SENSITIVITY APPROACH TO STUDY DOPPLER WIND LIDAR SAMPLING REQUIREMENTS FOR EXTREME WEATHER PREDICTION

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ABSTRACT

ESA is preparing to fly a space-borne Doppler wind lidar (DWL) in 2007 as part of the Atmospheric Dynamics Mission (ADM), called Aeolus (Ingmann, this issue). ADM will provide profiles of radial wind-component velocities, extending from the earth surface up to 25 km altitude at about 1 km vertical resolution. ADM is a demonstration mission with the focus on measurement quality rather than quantity. In an Observing System Simulation Experiment (OSSE) we demonstrated positive ADM impact on average, but the simulation period did not include extreme weather events with large forecast failures. So-called sensitivity computations can be used a posteriori to derive corrections to a meteorological analysis that prevent a forecast failure. These simulated analyses may be used as a basis to simulate DWL observations. Subsequent assimilation of these simulated DWL observations, together with all available real observations and the original background field may still result in forecast improvement, and as such indicative of the potential benefit of the new observing system. In order to provide useful results with such technique, it has to be ascertained that the sensitivity analysis error structures obtained are realistic, i.e., with the appropriate spatial scale, mass/wind balance, and amplitude. Even if realistic, the simulated structures should also checked to be consistent with all available real observations. Here we propose a methodology that potentially addresses these issues, and, after further testing, can be used to study DWL sampling requirements for extreme weather prediction.

1. INTRODUCTION

Many resources are spent on new observation types complementing the meteorological Global Observing System (GOS), or its Climate equivalent GCOS. The potential value of these observations for weather and climate analyses depends on:

1. the information content of the new observing system and its fundamental ability to complement the G(C)OS in describing the atmospheric circulation and mass field;
2. the ability of the (future) data assimilation system (DAS) to exploit this new information;

The first requirement is prime, the second could be a pitfall when testing the new observations in existing DASs. These are often not well tuned to exploit new data types, and extended trials are needed to test the consistency of the new data with the forecast model and analysis scheme characteristics.
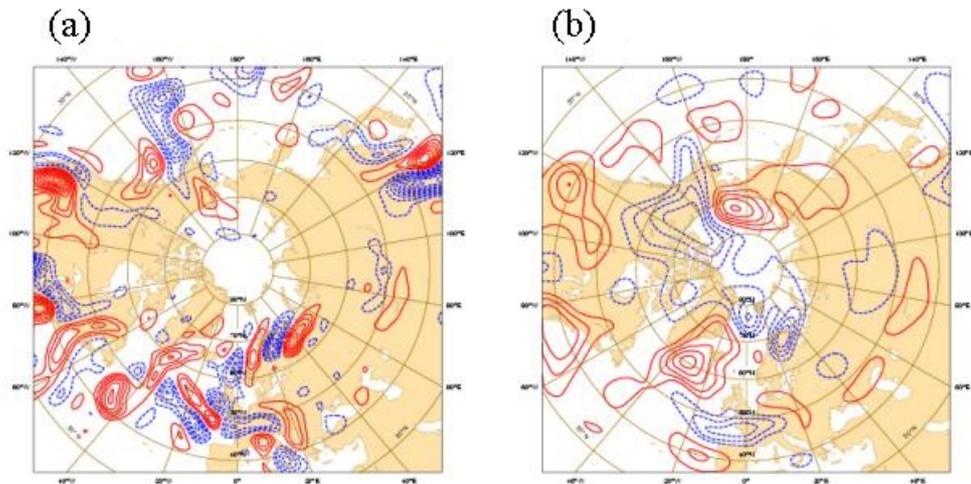
Figure 1. Sensitivity structures for temperature at 500 hPa that improve a 2-day ECMWF forecast. The norm for initial analysis change computation (see text) is either constrained by Total Energy (a) or by the B-matrix (b).

A greater consistency of observations and DAS is generally achieved in Observing System Experiments (OSE) or Observing System Simulation Experiments (OSSE), but for different reasons. The assimilation of existing observing systems is already tuned for beneficial analysis impact, whereas simulated (future) observing systems do often not fully capture the real observation error characteristics. However, OSSE calibration should guarantee the appropriate observing system impact (e.g., Marseille et al., 2000; Matsutani et al, 2004).

OSSE test the analysis and forecast impact of future and thus non-existing observing systems, whereas OSE test the impact of existing observing systems. OSE thus provide real impact of real observations in a given data assimilation system. The OSE are used to further test and improve the assimilation of certain data types, and to test the relevance of the different existing components of the GOS (WMO, 2004). Gaps in the GOS, for example the lack of wind profile data over the oceans, tropics, and Southern Hemisphere (SH), can be filled by new observing systems, like DWL. OSE cannot test the expected impact of such observations, since no existing observing system provides these data. OSE could for example be used to test the impact of existing wind profile observations over Northern Hemisphere land (Cress et al, 1999). Although indicative, it is however a priori not clear how exactly to extrapolate these results to the case of more uniform and complete wind profile coverage over the globe. To overcome this problem OSSE may be conducted, realistically simulating the atmosphere, all existing and newly expected observing systems, and thus assuring the appropriate sensitivity of the DAS to these different observation types (Marseille et al, 2000). It may be clear that OSSE require many human resources.

We investigate another and simpler methodology to infer the potential benefit of a DWL, and limit ourselves to cases of NWP forecast busts or failures. We aim at defining the observational requirements (quality and quantity) for a DWL to improve forecasts of extreme weather with focus on extreme events that were badly forecast operationally. To assess the added value of a DWL we generate synthetic wind profiles with a coverage that resembles possible future instrument designs and network scenarios. The main challenge remains in the combined NWP assimilation of real conventional observations and synthetic DWL observations. Strictly speaking, the simulation of synthetic lidar data requires the true atmospheric state but which is unknown. Alternatively, we use sensitivity structures to correct the (incorrect) forecast initial state and constrain that these structures do not conflict with conventional observations. Note that we inherently assume that the conventional observations do not provide the information to improve on the forecast initial state. This appears logical, since the observations were used to generate the failure, but should be tested.
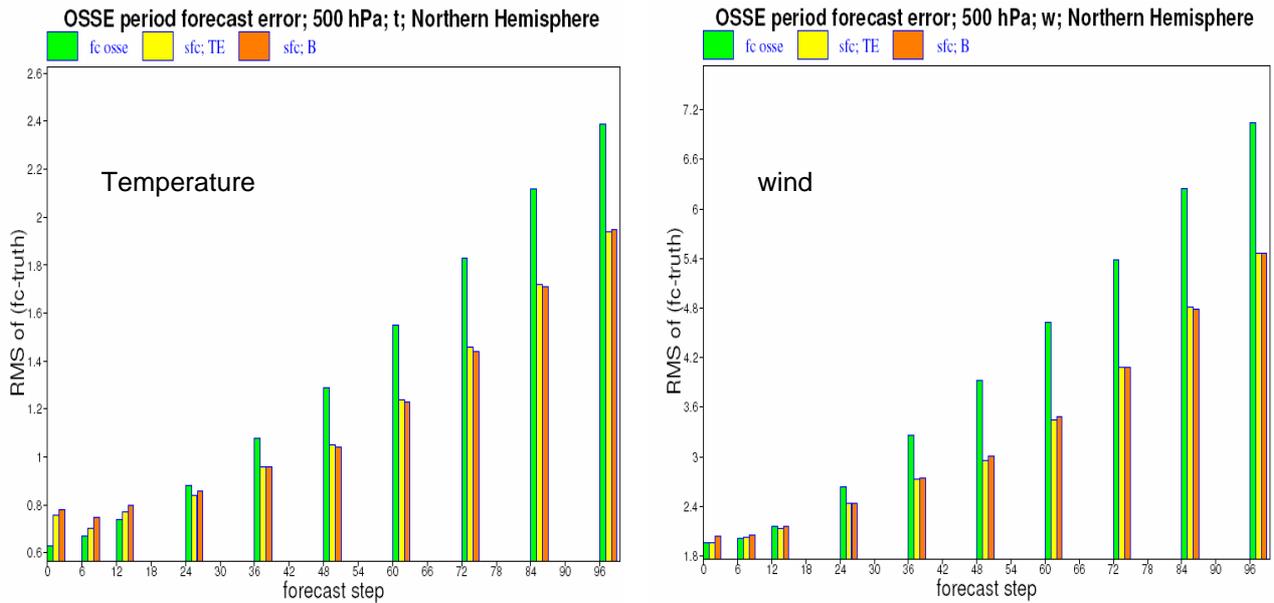
Figure 2. RMS error of OSSE fields (green), TE sensitivity fields (yellow, and B sensitivity fields (red), analysis and forecasts, versus forecast time in 6-hour steps. Left plot is for 500 hPa temperature, right for 500 hPa wind. Plots are for the OSSE period 5-15 Feb 1993.

Sensitivity computations are performed operationally at ECMWF as a diagnostic tool to trace back forecast errors to rapidly growing errors in the forecast initial state. We investigate the realism of these sensitive structures, based on both the total energy (TE) and background error covariance matrix (B) norm for the perturbations in the initial analysis (Barkmeijer et al, 1999), as depicted in Figure 1. Initially, we use the OSSE results that have the unique property of the true atmospheric state to be known, thus facilitating the interpretation of the tests. As such, the realism of the sensitivity structures and the methodology is first studied. We plan to sample these structures from space by DWL for a number of design and network scenarios and assess their potential to reduce forecast failures. The method could also be adopted for other observing systems, like, e.g., AMVs.

2.   SENSITIVITY STRUCTURES

The sensitivity structures displayed in Figure 1 show rather different spatial characteristics and amplitudes. The spatial characteristics and amplitudes, however, determine the required density of sampling (quantity) and required quality of the new observing system, respectively. Figure 2 shows TE and B-matrix norm analysis perturbations do reduce the 2-day forecast error by about 50%. The different TE and B structures give equal reduction in forecast error. However, the analysis perturbations do not reduce the analysis error, but rather amplify it, in particular for temperature (see also Isaksen, 2003). This may furthermore indicate that the perturbations are in conflict with the conventional observations, and, consequently, with synthetic DWL observations simulated from these perturbations. In next section we present a method to circumvent such conflicts. Overall, Figure 2 also suggests a better agreement of the TE norm perturbations with the OSSE analysis error then the B norm perturbations. This appears counterintuitive, since the analysis error covariances should be better constrained by the B matrix than by a rather arbitrary TE norm. A fundamental analysis of both procedures, based on TE and B, is ongoing in order to better understand the results. We anticipate a procedure can be implemented that results in sensitivity structures corresponding to the analysis error covariances with respect to

- spatial structure;
- mass/wind balance; and
- total amplitude.

Note that this does not imply a search for the real analysis error. Of course, it would be ideal to reduce the analysis error through the sensitivity computations, but there is not really a theoretical ground to expect such modification of the atmospheric state. The bottom line is that we seek for realistic perturbations rather than for real perturbations.
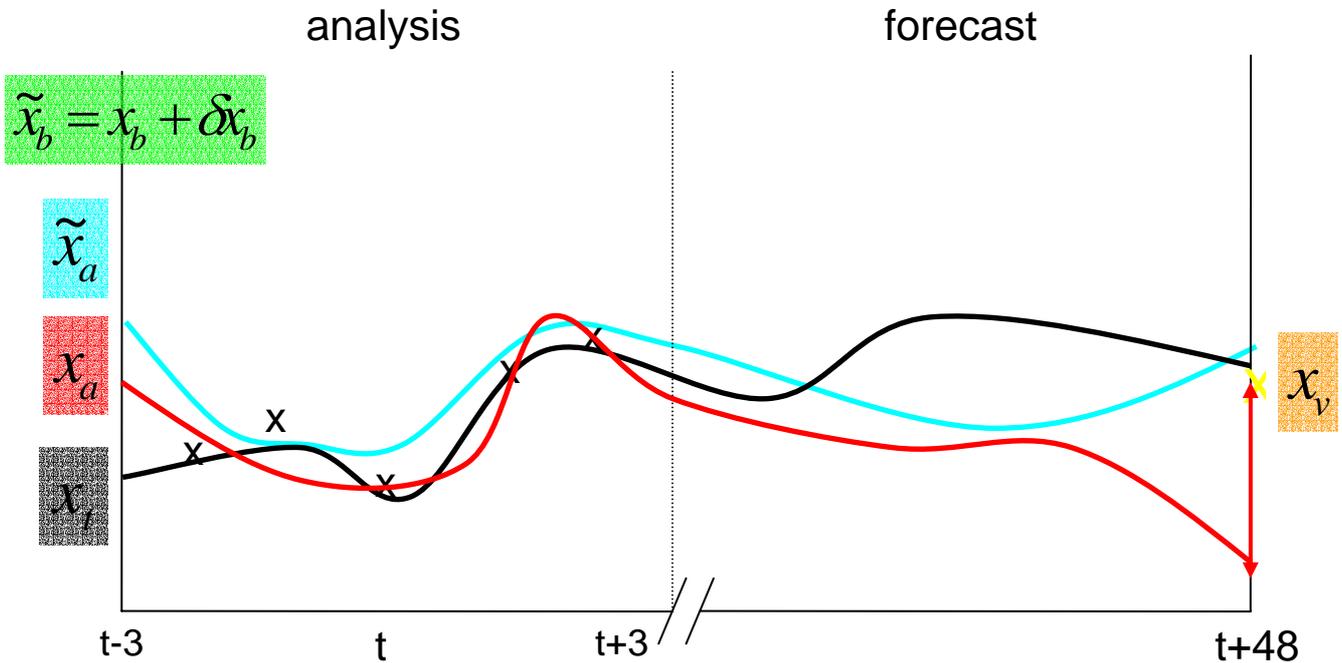

Figure 3. Schematic showing versus time truth x_t (black), the failed forecast and analysis x_a (red), and the corrected forecast $\tilde{x}_a$ (blue). The perturbation $\tilde{x}_a$ is based on a first guess sensitivity calculation δx_b to obtain the perturbed first guess $\tilde{x}_b$. Using this first guess and the observations (x) the perturbed analysis is computed.

3. CONFLICT OF SENSITIVITY STRUCTURES WITH REAL OBSERVATIONS

The sensitivity structures that constitute the initial analysis perturbation are not necessarily consistent with the conventional observations. In previous section evidence was even presented (Figure 2) that the perturbations generally increase the analysis error and, therefore, may be in conflict with the existing observations. Conflicts between the synthetic DWL observations and existing observations would never result in a proper assessment of the potential value of the DWL data to improve forecasts. This matter thus should be resolved.

Figure 3 depicts an approach that does prevent the above inconsistency. By computing a first guess perturbation rather than an analysis perturbation, we keep the capability to improve a 2-day forecast. If we presume that the most significant first guess perturbations are in observation-sparse areas, then a subsequent analysis should still reduce the 2-day forecast error. Preliminary tests indeed indicate that most of the capability to reduce the 2-day forecast error is kept in the perturbed analyses which are based on perturbed first guess and all existing observations; see Figure 4. Figure 4 was actually derived by computing analysis perturbations, followed by an analysis with the perturbed analysis used as background. As such, results are only indicative, since most observations are assimilated twice in this procedure. The perturbed analysis is pushed to the observations in data dense areas and maintains the first guess sensitivity structures in data sparse areas. The assimilated perturbations thus match with the conventional observations and at the same time maintain (part of) the forecast error reduction capability.
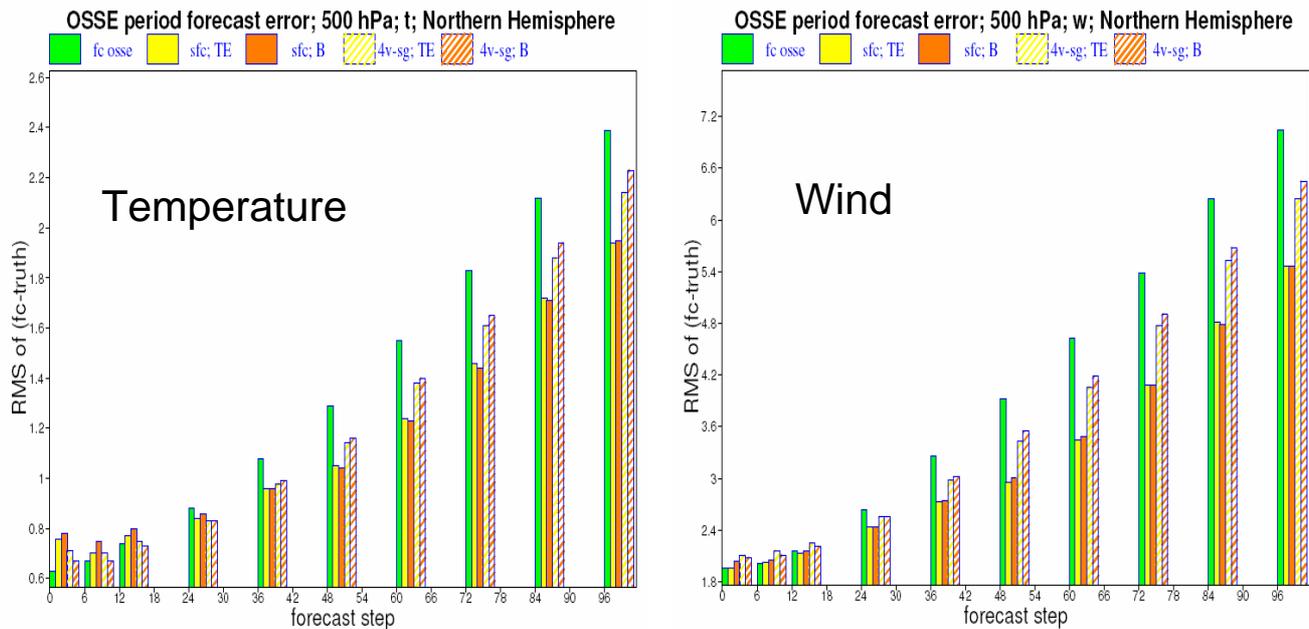
Figure 4. As Figure 2, but with a yellow column added indicating assimilated sensitivities with the TE norm and an orange column indicating assimilated sensitivities by the B norm.

4. CONCLUSIONS AND OUTLOOK

In the sensitivity computation the norm for the initial analysis perturbation does not much affect the capability to reduce forecast error. Current OSSE tests show that the perturbations do not match the "true" analysis error. However TE sensitivity patterns and B error structure functions are about similar, indicating that the analysis perturbations are realistic in spatial scale and amplitude. However, a counter-intuitive finding is that B-norm perturbations are rather large scale and less compatible with the B matrix spatial structure functions. A preliminary analysis indicates that this result may be expected, and that the objective function used for the sensitivity computation may need some reconsideration.

An open issue remains in the relative importance of the mass and wind perturbations, and this is under investigation.

We currently redo the OSSE assimilation experiment with the current ECMWF model, since this model is also used for the sensitivity computations, and such compatibility is required for good understanding of the procedure. Subsequently, we determine FG sensitivities and a modified FG used as input for the analysis cycle. This results in the perturbed analyses for which we verify the capability to reduce the 2-day forecast error. These perturbed analyses are input to synthesising the DWL observations. Several DWL scenarios will be tested for their ability to sample the realistically simulated analysis perturbations, and thereby improve the 2-day forecasts.

After that the OSSE work has resulted in a satisfactory procedure, it will be applied on real cases of 2-day forecast failure in order to test the DWL ability to reduce such forecast errors. By testing several DWL scenarios a synthesis of requirements on wind profile quality and quantity may be obtained. The ability of and requirements for other observing systems to do the same may obviously be tested by the same methodology. The methodology complements OSE and OSSE, since the former by definition cannot test the impact of new complements to the GOS, and the latter requires careful calibration and observation simulation.

5. ACKNOWLEDGEMENT

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