
Improved forecasts of extreme weather events by future space borne Doppler wind lidar

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Introduction

An important goal in operational weather forecasting is to reduce the number of forecast failures, in particular those with large socio economic impact. Forecast failures of high-impact weather are often due to lack of observations over data sparse areas, such as the Southern Hemisphere, Tropics and Northern Hemisphere oceans, over a prolonged period prior to the extreme event. International programmes such as the observing system research and predictability experiment (THORPEX¹⁾) show a growing interest in defining an observational network focussing on increased accuracy of high-impact weather forecasts. This network definition addresses fundamental questions related to observation strategies such as the relative merit of new polar orbiting satellites, giving a uniform global coverage of observations, versus e.g. targeting strategies where additional observations are constrained to pre-determined meteorologically sensitive areas. To answer these questions simulation experiments with state-of-the-art numerical weather prediction (NWP) models have proved great value to test future meteorological observing systems a priori on their ability to improve meteorological analyses and subsequently reduce the probability of forecast failures, which would make them a cost-effective investment.

A well established method is the Observing System Simulation Experiment (OSSE), but this requires many human and computational resources and strong international collaboration. Recently, a big step forward was made by the United States National Centers of Environmental Prediction (NCEP). A new set of OSSEs was prepared, based on a one-year high resolution synthetic true atmospheric state. This was generated by the European Centre for Medium-Range Weather Forecasts (ECMWF) by integrating the high resolution model over a one-year period, the so-called nature run. The research community working on data assimilation and the design of future observing systems will benefit from this effort since it provides a platform to participate in internationally collaborative OSSEs using the same nature run.

In this chapter, a new effective method, called Sensitivity Observing System Experiment (SOSE), is described

to assess the impact of future observing systems for NWP. An example demonstrates the added value of future space borne Doppler wind lidar (DWL) to reduce forecast failures of extreme weather events.

SOSE – Sensitivity Observing System Experiment

For lack of an established methodology to test the potential impact of prospective extensions to the Global Observing System (GOS), a new method called SOSE was developed. Because the density of the GOS is non-uniform it is of interest to investigate the benefit of complementary observing systems filling its gaps. Forecast errors on the short term (up to 48 hours) are mainly due to the evolution of errors in the forecast initial state (analysis). A major component of SOSE is the determination of a so-called adapted analysis, also denoted as ‘pseudo true atmospheric state’, that

- improves the 2-day forecast,
- is realistic in the sense that the spatial structures of the analysis adaptation resemble those of real analysis errors,
- is not in conflict with the existing (real) observations.

To generate such a pseudo truth fulfilling these requirements a methodology has been developed based on adjoint sensitivity structures²⁾ that represent the part of the analysis error that grows most rapidly in time and potentially causing the large forecast failures if not observed. The pseudo true atmospheric state is subsequently used for the simulation of the prospective observing system(s), i.e. the atmospheric state is interpolated to the observation locations of these prospective observing systems to generate ‘perfect’ observations. Next, realistic instrument and representativeness errors are added to these perfect observations to generate the synthetic observations. These synthetic observations are used together with real observations from the existing GOS in a state-of-the-art NWP model to assess the potential added value of the prospective observing system. Note that the analysis adaptation that defines the pseudo-truth represents the part of the analysis error that is not observed by the existing network. Obviously, when the new observing system

is capable of (partly) resolving the analysis adaptation, the 2-day forecast will improve.

Unlike a full-blown OSSE, SOSE can be applied to real extreme events that were 'badly' forecast operationally and it only requires the simulation of the additional prospective instrument. This property makes SOSE an effective tool to define observation requirements to reduce deficiencies in the current GOS, e.g. to maximize the probability to observe rapidly evolving meteorological structures with a large forecast impact, as shown in Figure 1. The observation requirements may be used to define observation strategies such as the design of a network including prospective observing systems. An application of the SOSE method is the assessment of the impact of future space borne Doppler wind lidar.

Space borne Doppler wind lidar

Despite continuous progress in the observation of meteorological variables from space by satellites, the meteorological observing system still lacks a uniform global coverage of wind profile observations. It has been recognized for a long time that lack of wind profile observations over the oceans is a major deficit of the current observing system network. In particular over the oceans additional wind observations can improve weather forecasting substantially. The European Space Agency (ESA) Atmospheric Dynamics

Mission (ADM), featuring the satellite named ADM-Aeolus³⁾ is a first step to fill in this gap and will provide wind profiles in otherwise data sparse areas (Figure 2) and thus may reduce the number of forecast failures. ADM-Aeolus is a demonstration mission scheduled for launch in 2009 and will be operational for three years.

ADM-Aeolus is a polar orbiting satellite carrying a Doppler wind lidar (DWL) for wind profile measurements all over the globe. A DWL emits laser light into the atmosphere and as the light propagates through the atmosphere part of the signal is scattered back to the instrument by atmospheric particles and molecules that are moving with the wind velocity. These moving particles cause the frequency of the backscattered signal to be Doppler shifted with respect to the transmitted signal. The time lag between the transmitted and received signal determines the distance of the scattering particle to the instrument. The frequency shift is related directly to the wind velocity along the laser beam line-of-sight (LOS). Consequently, ADM measures profiles of single horizontal line-of-sight (HLOS) wind components rather than the complete wind vector. The priority of this so-called explorer mission is on quality rather than quantity of retrieved winds. Anticipating on its success, there is a need to specify already wind observation requirements (both quality and quantity)

Forecast failures of high-impact weather are often due to lack of observations over data sparse areas

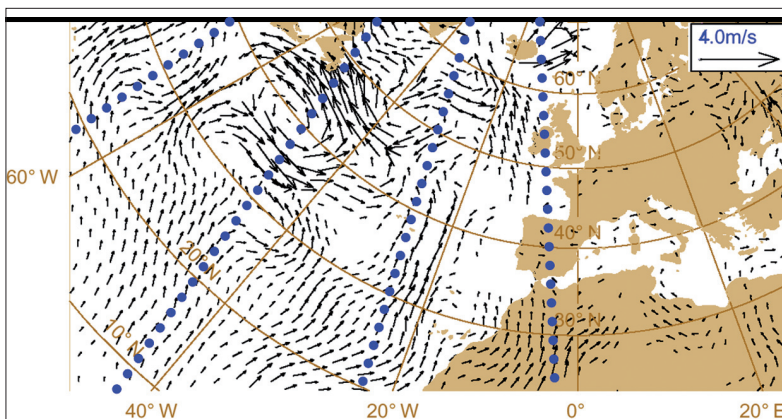


Figure 1. Typical 500 hPa wind structure over the North Atlantic not observed by the current global observing system, but causing a large forecast error over Europe 48 hours later. Overlaid, the sampling of future Doppler wind lidar profiles by the ADM-Aeolus mission.



Figure 2. Artist impression of the ESA earth explorer mission ADM-Aeolus that will provide a global coverage of wind information for the first time in history (courtesy ESA).

for the definition of an operational network of space borne DWL in the post-ADM era, beyond 2012, and projects have been initiated for this purpose.

In the PIEW (Prediction Improvement of Extreme Weather) project the SOSE method was used to test various DWL scenarios⁴⁾ on their capability to sample meteorologically sensitive areas not well captured by the current GOS, in particular over the Northern Hemisphere oceans. These scenarios included

- Dual-perspective; the data coverage of this scenario is identical to ADM-Aeolus but the complete wind vector is determined by measuring two line-of-sights with a 90 degree difference in azimuth angle,
- Tandem-Aeolus; a tandem of two ADM-Aeolus satellites, with one line-of-sight, and in one orbit plane separated by 180 degrees, giving twice the coverage of Aeolus, as shown in Figure 3. The number of wind component profiles measured by this scenario is twice the number of only one ADM-Aeolus and equals the number of single-component profiles of the dual-perspective scenario.

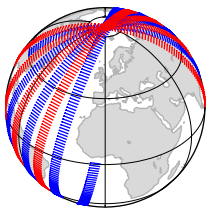


Figure 3. 12 Hours observation coverage for a tandem-Aeolus DWL scenario. Arrows start at measurement locations and point along the line of sight. Blue and red arrows correspond to the two Aeolus satellites.

To determine the measure of impact by the SOSE method, forty cases were selected from a database of worst ECMWF forecasts issued during the period 1998-2004, covering all seasons. For each case and both DWL scenarios a SOSE was conducted. Figure 4 shows the mean impact of the additional wind observations on the analyses and Figure 5 the sub-

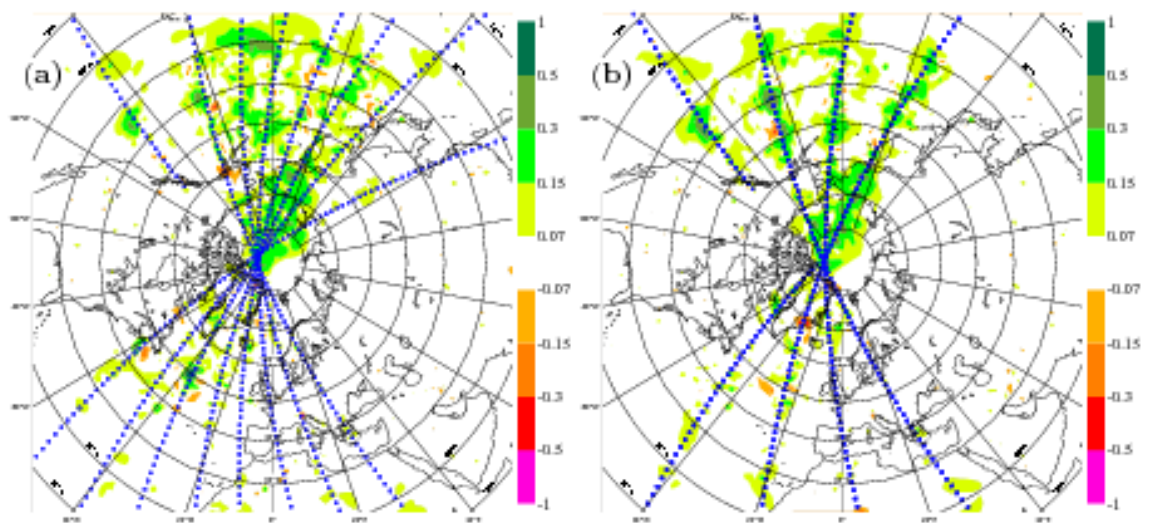


Figure 4. Mean 500 hPa wind (m/s) analysis impact for the tandem-Aeolus (left panel) and dual-perspective (right panel) DWL scenarios. Green/red spots denote positive/negative impact; the blue spots denote the DWL observation locations.

sequent impact on the 2-day forecasts. From these and other experiments it was concluded that Aeolus is capable to resolve part of the analysis adaptation in the data sparse areas giving an improved forecast after 2 days and beyond. In addition, it was found that

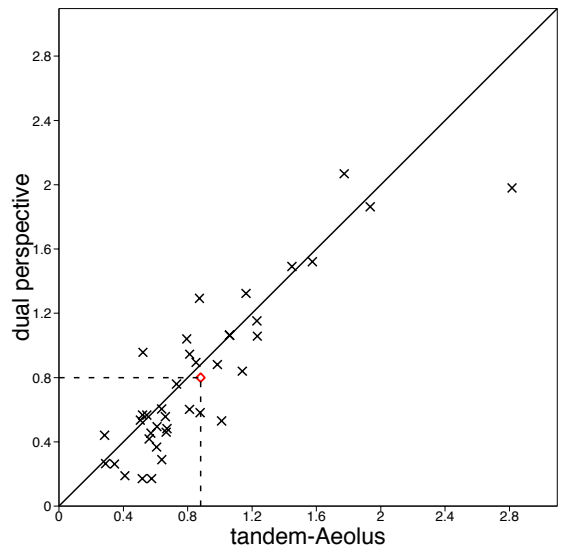


Figure 5. Scatter plot of 2-day forecast improvement of 500 hPa geopotential height (m) for the tandem-Aeolus and dual-perspective DWL scenarios. Each cross corresponds to one of the 38 cases; the red diamond denotes the mean value. The added value of the tandem-Aeolus scenario is larger than the dual-perspective scenario on average.

ADM-Aeolus is a first step to fill in this gap and will provide wind profiles in otherwise data sparse areas

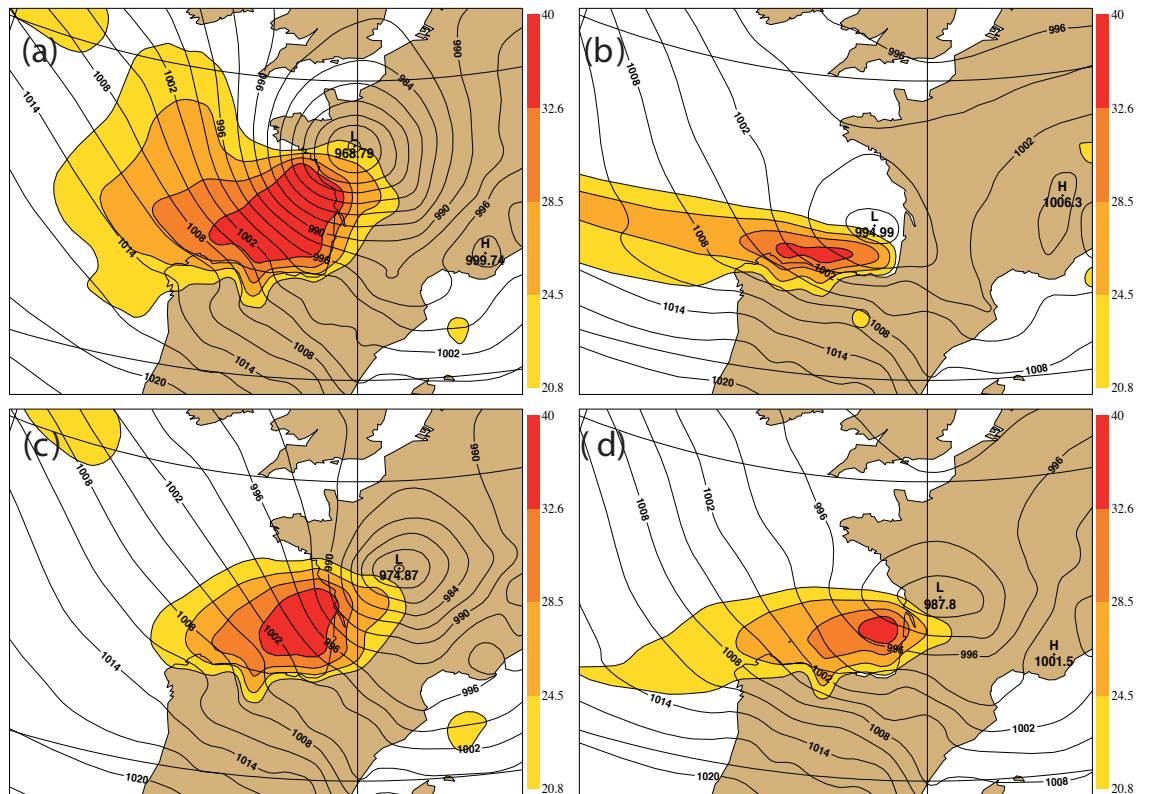


Figure 6. Christmas 1999 storm ‘Martin’. Surface pressure and wind gust at verification time 27 December 1999 18UTC for: a) the verifying analysis, b) the control 48-hour forecast, c) the pseudo-truth 48-hour forecast and d) the DWL (tandem-Aeolus scenario) 48-hour forecast. Solid lines denote the mean sea level pressure with 3 hPa contour interval. Shaded areas denote the surface wind gust (m/s) covering the range 9-12 Bft.

maximum impact is obtained by spreading the available information over extended areas, as achieved by a tandem-Aeolus scenario, rather than focussing on larger but more localized analysis improvements as achieved by the dual-perspective scenario. It was also found that the additional impact of an additional third ADM-Aeolus to the tandem-Aeolus is less than for an additional second Aeolus in the same orbit, demonstrating redundancy when flying more Aeolus-type instruments.

The 1999 Christmas storms

The December 1999 Christmas period was characterized by two storms named ‘Lothar’ and ‘Martin’ causing much havoc in Western Europe. Almost all operational NWP models failed completely to forecast these storms even on the short (48-hour)

term⁵). Here, we zoom in on the second Christmas storm ‘Martin’ that made landfall in Brittany (France) on 27 December 18 UTC (see Figure 6a), causing much damage over France and Germany in the following 24 hours. From Figure 6b it is clear that the 48-hour operational forecast from ECMWF starting on 25 December 18UTC completely failed to predict the location and intensity of the storm.

To answer the question whether additional DWL observations would have improved the forecast, the SOSE method was adopted and extended to a cycled mode implementation to generate a pseudo true trajectory⁶). This enables the simulation of DWL observations over a prolonged period prior to the forecast initial time and thus making full benefit of nowadays operational data assimilation systems to

propagate information from observations forward in time to next cycles in a constructive manner.

The forecast initiated with the 25 December 18UTC pseudo-truth represents the best achievable forecast in a cycled SOSE experiment and does predict a storm as shown in Figure 6c. Figure 6d shows that additional 60 hours of DWL observations from a tandem-Aeolus scenario over the period 23 December 06UTC until 25 December 18UTC improves the forecast substantially, reducing the forecast error by 62% relative to the maximum achievable reduction (from the pseudo-truth forecast). Although this result clearly demonstrates the added value of a DWL, the forecast in Figure 6d still does not predict a severe storm.

To complete this case, an ensemble experiment was conducted to quantify the probability of the occurrence of a severe storm. An ensemble of forecasts is generated by adding growing structures to the analysis. The subsequent spread in the ensemble forecasts is a measure for the predictability of the event. Two 50-member ensemble experiments were conducted, one for the control experiment including all existing observing systems (but without DWL), the so-called NoDWL experiment, and the other with synthetic DWL. For the NoDWL experiment 5 out of 50 members showed a storm in the Gulf of Biscay and over the French mainland in the 2-day forecast initiated at 25 December 18UTC. For the DWL experiment 11 members show a storm, meaning more than a doubling of the probability of forecasting

this storm when DWL observations would have been available. For the 54-hour forecast, when the storm has moved further over the French mainland, again 5 members show a storm in the NoDWL experiment against 15 members in the DWL experiment, clearly demonstrating the substantial impact an additional DWL would have had to forecast the Christmas 1999 storm 'Martin'.

Conclusions and outlook

Simulation experiments using state-of-the-art NWP models demonstrate the high potential to test a priori prospective meteorological observing systems on their ability to improve meteorological analyses and subsequently to reduce the probability of forecast failures. A flexible, effective and computationally efficient experimental tool is provided by SOSE as discussed in this paper. SOSE has been used to test ADM-Aeolus and various optional post-ADM DWL scenarios on their capability to improve numerical weather forecasts. An example demonstrates that space borne DWL would have improved the forecast of the Christmas 1999 storm 'Martin' substantially. SOSE experimental results may be used to determine observation requirements culminating in instrument design concepts for prospective (space borne) observing systems to extend the GOS. New experiments based on SOSE are in preparation, in collaboration with United States institutes, focussing on the definition of an operational network of space borne Doppler wind lidar in the post-ADM era beyond 2012.

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