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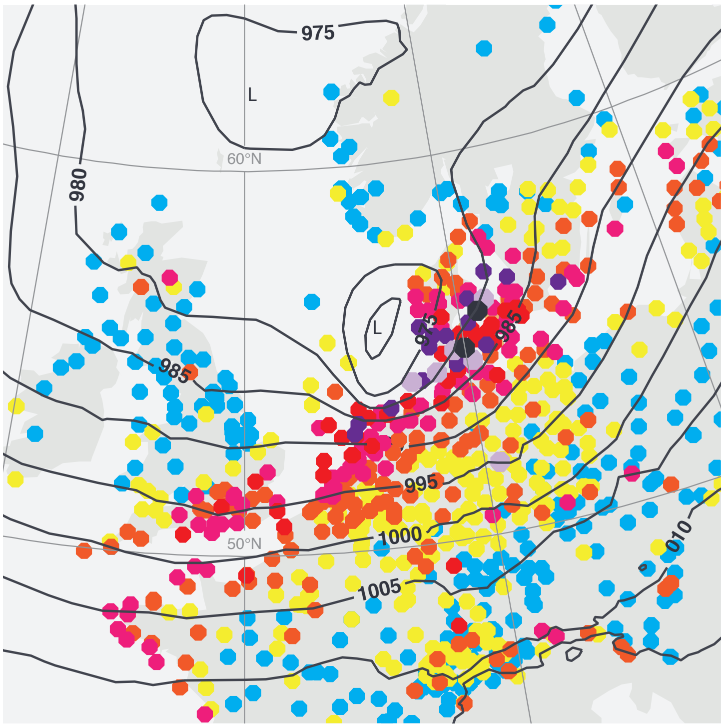

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The expected NWP impact of Aeolus wind observations

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Aeolus is an ESA Earth Explorer satellite mission with a Doppler wind lidar payload, expected to be launched in 2015. It will provide wind information with a global distribution, a part of the global observing system that is presently lacking. Additional wind observations will improve our understanding of the general circulation, especially in the tropics. They are also expected to be very valuable for numerical weather prediction (NWP). But it is important to assess the expected impact of a future observing system that is primarily intended to provide data for use in NWP. In particular, an agency responsible for a new observing system wants to know whether the planned benefits for NWP are likely to be realised. Therefore, impact studies for the Aeolus mission have been performed at ECMWF to assess the potential impact of the data on NWP.

The Aeolus mission will provide vertical profiles of single horizontal line-of-sight (HLOS) winds, perpendicular to the satellite track. See Boxes A and B for more information about ESA's Aeolus mission and the role of ECMWF.

Assessments of the expected impact of Aeolus data have been performed in the past (e.g. *Tan et al.*, 2007; *Stoffelen et al.*, 2006). However, the mission specifications have changed significantly since these studies, as has the ECMWF Integrated Forecasting System (IFS). Consequently it is necessary to carry out a new assessment.

It is not straightforward to quantify the impact of a future spaceborne observing system. A suitable way of doing this for Aeolus is to investigate the impact of real pre-existing (good quality) wind data in ways that could provide an insight into the expected impact of Aeolus winds. With that aim in mind, we conducted Observing System Experiments (OSEs) with dual component winds (i.e. the zonal and meridional wind components) converted into Aeolus-like single component (HLOS) winds.

We have evaluated the results by using traditional verification measures (e.g. root-mean-square error and anomaly correlation of forecasts verified against operational analyses). In addition, use has been made of the more recently developed analysis and forecast sensitivity tools for measuring the information content of the wind observations for the analyses and short-range forecasts. This article describes the most interesting results from the NWP impact studies.

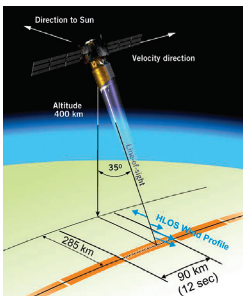
ESA's Aeolus mission

A

Aeolus is a European Space Agency (ESA) Earth Explorer mission, scheduled to be launched in July 2015 as part of the Living Planet Programme. The mission is intended to have a lifetime of three years. The Earth Explorers are designed to address critical and specific issues that are raised by the science community, while at the same time demonstrating breakthrough technology in observing techniques.

Aeolus will demonstrate the capability of a spaceborne Doppler wind lidar to make accurate, globally-distributed measurements (polar orbit) of vertical wind profiles in the troposphere and lower stratosphere (near surface to 30 km). It will measure single horizontal line-of-sight (HLOS) winds, perpendicular to the satellite track, by aiming a ultraviolet (UV) laser into the atmosphere and then detecting the Doppler-shift of the backscattered light from both molecules (clear air) and particles (clouds/aerosols). ADM-Aeolus is seen as a pre-operational mission, demonstrating new laser technology and paving the way for future meteorological satellites to measure atmospheric winds.

The Aeolus mission has suffered severe delays due to problems encountered with the state-of-the-art UV laser technology. There are still some significant instrument tests to be passed before we can be confident of the July 2015 launch date.



Further details on the mission can be found from the ADM-Aeolus Science Report (2008) and from *Stoffelen et al.* (2005).

ADM Aeolus satellite. Schematic view of the ADM-Aeolus measurement geometry (credits: ESA/ADM-Aeolus project).

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Wind data information content

The information content of observations used in the ECMWF assimilation system can be quantified by several diagnostic measures (*Cardinali et al.*, 2004; *Cardinali*, 2009).

- Observation Influence (OI) which provides information about the influence of the observations on the analysis (analysis impact). OI is defined as the Degrees of Freedom for Signal (DFS) per observation.
- Forecast Error Contribution (FEC) which quantifies the impact of observations on the reduction of the 24-hour forecast error (forecast impact).

We have applied these measures in our impact studies and the results were compared. The impact of all active wind observations on the ECMWF analyses is assessed in terms of OI (Figure 1a). The corresponding impact on short-range forecasts is given by FEC per observation (Figure 1b). All active wind observations includes ships, drifting buoys, radiosondes, dropsondes, wind profilers, aircraft, scatterometers and satellite atmospheric motion vectors.

The diagnostics were taken from an experiment (using the IFS cycle Cy37r2) where we assimilated all the operationally-used observations. Both measures (OI and FEC per observation) show that most benefit from the current wind observations is obtained in the upper troposphere and lower stratosphere (50–100 hPa for analysis impact and 100–200 hPa for the short-range forecasts). Based on these diagnostics the largest impact of Aeolus observations can be expected to occur at these levels, since this is where the current observing system is providing most impact per observation. Other studies (not shown) revealed that, for the version of the IFS used in the experiments, the importance of wind observations is larger in the tropics than at mid-latitudes. This is also confirmed by the OSE results described later in this article.

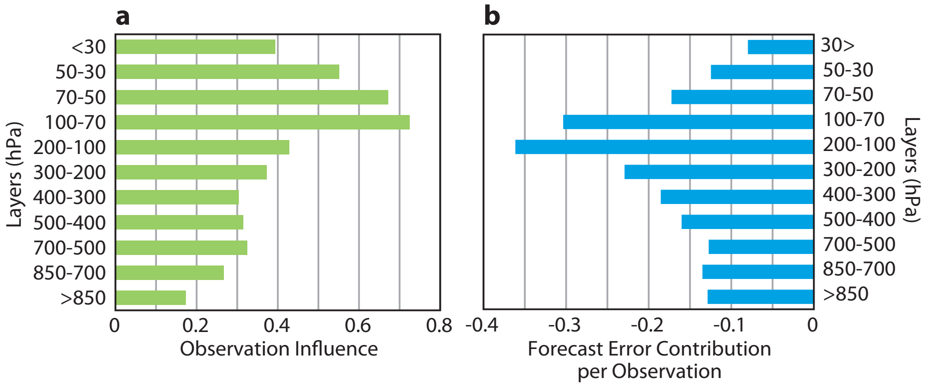


Figure 1 Information content of wind observations as a function of pressure (hPa) in terms of the global average of (a) Observation Influence (OI) and (b) Forecast Error Contribution (FEC) per observation. Period: September, 2011.

Role of ECMWF

B

ECMWF is contracted by ESA to produce Aeolus wind products suitable for NWP. In particular, ECMWF is responsible for the development of the wind retrieval software through collaboration with KNMI (Royal Netherlands Meteorological Institute), Météo-France and DLR (German Aerospace Centre) – see *Tan et al.* (2008). ECMWF has been chosen as the Meteorological Processing Facility so it will provide wind products (referred to as Level-2B wind products) and auxiliary meteorological data products for ESA in an operational manner during the mission's lifetime.

ECMWF will also be responsible for the monitoring of Aeolus wind retrievals, and will assess the impact of Aeolus winds on the global NWP system. The intention is to assimilate HLOS winds operationally if they are shown to provide positive impact.

ECMWF will also participate in readiness tests, calibration/validation activities and the mission's commissioning phase.

The Aeolus processing software along with detailed documentation is made available for NWP centres from the website: http://data-portal.ecmwf.int/data/d/software/aeolus.

It is expected that an increase in wind profile information will be a valuable addition to the global observing system, as was again recently identified by a WMO expert team (Andersson & Sato, 2012). If Aeolus observations are of sufficient quality, they are expected to provide a significant positive impact on global NWP. Therefore, ECMWF has been separately contracted to investigate the expected impact of Aeolus data given some significant changes to the mission design over recent years.

Denial experiments

We have performed data denial experiments (OSEs where some observations are withdrawn from the data assimilation) to help to understand the role of observation sampling for spatially-dense observing systems used in the ECMWF data assimilation. This is of relevance to Aeolus, since observations will be densely sampled along the orbital track.

In particular we considered globally-distributed aircraft observations (temperature and wind vector) and Japanese wind profiler data (wind vector only) for the densely-sampled data. The aircraft data has a wide coverage at reasonably high spatial sampling (along flight paths) and the Japanese wind profiler network is one of the densest in the world (but only covering a relatively small part of the globe). The other in-situ wind observations (e.g. radiosondes) have lower spatial density; therefore they are unsuitable for evaluating the redundancy aspects of Aeolus observations. Here we do not discuss the results with the Japanese wind profilers since they were inconclusive (perhaps due to the small geographical area), but we summarise the main results of the aircraft denial study.

We carried out the aircraft OSEs by thinning aircraft observations to a horizontal spacing of 150 km and a vertical spacing of 50 hPa (instead of the operational values of 60 km and 15 hPa). The denser operational sampling provides on average a 47% increase in the number of observations; the difference is largest near the surface due to the ascent and descent of aircraft near airports.

Figure 2 shows the information content of the two experiments in terms of FEC diagnostics. This illustrates that the additional observations (with close proximity to others) do not provide a corresponding increase in information content. In other words, the extra aircraft observations are partially redundant due to the capability of the data assimilation to propagate information typically 200–400 km away from the location of an observation.

The results given in Figure 2 have important implications for the expected impact of the Aeolus mission, since (as discussed in Box C) the measuring technique has been changed from the original Burst Mode (BM) to the more densely-sampled Continuous Mode (CM). To some extent, the aircraft thinning study can guide our expectations about the impact of Aeolus CM as compared to BM. We can conclude that the CM will not provide significantly more impact than the BM because of the described redundancy.

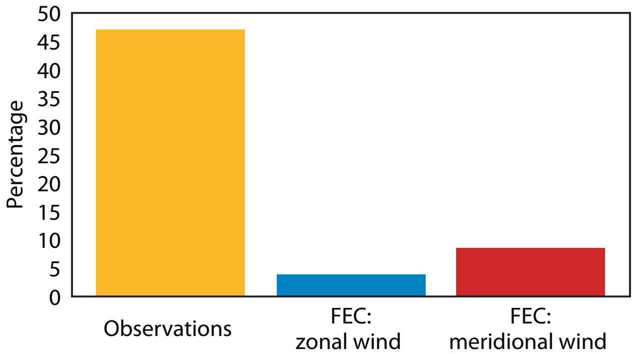
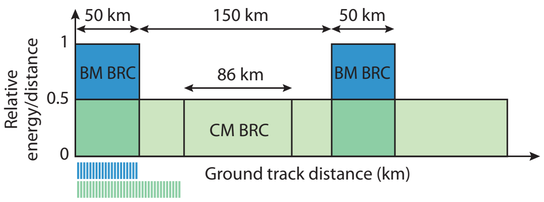


Figure 2 The impact of the increase in spatial density of aircraft observations (control versus denial experiment) as measured by the globally-averaged FEC diagnostics (also averaged vertically). The yellow histogram shows the increase in observation amount. The blue and red histograms show the increase in the zonal and meridional wind FEC values. All figures are the percentage increase of values as compared to the denial experiment. Period: September, 2011.

Aeolus processing and operations concept changes

C

Our studies paid particular attention to the fact that the operational concept of Aeolus has recently been changed from the so-called Burst Mode (BM, with a high temporal frequency of laser shots, but with gaps when the laser is not fired) to Continuous Mode (CM, half the temporal frequency of laser shots, but without any gaps) for engineering reasons – see the figure below. Also, the lidar laser energy will be reduced (at least for the start of the mission) by one third, in order to reduce the risk of laser-induced damage and ensure the three-year lifetime of the mission. These technological changes influence the spatial distribution and accuracy of the Aeolus wind data and consequently they had to be taken into account in the study of expected NWP impact.



Operational concept of Aeolus. Comparison of the concepts for the Aeolus Basic Repeat Cycle (BRC) for the Burst Mode (BM) and Continuous Mode (CM).

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Line-of-sight data assimilation experiments

The ability of the IFS to assimilate HLOS winds has been in place since around 2006, but until now no data assimilation studies have been carried out using HLOS data derived from real wind observations. Some experiments using HLOS winds will now be described.

Numerical tools were developed to convert vector wind observations (i.e. with zonal and meridional wind components available) to Aeolus-like HLOS wind observations. As with the previous studies, this allows us to use real wind observations from the current observing system for the investigations. HLOS wind information was extracted from radiosondes, aircraft and wind profiler observations. The HLOS winds were chosen to point in the zonal direction for most experiments, since the real Aeolus data will be close to the zonal direction for the tropical and mid-latitude portions of the orbits (typically 10° of zonal wind direction).

We designed and executed several OSEs, but here we highlight just two main results from these studies.

- We compared the impact of HLOS and vector winds to that of mass (temperature and humidity) observations. This examines the importance of wind observations for global NWP. However, we have to be careful with the interpretation of the results because wind is measured by radiosondes, aircraft and wind profilers, but temperature is only measured by radiosondes and aircraft (and humidity uniquely by radiosondes).
- We studied the ability of the data assimilation system to utilise single component HLOS winds compared to vector winds (both components). In this study one should keep in mind that for the control run the radiosonde, aircraft and wind profiler observations were removed, thereby significantly degrading the observing system.

Comparing the impact of HLOS and vector winds and mass observations

Figure 3 shows the impact of HLOS (zonal) wind, vector wind and mass observations on zonal wind predictions. The corresponding results for the impact on temperature are shown in Figure 4. The impacts are quantified in terms of the percentage reduction in the root-mean-square errors relative to a control without any of the examined observation information. For each figure, the impact is split into the northern hemisphere extra-tropics and the tropics.

Figure 3 shows that, out of the total impact obtained from all observation information, HLOS and vector winds have a significant impact on the zonal wind forecast for 12 hours to 3 days, especially for the tropics. This is also true for longer forecast ranges (not shown).

As shown in Figure 4, the HLOS and vector winds are less useful for forecasts of temperature than for zonal wind – adding temperature and humidity observations at lower levels provides significantly more impact. However, winds can provide larger impacts at higher altitudes (see also the diagnostics illustrated in Figure 1), more so in the tropics than in the extra-tropics. The impact of wind observations for improving the wind and temperature forecasts highlights the important role of wind observations and the potential benefit of using Aeolus data.

We now compare the information content of HLOS and vector winds. Figures 3 and 4 show that almost everywhere the HLOS winds are able to provide more than 50% (typically 70% to 75%) of the vector wind impact; this is due to the multivariate nature of the assimilation scheme spreading the information from the observation to other variables. The degree of impact varies slightly with the forecast variable, region and altitude, but generally the HLOS winds are more useful in the tropics. Consequently there is a promising indication that Aeolus data will have a beneficial impact in the tropics. Note, however, this result does not show that the zonal wind component is more important than the meridional component – this can only be assessed by carrying out a similar study which compares the impact of the meridional wind component and vector wind (both components).

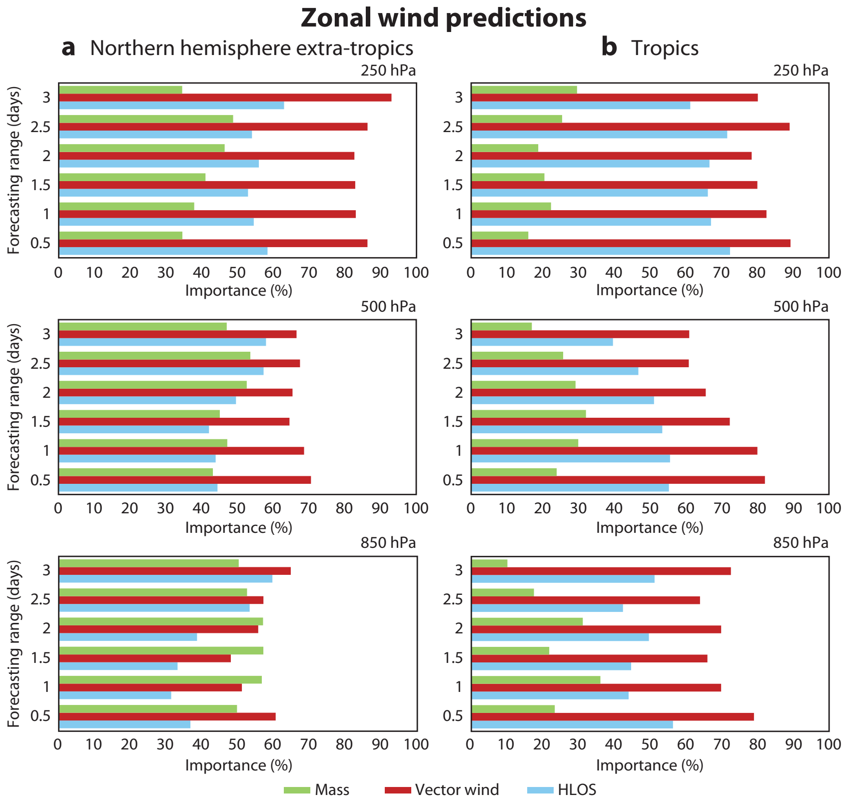

Figure 3 The importance (in percentage) of HLOS (zonal) wind, vector wind and mass observations for the zonal wind predictions for (a) northern hemisphere extra-tropics and (b) tropics for 250 hPa (upper panels), 500 hPa (middle panels) and 850 hPa (lower panels). Blue colours show the impact of HLOS winds, red colours show the impact of the vector winds and green colours show the impact of mass information. The vertical axis is the forecast range from 0.5 day to 3 days.

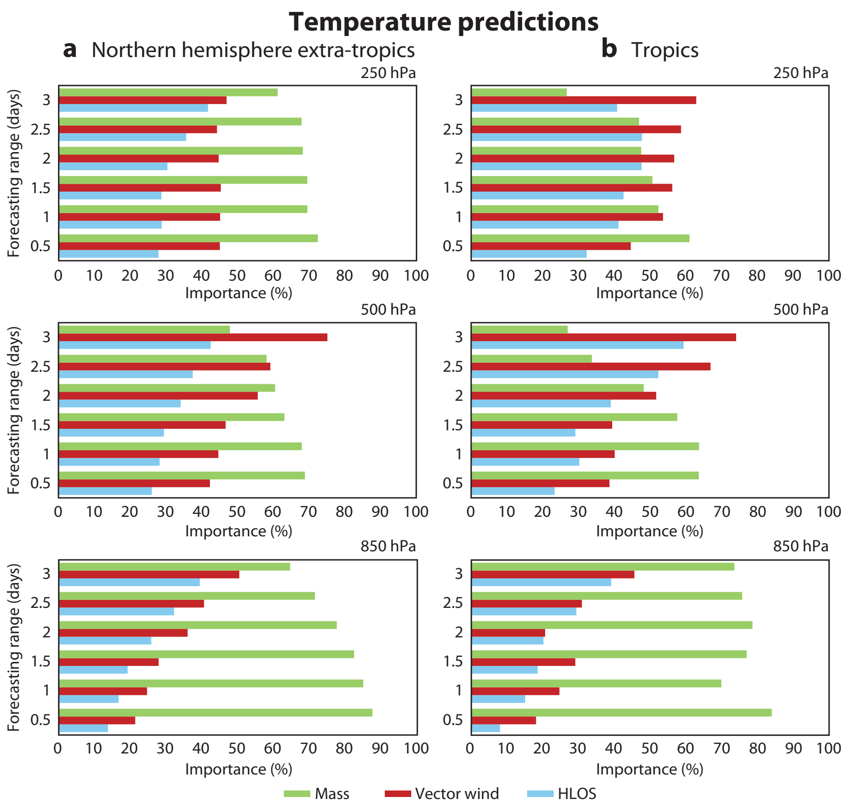

Figure 4 As figure 3, but for the importance (in percentage) of HLOS (zonal) wind, vector wind and mass observations for the temperature predictions.

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Spatial distribution of the impact of HLOS winds

We investigated the spatial distribution of the impact of HLOS winds. Figure 5c shows the impact of HLOS data compared to the experiment where no observation information from radiosondes, aircraft and wind profilers was assimilated. It is clear that the largest impact is obtained in the tropical region (despite observations being sparsely distributed there, as can be seen in Figures 5a and 5b showing the locations of the observations), with the highest impact being around the aircraft cruise level. This impact is mostly seen outside convectively active areas such as the Atlantic south of the equator, the Pacific at the equator and Australia (there is little convective activity because the Intertropical Convergence Zone (ITCZ) is further north). One possible explanation is that the degraded observing system is unable to simulate the tropical circulation properly, which is corrected by the additional wind information.

The lack of impact for the southern hemisphere is due to the sparsity of observations (see again the coverage of all the data and the profilers in Figures 5a and 5b). Aeolus will have a much more uniform global coverage than the conventional data used in this study; therefore we can expect Aeolus to provide a significant positive impact in areas where there are few direct wind observations.

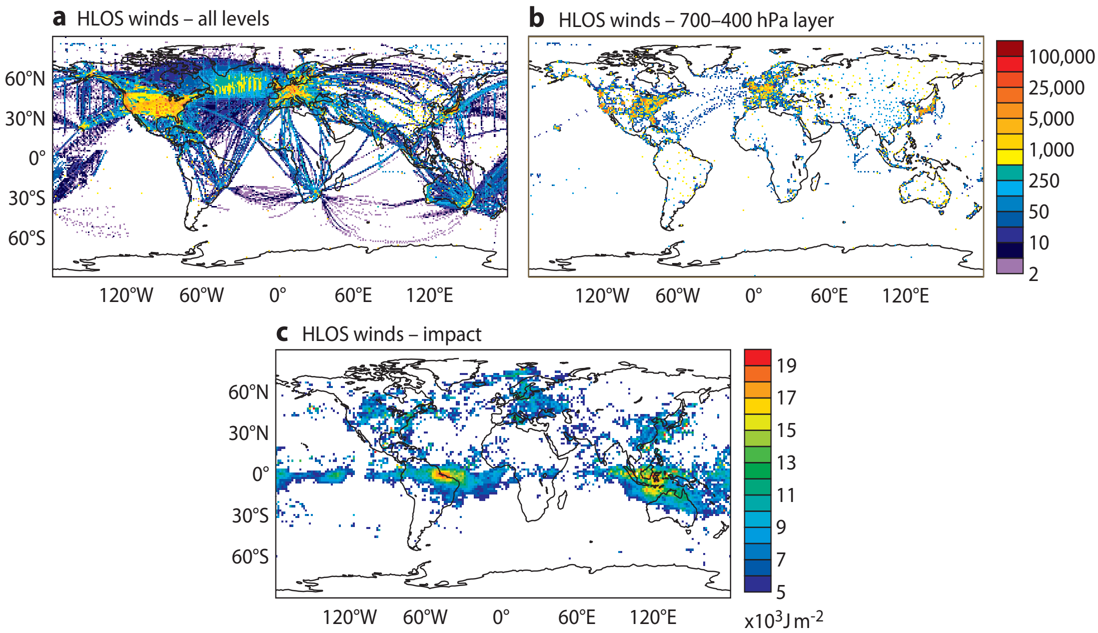

Figure 5 The distribution of HLOS data used in the experiments for (a) all vertical levels and (b) the 700–400 hPa layer (this highlights the radiosonde locations). (c) The impact of HLOS winds as measured by the decrease of the mean integrated total energy (in Jm^{-2}) of the 24-hour forecast error compared to the experiment without wind, temperature and humidity data.

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Impact of increased random and systematic errors

As discussed in Box C, Aeolus wind quality might be reduced due to technical reasons. In order to assess how this could change the NWP impact we carried out some experiments to assess the effect of degrading the quality of HLOS observations. To achieve this we ran experiments that independently increased the random and systematic errors of the HLOS observations.

The impact of random errors was tested by increasing observation errors by 25%, 50% and 100% (this involved modifying the assigned data assimilation observation error and adding Gaussian noise to the observation values in line with the increases). The results are summarised for the northern hemisphere extra-tropics by Figure 6 in the form of the ECMWF scorecard for verification against operational analyses.

The scorecards show the significance of changes in the root-mean square error and anomaly correlation between the HLOS experiment and its reference for various variables and levels. It shows that the 25% HLOS observation degradation (this is the most realistic level expected for Aeolus) results in a very small decrease in NWP impact (with respect to the no degradation case). The deterioration increases with the further enlargement of the observation error, but the deterioration is still small even for the 100% case (when the observation error is, for example, increased from 2 m/s to 4 m/s). This implies that the planned increase of random errors for Aeolus is not a major concern from the point of view of global NWP impacts of the mission. CM helps to some extent by also providing observation information redundancy due to the high sampling along the orbit.

The testing of the effect of systematic observation error comprised experiments where we added a 0.5 m/s, 1 m/s and 2 m/s constant positive bias to the observations (without any changes in assigned observation errors). The impact of systematic errors is shown via scorecards in Figure 7, but now the experiments are compared to the control without wind, temperature and humidity observations.

From the scorecards it is clear that the degradation is much larger than was the case for the random errors with our chosen levels of systematic error. In particular, unbiased HLOS winds give a very significant positive impact, which becomes a very significant negative impact when the winds are biased by 2 m/s. This means that biases (at magnitudes possible for Aeolus) can be very detrimental for the Aeolus observations and they should be avoided by every possible means (or at least these biases should be understood with a view to correcting them). The actual level of systematic errors for Aeolus is unclear; this will be investigated in the near future.

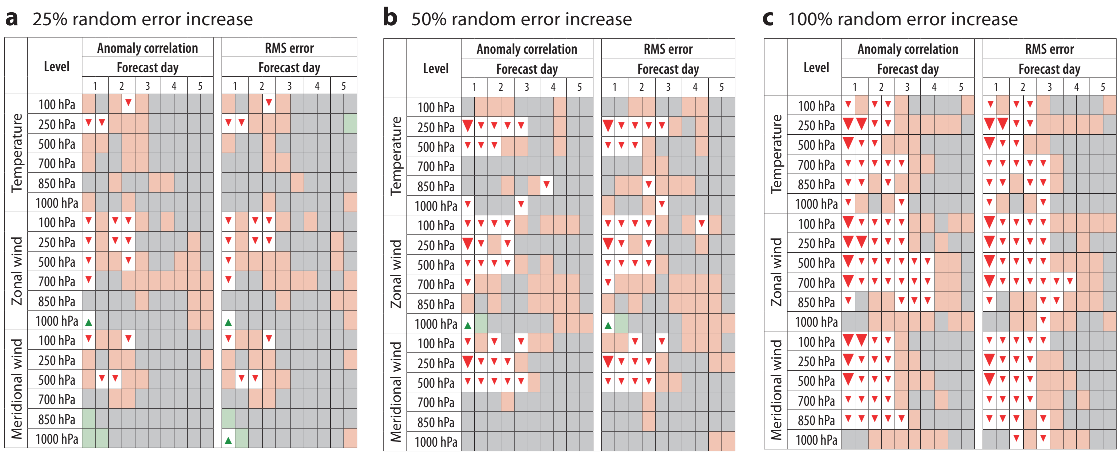

Figure 6 Scorecards for the northern hemisphere extra-tropics for (a) 25%, (b) 50% and (c) 100% observation error increase with corresponding observation Gaussian noise being added. Red (green) triangles indicate significant degradations (improvements) for the HLOS experiment with random errors compared to the experiment without any random error. Green and red shadings indicate differences which are not statistically significant, and grey shading indicates little difference.

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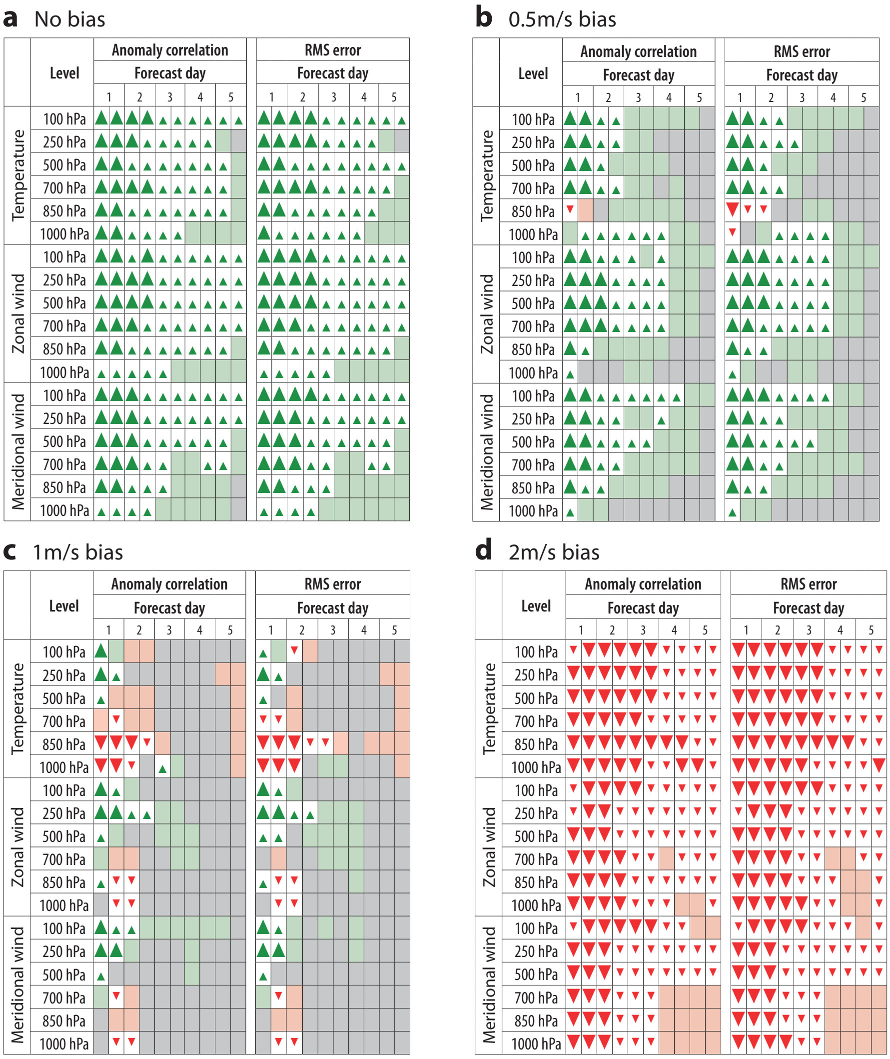

Figure 7 Scorecards for the northern hemisphere extra-tropics for (a) no bias and (b) 0.5 m/s, (c) 1 m/s and (d) 2 m/s positive bias added to the observations. Green (red) triangles indicate significant improvements (degradations) for the HLOS experiment with systematic errors compared to the experiment without HLOS (and temperature and humidity) data. The green, red and grey shadings have the same meaning as in Figure 6.

Summary and outlook

This article presented some investigations of the impact of assimilating Aeolus-like single component wind data, with emphasise on the most important results of the impact studies conducted in the framework of an ESA-ECMWF study. The results confirm that additional wind information (of Aeolus quality) is likely to be highly beneficial for global NWP. This statement remains true even with an increase of random observation errors (with the expected 25% decrease in accuracy of the Aeolus satellite due to limitations of the laser output energy), but systematic errors greater than 0.5 m/s are very damaging.

The Aeolus team at ECMWF is confident that the mission will provide positive global forecast impacts if the random errors remain around 2–3 m/s and the systematic errors can be kept below 0.5 m/s.

Further reading

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More up-to-date information on Aeolus can also be found on ESA's website:
http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/ADM-Aeolus/ESA_s_wind_mission

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