulates the errors of the hour, should the small scales be treated only using the error covariances? What are the small scales? One idea is that this can be defined as the scale where the energy spectrum has a slope -5/3 reflecting divergence-dominated dynamics.

It is well known that surface conditions play an important role in initializing convection. Presuming that processes driven by orography have increased predictability, should the lower troposphere be the focus of MDA? Or, are the errors in the free atmosphere more relevant (e.g. deep convection, large-scale errors in initial and lateral boundaries)?

A lack of wind observations

Basic understanding of the coupling between the mass and the wind field in the NWP models is based on the adjustment process as first discussed by C.G. Rossby almost 80 years ago. It suggests that for the initialization of mesoscale processes we need wind observations more strongly than the observations of mass variables. Although this argument originally applied to dynamical processes involving no changes of the phase of water, it has successfully served the NWP community over several decades. The same argument has also been successfully employed to argue about a significant benefit of the profiles of line-of-sight winds from the ADM-Aeolus mission [9]. It was shown that wind profile observations distributed in space and time are needed especially in the tropics and on the mesoscale.

At the same time, recent results from DA studies with scatterometer data and aircraft data of types Mode-S and GADS agree that adding new wind observations is a challenging task [10,11,12,13]. In spite of relatively small estimated observation errors, the impact of new observations is quickly lost in forecasts. One clear reason is model bias. Observational information is lost within a couple of hours when the model returns to its biased climatology. Other reasons remain poorly understood and they may be related to the impact of the applied background-error covariances in relation to the mesoscale model (im)balance and model dynamics, including the errors in synoptic scales in the initial state as well as in LB fields. In any case, we can question if DA, which corrects the errors of the hour, is expected to produce improved forecasts for longer than a few hours? Is an initial three-hour long improvement in the convection forecast what the MDA can at most achieve with respect to global NWP models due to the predictability of these scales? These questions may be addressed in OSSE-type experiments, taking into account the initial and LB errors on the synoptic scales.

Mesoscale data assimilation and balance issues

The basic question is whether the balance matters at the mesoscale, especially in hybrid ensemble DA methods? If balance in MDA does matter, what are the relevant balance constraints? Are analytically derived balances that describe climatology of short-term forecast errors at mesoscale still useful? How significant is the harm caused by the applied homogeneity and isotropy assumptions? The climatological balances are based on the hydrostatic approximation and produce hydrostatic DA increments. An open question is whether non-hydrostatic increments added during the DA step would improve the initialization of the model?

Following the spectrum of atmospheric energy, energy variance on the mesoscales is of the order of a couple of Joules per kg. In other words, the mesoscale analysis increments added in a DA step are energetically very small. Superposed on synoptic-scale features, they can be quickly lost for many reasons, even if they result from high-quality wind observations, as discussed above.

In spite of all progress in DA, transient features following moist adjustment are not well understood. In the ECMWF model global 4D-Var DA, significant wind increments are coming from the humidity observations and they lead to better short-range forecasts [14]. This however does not mean that the coupling between the moisture and winds in 4D-Var is well understood. Furthermore, when deep convection is not parametrized, natural question arises as to whether the hydrometeors, especially when assimilating radar data, should be updated in the analysis step or if this should be left to the microphysics scheme.

Mesoscale DA studies have shown that significant mesoscale forecast failures are related to a poorly initialized moisture field. Moreover, imposed structure functions are shown to degrade both moisture analysis and forecast quality if they poorly represent the actual situation, indicating the importance of flow-dependent balance relationships [11]. Analysis of the moisture is especially difficult due to Gaussian error assumptions of all data assimilation methods used operationally today. At present the ensemble techniques are used to carry on the evolution of flow-dependent uncertainty, advocating this approach by dispensing with expensive developments of tangent linear and adjoint simplified physics which is required for 4D-Var. The complication here is that the covariance inflation and the covariance localization, which are commonly applied in the ensemble techniques to allow for an affordable ensemble size, affect the coupling between the mass and wind fields in the model and its forecast errors. Even simple multiplicative inflation can affect enstrophy leading to even greater importance of wind observations in order to control it [15].

The coupling between the moisture and wind fields is considered crucial for the optimal initial state. With both fields poorly observed, idealized and OSSE studies of DA with simulated mesoscale observations may be a way to better understand the mesoscale balance issues and the need and prospects for the initialization of inertio-gravity waves in a saturated moist atmosphere.

4 Concluding remarks

In global models, OSSE experiments have usually been used to estimate the potential impact of new observing systems. In particular, the perfect-model OSSEs provides an understanding of dynamical and physical aspects free of the model error. The significant challenges in MDA listed in this summary suggest that controlled, OSSE type of experiments with mesoscale models can be useful for the quantification of the relative impact of the various issues discussed. Primarily, the implications of the evidently significant role of analysis uncertainties on larger scales and the short-range error growth on small scale NWP are yet to be quantified. Some inertio-gravity waves may be possible to initialize better in DA step by a multivariate approach. This and similar topics call for a stronger collaboration between the weather services and atmospheric science research at European universities.

5 References

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