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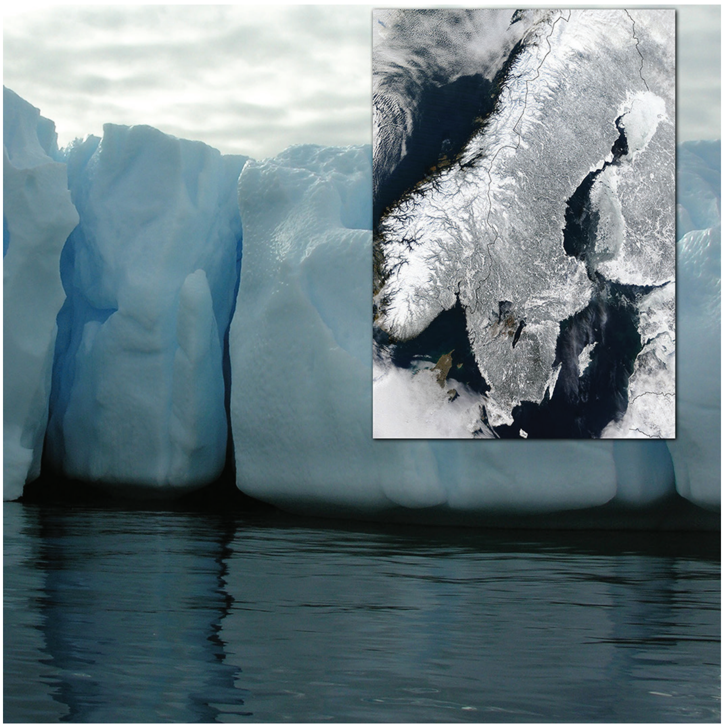

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The ADM-Aeolus satellite to measure wind profiles from space

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ECMWF is currently preparing for the arrival of wind profile measurements from the ADM-Aeolus satellite, with expected launch in 2008. The Atmospheric Dynamics Mission (informally known as ADM, but more correctly referred to as Aeolus) is the second of the Earth Explorer Core Missions of the European Space Agency (ESA). For further information see *Stoffelen et al.* (2005) or go to:

www.esa.int/export/esaLP/earthexplorers.html.

ESA has placed a contract with ECMWF to develop the software to produce and deliver two of the mission's official data products:

- Retrieved wind profiles (level 2B data products);
- Aeolus-assisted wind profiles from analyses (level 2C data products).

Part of the software will be portable and made available to the meteorological community at large; this is to facilitate widest possible use of the Aeolus data soon after they first become available. Currently, the algorithm to retrieve representative winds and the portable codes are being developed in collaboration with Météo-France/GAME, KNMI, DLR and LMD/IPSL[1]. After launch, ECMWF will be responsible for monitoring the Aeolus data: assessing their quality, producing the 2B/2C data set routinely, and updating and distributing relevant software for use at other NWP centres.

The objective of Aeolus is to demonstrate, for the first time, the capability of measuring wind profiles from space using a Doppler wind lidar (DWL) on a polar orbiting platform. Aeolus is designed to provide high-quality profiles from the surface up to 30 km, the wind information being single-component in the horizontal direction of the instrument's line-of-sight (HLOS), perpendicular to the satellite track. The viewing geometry is shown in Figure 1. The instrument design includes a Rayleigh channel for detecting molecular scattering and a Mie channel for cloud and aerosol scattering. The combination of the two channels will enable good quality HLOS wind retrievals in 0.5, 1.0 and 2.0 km layers (near the ground, in the free troposphere and in the stratosphere, respectively) except where the view is restricted by thick clouds. Simulated six-hour data coverage is shown in Figure 2. The intention is to have the satellite in orbit from 2008 to at least 2011.

Wind accuracy in numerical weather prediction

An illustration of the accuracy to which the global wind-field is currently known is shown in Figure 3. This shows an estimate of the standard deviation of error in the east-west wind component at 250 hPa (approximately 10 km) in ECMWF analyses. The distribution of errors is a product of atmospheric wind variability on the one hand, and the availability of accurate observations, on the other. We see that wind analysis errors are small in data dense areas (e.g. North America, Europe, Japan and Australia) and in regions with little wind variability (e.g. parts of the sub-tropics). Wind errors tend to be large in most parts of the tropics, in the storm-tracks over oceans (e.g. southern oceans, North Pacific, North Atlantic) and along the sub-tropical jet extending from the southern Mediterranean region to northern China. It is in these areas, where current data assimilation systems have relatively high wind uncertainties, that the main analysis impact can be expected from Aeolus wind profile data.

1 GAME = Groupe d'Etude de l'Atmosphere Meteorologique,
KNMI = Koninklijk Nederlands Meteorologisch Instituut,
DLR = Deutsches Zentrum für Luft- und Raumfahrt,
LMD/IPSL = Laboratoire de Météorologie Dynamique / Institut Pierre-Simon Laplace

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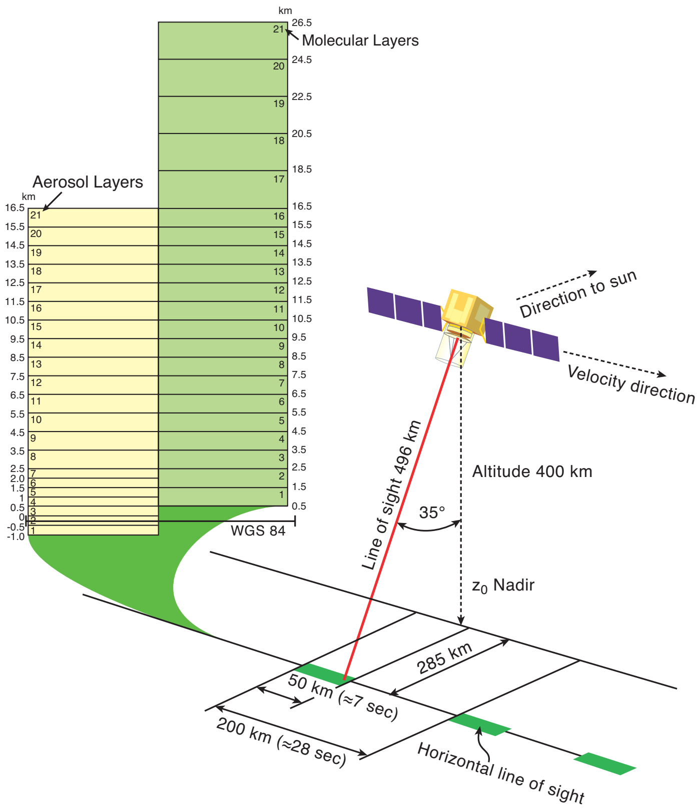

Figure 1 ADM-Aeolus viewing geometry and vertical resolution (Courtesy ESA). Laser light is emitted from the satellite. A small fraction of the light is backscattered and its frequency shift (which is wind-induced) is measured in two channels by the onboard receivers: Mie for aerosol returns and Rayleigh for molecular returns. The combination of the two channels will enable good quality HLOS wind retrievals from 27–30 km to the surface in 0.5, 1.0 and 2.0 km layers as indicated, except where the view is restricted by thick clouds.

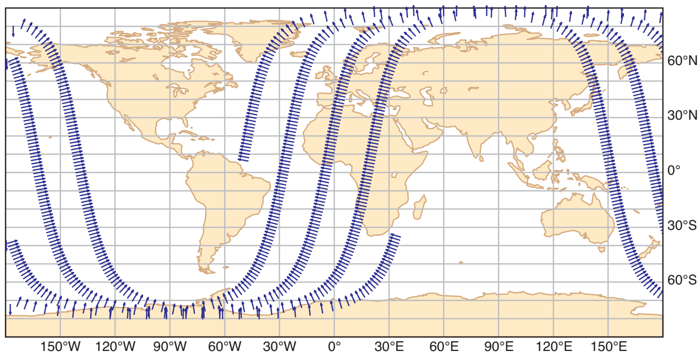

Figure 2 Simulated ADM-Aeolus data coverage and HLOS directions in a six-hour period.

Simulation of Aeolus measurements and their accuracy

The accuracy of the Aeolus wind measurements will not be uniform. The signal-to-noise ratio will primarily depend on the intensity of the backscattered laser light. In the Mie channel the backscattering depends on the presence and thickness of clouds, and the concentration of aerosol, whereas in the Rayleigh channel it depends on the density of air. It is expected that the Aeolus instrument will receive sufficient backscatter from the layers of clear air above clouds, from cloud-top layers, from layers in and below thin clouds, and from layers with sufficient aerosol in the lower parts of the atmosphere.

It is important to consider whether Aeolus will provide significant numbers of high-quality data in the meteorologically most interesting regions, i.e. where incipient storms tend to occur and where storm systems develop. These so-called ‘sensitive areas’ tend to be associated with high cloud cover (*McNally,* 2002). Therefore, the yield and quality of Aeolus wind profiles has been investigated (*Tan and Andersson,* 2005) through detailed simulations, given realistic cloud distributions and climatological estimates of aerosol concentration.

The simulations of backscatter and instrument performance have been carried out using the LIPAS (Lidar Performance Analysis Simulator) software (*Marseille and Stoffelen,* 2003). Given as input vertical profiles of atmospheric parameters (temperature, pressure, wind speed and direction, cloud fraction and aerosol concentration) LIPAS outputs a simulated Aeolus horizontal line-of-sight (HLOS) wind as well as corresponding estimates of measurement accuracy. The user specifies parameters such as the observation resolution, shot-accumulation length and pulse repetition frequency.

The Aeolus observation accuracy is provided as a sum of observation error and representativity error variances. Thus, LIPAS provides the simulated measurements and their accuracy as required for realistic impact studies. The mission- specified requirement on observation error for the Level-2B HLOS wind component data is set to 1 ms^{-1} below 2 km altitude and 2 ms^{-1} above. After addition of representativity error, Aeolus observations meeting the mission requirements are expected to receive weights comparable to those given to radiosonde and wind profiler wind observations in the ECMWF data assimilation system (*Tan and Andersson,* 2005).

Examples of LIPAS simulations of the expected yield of Aeolus winds are shown in Figure 4. The coloured markers show the percentage of good-quality data; that is those meeting the mission-specified accuracy requirement in terms of random error. This is shown separately for wind retrievals from the Rayleigh (molecular) channel in the mid-troposphere (Figure 4(a)), and for the Mie (aerosol) channel near the surface (Figure 4(b)). These simulations are for the period 10 January to 28 February 2003 and are based on cloud cover as provided by the ECMWF forecast model at full operational resolution (T511, or ~40 km), climatological aerosol distributions, and other meteorological inputs from the ECMWF model. We see that the yield of good data is high (>50 %, green markers) in most regions, even in the storm-tracks in the mid-troposphere. The yield is lower (red markers) mainly in the most persistently cloudy regions (i.e. the ITCZ and at low levels in the storm-tracks). At higher levels (not shown) the yield of good data is near complete.

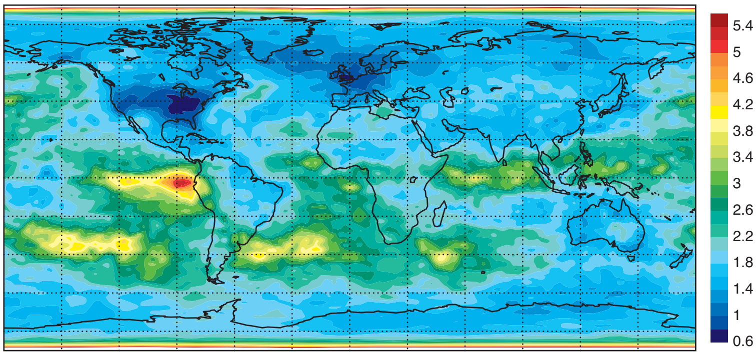

Figure 3 An estimate of wind analysis uncertainty (east-west wind component at 250 hPa, in ms^{-1}) in the Autumn 2001 version of the ECMWF data assimilation system showing maxima in the tropics, and the oceanic storm track regions. Errors tend to be smaller in data-dense regions and where wind variability is less. The estimate is based on the spread between the ten members of an ensemble of assimilations, 1–31 October 2000.

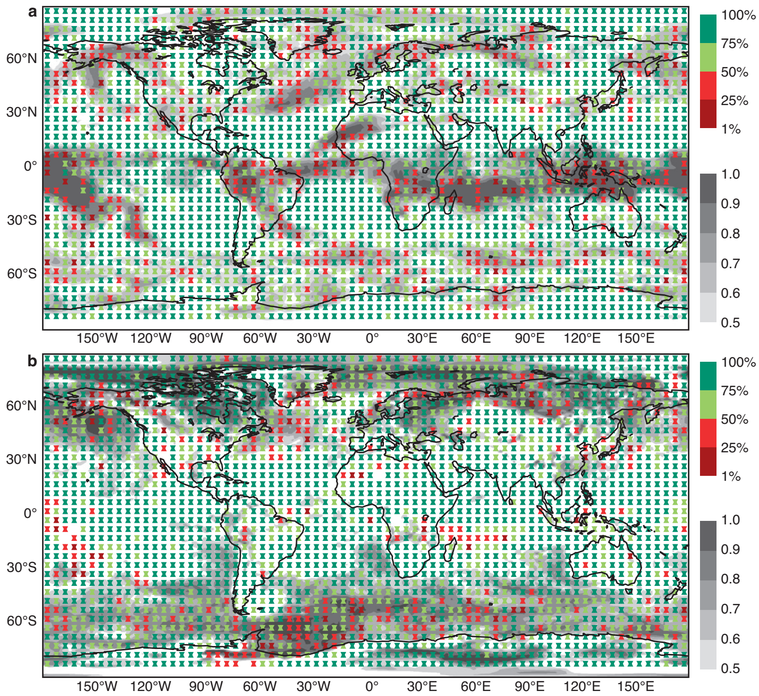

Figure 4 Simulated ADM-Aeolus yield of good-quality data for (a) the Rayleigh (molecular) channel at 4–5 km and (b) for the Mie (aerosol) channel at 0.5–1 km, in terms of percentage of good data in each 5×5 degree box meeting mission requirements as represented by green and red markers (see legend). Based on simulations through the period 10 January to 28 February 2003. Grey shading shows ECMWF cloud cover at (a) 4–6 km and (b) 0–3 km within the study period.

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Impact assessment using ensemble simulations

The global impact of Aeolus data has most recently been investigated through assimilation ensemble experiments (*Tan and Andersson,* 2004). This is a novel approach that is being developed and applied for the first time in these Aeolus simulations. The original assimilation ensemble method (*Fisher,* 2003a) was thus extended to assess the impact of different observations types: simulated Aeolus data and, for calibration purposes, radiosonde plus wind profiler data. This has required the generation of new ensembles that differ in the observations made available to assimilate.

Three ensembles were generated, and each ensemble consisted of four independent members; each member was run for the period 10 January to 28 February 2003. The three ensembles differed in the observations that were assimilated as follows.

- ***Control:*** All observational data as used in the 2004 ECMWF operational system.
- ***Aeolus:*** As Control with simulated Aeolus data added.
- ***NoSondes:*** As Control but radiosondes and wind-profilers were removed.

Statistics, such as the spread within a particular ensemble, were compiled for the period 16 January to 28 February 2003 (to disregard common initial conditions). A beneficial impact of observational data corresponds to a reduction in ensemble spread. Comparison of the Control and NoSondes ensembles permits essential calibration of the results, and facilitates a relative assessment of Aeolus and radiosonde impacts.

Development of the methodology taken here was motivated by two significant advantages over the traditional approach using an Observing System Simulation Experiment (OSSE) for assessing the impact of anticipated data. The first is that the method is based on real observations thus obviating the need to simulate observations other than the anticipated new data (Aeolus in this case). The second is that, whereas OSSE results are difficult to interpret because of uncertainties surrounding the role of simulation biases, the situation is not so severe in the assimilation ensemble approach. This is because the ensemble approach has permitted the development of diagnostics based on relative differences between ensemble members, offering much more scope for cancellation of bias effects.

The results in Figure 5 suggest that the main benefits from Aeolus (compared to Control) for analysed wind fields will be found over ocean regions in both hemispheres and in the tropics, and over parts of central Asia. These regions have been identified as priority areas for improvement. A calibration factor of order 2 is required to obtain values commensurate with actual wind uncertainties in the ECMWF system. The large impact in the tropics is noteworthy. It is likely that the Aeolus wind data will help determine the moisture-convergence at low levels in the region of the ITCZ, as well as the divergent outflow in the upper troposphere. It is hoped that the Aeolus data will help maintain a more correct intensity of the Hadley circulation than is currently the case at ECMWF in the operational system and ERA-40 climate re-analyses.

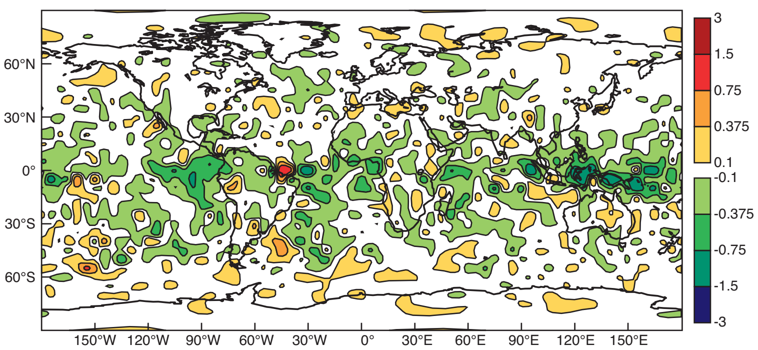

Figure 5 Impact in terms of 200 hPa zonal wind component (ms^{-1}) of ADM-Aeolus wind profile data as deduced from the difference in data assimilation ensemble spread between two ensembles: Control and ADM. Green shading indicates that the ensemble spread (i.e. the analysis error) is reduced using the ADM data, with orange indicating that it is increased (see legend). Shading in the range -0.1 to 0.1 is suppressed.

Information Content

We have complemented the above result with an assessment in terms of information content. Practical methods for computing information content (degrees of freedom for signal - DFS) in the observations and analyses have recently been developed (*Cardinali et al.,* 2004; Fisher, 2003b) within the context of the global 4D-Var assimilation system. The profiling observing systems that Aeolus can most usefully be compared with are the radiosondes and wind profilers. Using the method of *Fisher* (2003b) information content was computed for each of the experiments Control, Aeolus and NoSondes, defined above.

It was found that in terms of wind information in these experiments the radiosondes plus wind profilers provide 3153 DFS and Aeolus provides 2454 DFS (see Table 1). These results are in keeping with the expected quantity, accuracy and coverage of the simulated Aeolus data. Radiosondes and wind profilers provide slightly more information in absolute terms, but require proportionately more observations to achieve this. Aeolus observations provide more information per datum because they are able to contribute information in regions that are currently poorly observed (i.e. over ocean regions in both hemispheres and throughout the tropics).

Future work

In the years leading up to the launch of the Atmospheric Dynamics Mission Aeolus, further simulations will be carried out using the new data processing software, currently under development. In particular there will be studies of quality control issues and how to achieve representative along-track averaging in heterogeneous cloud and aerosol conditions. First Aeolus-like atmospheric data will be available in 2006 obtained from an airborne version of the Aeolus Doppler wind lidar to be flown by a DLR team, in ESA-funded campaigns.

Data	TEMP+PILOT winds to 55 hPa	ADM-Aeolus line of sight winds
Number of data	74,682	28,979
DFS	3153	2454
Data per DFS	23.7	11.8

Table 1 Information content in TEMP (radiosonde) and PILOT winds and ground-based wind profiler data from the surface to 55 hPa and in simulated ADM-Aeolus single line-of-sight data, in data assimilation experiments with the ECMWF 4D-Var system.

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Further reading

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