IMPACT ASSESSMENT OF A DOPPLER WIND LIDAR IN SPACE BY OSSE

Ad Stoffelen and Gert-Jan Marseille

Ad.Stoffelen@knmi.nl
Royal Netherlands Meteorological Institute, KNMI

ABSTRACT

ESA has approved the Atmospheric Dynamics Mission (ADM) to bring a Doppler Wind Lidar (DWL) in space. The objective of this mission is provide atmospheric wind information to demonstrate improvements in atmospheric analyses and weather forecasts. The ADM DWL will provide good accuracy profiles rather than a large coverage. The coverage requirement was based on the required ability to demonstrate impact of the ADM DWL in atmospheric analyses and forecasts. In an end-to-end simulation we set out to verify these improvements and to test the assimilation of ADM DWL winds in a state-of-the-art Observing System Simulation Experiment (OSSE). As expected, the DWL data have locally both positive and negative impacts but good quality profiles appear to result in clear and beneficial impacts on balance. On the other hand, low quality profiles generated in cloudy scenes appear to result often in negative analysis impacts, probably due to the poor handling of these data by the data assimilation system. This confirms the hypothesis that observation quality is of pertinent importance, but also that OSSEs can be used to tune data assimilation systems. On average, we demonstrate that realistically simulated ADM DWL profiles beneficially impact both the analyses and forecasts. We believe that our impact results in the northern hemisphere are indicative of the expected impact of adding ADM DWL data to the Global Observing System of as foreseen in 2006 and beyond.

1 OBJECTIVE

ESA has recently approved a Doppler Wind Lidar (DWL) to fly on a free-flyer platform orbiting dawn-dusk at 400 km altitude (see Ingmann et al in this volume). Rigorous trade-off studies during the Atmospheric Dynamics Mission (ADM) phase-A have resulted in the definition of a lidar concept, hereafter named ADM_UV, operating in the ultraviolet part of the spectrum at 355 nm laser wavelength. In order to guarantee the demonstration value of this mission for Numerical Weather Prediction (NWP) and in climate studies, extended atmospheric analyses and forecast runs are needed to better quantify this potential DWL impact and to address specific issues of concern during the ADM development, such as profile quality and coverage.

The objective of our study is demonstration of the impact on atmospheric circulation and on NWP of wind profiles from the ADM and comparison to the impact of conventional wind profiles (TEMP/PILOT) with respect to the existing Global Observing System (GOS). This demonstration is made by means of OSSEs (Observing System Simulation Experiments). It serves to consolidate the requirements for an operational mission by assessing the sensitivity of the impact of ADM_UV to key mission parameters to aid in the design of future operational missions, as well as to demonstrate the impact of the minimum useful requirements and performance of the Atmospheric Dynamics Earth Explorer Mission.

2 NEED FOR WIND PROFILES

The quality of state-of-the-art NWP is among other things determined by the availability and quality of meteorological observations. NWP models have improved much over the last decades, and advanced 4D-var techniques are now being used for the analysis. The spatial resolution of global circulation models has as well improved, which leads to a need for more observations on the sub-synoptic scales. On these scales the wind field, rather than the atmospheric temperature or humidity fields determines the atmospheric dynamics. Furthermore, the prime factor determining meteorological instability is vertical wind shear. In the tropics, for an accurate definition of the Hadley circulation, 3D wind information has been lacking. Conventional wind profile data lack coverage and a uniform distribution over the globe, and are particularly needed over the oceans and in the tropics and southern hemisphere.

For the study of climate processes extensive reanalyses experiments are being conducted. These experiments use the technique of data assimilation, as used for NWP, to establish long time series of the weather in support of climate studies. In the OSSE evaluation we investigated extensively the analysis impact of wind profile data, thus supporting the climate application.

Recent OSEs (Observation System Experiments) by the European Centre for Medium-range Weather Forecasts (ECMWF) (Isaksen, 1998, and Kelly, 1997) have confirmed the relevance of tropospheric wind profile data for NWP. ECMWF tested this in a series of experiments where they excluded conventional wind profile observations (TEMP/PILOT), or parts thereof in the free troposphere, and compare to experiments where conventional (TEMP), or satellite (TOVS) temperature or humidity profile data, or single level observations, were excluded. In more recent experiments (Kelly, 2000) TEMP/PILOT wind profile observations seem to have less impact, probably because of the increasing amount of aircraft wind profile reports over the land areas where TEMP/PILOT are launched, and because of the rapidly decreasing number of TEMP/PILOT.

Complementary experimentation has been performed at the Deutcher Wetter Dienst (DWD) to test the impact of continental North American wind profile observations (Wergen, 1998). These experiments confirm largely the importance of wind profile data, compared to the importance of temperature/humidity data. In the OSE experiments, a small number of (good quality) wind profiles already shows a positive impact on the quality of NWP. TEMP/PILOT OSE work with the US National Center for Environmental Prediction, NCEP, NWP model confirms some of these conclusions. In line with this, the ADM requirements have been focussing on quality rather than quantity over the last few years, in accordance with the WMO (1998) requirements. Moreover, past experience in data assimilation shows that quality can usually not be traded off against quantity without a degrading effect.

The results and conclusions of OSEs give an insight into the effect that a particular type of existing observation has in the existing data assimilation system. However, it is difficult to easily draw from this conclusions on the added value of supplementary measurements on the meteorological analyses and forecasts. This added value may be investigated through OSSEs. Météo France has run OSSE experiments with the French Arpege NWP model, in order to test the impact of the OSSE data base

DWL wind profiles from a 10 micron laser attached to a free flyer satellite in a polar orbit (Cardinali et al, 1998). The assimilation experiments were performed with a low-resolution version of the NWP model (T42), and as expected the DWL impact could be well demonstrated.

DWL OSSEs performed in the United States indicate an impact even for low measurement accuracy. However, the forecast quality was almost exclusively based on DWL information from the southern hemisphere and therefore show obviously an improvement against the control analysis which did not contain relevant observations in this area.

For an operational system, the impact on NWP often depends on the skill of the data assimilation system used. Therefore it is worthwhile to perform an OSSE with the state-of-the-art ECMWF 4D-var system in order to consolidate the requirements for an operational mission.

3 OBSERVING SYSTEM SIMULATION EXPERIMENT DESCRIPTION

Most of necessary preparatory work to perform the OSSEs has been the result of many studies, started in the early 1990's (Stoffelen and Becker, 1994), (Becker et al, 1995), (Stoffelen and Marseille, 1998). To build up a database of simulated observations one needs a description of the atmosphere over a certain time period. For this purpose, a "true" atmosphere is generated through a long integration period of a forecast model, initiated with an atmospheric analysis. This is called the "nature run". The nature run we use in this study was the result of a 30-day integration, initiated on 5 February 1993 00 UTC and ended on 7 march 1993 00 UTC. Integration was performed with the operational forecast model at ECMWF in 1993, *i.e.* T213 horizontal grid and 31 levels vertically.

To realistically simulate the UV Doppler Wind Lidar as proposed for the ESA Core Explorer Atmospheric Dynamics Mission, the cloud distribution of the nature run is important. Musatani and Campana (1999) had a closer look to the nature run clouds, but no serious deficiencies were found. However, the relative lack of PBL clouds over the oceans as compared to satellite observations may be improved. On the other hand, we found that in the PBL over the ocean, the DWL impact is very limited due to the presence of the ASCAT scatterometer in the OSSE.

The generated OSSE database includes simulated observations of conventional meteorological observation systems and three infrared lidar concepts that were proposed in the mid 1990's. More recently a simulation of the ADM_UV concept was carried out using the LIPAS simulation tool (Veldman, 1999). It includes simulation of data coverage according to the ADM user requirements and realistic profile quality simulation according to expected instrument characteristics and spatial and temporal representation of the observations. A pre-OSSE analysis to assess profile quality in clear air, *i.e.* without clouds, and the impact of clouds on atmospheric penetration has been carried out (ESA, 1999). Moreover vertical wind shear and tropical humidity flux visibility were assessed in relation to clouds. After validation, the new concept was added to the OSSE database at ECMWF.

To compare the existing observational network as generated in Stoffelen et al. (1994) with the current operational network we compared the observation statistics of the OSSE with the operational observation statistics in the February period of 1999. The OSSE uses about twice more radiosondes (TEMP/PILOT) with furthermore apparent higher quality, less aircraft reports (AIREP), less Cloud Motion Winds reports (SATOB) and less drifting buoys (DRIBU). The increased number of ascend and descend AIREP may complement the radiosonde wind profile decrease however. The increased number of single level wind data probably has much less of a compensating effect (see also ESA, 1999).

The stratospheric extrapolation used to simulate TOVS and ATOVS observations for the OSSE data base is incompatible with the current use of (A)TOVS. Moreover, an appropriate bias correction did not exist for the OSSE data. OSSEs including TOVS data would be better capable of assessing the relative benefit of temperature and wind sounding in the southern hemisphere and tropics. However, we believe that the complementary effect of TOVS-alone in the northern hemisphere is limited on the 1993-like GOS of the OSSE data base, and thus the OSSE results representative of the expected impact in the northern hemisphere.

The other element of an OSSE is a state-of-the-art data assimilation system (DAS), Here we describe the OSSEs performed with the ECMWF IFS at spectral truncation T319 and 51 levels to demonstrate the impact of the ADM_UV concept on NWP and atmospheric circulation analyses.

Another aspect of the NWP model used in the DAS is related to its capability to in time realistically diverge from the nature run model, just like NWP models diverge from truth. In case of a so-called

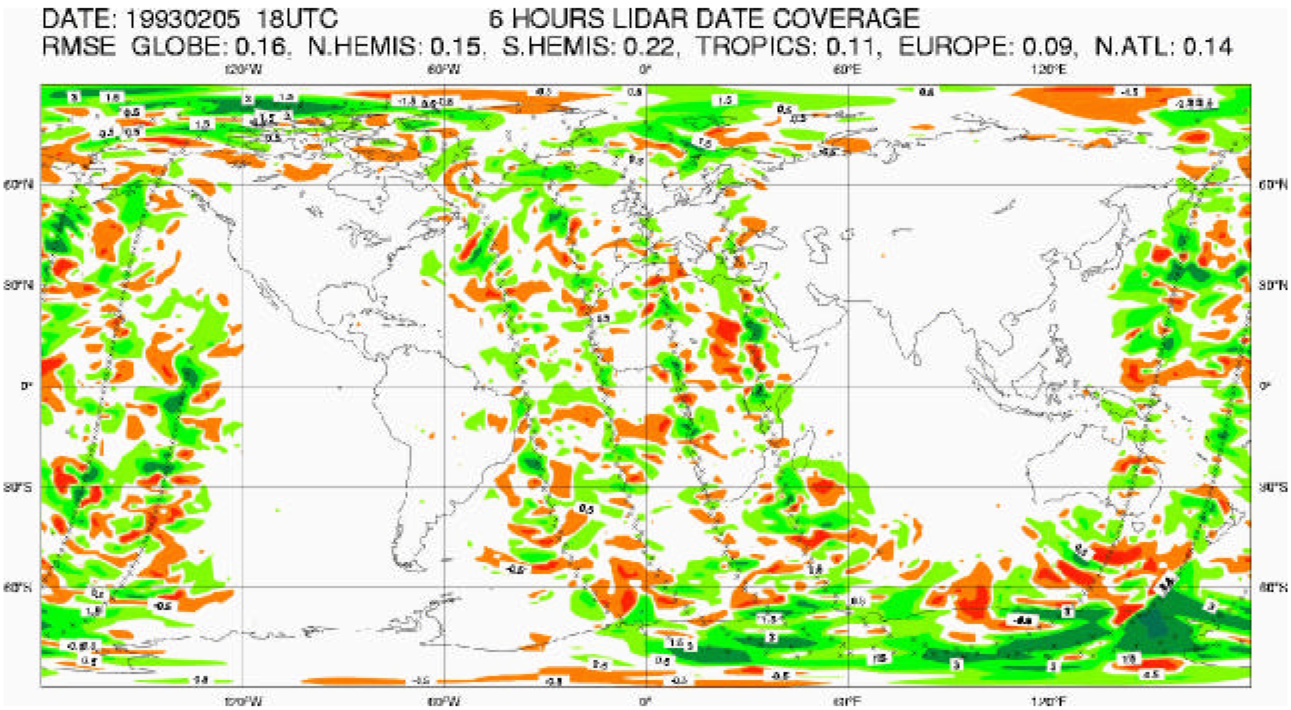

Figure 1: OSSE impact of the first 6 hours of ADM_UV profiles at 500 hPa for vector wind. Green areas denote DWL closer to the nature run, whereas orange/red areas denote NoDWL closer to the nature run. Crosses depict the location of the DWL component wind profiles.

fraternal twin problem, the similarity of the nature run and DAS model time evolution is much larger the similarity of truth and the DAS model. In that case observations have less (no) beneficial impact and is the OSSE DAS unrealistic in handling the observations. We extensively analysed the statistical properties of the DAS, in order to verify that observations are handled realistically. Moreover, we verified that the ECMWF model has changed dramatically since 1994 (Haseler, 2000), and compared the OSSE forecast skill to operations (see section 4).

NoDWL and DWL experiments were run respectively denying and including the ADM_UV wind profiles from 19930206 at 12 UTC until 19930220 at 12 UTC. Results were mutually compared, but also to the nature run , providing precise information on the consequences of the simulated errors.

4 DWL ANALYSIS IMPACT

Figure 1 shows the impact due to 6 hours of lidar data. As expected for any system, the impact is both positive and negative depending on the stochastic error properties of the observations. Due to the spatial filtering properties of the DAS the impact extends much beyond the profile locations. ADM_UV has a clear and demonstrable positive impact on the analyses in the northern hemisphere. In the tropics and southern hemisphere the impact is overwhelmingly positive, but here the OSSE observing system is not representative of the real world observing system. In particular in the southern hemisphere, the incapability to realistically use satellite temperature sounding measurements is regretful.

Figure 2 shows the quality of the simulated data over the ten-day period on a map and figure 3 shows their analysis impact at 500 hPa. Good quality ADM_UV wind observations have a clear and beneficial impact on the analyses. Note for example at 500 hPa the NW-SE oriented bands west of Australia and South America.

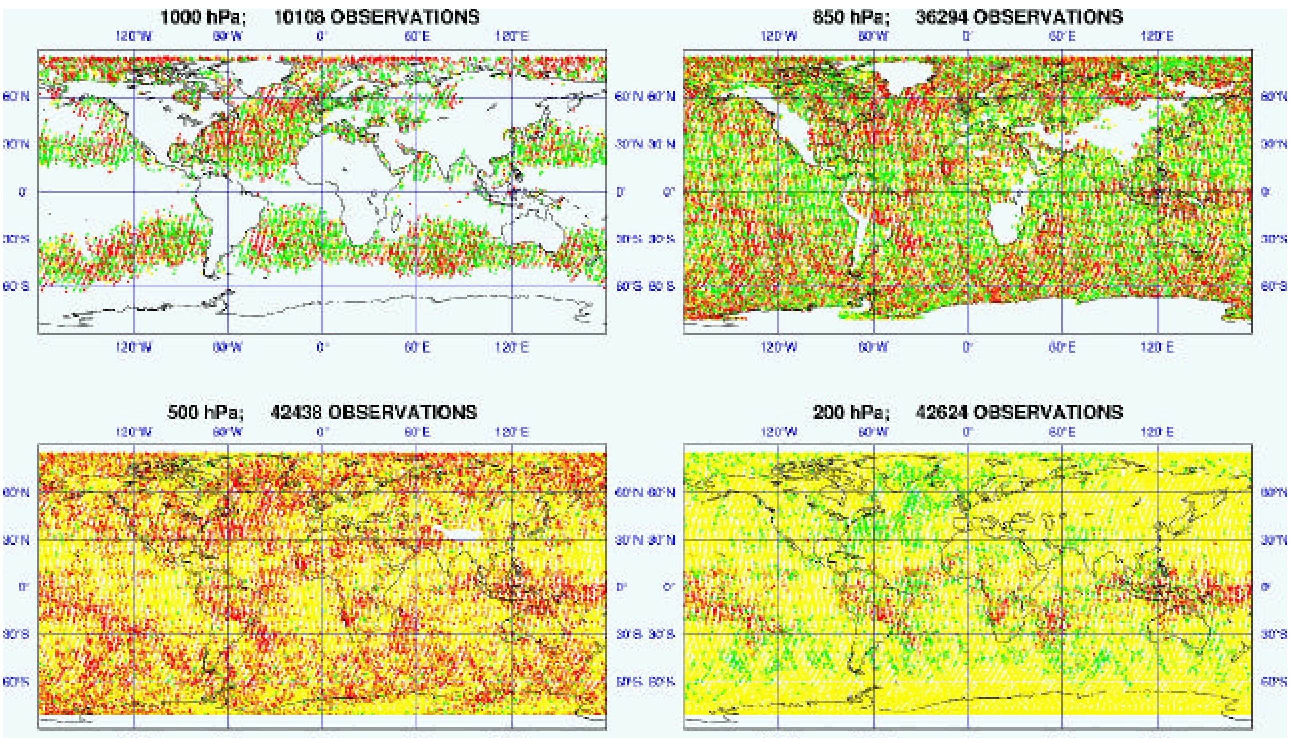

Figure 2: The quality of ADM DWL observations at 1000 hPa, 850 hPa, 500 hPa, and 200 hPa over the whole assimilation period, where red, orange, yellow and green dots represent respectively very low, low, good, and very good quality winds, corresponding to better than respectively 3.2, 2.4, 1.6, and 0.8 times the requirement of 2-3 m/s (depending on height). White areas include the surface return and are not used. Red areas generally have optically significant cloud aloft.

However, inaccurate ADM_UV data causes locally mean negative impacts. This occurs probably because those observations are not properly weighted against the background model fields in the analysis. In the local absence of good quality observations the background error estimate becomes poor, probably frequently resulting in detrimental observation impacts in the analysis. In areas with

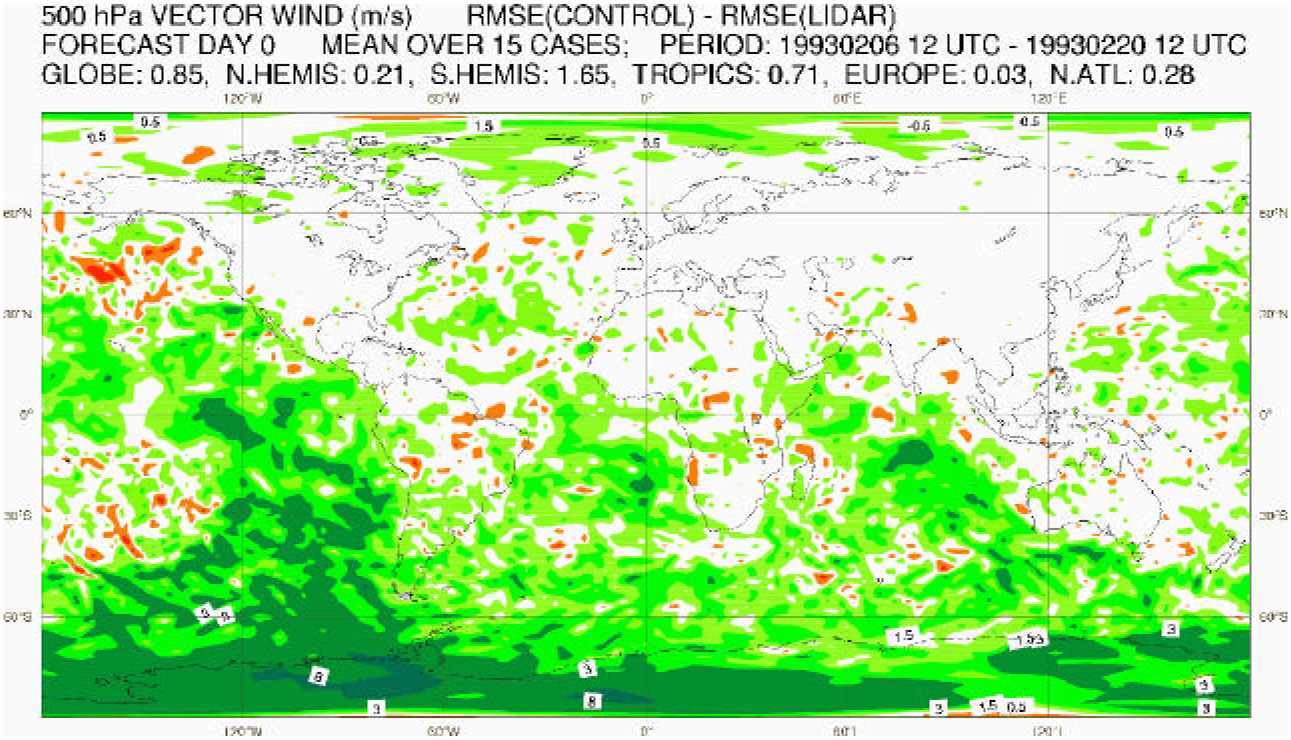

Figure 3: OSSE mean 15-day analysis impact of the ADM_UV profiles at 500 hPa for vector wind. Green areas denote DWL closer to the nature run, whereas orange/red areas denote NoDWL closer to the nature run. Some mean beneficial impacts are shown for some regions on top of the plot. Mean regional detrimental impacts exist in cases where generally optically thick cloud resides aloft (figure 2).

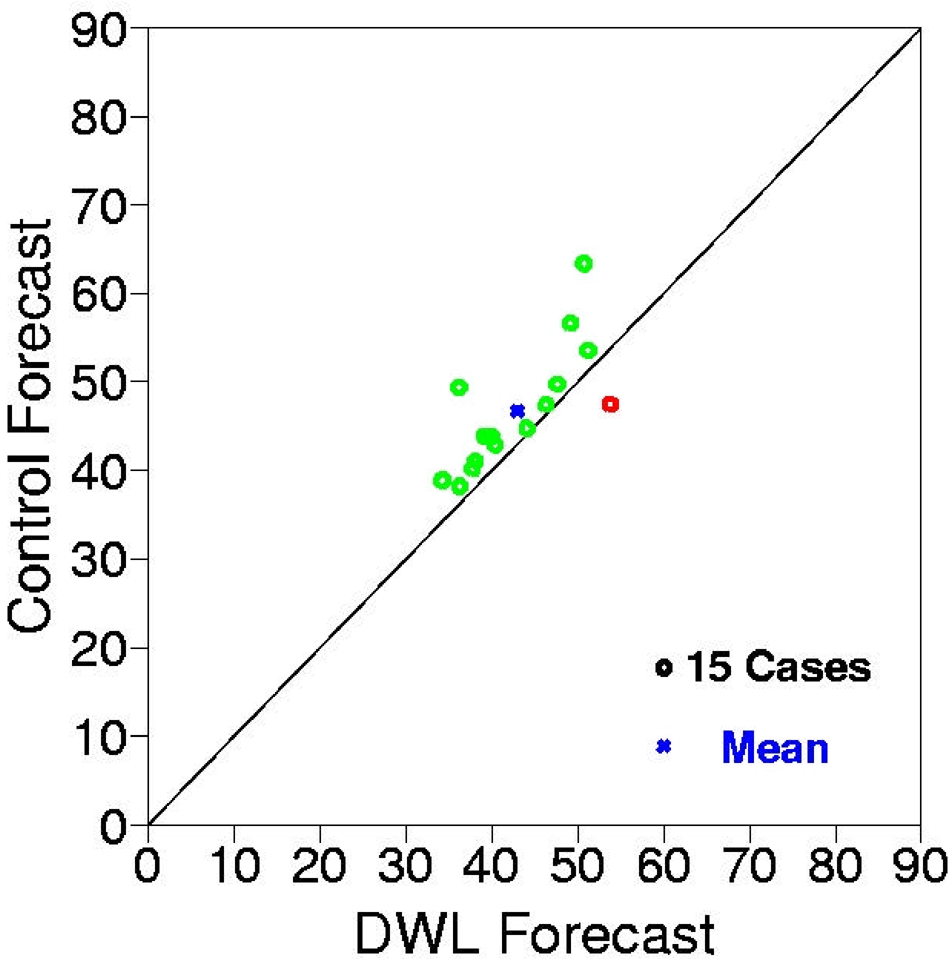

Figure 4: DWL versus NoDWL (control) 4-day geopotential forecast errors [m] for 15 forecast from 12 UTC on 6 to 20 February (dots) and their mean (cross). Beneficial impacts are green whereas detrimental ones are red.

extensive high-level cloud cover negative impacts were most frequent. Compare for example the red dot areas at 200 hPa in figure 2 with the orange and white areas in figure 3.

5 DWL FORECAST IMPACT

The average benefit of lidar data on medium-range forecast in the OSSE was about 0.25 days in the northern hemisphere (above 20N). Local impacts varied and were up to 0.5 days, for example for Europe. To test the significance of our results we verified that time series of forecast skill showed sufficient variability. On the other hand, in a clear majority of cases was the DWL forecast better than the control, as shown for example in figure 4.

Some large and beneficial forecast impacts of ADM_UV can traced back to areas with large analysis impact. Similarly, regional detrimental effects propagate into the forecast.

The forecast skill achieved in the OSSE falls within the range of operational forecast skills, as depicted in figure 5. This is another indication that the dissimilarity between the nature run ("truth") time evolution and DAS model evolution is realistic, and no fraternal twin problem existent.

6 CONCLUSIONS

ADM_UV has a clear and demonstrable positive impact on the analyses and forecasts in the northern hemisphere. In the tropics and southern hemisphere the impact is overwhelmingly positive, but here the OSSE observing system is not representative of the real world observing system. Good quality ADM_UV wind observations have a clear and beneficial impact on the analyses. Some large and beneficial forecast impacts of ADM_UV can traced back to areas with large analysis impact. The average benefit of lidar data on medium-range forecast in the OSSE was about 0.25 days in the northern hemisphere (above 20N). Local impacts varied and were up to 0.5 days, for example for Europe.

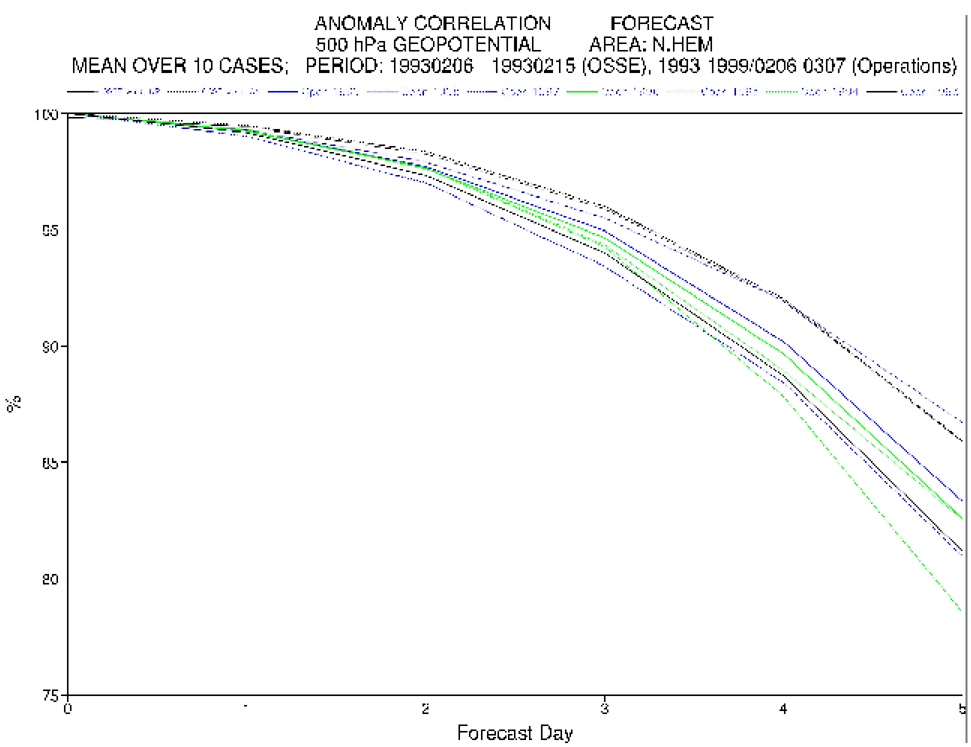

Figure 5: 500 hPa geopotential anomaly correlation between analysis and forecast for the OSSE, and for operational February forecasts for the years 1993 to 1999. For the range 3 to 5 days the OSSE forecast skill is equal to the median and representative for all scores. The OSSE system thus exhibits realistic forecast skill.

However, inaccurate ADM_UV data causes regionally negative impacts. We may conclude from this that

- The tuning of data assimilation systems is very important for achieving beneficial observation impact and OSSE could be used for this;
- Quality control on real ADM_UV observations is very important in cloudy regions.

We rigorously tested the presence of a so-called fraternal twin problem, but found no substantial evidence of such a problem.

Although we have verified in this study that ADM_UV is indeed capable of demonstrating the potential value of space-borne wind profile observations for improving atmospheric analyses and NWP, this study was of a limited nature and more experimentation is recommended, including the use of (A)TOVS or other foreseen extensions of the GOS such as with AIRS or IASI.

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