

Impact assessment of prospective spaceborne Doppler wind lidar observation scenarios

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ABSTRACT

Anticipating on the success of ADM-Aeolus there is a need to specify the wind observation requirements for the definition of an operational network of spaceborne Doppler wind lidars (DWL) in the post-ADM era, beyond 2012. As a first step, Sensitivity Observing System Experiments (SOSE) have been conducted to investigate the added value of various DWL scenarios in real events with bad forecasts. A database of cases covering the worst 2-d forecasts over Europe and North America for each season over the 1998–2004 period was used for this purpose. Considered DWL scenarios include (i) trains of the Aeolus-type instrument to increase the coverage of single wind components, (ii) a scenario having the same coverage as Aeolus but measuring the complete wind vector and (iii) a targeting scenario giving maximum coverage over the storm track regions. For the Northern Hemisphere extratropics it was found that a DWL network providing a geographically uniform sampling is more beneficial for numerical weather prediction (NWP) than a network providing larger but more localized improvements. A network of Aeolus-type satellites fulfils this goal. The added benefits of a second and third Aeolus in orbit are, respectively, 70 and 110% of the benefit of a single Aeolus DWL.

1. Introduction

Forecast failures of high-impact weather are often due to lack of observations over data sparse areas over a prolonged period prior to the extreme event, for example, ESA (1999). The Atmospheric Dynamics Mission (ADM-Aeolus), Stoffelen et al. (2005), will provide wind profiles in otherwise data sparse areas and thus may reduce the number of such forecast failures. ADM is scheduled for launch in 2008 and will be operational until 2011. ADM is a demonstration mission measuring profiles of single horizontal line-of-sight (HLOS) wind components (Marseille and Stoffelen, 2003; Tan and Andersson, 2005) with priority on quality rather than quantity of retrieved winds. Anticipating on its success, there is a need to specify wind observation requirements (both quality and quantity) for the definition of an operational network of spaceborne Doppler wind lidars (DWLs) in the post-ADM era.

The objective of this paper is to test various DWL scenarios on their capability to measure rapidly growing structures not measured by the current global observing system (GOS) therefore potentially causing large forecast failures already on the short term (up to 2 d). We use badly forecast past weather events in this study. The results may be used for the specification of ob-

servation requirements for wind quality and coverage that could serve as input for the design of DWL follow-on missions for operational meteorology in the post-ADM era. In addition, the results provide an indication of the relative merit for NWP of large but localized analysis improvements, for example, through observation targeting strategies, versus geographically more distributed improvements, for example, as brought by a polar orbiting satellite system. This fundamental question fits well in the objectives of international programs like THORPEX, for example, Shapiro and Thorpe (2004), to reduce the occurrence of forecast failures in particular those with large socio-economic impact.

A well established method to assess the impact of existing observing systems for NWP is by so-called Observing System Experiments (OSE), for example, Kelly (2004). OSE cannot be conducted for prospective, yet non-existing, and complementary observing systems. A companion paper, Marseille et al. (2007a), describes a new type of observing system experiment to assess the potential added value of extensions to the GOS in real cases. In this so-called sensitivity observing system experiment (SOSE) a synthetic but realistic atmospheric state, hereafter named pseudo-truth, is defined by adapting the incorrect forecast initial state (analysis) using adjoint sensitivity structures. The pseudo-truth is subsequently used for the simulation of the new instrument. Since the pseudo-truth is constructed such that it is compatible with observations from existing observing systems SOSE requires only the simulation of the new instrument which

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makes it a computationally efficient tool as compared to, for example, full blown observing system simulation experiments (OSSE), see for example, Stoffelen et al. (2006). It was shown in Marseille et al. (2007a) that the correction of the analysis, to generate the pseudo-truth, constitutes that part of the atmospheric structures that are not observed by the existing observing network. New observing systems may fill in to observe these structures. This is verified in analysis and forecast experiments for real cases in the past that were badly forecast. In the analysis real observations from existing observing systems are used in conjunction with synthetic observations from the new instrument and when the new observing system is capable of (partly) observing the otherwise unobserved analysis corrections, it will contribute to improve the 2-d forecast.

A database of badly forecast past events is presented in Section 2. Next, the SOSE experimental setup for these events is described. Clouds play a crucial role to measure complete wind profiles from space by a DWL (Marseille and Stoffelen, 2003; Tan and Andersson, 2005). Section 3 discusses a so-called pre-SOSE or statistical evaluation to provide a first indication of general DWL feasibility to observe sensitivity structures in the presence of clouds. Section 4 describes the simulation of DWL observations for a number of DWL scenarios. These scenarios are evaluated with impact experiments as described in Section 2. The results are discussed in Section 5, culminating in recommendations for the definition of an operational network of spaceborne DWLs to extend the GOS as discussed in Section 6 together with the summary and conclusions.

2. SOSE experiment preparation

A SOSE experiment is composed of three steps (i) definition of a pseudo-true atmospheric state for a real case, (ii) generation of synthetic DWL observations using the pseudo-truth as true atmospheric state and (iii) analysis and forecast experiments using synthetic DWL observations and real observations from all existing observing systems simultaneously in the ECMWF 4D-Var system. The second and third step are discussed in Sections 4 and 5, respectively. For the first step, a database of supposedly poorly observed extreme weather developments is selected for which, consequently, the short-term forecast was relatively poor. Complementing the GOS by a DWL in such poorly observed meteorologically sensitive areas would expectedly improve the forecast skill. In this paper we focus on cases in the Northern Hemisphere extratropics above 30° latitude.

2.1. Database of events with bad forecasts

To monitor the performance of the model, ECMWF archives forecast scores on a daily basis. Archiving is restricted to 12UTC forecasts. The ECMWF verification archive was used to select cases of relatively large forecast failures of the ECMWF model over the period 1/1/1998 until 25/9/2004 with a focus on the ver-

ification areas Europe and North America. For each verification area and for each season the 10 worst 2-d forecasts of 500 hPa geopotential height were selected. The dates and corresponding forecast errors are summarized in Table 1. From the database of 80 cases in Table 1 a selection of 37 highlighted cases was made for the impact experiments such that (i) the main focus is on the worst cases, (ii) the results must be representative for all seasons and (iii) consecutive dates were selected when possible to reduce the computational burden, in particular to minimize the window length for the re-run of cases, see below. An additional case (25 December 1999, 12 UTC) was added to the list, since it falls within the Christmas 1999 storm period and is known as an extreme event used in many case studies. It will be shown that the total number of 38 cases is sufficient to show statistical significance of the results.

2.2. Experimental setup

A proper SOSE experiment requires a sensitivity computation, for the definition of the SOSE analysis correction, see Marseille et al. (2007a), with the same model that produced the forecast. A practical problem is that old model versions that produced the forecast failures in the past, are no longer available for experimentation. Therefore, a re-run of all cases with a recent version of the operational model is required. The model version operational at ECMWF from October 2003 until March 2004 (26r3) was used for this purpose. A re-run experiment for a single case with the 2-d forecast initiated at day dd requires a 4 d experimental window. The re-run is started at $dd - 2$, initiated with model fields from the ERA-40 re-analysis experiments (Uppala et al., 2005). This 2-d lead period is necessary to relax possible biases induced at initial time through the use of different model versions, that is, 26r3 for the re-run and 23r4 that was used for ERA-40. The re-run experiment finishes at $dd + 2$ to provide the verifying analysis for the 2-d forecast that is needed for the sensitivity computation. The re-run experiments use observations from the ERA-40 observation database and the 4D-Var system with a 6-h assimilation window was used for the analysis.

Re-run experiments have been conducted for the 38 cases in the database. It was found that bad forecasts, from older model versions, are still bad for the recent model version, an indication that lack of observations probably caused the forecast failures. Yet, the recent model version performs better on average, an indication of ECMWF model and/or data usage improvement over the last decade, see Fig. 1.

Analyses and forecasts from the re-run experiment are used to define the pseudo-truth and subsequent SOSE analysis correction as described and schematically displayed in Fig. 1 of Marseille et al. (2007a). The procedure is briefly summarized below. The forecast from the background state at day dd is verified against the analysis at $dd + 2$. The resulting forecast error is used as input for an adjoint (background) sensitivity computation using the background error covariance matrix in the initial time norm.

Table 1. Ten worst 2-d forecasts per season of ECMWF 500 hPa geopotential height over the period 1/1/1998 until 25/9/2004. The basedate (yyyymmdd) denotes the start of the 12UTC 2-d forecast. Root mean squared errors (RMSE) have been computed for the verification areas Europe, bounded by (N/W/S/E) (75.0/–12.5/35.0/42.5) and North America bounded by (60.0/120.0/25.0/–75.0). Italics dates have *not* been used in the SOSE experiments

Europe		North America	
Basedate	RMSE	Basedate	RMSE
Winter (December, January, February)			
19990114	52.500	20000201	56.630
20000208	47.982	19990211	53.935
19991226	46.475	20000202	48.832
19990128	45.102	19981213	43.604
19990202	44.279	<i>20011211</i>	<i>42.168</i>
<i>19980108</i>	<i>41.792</i>	19990201	42.010
<i>20000116</i>	<i>41.202</i>	19990210	41.156
<i>19980205</i>	<i>37.907</i>	<i>20020108</i>	<i>40.116</i>
<i>19981208</i>	<i>37.849</i>	19991221	39.044
19981212	37.270	19991218	38.801
Spring (March, April, May)			
19980325	42.273	19990412	60.460
19980326	40.983	<i>20000316</i>	<i>42.285</i>
<i>19980525</i>	<i>36.122</i>	20000330	39.762
19980321	35.533	20000329	39.582
<i>19980322</i>	<i>35.073</i>	<i>20010403</i>	<i>39.419</i>
19980324	34.549	<i>19980503</i>	<i>39.228</i>
<i>19990517</i>	<i>32.985</i>	<i>19980426</i>	<i>35.391</i>
<i>19980422</i>	<i>32.491</i>	<i>19990529</i>	<i>34.741</i>
19980323	32.317	<i>19990325</i>	<i>34.316</i>
19980330	32.197	19980329	33.981
Summer (June, July, August)			
<i>20040613</i>	<i>27.751</i>	19980603	32.263
<i>19990618</i>	<i>27.543</i>	<i>20000612</i>	<i>30.351</i>
19980611	27.417	<i>20000619</i>	<i>29.416</i>
19980607	27.015	19980610	29.283
<i>19990624</i>	<i>26.970</i>	<i>20000611</i>	<i>28.268</i>
<i>20010617</i>	<i>25.707</i>	<i>19990604</i>	<i>27.374</i>
19980613	25.564	<i>19990614</i>	<i>26.323</i>
<i>19990615</i>	<i>25.506</i>	<i>19980621</i>	<i>25.579</i>
<i>20020815</i>	<i>25.356</i>	<i>20020801</i>	<i>25.447</i>
<i>19990601</i>	<i>25.345</i>	19980609	25.407
Autumn (September, October, November)			
<i>20001012</i>	<i>43.533</i>	19981004	56.571
19991028	39.006	<i>19981127</i>	<i>41.826</i>
19981007	38.857	19981005	38.878
<i>19981129</i>	<i>35.797</i>	<i>20031117</i>	<i>35.860</i>
<i>19980913</i>	<i>34.094</i>	20011011	35.568
<i>20000924</i>	<i>33.925</i>	19991029	35.279
<i>19991116</i>	<i>33.648</i>	<i>20001123</i>	<i>33.967</i>
<i>19981125</i>	<i>33.447</i>	20011012	33.839
<i>20000925</i>	<i>33.215</i>	<i>20011126</i>	<i>33.810</i>
<i>20011122</i>	<i>32.623</i>	<i>19991015</i>	<i>33.190</i>

The resulting key background error is used to correct the background. The corrected background is merged with observations from existing observing systems in an analysis to generate the SOSE analysis (pseudo-truth). The SOSE analysis correction is defined as the difference between the pseudo-truth and control analysis, using the GOS only, and constitutes that part of the atmospheric structures not observed by the existing GOS. Figure 2 shows that the energy of **B**-matrix norm sensitivities peaks near 350 hPa with maximum energy in the large-scales (about 1500 km near wavenumber 13) in agreement with Marseille et al. (2007a). The sensitivities are adapted by existing observations in the subsequent analysis. This reduces the energy in the resulting SOSE analysis corrections because of reduced amplitude of the sensitivity structures over the data dense continents where the analysis is generally already good. This also explains the peak at wavenumber 2 in the lower right-hand panel of Fig. 2, that represents land-sea transition, that is, regions with minimum and substantial correction of the analysis. In addition, from the lower panels it is concluded that observations flatten the spectrum, introducing smaller scale structures in the SOSE analysis correction, compatible with real analysis errors, see Marseille et al. (2007a).

A potential problem of measuring winds with a DWL from space is the presence of clouds. Optically dense clouds obscure the underlying atmosphere and potentially limit the lidar beam to penetrate the lower atmosphere. This would imply that any DWL scenario will have no or very limited impact in case that meteorologically sensitive areas, not observed by the existing GOS, are covered by optically dense clouds. To address this issue, SOSE analysis corrections have been computed for a selection of cases in the database, see Table 1. Next, the correlation of these corrections with cloud presence is examined in a so-called pre-SOSE statistical analysis. It is shown that cloud poses no fundamental problem for impact assessment of DWL scenarios through SOSE.

3. General feasibility of DWL to detect SOSE analysis corrections

A first indication of potential impact of a DWL in a SOSE is by correlating the analysis corrections, defining the pseudo-truth, with clouds. In the worst case, there is a strong correlation between meteorologically sensitive areas and overlying dense clouds. Then any DWL scenario will fail to observe the sensitive structures, not observed by the current GOS, thus limiting SOSE as a useful tool to discriminate between the added value of different DWL scenarios.

Here we adopt the method of McNally (2002). to correlate SOSE analysis corrections with ECMWF model clouds. Let P be the absolute value of the SOSE analysis correction, to avoid cancellation of positive and negative corrections, and F a function that describes the observability of the phenomenon. We define observability as a function of overlaying cloud cover, C_c ,

Fig. 1. Scatterplots of 500 hPa 2-d forecast error of geopotential height ($\times g^{-1}$) (m) for the operational model (OPER) at the time of the event versus a recent (26r3, 2003) model cycle (RE-RUN), (a) over Europe and (b) over North America. Each cross corresponds to one of the 38 cases. The red diamond denotes the mean value of all cases. The straight solid line represents equal quality of both models.

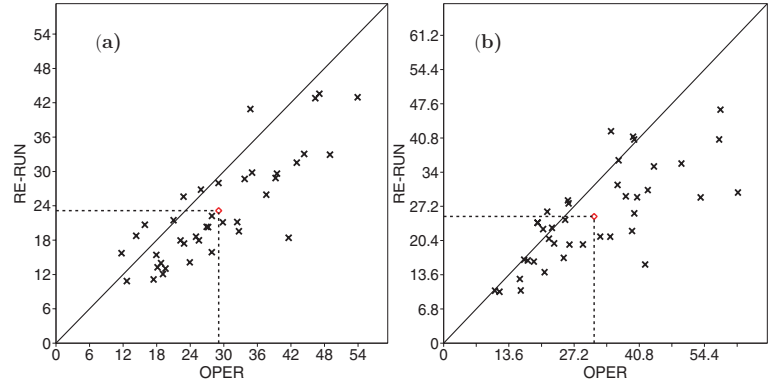
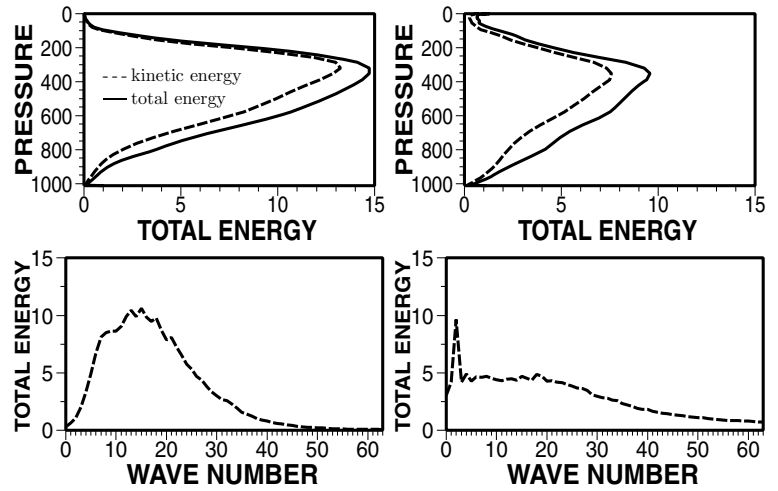


Fig. 2. Mean vertical profiles of total energy (top row) and the horizontal total energy spectrum (bottom row) in $\text{kg m}^2 \text{s}^{-2}$ for **B**-matrix norm background sensitivities (left-hand column) and SOSE analysis corrections (right-hand column). The mean is taken over the cases in Table 1. Dashed and solid lines in the top row correspond to kinetic and total energy, respectively.



and two-way cloud transmission, τ_c , as follows

$$F(C_c, \tau_c) = (1 - C_c) + C_c \cdot \tau_c \quad (1)$$

therefore taking into account observability in scenes of broken cloud and the penetrating properties of laser light for optically thin cloud layers such as cirrus. Values for C_c and τ_c and thus for F are between 0 and 1. In case of multiple cloud layers the value of the layer with the largest coverage is used for C_c . Values for F are computed for each model grid box. The observed analysis correction, P^* , is defined through

$$P^* = \overline{P \cdot F(C_c, \tau_c)}, \quad (2)$$

the overbar denoting the average over a number of cases. We define analysis correction observability, P_{obs} , through

$$P_{\text{obs}} = \frac{P^*}{\overline{P}} \times 100\%. \quad (3)$$

The maximum value of 100% for P_{obs} is reached in case of a cloud-free atmosphere for which $C_c = 0$. The minimum value of 0% is reached in case of complete cloud cover, $C_c = 1$, and the overlying clouds completely obstructing the transmission of laser light, that is, $\tau_c = 0$.

The methodology described above has been applied to the 38 SOSE analysis corrections discussed in the previous section. Model cloud was used for cloud cover and cloud transmission where the latter is determined from a parametrization using model cloud liquid water and cloud ice content (Marseille and Stoffelen, 2003). The left-hand panels in Fig. 3 show the mean analysis correction with maximum amplitude over the data sparse oceans in the mid-troposphere. Note that the amplitude of the analysis corrections is smaller than real analysis errors as a consequence of the implementation of SOSE in single-cycle mode, see Marseille et al. (2007a). From the right-hand panel it is clear that despite the presence of clouds still a substantial part of these structures are observable for a DWL. The corresponding observability according to eq. (3) is 75% at 500 hPa. Similar results have been produced at other pressure levels, see Table 2. Taking into account that most of the energy in the analysis corrections is located in the upper troposphere near 350 hPa, see Fig. 2 it is clear that most of the corrections may be well observed by a spaceborne DWL.

The same procedure has also been applied to the 2-week OSSE period of February 1993 as discussed in Marseille et al. (2007a) and the result (not shown) is quite similar to the winter result in

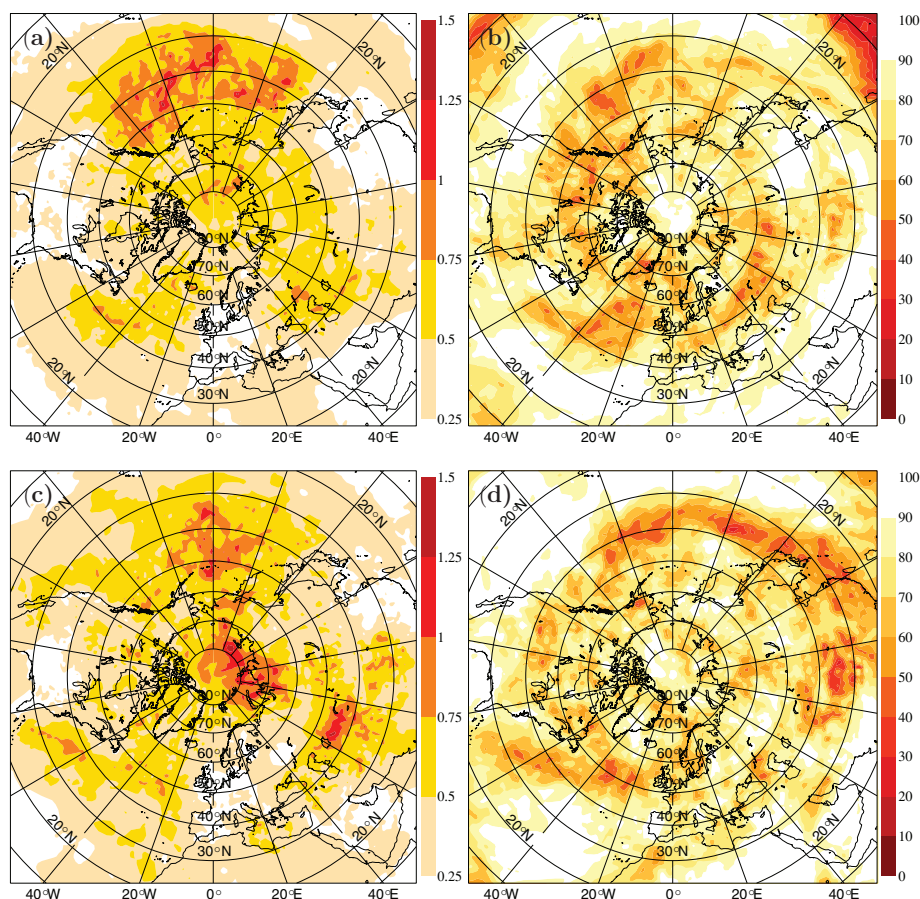


Fig. 3. SOSE analysis correction observability. Left-hand panels, mean 500 hPa SOSE wind analysis corrections (ms^{-1}), $\bar{P}$, for selected cases in Table 1. Right-hand panels, DWL observability (%) P_{obs} , eq. (3), of the corrections in the left-hand panels. The top row corresponds to autumn/winter cases, the bottom row to spring/summer cases.

Table 2. SOSE analysis observability (%) by spaceborne DWL as a function of pressure and season. Percentages correspond to averaged values over the global regions Northern Hemisphere/Atlantic/Pacific defined through (N/S/W/E) is (90/20/–180/180), (75/20/–75/–5) and (75/20/140/–120), respectively

Percentage	200 hPa	500 hPa	700 hPa	1000 hPa
Autumn/winter	99/99/99	75/75/73	63/63/61	41/38/32
Spring/summer	99/99/99	73/73/75	63/64/64	41/37/33

Fig. 3. Most striking difference are the larger areas over the European and North American continents with negligible analysis correction for the OSSE period that can be explained by the more dense continental network of radiosondes in the early 1990s. In addition, the amplitude of the analysis corrections is larger over the data sparse oceans for the 1993 period which can be explained by a more sparse observing network over the oceans in the OSSE experiment (No TOVS radiances, less AIREPS) than the current GOS. Consequently, nowadays analysis errors are smaller over the oceans than in the 1993 OSSE, requiring less adaptation.

The presented observability of sensitivity structures is more optimistic for an active satellite system like a DWL than for passive infrared satellite radiance instruments like IASI and AIRS, showing that the presence of clouds is more serious for passive sounders in particular for large amounts of high clouds, McNally (2002). High cirrus clouds are generally transmissive for a lidar and the horizontal oversampling of ADM-Aeolus will generally still provide good quality observations in partially cloudy scenes from the shots in between (Marseille and Stoffelen, 2003; Tan and Andersson, 2005). Finally, in McNally (2002) the total energy norm was used at initial time in the sensitivity computation giving most of the energy of the sensitivity structures lower in the atmosphere, near 600 hPa, than when using the background error covariance matrix at initial time as in SOSE, producing more realistic balanced structures with a maximum energy near 350 hPa, see Fig. 2, and thus less sensitive to clouds.

4. Simulation of DWL scenarios

The five DWL scenarios used in the SOSE impact experiments are described in the next subsection. Next, the procedure of

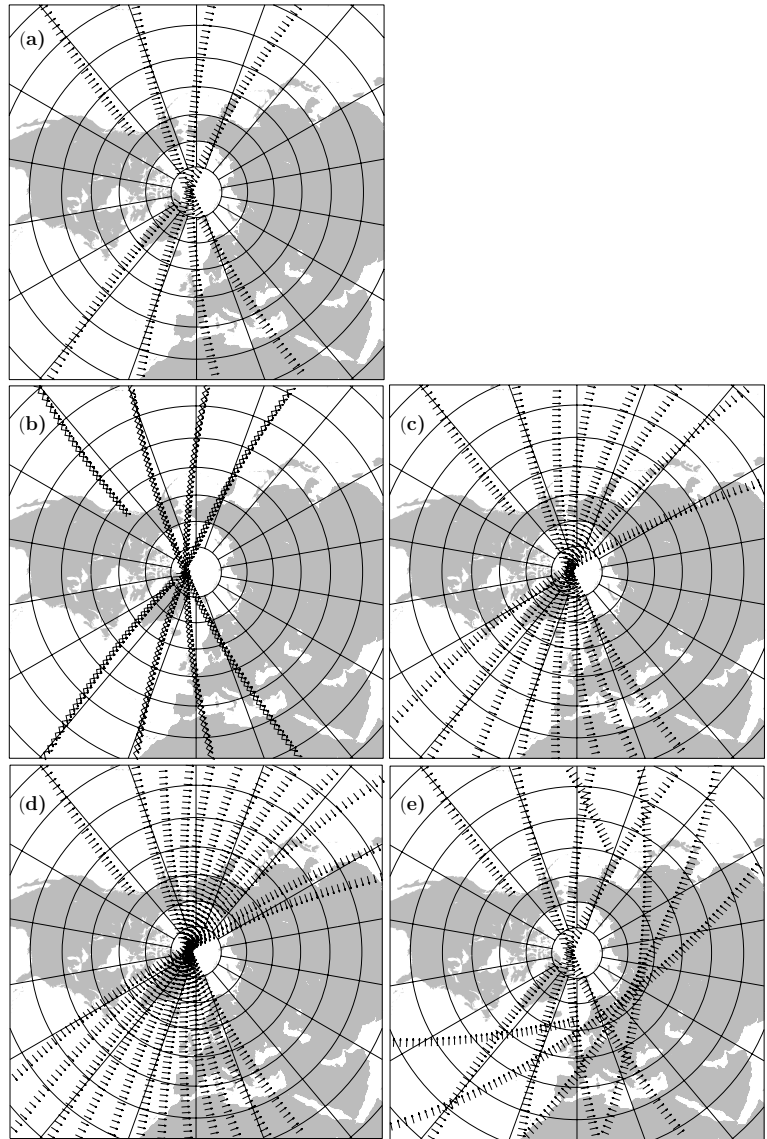


Fig. 4. Six hour coverage of DWL scenarios (a) Aeolus, (b) dual-perspective, (c) tandem-Aeolus, (d) triple-Aeolus and (e) dual-inclination. Arrows denote the wind profile locations and instrument view angle.

DWL observation simulation, including observation errors, is described.

4.1. DWL sampling scenarios

The main driver for the selection of possible future candidates for an operational DWL mission is to build on the heritage of Aeolus, anticipating on its success. To achieve increased coverage and/or dual-perspective capability, constellations of Aeolus-type instruments are proposed. The following five DWL scenarios are considered.

4.1.1. Aeolus. Aeolus is the reference scenario, measuring profiles of HLOS wind components. Aeolus flies in a dawn-dusk orbit with 97.2° inclination angle. The DWL is a single-perspective instrument, scanning at 90° with respect to the satellite track, that is, looking to the right-hand side. A profile of line-

of-sight wind components is obtained every 200 km along track. More detailed information on Aeolus is found in, for example, (ESA, 1999; Marseille and Stoffelen, 2003; Tan and Andersson, 2005; Stoffelen et al., 2006). Figure 4a gives an indication of data coverage. Because we focus on the Northern Hemisphere extratropics, the satellite track locations have been selected to maximize DWL coverage over the data sparse oceans, where maximum added value of DWL is expected, in agreement with the left-hand panels in Fig. 3.

4.1.2. Dual-perspective scenario (DP). The data coverage of the dual-perspective scenario is identical to Aeolus but this scenario measures the complete wind vector by measuring two line-of-sights with a 90° difference in azimuth angle, see Fig. 4b. There are several possible implementations to accomplish a dual-perspective scenario, for example, by a single satellite carrying two lasers or two satellites in one orbit, both with a single

laser operated at different viewing angles. The pros and cons of these implementations is not an issue of this study, merely the yield of the ensuing wind observations for NWP.

The number of wind component profiles measured by the dual-perspective scenario is twice the number of Aeolus. Since both lasers point at different angles it is possible, in principle, to collocate both observations to retrieve wind vector profiles, although this is not a pre-requisite for use in NWP.

4.1.3. Tandem-Aeolus scenario (T_2A). In this scenario two Aeolus satellites are positioned in the same orbit plane, with a phase difference of 180° or about 50 min. The distance between both observation tracks is 12.5° longitude or about 1400 km at the equator, 700 km at 60° latitude and 240 km at 80° latitude, therefore showing a minimum of observation redundancy even at high latitudes, see Fig. 4c.

The number of wind component profiles measured by the tandem-Aeolus scenario is twice the number of Aeolus and equals the number of single-component profiles of the dual-perspective scenario, that is, the tandem-Aeolus scenario and the dual-perspective scenario have equal numbers of HLOS component measurements. Note that some wind vector information is obtained near the poles, despite the single-perspective view.

4.1.4. Triple-Aeolus scenario (T_3A). To complete the picture of trains of Aeolus' in orbit, this scenario adds a third Aeolus. The three Aeolus instruments are positioned in the same orbit plane with a phase difference of 120° . Observation redundancy increases in particular at higher latitudes, see Fig. 4d, so it is expected that more than three Aeolus in orbit will result in substantial wind profile redundancy. The number of wind component profiles measured by this triple-Aeolus scenario is three times the number of Aeolus.

4.1.5. Dual-inclination scenario (DI). This scenario includes two Aeolus-type satellites in separate orbit planes and with different inclination angles of 97.2° , as for Aeolus, and 70° . The rationale behind this scenario is that two Aeolus-type satellites in orbit planes with different inclination angles enable targeting of a specific geographic region, for example, the storm-track region with a 70° inclination angle, see Fig. 4e. In addition, observation redundancy near the poles is reduced and a DI scenario mimics a dual-perspective scenario in regions where the tracks cross, using Aeolus-type (single HLOS) satellites. We note that the technical feasibility of a DWL in a 70° inclined orbit is unfavourable due to loss of several Aeolus design optimizations.

The number of wind component profiles measured by the dual-inclination scenario is twice the number of Aeolus and equals the number of single-component profiles of the dual-perspective and tandem-Aeolus scenarios.

4.2. DWL simulation

For the simulation of HLOS wind components and its error characteristics the lidar performance analysis simulation tool (LIPAS), as described in Marseille and Stoffelen (2003), has been

used that is briefly summarized here. First, an orbit simulation is performed to locate the positions of the DWL profiles. Atmospheric parameters are retrieved from the pseudo-truth fields and spatially interpolated (both horizontally and vertically) to the DWL locations as in Fig. 4. We assume that all DWL observations within a 6-h time window are measured at a single time instant and as such no time interpolation is required. Interpolated winds are used for the simulation of profiles of HLOS wind components for the given satellite geometry. Interpolated temperature and cloud variables are used to compute the cloud optical properties and cloud penetrating capability of the lidar beam. The ADM-Aeolus lidar is operated at 355 nm wavelength in the ultraviolet part of the electromagnetic spectrum. As the laser light penetrates the atmosphere, part of the signal is scattered back to the instrument by molecules and particles (aerosol, cloud). The collected signal is processed to retrieve the Doppler shifted frequency of encountered particles and molecules that is directly related to the velocity of the ambient wind. The quality (error) of retrieved wind is related to the strength of the collected signal which in turn is a function of atmosphere scattering and extinction properties. Molecular scattering and extinction is well known from physical principles given the atmospheric temperature. Aerosol backscatter and extinction are much less well known and show large variability over the globe, both spatially and temporally, see for example, Vaughan et al. (1995), Winker et al. (1996), Spinhirne et al. (2005). The same approach as described in Marseille and Stoffelen (2003) has been adopted to extract vertical profiles of aerosol backscatter and extinction from a climatology database. Due to lack of information on atmosphere scattering variability over the 50 km Aeolus accumulation length a horizontally homogeneous aerosol distribution was assumed.

The instrument hardware equipment separates the collected molecular and particle signals. Both signals are processed independently, giving two HLOS wind solutions for each altitude bin, from which the one with the lowest expected standard deviation of error is selected. The resolution of retrieved wind profiles is 500 m between 0 and 2 km, 1000 m between 2 and 16 km and 2000 m between 16 and 26 km. Typical values for the standard deviation of HLOS wind errors, including representativeness error, are $1\text{--}2\text{ ms}^{-1}$ in the boundary layer, $2\text{--}3\text{ ms}^{-1}$ up to 15 km and $3\text{--}4\text{ ms}^{-1}$ between 15 and 26 km, see Marseille and Stoffelen (2003). No bias and no correlation have been assumed for the simulation of HLOS wind errors. The simulated DWL profiles have been archived in BUFR format at ECMWF.

5. Results

This section presents the results of the SOSE experiments conducted for 38 cases selected from the database of bad 2-d forecasts in Table 1. The impact of the various DWL scenarios is measured by their capability to resolve the SOSE analysis corrections and the subsequent forecast improvement. It will be shown that 38 cases is sufficient to show statistical significance

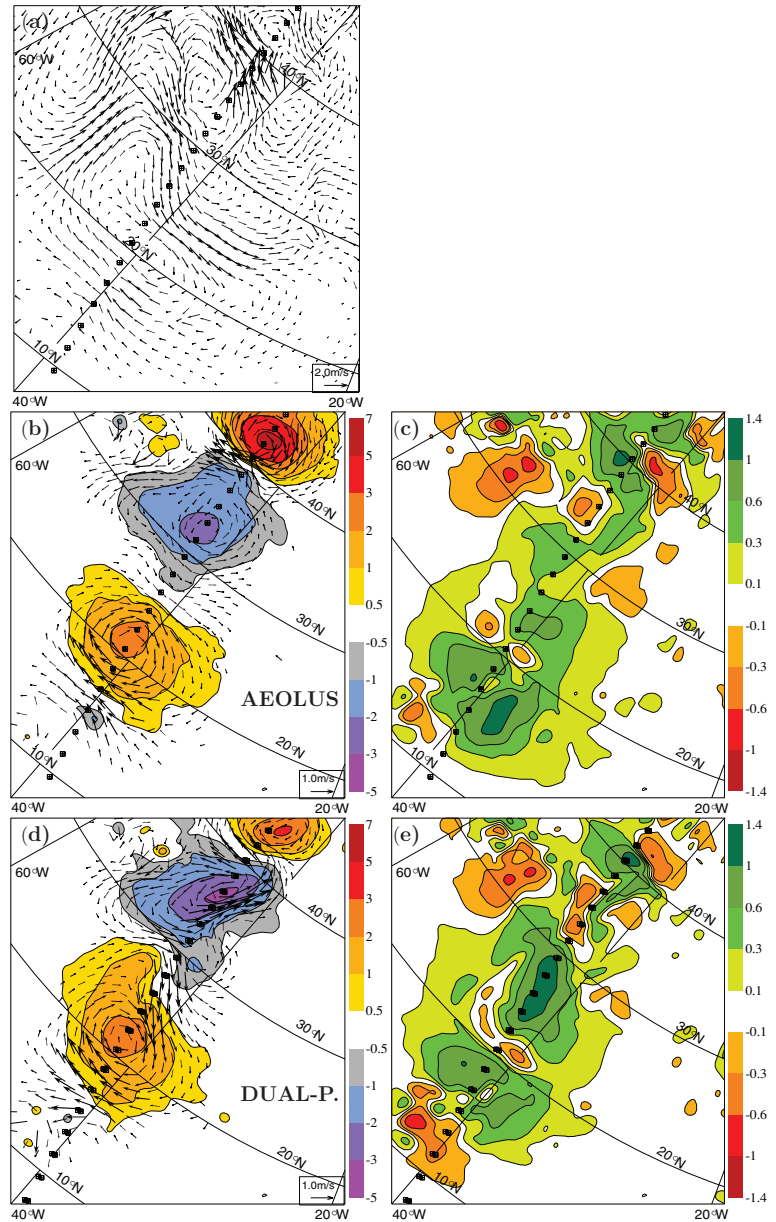


Fig. 5. DWL impact at 500 hPa over the Atlantic for case 28 January 1999 12UTC. (a) Reference SOSE analysis correction. Wind (ms^{-1}) and geopotential height ($\times g^{-1}$) (m) analysis increment for the Aeolus (b) and dual-perspective (d) scenario and analysis impact for the Aeolus (c) and dual-perspective (e) scenario. Overlaid are the DWL locations along the satellite track. green/red shaded areas denote positive/negative DWL impact. Note the different unit lengths for the wind arrows in panel (a) and panels (b, d).

of the results. First, the added value of measuring the complete wind vector (dual-perspective scenario) instead of a single HLOS wind component (Aeolus) is demonstrated in a case study.

5.1. Case study

The 2-d forecast initiated at 28 January 1999 12 UTC resulted in a bad forecast of the flow over Europe (not shown). An experiment using existing observations only is in the remainder denoted control or NoDWL experiment. The scheme in Fig. 1 of Marseille et al. (2007a) produces the pseudo-truth and subsequent SOSE analysis correction (pseudo-truth minus control analysis) as displayed in Fig. 5a. Overlaid are the DWL loca-

tions along the satellite track for the Aeolus and dual-perspective scenario. Note that for the latter scenario two LOS wind components, separated by 90° , are measured at each location thus resolving the complete wind vector in principle. Further it is noted that Fig. 5 only shows the result at 500 hPa but in fact the SOSE analysis correction extends over the complete three-dimensional atmosphere.

The pseudo-truth is used for the simulation of DWL winds for both scenarios. Next, a new analysis is performed, initiated with the same background that yielded the control analysis, using real existing observations only, but now using synthetic DWL observations in addition. These experiments are in the remainder denoted (SOSE) DWL experiments.

Figures 5b and d show the analysis increments induced by DWL for the Aeolus and dual-perspective scenario, respectively. These are most substantial close to the satellite track as expected and show relevant analysis characteristics. The analysis is dominated by the spatial filter functions that constrain mainly barotropic (vertical) and rotational fields. A wind component increment perpendicular to the track would as such provide both a vortex in the uptrack and the downtrack direction, albeit of opposite sense. Moreover, the filter structure functions are balanced in wind and temperature, such that the uptrack and downtrack vortex centres are associated with a positive and negative temperature increment. The sign of both the vortex and temperature increment depend on the sign of the ADMLOS wind innovations, that is, left or right to the track. Since for Aeolus all increments are perpendicular to the flight track, this means that we expect both vortex centres and temperature increments centred on the ADM track. On the other hand, for the dual perspective scenario, the wind innovations can be in any direction and therefore imply off-track vortices.

The resolved vortex structure Fig. 5b and d near (22N, 41W) is quite similar for both scenarios. The added value of measuring the complete wind vector instead of a single wind component is clear when zooming in to the inclined wind structure over the Atlantic at (25N, 42W) in Fig. 5a. Aeolus is not well capable to resolve this structure in Fig. 5b, while the dual-perspective scenario resolves this structure much better, see Fig. 5d.

We note that increments for the single perspective scenarios are not purely zonal, nor are vortices always precisely on the track. The main reason is in the temporal consistency that is required in the 4D-Var approach, and in the ADM oversampling of the spatial structure functions, both in the horizontal, along-track, and vertical directions, providing some redundancy in the measurements.

Although illustrative, analysis increments do not provide a clear answer on the added value of different DWL scenarios for NWP, because increments can be beneficial, reducing the analysis error, or detrimental, increasing the analysis error. Therefore, we define analysis impact, Δ_{an} , as the difference between the absolute values of the analysis errors for the control and SOSE DWL experiments:

$$\Delta_{an} = |x_a^c - x_t^p| - |x_a^d - x_t^p|. \quad (4)$$

Here, x_a^c and x_a^d denote the analysis for the NoDWL and DWL experiment, respectively, and analysis error is defined with respect to the pseudo-truth, x_t^p . Δ_{an} is a matrix with elements corresponding to model field grid points. Positive/negative elements imply a positive/negative impact of DWL observations on the analysed meteorological parameter.

Figure 5c and e show analysis impact for the Aeolus and dual-perspective scenario, respectively. On average, the impact of DWL observations to the analysis is positive for both scenarios. Their performance is quite similar near the lowest vortex centred at (22N, 41W), however the inclined structure in be-

tween the lowest and middle vortex is better resolved by the dual-perspective scenario. On the other hand, the shape of the middle vortex is quite different giving better performance of Aeolus locally, for example, near (36N, 40W) and (44N, 42W).

5.2. DWL impact statistics

The added value of the five DWL scenarios for NWP is assessed by SOSE based on the 38 selected cases described in Section 2.

5.2.1. DWL impact on analyses. For a large sample of cases, the root-mean-square (RMS) instead of the absolute value is used in Eq. (4) to compute analysis impact. Figure 6 shows the analysis impact for the five DWL scenarios based on NoDWL and DWL experiments. From the geographical distribution it is concluded as follows:

(1) Analysis corrections induced by DWL observations are limited to regions close to the satellite track in single time SOSE experiments as conducted here.

(2) The impact over the Pacific is substantially larger than over the Atlantic for all DWL scenarios, mainly because the analysis corrections are larger over the Pacific on average.

(3) The large positive impact (solid areas) over the North Pole is due to the large DWL coverage.

(4) Negative impacts (dotted areas) are mainly found over land where analysis corrections are relatively small in particular over data dense areas. Although the DWL weight correction reduces the impact of DWL over these areas, see Marseille et al. (2007a), their weight still seems too large occasionally resulting in negative impact. This is an indication that a more sophisticated weight correction than the simplistic scheme proposed in Marseille et al. (2007a) is needed.

(5) Although improvements off the track can be noted for DP, it is clear that DP performs best close to the satellite tracks. On the other hand, the additional coverage of T₂A helps in resolving large-scale zonal corrections and performance is more spatially uniform.

(6) The added value of having a third Aeolus-type satellite in orbit is mainly limited to the Atlantic region. Here, the analysis has improved with more than 15% as compared to T₂A, see Table 3. The Northern Pacific is already well covered by the T₂A scenario. An additional satellite improves the analysis by less than 5%.

(7) The more exotic dual-inclination scenario aims at maximizing DWL coverage over the storm track regions. This scenario is also motivated by the fact that high latitudes are already well covered by Aeolus. A disadvantage of this scenario is a relative large coverage over the data dense continents giving not much added value there. As expected, DI performs worse on average as compared to DP and T₂A with the same number of observations. However, from Fig. 6 and Table 3 it is concluded that DI is capable to provide better analyses over the targeted Atlantic region, an indication that a targeting strategy may be beneficial.

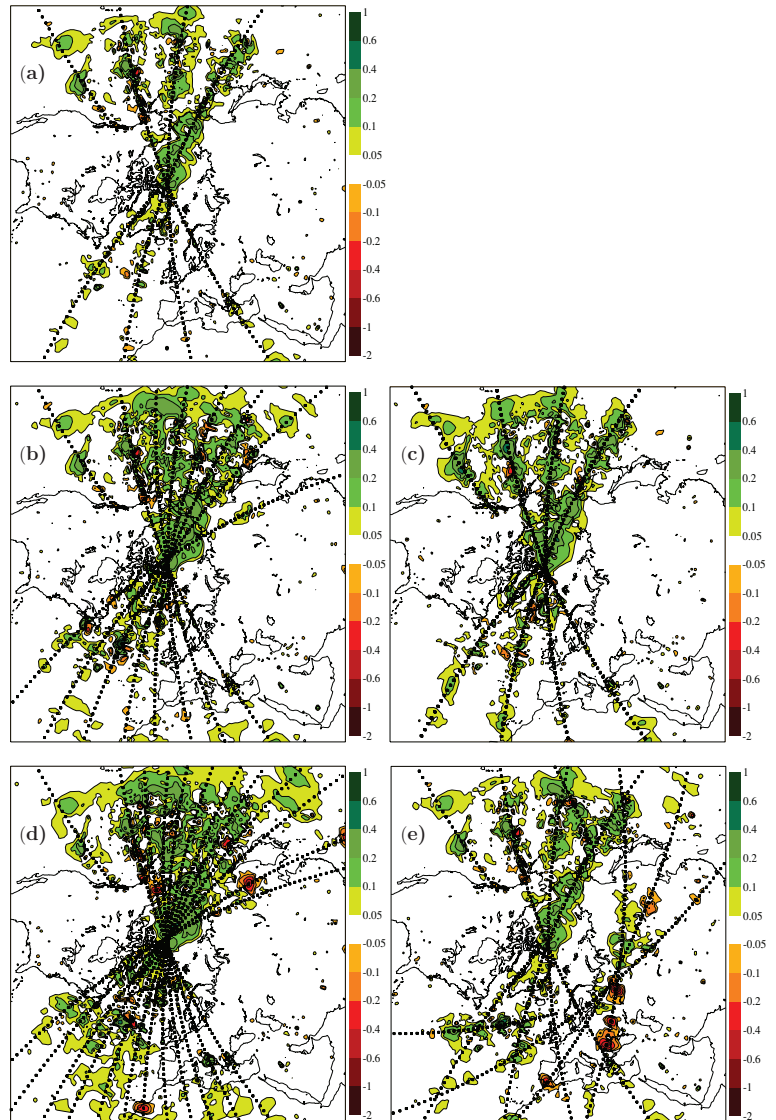


Fig. 6. DWL impact on 500 hPa wind analysis (ms^{-1}), averaged of 38 cases for five DWL scenarios: (a) Aeolus, (b) tandem-Aeolus, (c) dual-perspective, (d) triple-Aeolus and (e) dual-inclination. Solid/dotted areas denote positive/negative impact. Overlaid are the DWL satellite tracks, representing 6 h of orbiting.

Table 3 summarizes the analysis impacts from Fig. 6 for four verification areas: North Atlantic, North Pacific, North Pole and the complete Northern Hemisphere extratropics. These regions have been selected because of their relative large DWL coverage, in particular for the first three regions. From Table 3 it is concluded that T_2A improves the analysis by 76% as compared to Aeolus when averaged over the extra-tropical Northern Hemisphere. DP achieves a 65% analysis improvement. The performance of DP is better over the Pacific, but note the larger number of observations over this area for DP than for T_2A . Both scenarios do not double the impact of Aeolus, indicating some redundancy in the DWL observations in particular at high latitudes.

Values for analysis impact in Table 3 may seem rather small, in the order of a couple of (cm s^{-1}). This is because of a relative small DWL coverage over the verification areas and noting that analysis corrections induced by DWL observations are limited

to regions close to the satellite track in single time SOSE experiments as conducted here. We note that analysis corrections close to the satellite are in the order of ms^{-1} , see for example, Fig. 5.

The plots in Fig. 7 give an indication of the spread of analysis impact for the 38 cases and are as such an indication for the statistical significance of the results in Table 3. This can be checked through a statistical Student's t -test that provides a confidence level for accepting the hypothesis that one scenario performs better than the other, based on sample size and the sample standard deviation. For the Northern Hemisphere verification area we conclude that

(1) Dual-perspective is better than Aeolus with more than 99.9% confidence. Note from Fig. 7 that due to the statistical nature of data assimilation, occasionally negative impacts may occur, see for instance the dotted areas in Fig. 5. The same

Table 3. Mean DWL impact on 500 hPa wind analysis, Δ_{an} (ms^{-1}), see eq. (4) for five DWL scenarios: Aeolus, dual-perspective (DP), tandem-Aeolus (T_2A), dual-inclination (DI) and triple-Aeolus (T_3A) and global regions (N/S/W/E) are N.Hemis (90/20/–180/180), N.Atlantic (75/20/–55/–12.5), N.Pacific (75/20/145/–130), N.Pole (90/75/–180/180). The mean is taken over 38 cases

(ms^{-1})	N.Hemis	N.Atlantic	N.Pacific	N.Pole
Aeolus	0.017	0.017	0.042	0.044
DP	0.028	0.022	0.068	0.069
T_2A	0.030	0.033	0.063	0.078
DI	0.021	0.035	0.047	0.045
T_3A	0.033	0.038	0.066	0.092

argument applies to explain that sometimes (7 out of 38 cases) Aeolus performs better than dual-perspective.

(2) Tandem-Aeolus is better than dual-perspective with 85% confidence

(3) Triple-Aeolus is better than tandem-Aeolus with 90% confidence.

These results show that flying more DWLs in space improves the analyses as expected, but also that the additional impact of a third Aeolus is less than for an additional second Aeolus in one orbit, demonstrating redundancy when flying more Aeolus-type instruments. Also, comparing the performance of tandem-Aeolus and dual-perspective it is concluded that although the overall performance is in favour of the former, the sample of 38 cases is somewhat limited to draw a firm conclusion at this stage.

5.2.2. *DWL impact on forecasts.* Forecast impact of DWL observations, Δ_{fc} is defined as the difference of the RMSE of the forecasts, x_f^c , initiated with the control (NoDWL) analysis and of the RMSE of forecasts, x_f^d , initiated with the DWL analyses:

$$\Delta_{fc} = \text{RMSE}(x_f^c, x_v^c) - \text{RMSE}(x_f^d, x_v^c) \quad (5)$$

similar as in the previous section for analysis error. The forecasts are verified against the analysis, x_v^c , 2 d later. A positive/negative

value for Δ_{fc} implies a positive/negative impact of DWL observations on the 2-d forecast over the verification area. Figure 8 shows the geographical distribution of the mean forecast improvement as achieved by the five DWL scenarios and a reference maximum achievable improvement from a complete recovery of the pseudo-truth. Again, T_2A performs better over Europe, but DP performs better over North America as expected from the larger DWL coverage and the resulting better analyses over the Pacific, see the previous section. Also the additional impact of a third Aeolus for the Atlantic and Europe is clear when comparing the T_2A and T_3A impacts.

The results are summarized in Table 4 for a number of verification areas. Again, the values of forecast improvement may seem small, in the order of decimetres to metres. However, taking into account an average ECMWF model improvement of 1 m yr^{-1} over the last 15 yr for the Northern Hemisphere 500 hPa geopotential height field, WMO (2004), the 0.53 m improvement for Aeolus up to 1 m for T_3A is substantial, considering that SOSE experiments were conducted in single-cycle mode using 6-h of DWL observations only.

Table 5 shows that the forecast improvement is not limited to 500 hPa 2-d forecasts but extends to the medium-range and other pressure levels. Here, mean values over the entire extratropical Northern Hemisphere are presented which provides a fair comparison between the DP and T_2A scenarios because of an unevenly distribution of DWL observations over the oceans, in particular over the Pacific. At day 5 the forecast improvement has more than doubled compared to day 2. On the short term up to day 2 the forecast improvement is largest near 500 hPa, where the SOSE analysis adaptations have maximum amplitude, see Marseille et al. (2007a). Upward propagation of the adaptations gives maximum forecasts improvements near 200 hPa at day 5. After day 5 the forecast impact drops. This is not surprising since model errors rather than errors in the forecast initial state dominate the forecast error in the far medium range. Surprisingly this drop of impact is not observed for the tandem-Aeolus scenario.

Figure 9 shows the case-by-case impact of DWL on the forecast of the 500 hPa geopotential height field. From a statistical

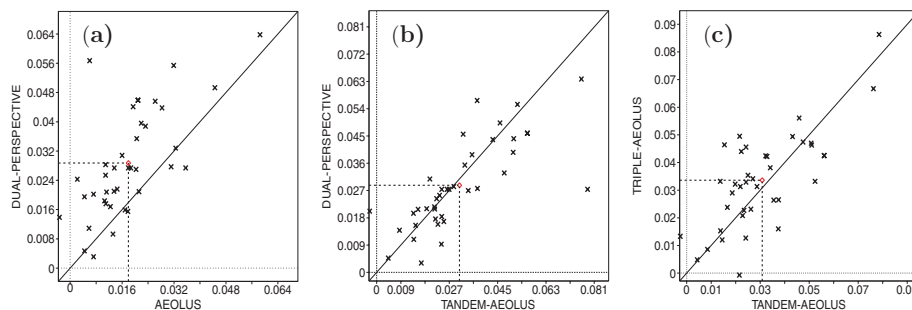


Fig. 7. Scatterplots of DWL impact on 500 hPa wind (ms^{-1}) analyses for (a) Aeolus versus dual-perspective, (b) tandem-Aeolus versus dual-perspective and (c) tandem-Aeolus versus triple-Aeolus. The verification area is the Northern Hemisphere extratropics above 20°N. Each cross corresponds to one of the 38 cases. The red diamond indicates the mean value of all cases. The straight line represents equal impact of both scenarios.

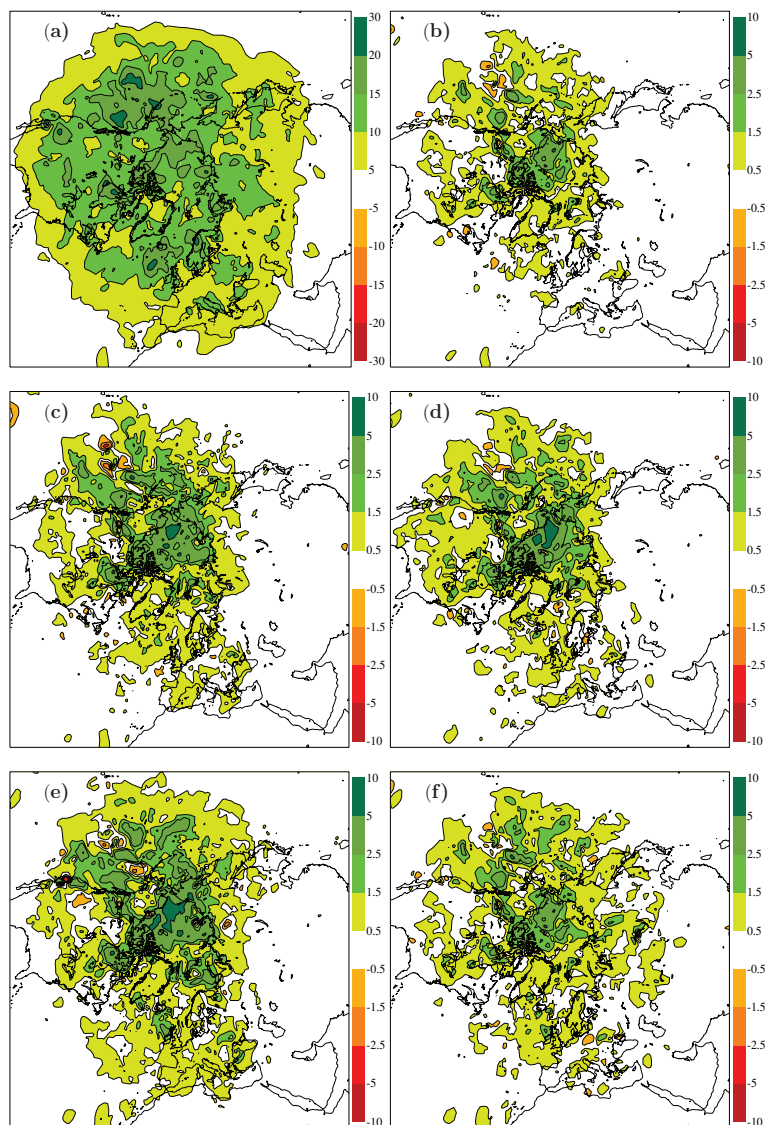


Fig. 8. DWL impact on 2-d forecast of 500 hPa geopotential height (m), averaged over 38 cases for (a) reference, maximum achievable impact from a complete recovery of the SOSE analysis correction and five DWL scenarios: (b) Aeolus, (c) tandem-Aeolus, (d) dual-perspective, (e) triple-Aeolus and (f) dual-inclination. Solid/dotted areas denote positive/negative impact.

Student's t -test it is concluded that:

- (1) Dual-perspective is better than Aeolus with more than 99.9% confidence.
- (2) Tandem-Aeolus is better than dual-perspective with 97% confidence.
- (3) Triple-Aeolus is better than tandem-Aeolus with more than 99.9% confidence.

The additional impact of a second Aeolus in orbit is clear from these results, but also the added value of a third Aeolus in orbit is more clear when considering forecast impact than analysis impact in the previous section. This again shows that small analysis improvements in meteorologically sensitive areas may result in large forecast improvements. Also, the tandem-Aeolus scenario samples sensitive areas significantly better than dual-perspective.

The conclusions still hold when discriminating between regions of extreme and common events, where the operational forecast is already reasonable. This is not shown here, but results may be found in fig. 4.15 of Marseille et al. (2006) that shows a similar picture as Fig. 9b but discriminating between extreme and common events. The DWL impact on the forecast of common events is smaller on average as expected but still substantial. This is explained by the fact that the DWL analysis impact is rather similar for both type of events because the SOSE analysis corrections are of the same order of magnitude for both extreme and common events. The main difference is in the growth rate of these structures. This result is important for operational NWP showing consistency of the conclusions for all weather events.

Another way of presenting forecast impact is by relating the achieved forecast improvements from Table 4 to the maximum

Table 4. Mean DWL impact on the 2-d forecast of 500 hPa geopotential height (m) for five DWL scenarios: Aeolus (A), dual-perspective (DP), tandem-Aeolus (T₂A), dual-inclination (DI) and triple-Aeolus (T₃A) and global regions are (N/S/W/E) are NHem (90/30/–180/180), Eur (75/–12.5/30/45), NATl (75/30/–55/–12.5), NAmer (75/–130/30/–55), NPac (75/30/145/–130) and NPole (90/75/–180/180). The mean is taken over 38 cases

(m)	NHem	Eur	NAtl	NAmer	NPac	NPole
A	0.53	0.25	0.27	0.60	0.82	1.23
DP	0.80	0.32	0.39	0.93	1.28	1.80
T ₂ A	0.88	0.48	0.47	0.81	1.43	2.00
DI	0.72	0.39	0.41	0.63	1.07	1.36
T ₃ A	1.09	0.74	0.58	0.98	1.70	2.35

Table 5. Mean DWL impact for the extra-tropical Northern Hemisphere on 2,5 and 10-d forecasts of 500/200 hPa geopotential height (m) for four DWL scenarios: Aeolus (A), dual-perspective (DP), tandem-Aeolus (T₂A) and triple-Aeolus (T₃A). The mean is taken over 38 cases

(m)	2-d	5-d	10-d
A	0.53/0.40	1.00/1.06	0.14/0.30
DP	0.80/0.60	1.58/1.74	0.27/1.34
T ₂ A	0.88/0.69	1.90/2.09	1.98/2.42
T ₃ A	1.09/0.87	2.03/2.24	0.23/0.61

achievable forecast improvement, that is, from the forecast initiated with the pseudo-truth, see Fig. 8a. This is summarized in Table 6 from which we conclude that:

- (1) The added value of dual-perspective and tandem-Aeolus over Aeolus is 51 and 66%, respectively.
- (2) The added value of having a third Aeolus-type satellite in orbit is mainly limited to the Atlantic region. Here, the analysis has improved with 15%, see the previous section, as compared to T₂A, but resulting in a 53% improved forecast over Europe. The

Northern Pacific is already well covered by the T₂A scenario. An additional satellite improves the analysis by 5%, yet giving a forecast improvement of 19% over the North Pacific and 23% over North America.

(3) The forecast improvement over Europe brought by the storm-track targeting DI scenario is larger than DP but smaller than T₂A for about similar DWL coverage for all three scenarios over the Atlantic. In particular the forecast improvement in the European coastal region is more substantial than for the other scenarios, see Fig. 8.

A Similar analysis in Table 7 shows that conclusions of presented DWL impact results at 500 hPa extend over the full vertical atmosphere, with a maximum relative impact between 700 and 500 hPa.

6. Summary and conclusions

Anticipating on the success of ADM-Aeolus, there is a need to specify wind observation requirements (both quality and quantity) for the design of an operational network of DWLs in the post-ADM era. Here we initially focus on the added value of DWLs to reduce extreme forecast failures with sometimes large socio-economic impact. Lacking an established methodology to test the potential impact of prospective capability extensions to the GOS in real atmospheric cases we developed such a method, called Sensitivity Observing System Experiment (SOSE) which is described in a companion paper. The major component of a SOSE is the definition of a realistic atmospheric state that fits with the observations of all existing observing systems and at the same time does improve the NWP forecast. This is achieved by a realistic adaptation of the forecast initial state (analysis). This adapted atmospheric state is denoted pseudo-truth and is used to simulate the new observing system(s). As such, a consistent GOS with extended capability is established and simulated and existing observations are ready to be used simultaneously in the SOSE. The better the prospective observing system is capable of observing the otherwise unobserved part of the pseudo truth, the

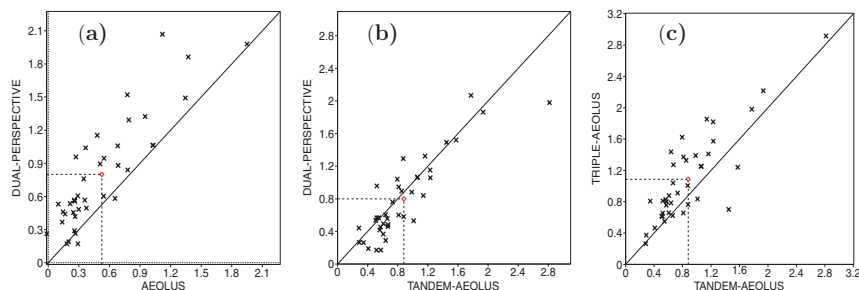


Fig. 9. Scatterplots of DWL impact on 2-d forecast of 500 hPa geopotential height (m) for (a) Aeolus versus dual-perspective, (b) tandem-Aeolus versus dual-perspective and (c) tandem-Aeolus versus triple-Aeolus. The verification area is the Northern Hemisphere extratropics above 30°N. Each cross corresponds to one of the 38 cases. The red diamond indicates the mean value of all cases. The straight line represents equal impact of both scenarios.

Table 6. Mean 2-d forecast improvement (%) of 500 hPa geopotential height from DWL observations relative to the maximum achievable improvement, that is, for complete recovery of the SOSE analysis correction

(%)	NHem	NAtl	Eur	NPac	NAmer	NPole
Aeolus	4.8	2.5	2.8	6.4	5.2	10.0
DP	7.3	4.0	3.3	10.0	8.2	14.7
T ₂ A	8.1	4.9	4.9	11.2	7.1	16.3
DI	6.6	4.3	4.0	8.4	5.6	11.1
T ₃ A	10.0	6.1	7.5	13.3	8.7	19.2

Table 7. Mean 2-d forecast improvement (%) of geopotential height as a function of pressure level. Improvement from DWL observations is relative to the maximum achievable improvement. Verification area is the Northern Hemisphere extratropics above 30°N

(%)	200 hPa	500 hPa	700 hPa	1000 hPa
Aeolus	3.5	4.8	4.7	4.2
DP	5.3	7.3	7.2	6.2
T ₂ A	6.0	8.1	8.0	6.7
T ₃ A	7.7	10.0	9.5	7.4

more beneficial impact it has and the larger the NWP forecast improvement will be.

Marseille et al. (2007a) verify the characteristics of the pseudo-truth and conclude that SOSE are useful for relative impact assessment. The here described SOSE implementation is a single-cycle experiment, meaning that synthetic observations are added in only one assimilation window. As such the observation impact is not representative of the expected absolute impact of the observing system in operational NWP, since data assimilation systems are capable to propagate information from observations forward in time to next cycles in a constructive manner and as such increase the impact of the observations under investigation. However, a single-cycle SOSE is useful to compare the relative impact of various observing system sampling scenarios, strategically complementing the GOS.

To assess the absolute added value of DWL in extreme weather events it is recommended to conduct the SOSE experiments in cycling mode as in Marseille et al. (2007b). As such, a pseudo true atmospheric state can be generated over a longer term consecutive period prior to the extreme event. The full daily global observation coverage would be considered, and no regional preferences would remain. In addition, better use is made of the properties of nowadays data assimilation systems to propagate observational information progressively forward in time to next assimilation cycles. Application of a cycled SOSE to the Christmas 1999 period is discussed in Marseille et al. (2007b) and indicates that a tandem-Aeolus scenario would have improved the forecast of the second Christmas storm ‘Martin’, that

caused much havoc over Europe, substantially if it would have been available at that time. Here, we report on the single-cycle experiment for relative DWL impact assessment.

A total of 38 cases with forecast initial states (analyses) producing large local 2-d forecast failures in the northern hemisphere extratropics were selected for the four different seasons. All cases focus on the 12 UTC analysis period and employ identical sampling tracks in the Atlantic and Pacific Ocean, where the adaptations are largest. The 12 UTC sampling thus positively affects the simulated performance. On the other hand, the experiments ignore effects in the data assimilation system achieved by continuously adding prospective observations over several days (cycling) and thus underestimate the impact.

For an Aeolus follow-on, complex laser scanning geometries distributing the limited laser power over large swath areas appear rather unfeasible. Consequently, impact experiments using SOSE were conducted for the following five DWL scenarios which exploit the ADM-Aeolus heritage:

- (i) Aeolus, for reference, measuring profiles of a single wind component;
- (ii) DP, dual-perspective, measuring profiles of wind vectors;
- (iii) T₂A, a tandem of two Aeolus in one orbit plane;
- (iv) T₃A, triple-Aeolus with three Aeolus in one orbit plane and
- (v) DI, a dual-inclination scenario targeting the storm-track region.

The number of wind component profiles measured with DP, T₂A and DI is thus the same and twice the number of Aeolus.

Aeolus is indeed capable to resolve part of the analysis error structures in the otherwise data sparse areas giving an improved forecast after 2 d and beyond. Measuring the complete wind vector (DP scenario) gives ‘only’ a 50% forecast improvement despite a doubling of the observations. A larger 66% improvement over Aeolus is achieved by a more uniform geographical distribution of LOS observations (T₂A scenario). An additional third Aeolus in orbit (T₃A scenario) improves the analysis over the Pacific marginally, yet giving a substantial additional 23% forecast improvement over North America. A more substantial reduction of the analysis error is achieved over the Atlantic resulting in an additional 50% forecast improvement over Europe. The more exotic DI scenario achieves the best performance over the Atlantic, indicating that a targeting strategy may be effective. The geographical distribution of profiles is somewhat inclined to the Atlantic for DI, and to the Pacific for DP. This appears to affect the relative regional forecast scores. The overall results appear representative of both the areas with large and nominal forecast impact.

We note that through the addition of DWL observations encouraging forecast improvement is achieved ranging from 1.5 h forecast improvement (or 0.5 yr ECMWF model improvement) for Aeolus to 2.5 h for T₂A and 3 h (or 1 yr ECMWF model improvement) for T₃A. These seemingly modest improvements

of the 2-d forecasts compare favourably to the relative impacts of existing observing systems in OSE studies with the full observing system in state-of-the-art data assimilation systems WMO (2004), even though the single-cycle SOSE pseudo-truth only represents part of the potential total forecast improvement.

It is clear from the experiments that uniform DWL profile coverage is more important than measuring in dual perspective (T_2A better than DP). Apparently, the vertical and along-track projection of the DP increments causes some implicit wind component observation redundancy, not present for the T_2A . However, near the equator the coupling between zonal and meridional wind vanishes and measurements of the meridional wind are necessary to obtain a uniform quality analysis. Both the requirements of extratropical coverage and tropical perspective may be achieved by yet another tandem scenario that was not studied here. The tandem would exist of an Aeolus satellite and a companion satellite with a DWL looking backwards, Dubock (2006), in the same orbit plane, but shifted in orbit phase by about 140° . Based on our experiments, we expect that this constellation would perform similar to T_2A in the extratropics, but this needs to be investigated.

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