THE ATMOSPHERIC DYNAMICS MISSION FOR GLOBAL WIND FIELD MEASUREMENT

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The *ADM-Aeolus* mission will provide global wind profile observations with the aim to demonstrate improvement in atmospheric wind analyses for the benefit of numerical weather prediction and climate studies.

During the past 15 yr the European Space Agency (ESA) has been evaluating the prospects for a spaceborne Doppler wind lidar (DWL) for measurement of the global wind field. Early concepts had been developed by the Doppler lidar working group (ESA 1989). These preparatory activities, including theoretical studies, technical developments, and field campaigns, have been described in a "Report for mission selection" (ESA 1999). This report was presented to the European Earth Observation community at a selection meeting. Four candidate Earth observation missions were considered, and the atmospheric dynamics mission for wind profile measurement was selected as the second of these Earth Explorer core missions to be implemented. It is now an approved mission of the European Space Agency with a target date for launch in 2007.

The primary aim of the *Atmospheric Dynamics Mission* (*ADM-Aeolus*) of the European Space Agency is to provide global observations of vertical wind profiles. Presently, knowledge of the 3D wind field over large parts of the Tropics and major oceans is quite incomplete. This leads to major difficulties both in studying key processes in the coupled climate system and in further improving the numerical forecast systems. Progress in climate modeling is intimately linked to progress in numerical weather prediction (NWP). The wind profile measurements provided by *ADM-Aeolus* are expected to demonstrate improvements in such atmospheric modeling and analysis.

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These advances will, in turn, enhance the long-term databases being created by NWP data assimilation systems to serve the climate research community. As such, *ADM-Aeolus* promises to also provide data that are needed to address some of the key concerns of climate research, including climate variability, validation and improvement of climate models, and process studies that are relevant to climate change.

The concept of the mission is explained in Fig. 1. A very high performance DWL will be accommodated on a satellite flying in a sun-synchronous orbit at an altitude of ~400 km, and will provide near-global coverage (see Fig. 2). The DWL is an active instrument that fires pulses of laser light toward the atmosphere along a line of sight (LOS). In the return signal, backscattered light from molecules and particles at different levels in the atmosphere is collected and a sequence of Doppler frequency shifts is measured. The Doppler shift depends on the velocity in LOS direction of the scattering particles that move with the airflow. Thus, it allows the determination of the mean wind component velocity profiles.

Meteorological implications and utilization of such a system are discussed in the following section. The section titled "*ADM-Aeolus* Doppler wind lidar description" discusses technical aspects of a 355-nm-wavelength direct detection scheme and receiver system combining two interferometers for both molecules and larger particles. Conclusions are presented in the last section.

METEOROLOGICAL IMPACT OF WIND PROFILE MEASUREMENTS.

Impact for numerical weather prediction. Reliable instantaneous global analyses of winds are needed to improve the understanding of atmospheric dynamics and climate processes, and also to improve the quality of NWP models. Indeed there is a synergy between advances in climate-related studies and those in NWP, because climate studies are increasingly using analyses of atmospheric (and other) fields from data assimilation systems that are designed originally to provide initial conditions for operational weather forecasting models. These scientific applications are severely limited by the lack of direct three-dimensional wind information over the oceans, the Tropics, and the Southern Hemisphere, where radiosonde observations are scarce.

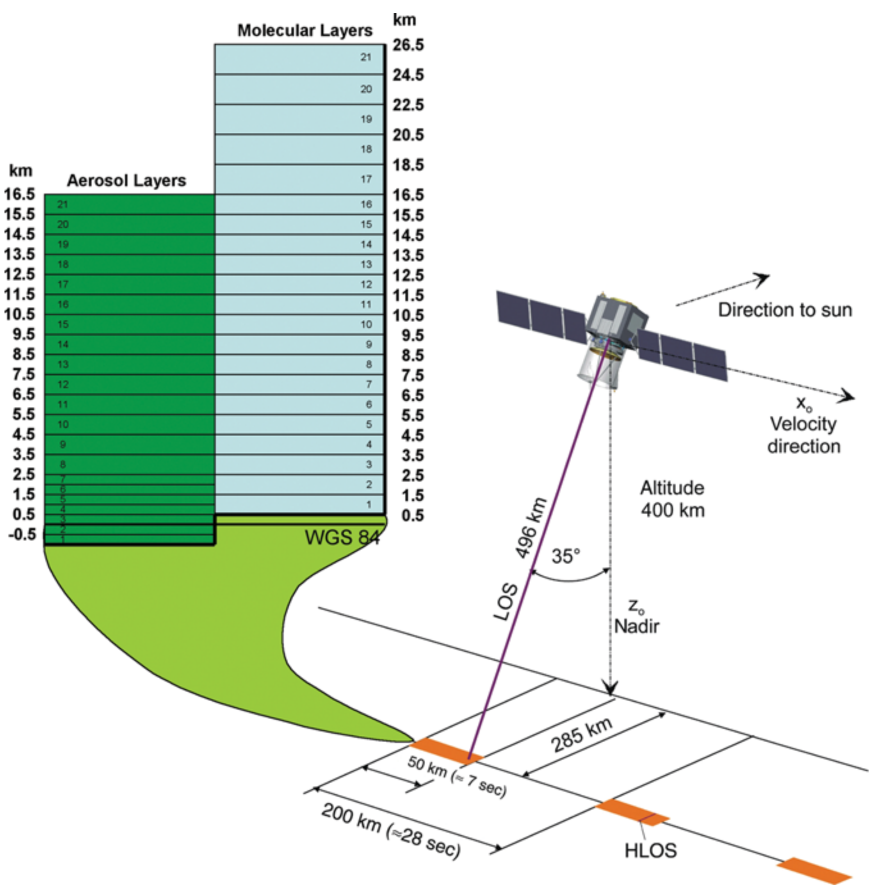

FIG. 1. Doppler wind lidar principle and measurement geometry: The lidar emits a laser pulse toward the atmosphere, then collects, samples, and retrieves the frequency of the backscattered signal. The received signal frequency is Doppler shifted from the emitted laser light due to the spacecraft motion, Earth rotation, and wind velocity. The lidar measures the wind projection along the laser line of sight, using a slant angle versus nadir. Also shown is the mapping of atmospheric heights to layers measured by the detector. The vertical as well as the horizontal values can be programed, providing observation flexibility.

CURRENT METEOROLOGICAL OBSERVATIONS AND THEIR LIMITATIONS. A wide variety of observation types are currently available routinely for assimilation in NWP systems. They constitute the Global Observing System (GOS) at the basis of operational weather forecasting and climate studies. The different observation types can be classified in the following way:

1) Surface data: These are the synoptic reports from land stations and ships, moored and drifting buoys, and scatterometer winds from satellite radars [such as European Remote Sensing (ERS) and Seawinds]. The surface data provide valuable information on the location and intensity of weather systems and good estimates of surface winds over both land and the oceans. However, these data naturally do not provide any profiling information.
2) Single-level upper-air data: These include measurements obtained from en route aircraft, and the atmospheric motion vectors (AMVs) that are obtained from geostationary or polar satellite imagery. The aircraft data provide frequent and accurate profiling information at main airports, and horizontally dense coverage along the main air traffic routes. However, from a global perspective the coverage is insufficient. The wind information in the AMVs is more uncertain than that from in situ data, because the intrinsic assumption that tracked features (mainly clouds) in the images is advected by the atmospheric flow and is not always true. The height assignment of the derived winds can also be problematic, leading to biases and systematic errors. Geostationary satellite AMVs provide good global coverage within approximately 50° of the equator, while polar satellite AMVs are useful above 70° latitude.
3) Multilevel upper-air data: These consist of radiosondes, pilot balloons, radar wind profilers, measurements obtained from aircraft during landing and takeoff, and sounding data from polar-orbiting satellites. The satellite sounders provide good global coverage of microwave and infrared radiance data, which can be assimilated directly for an accurate definition of the global temperature and humidity fields (Andersson et al. 1994). Radiosondes and pilots constitute the main source of global wind profiling information, with good availability mainly from the continents in the Northern Hemisphere.

Despite the sophistication of modern data assimilation methods (e.g., Rabier et al. 1998), large uncertainties remain in some wide areas of the globe, especially for the wind field. Over the oceans the upper-air wind analysis relies mainly on spaceborne radiance observations, which, when coupled with accurate surface pressure information and geostrophic adjustment theory, can provide some information, indirectly, also on the wind field. In the Tropics the geostrophic assumption is not valid, and direct measurements of the wind are required to produce accurate analyses of the atmospheric flow. The wind information is essential

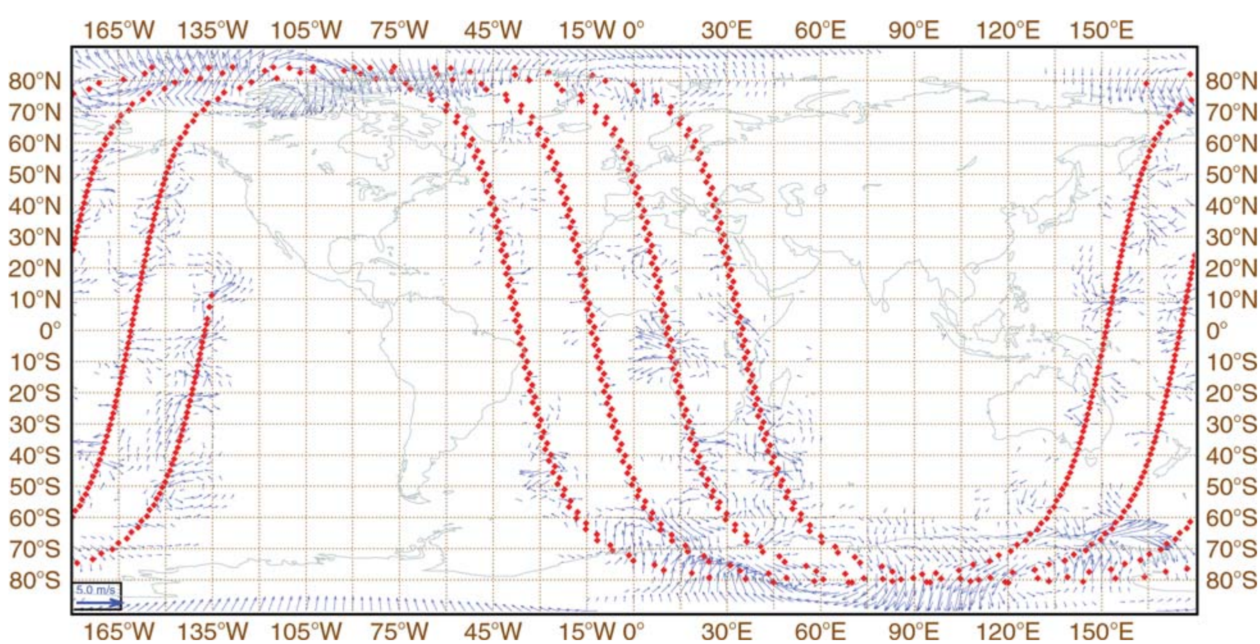

Fig. 2. ***ADM-Aeolus*** **DWL coverage in a 6-h time window (dots). The 925-hPa-level analysis wind impact of the simulated LOS DWL data in the ECMWF observation system simulation experiment (Marseille et al. 2000) is also shown (arrows).**

in the Tropics because it governs the dynamics. In the extratropics, wind data are the primary source of information for small horizontal scale features and deep vertical structures (small scales compared to the Rossby radius of deformation), as depicted in Fig. 3. It is only for the large horizontal scale features and shallow vertical structures that the wind field can be derived from the mass field in the assimilation process with reasonable accuracy (large scales compared to the Rossby radius of deformation). A space-based DWL provides wind profile information globally, which is of value particularly in the Tropics and over the oceans where such observations are otherwise lacking.

Prospect of DWL observations. One important aspect to be considered for NWP is the detectability of precursor features. Atmospheric structures that are precursors to the development of extratropical cyclones can often be identified in areas where cyclogenesis takes place. In the preparation of the *ADM-Aeolus* mission, vertical wind shear has been studied as a relevant example. Midlatitude weather systems are believed to have their origin in processes that are encapsulated in the theory of baroclinic instability. A suitable measure of the baroclinicity is provided by the Eady growth rate index (e.g., Hoskins et al. 1978; Hoskins and Valdes 1990) in which the vertical wind shear is the main variable.

The mean vertical wind shear varies with the geographical region, height, and wind component, but lies generally between 3 and 4 m s^{-1} per kilometer depth. The distribution of the shear angle with respect to north is very anisotropic and dominant in the zonal direction in most geographical regions. According to its current design, *ADM-Aeolus* will measure Doppler shift in the across-track direction and vertical wind shear in the zonal direction will be relatively well resolved.

The detectability of vertical wind shear was studied by Stoffelen and Marseille (1998) and Veldman et al. (1999) using a realistic *ADM-Aeolus* simulator (Marseille and Stoffelen 2003). They investigated the DWL signal return and wind retrieval quality (horizontal LOS wind component) for the 25% of cases with the strongest wind shear at each vertical level in the forecast model of the European Centre for Medium-Range Weather Forecasts (ECMWF). It turned out, as illustrated in Fig. 4, that the signal strength and the corresponding wind retrieval quality were quite similar in the middle and upper troposphere to cases without strong vertical wind shear, and, as such, the occurrences of shear and cloud were not very well correlated. It was furthermore noted that relatively few returns with very good quality appeared when strong shear was measured, because this only occurs in the case when shear is determined from two subsequent cloud layers, which is relatively unlikely. A relatively low detectability of wind shear was observed only in the lower troposphere in the storm-track region, despite the occurrence of aerosol returns at this level. This is probably due to the correlation of shear and boundary layer cloud at this level. Therefore, it was concluded that *ADM-Aeolus* will likely have the ability to observe vertical wind shear in broken cloud conditions, though with a reduced capability close to the surface. Here, other wind measuring systems will remain important (e.g., surface stations and scatterometer).

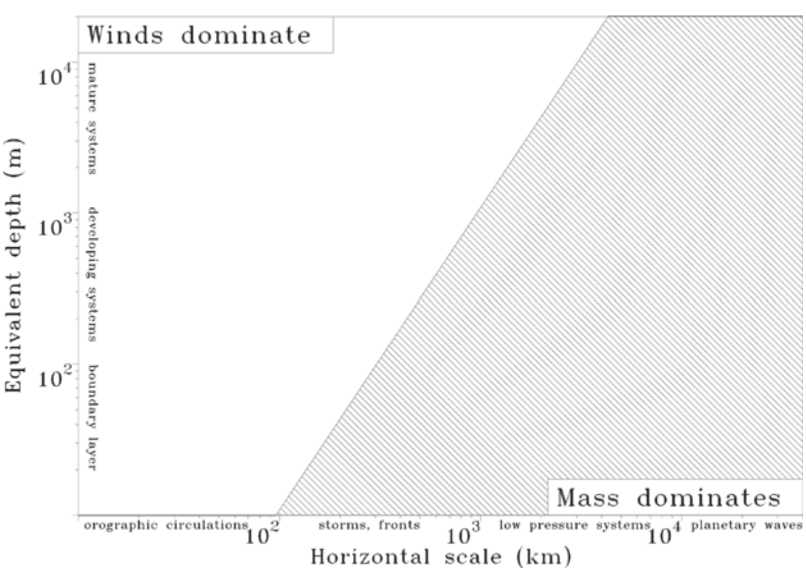

Fig. 3. Rossby radius of deformation for a latitude of 45° as a function of horizontal scale and equivalent depth. Open area denotes the range within which the wind field dominates the atmospheric dynamics, and three-dimensional wind measurements are important.

Wind profile observing system experiments. Even at very short range, NWP models can be hit by severe failures, which, although it cannot always be proven, are suspected to be due to a lack of meteorological observations in precursor areas, which are critical for the initial state of these models. One example is the storm of 24 December 1997 (now called the "Christmas Eve Storm"),

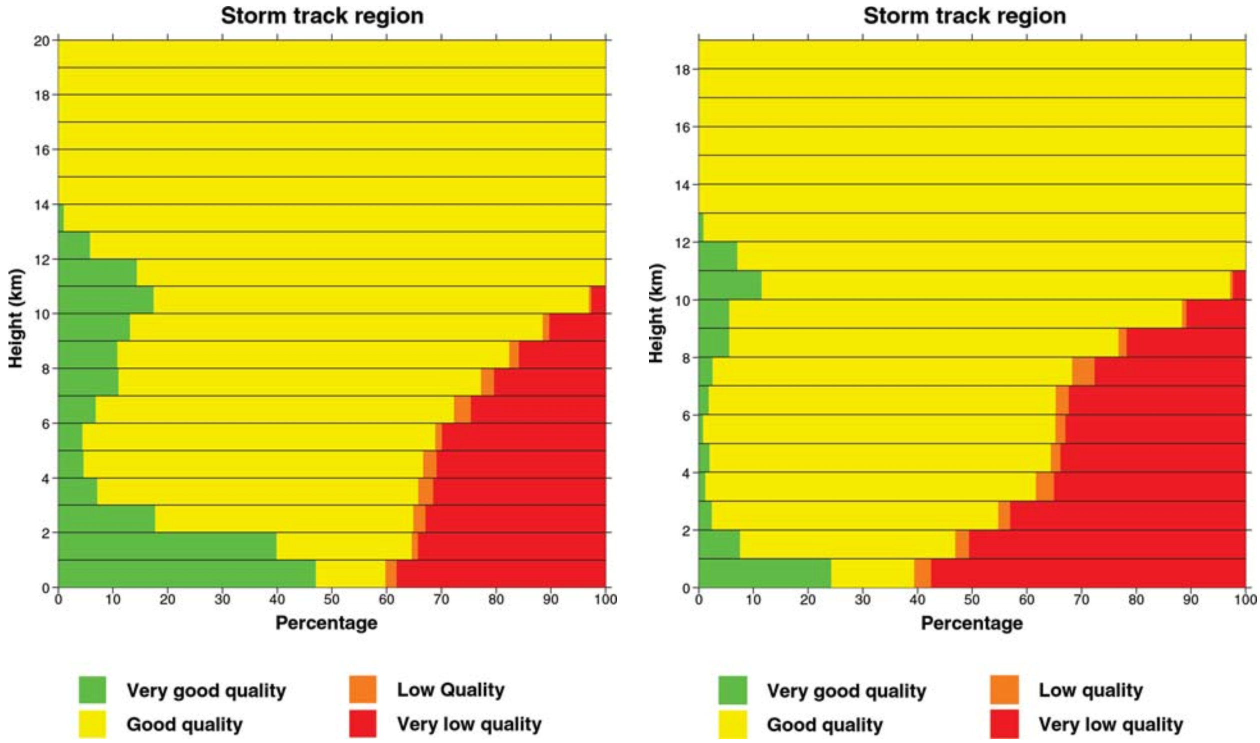

Fig. 4. Simulated performance classification of the *ADM-Aeolus* DWL in the storm-track region between 40° and 60° latitude (a) for all profiles, and (b) only for the data points at each level with the 25% strongest wind shears. The classification categories for wind error standard deviation denoted respectively very good, good, low, and very low are separated by the subsequent approximate thresholds of 1.4, 2.8, and 4.2 m s^{-1} (for details, see Marseille and Stoffelen 2003). Wind shear detectability is only weakly correlated with the occurrence of cloud (Stoffelen and Marseille 1998; Veldman et al. 1999).

which deepened very quickly in the middle of the Atlantic Ocean on 23 and 24 December 1997, then hit Ireland and the Irish Sea in the afternoon of the 24th, and finally the north of England and Scotland. The forecasts of the storm from all of the operational models were very poor, even at very short range as illustrated in Fig. 5. The examination of the different operational analyses on the 22 and 23 December, together with the satellite imagery, indicates that these analyses were often unable to accurately catch the different weather systems (cyclogenesis, developing waves, and their precursors), possibly because of strong cross-Atlantic circulation, rapid baroclinic developments, and insufficient data coverage (e.g., Hello et al. 2000). Studies are ongoing to determine the potential of *ADM-Aeolus* in such cases.

Detailed studies of extreme cases are just one way to evaluate the potential impact of an observing system. Another and more general way is to run "impact studies" (comparisons of analyses and forecasts with and without the observing system) on longer periods (typically a few weeks) and to evaluate the results by extracting signals, which are averaged over those periods. These impact studies are called observing system experiments (OSEs) when an existing observing system is studied, and observing system simulation experiments (OSSEs) when a future observing system is studied through simulation of the new data.

Several OSSEs and OSEs have been run in the past, which are relevant for a spaceborne wind lidar (see also Baker et al. 1995). In one particular OSE, run by Cress and Wergen (2001), real wind data from North America radiosondes and aircraft were tested in order to show the impact of accurate 3D wind observing systems on a small portion of the earth. Figure 6 shows the impact on global analyses of not using wind observations over North America. After 11 days of assimilation, the differences, initially located on North America, had propagated not only downstream over the Atlantic Ocean (areas often critical for forecasts over Europe), but also along the whole tropical belt, thus highlighting the uncertainties in analyzing the wind field. Figure 6 stresses once more the need to observe the wind directly in the Tropics, because it is impossible to reconstruct from other observations through a proper atmospheric mass/wind balance (Žagar 2004). Also, outside the Tropics, accurate wind observations appear to be more important than tem-

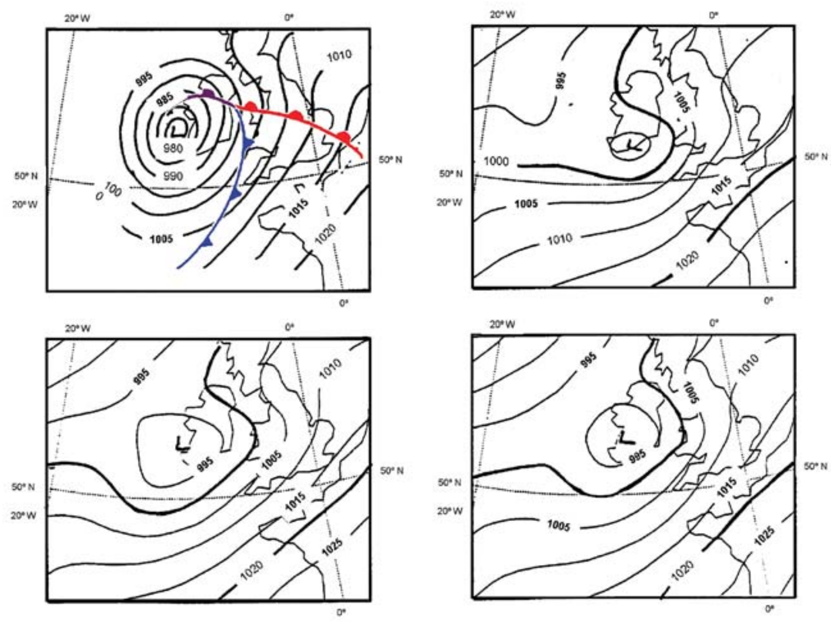

Fig. 5. Analysis and forecasts of the Christmas Eve Storm—mean sea level pressure (MSLP) maps illustrating the Christmas Eve Storm, which hit the British Isles on 1200 UTC 24 Dec 1997, after a rapid development from the middle of the Atlantic Ocean (courtesy A. Persson, ECMWF). Top left: manual analysis for 1200 UTC 24 Dec 1997; Top right: ECMWF 12-h forecast from 0000 UTC 24 Dec 1997 (valid 12 UTC); Bottom: equivalent 12-h forecasts from the (left) Met Office and (right) Deutscher Wetterdienst models.

perature observations for the quality of NWP models. This has been shown by several impact studies (see, e.g., Cress and Wergen 2001).

Marseille et al. (2000) performed an OSSE for *ADM-Aeolus* in a state-of-the-art data assimilation system to verify the expectations based on earlier OSE and OSSE. Marseille and Stoffelen (2003) describe the *ADM-Aeolus* DWL simulator that is used in this study.

Importance for climate studies. Climate change issues have received substantial attention in recent years due to the increasing awareness that human activities may modify the climate of the earth (Houghton et al. 2001). An increased greenhouse effect due to rising levels of carbon dioxide in the atmosphere is the most probable cause of the recent global warming. There are also other greenhouse gases in the atmosphere—the most important one being water vapor, which dominates over carbon dioxide in terms of the total greenhouse warming. The water vapor feedback is crucial in determining climate change sensitivity. An increased heating at the earth's surface will lead to an increase in atmospheric water vapor concentrations and, thus, a further heating implying a positive feedback. Some authors, however, have argued that in the Tropics feedbacks involving water vapor, clouds, and circulation changes may even act to decrease climate change sensitivity (see, e.g., Lindzen et al. 2001). A very important question is how a further increase in carbon dioxide and other man-made greenhouse gases may affect the total climate system. The most effective tools available to answer such questions are physically based climate models that closely resemble NWP models. All of the benefits of wind data discussed in previous sections, relating to NWP models, are, thus, also relevant to atmospheric/oceanic circulation models that are used for climate studies. The ocean and the atmosphere act together as a heat engine, where the differential heat input from the sun generates turbulent motion fields that are not adequately covered by the present-day observing system. The *ADM-Aeolus* mission for the first time sets out to globally observe this motion.

Climate change simulations have been performed with a range of atmosphere–ocean general circulation models (AOGCMs) and projections of future climate change differ considerably between different models (Houghton et al. 2001). All models are based on the same fundamental physical and numerical principles, but their representation of physical processes (parameterizations) differ. Examples of such parameterized processes are cloud representation and radiation calculations. A particular AOGCM can be compared to the observed climate through control simulations of past climate change, and the parameterized processes can be compared with observations of clouds and radiation either in situ or from space. If discrepancies are found, changes in the formulations of parameterizations can be tested to see if the simulations improve. A fundamental difficulty with such comparisons is the nontrivial relation between changes in parameterizations and the circulation response of an AOGCM. If, for example, the heating rate in a cloud parameterization scheme is changed this will affect the heat transfer between the ocean and the atmosphere,

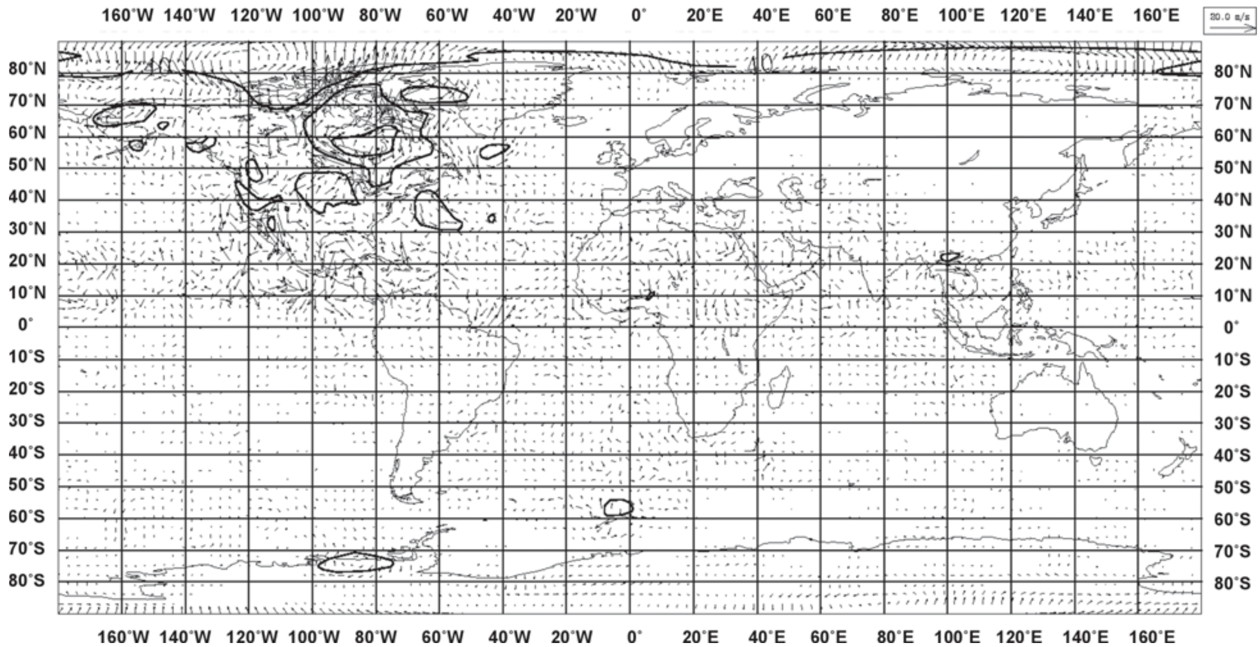

FIG. 6. Difference in the wind and geopotential analysis at 500 hPa caused by not using wind profile observations from radiosondes, pilots, and aircraft over the United States and Canada during 11 days of assimilation. The fields are valid for 30 Jan 1998; the contour interval for height is 20 gpm.

which in turn will change the large-scale wind divergence in the atmosphere. Tropical circulation systems are very much determined by the wind field and changes in the distribution of water vapor that to a large extent determine climate change feedback sensitivity (Cess et al. 1990, 1996, 1997). However, the latter is mainly controlled by advection (Pierrehumbert and Roca 1998). The interaction between cloud field heating patterns and the large-scale tropical circulation may thus give rise to intricate circulation pattern changes when only convective heating parameterizations are changed. Comparing a model simulation with observations of clouds and radiation is not sufficient to understand how well a model simulates an observed phenomenon. The wind field must also be determined in order to obtain a full understanding of the effect of parameterization changes.

In Fig. 7 (adapted from Kistler et al. 2001), the zonally and temporally averaged wind field is shown for a 15-yr period in the tropical region, and results from both the ECMWF and the National Centers for En-

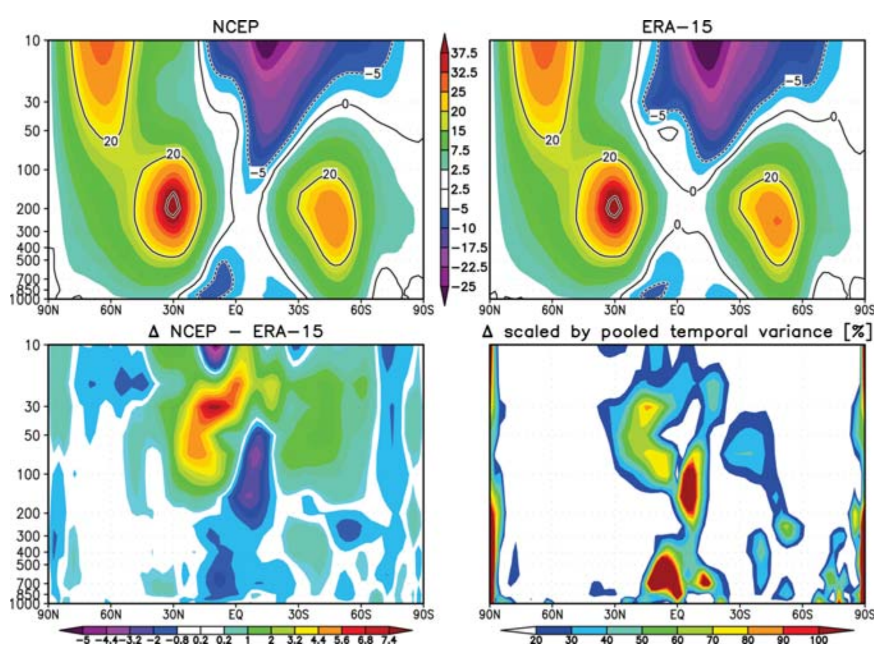

FIG. 7. Comparison of the zonal average of the zonal wind component for the (top left) NCEP–NCAR reanalyses and (top right) 15-yr ECMWF Re-Analyses. The fields are Dec, Jan, Feb averages between 1979 and 1994. The difference in the reanalyses and the difference scaled by the total temporal variance (%), are displayed in the bottom panels (after Kistler et al. 2001).

vironmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalyses are used. The difference between the reanalyses is substantial in the tropical region; the shift in the wind field is of the same order as the wind field itself. Both reanalyses use the same observation database; the differences occurring are, thus, due to differences in the assimilating models. As noted above, the model differences are mainly coupled with parameterizations of clouds and radiation. A conclusion from these results is that the presently available observations are not sufficient to constrain the wind field in the Tropics. More wind profile observations are needed.

Model simulations of future climate change show a large spread, and some of this spread is due to differences in the parameterization of atmospheric processes. An intercomparison between state-of-the-art AOGCMs shows that projected changes in temperature and precipitation differ considerably between models under the same greenhouse gas concentration change scenarios (Räisänen 2001). These differences are even more marked when regional climate change is considered, Timmerman et al. (1999) and Noda et al. (1999) have investigated the change in El Niño patterns under global warming and found contradictory results using different AOGCMs.

The impact of the wind observations is, however, not limited to tropical regions. It has been suggested that global warming can alter the statistics of midlatitude disturbances (Carnell and Senior 1998), and this may, in turn, lead to changes of larger-scale circulation patterns. Regional climate change very much depends on the statistics of these large-scale patterns, and more comprehensive wind data will help in the understanding of processes that govern regional climate change.

ADM-Aeolus *observation of the tropical circulation.* The *ADM-Aeolus* mission will provide a much improved wind dataset to be used for climate process studies. As noted before, it is necessary to assimilate the wind data in a NWP-based data assimilation system to provide a dynamically consistent set of atmospheric climate states to be used for climate model development and climate process understanding. Main improvements are expected in tropical areas where present wind profile observations are very sparse. From dynamical considerations it can be determined that the wind field is the governing atmospheric state variable in the Tropics, and wind data are thus most crucial in these regions. In line with this, after defining the appropriate mass–wind relationships for the effective assimilation of the wind data (e.g., Žagar et al. 2004a,b), assimilation of *ADM-Aeolus* line-of-sight winds in the tropical region shows a clear positive impact within an idealized framework (Žagar 2004).

Important variables in the tropical circulation and the hydrological cycle are heat and humidity transport. Stoffelen and Marseille (1998) and Veldman et al. (1999) studied the detectability of tropical fluxes of heat and humidity in cloudy areas. Obviously, processes of humidity transport, condensation, and precipitation are often associated with cloud. On the other hand, multiple shots in the case of cloud porosity (Winker and Emmitt 1998) can enhance the detectability of atmospheric heat and humidity fluxes in cloudy conditions as discussed in ESA (1999).

As an example of the usefulness of the *ADM-Aeolus* DWL for studying atmospheric processes that are associated with the energy balance, Fig. 8a shows the wind performance classification in the Tropics for those meridional moisture fluxes that are larger than the mean plus one standard deviation of the flux variability at the level considered. By comparing these types of histograms with the corresponding histograms of performance classification for all flux conditions (Fig. 8b), it can be concluded that many returns from clouds appear in moist air at all geographical locations. At the lowest altitudes in the middle and lower troposphere, cloud obstruction of the moisture flux is most substantial. Aerosol scattering provides generally improved performances in moist conditions with respect to the molecular scattering signal. However, extensive cloud fields in the planetary boundary layer may prevent sampling of the lowest atmospheric layer over relatively large regions.

Thus, assuming that LOS winds can be measured at cloud-top heights that are representative for the general flow, a DWL in space provides essential information on the tropical circulation in the upper troposphere. On the other hand, clouds obscure the detectability of moisture fluxes in the middle troposphere, particularly in the Tropics. Due to the presence of aerosol scattering, the near-surface moisture flux is clearly visible in the majority of cases.

Observational requirements for data assimilation. Like many other meteorological observations, the spaceborne LOS wind component profiles by themselves seem at first glance to be of limited value, but in the context of atmospheric data assimilation systems they would in fact be an essential component of the GOS, just like radiosonde wind profiles today. For a mission intended to demonstrate the feasibility of a full-scale spaceborne wind observing system to improve global atmospheric analyses, the requirements for data quality and vertical resolution are the most stringent and most important to achieve. Under this assumption, the density of profile observations is of lower priority among the requirements. However, the derivation of the coverage specification is supported by weather forecast impact experiments. These included the inputs of the conventional wind profile network, which is thin and irregular but of key importance (see the section titled "Impact for numerical weather prediction"). Moreover, the coverage specification is compatible with the World Meteorological Organization (WMO) threshold requirements. The WMO recognizes the prime need for wind profile data (WMO 2000) and has defined wind profile measurement requirements (WMO 1996, 2001).

The full wind vector consists of two horizontal and a vertical component. The average vertical wind component is small over a typical meteorological model grid box (Courtier et al. 1992) and is, in general, negligible. A lidar instrument can only observe the component along its LOS. Because the horizontal components are needed, the horizontal projection of the LOS winds (HLOS) is the quantity of interest.

To provide the two horizontal wind components, the same volume needs to be viewed from two different azimuth angles. Because this requirement imposes severe technical constraints, an alternative solution to demonstrate a spaceborne DWL is to provide one component only. The provision of only one wind component is no technical limitation to modern data assimilation schemes, just as it is possible to assimilate a temperature measurement without a wind measurement. Figure 2 depicts the simulated analysis wind impact of a few tracks of *ADM-Aeolus* DWL data.

Lorenc et al. (1992) performed an OSE where either no, one, or two components of a cloud motion wind (CMW) vector were assimilated, and they found half of the beneficial forecast impact when only one wind component, rather than both, was used. Thus, it appears that single-component HLOS winds can provide significant NWP improvement. Moreover, in an additional experiment, where 50% of all CMW vectors were randomly removed, 50% of the beneficial forecast impact of all CMW was also found indeed. Thus, the expected analysis and forecast impact of two-wind-component measurements is the same for two collocated orthogonal components and for two spatially well-separated measurements of one single component. These findings are further supported by impact studies (Leike et al. 2001; Marseille

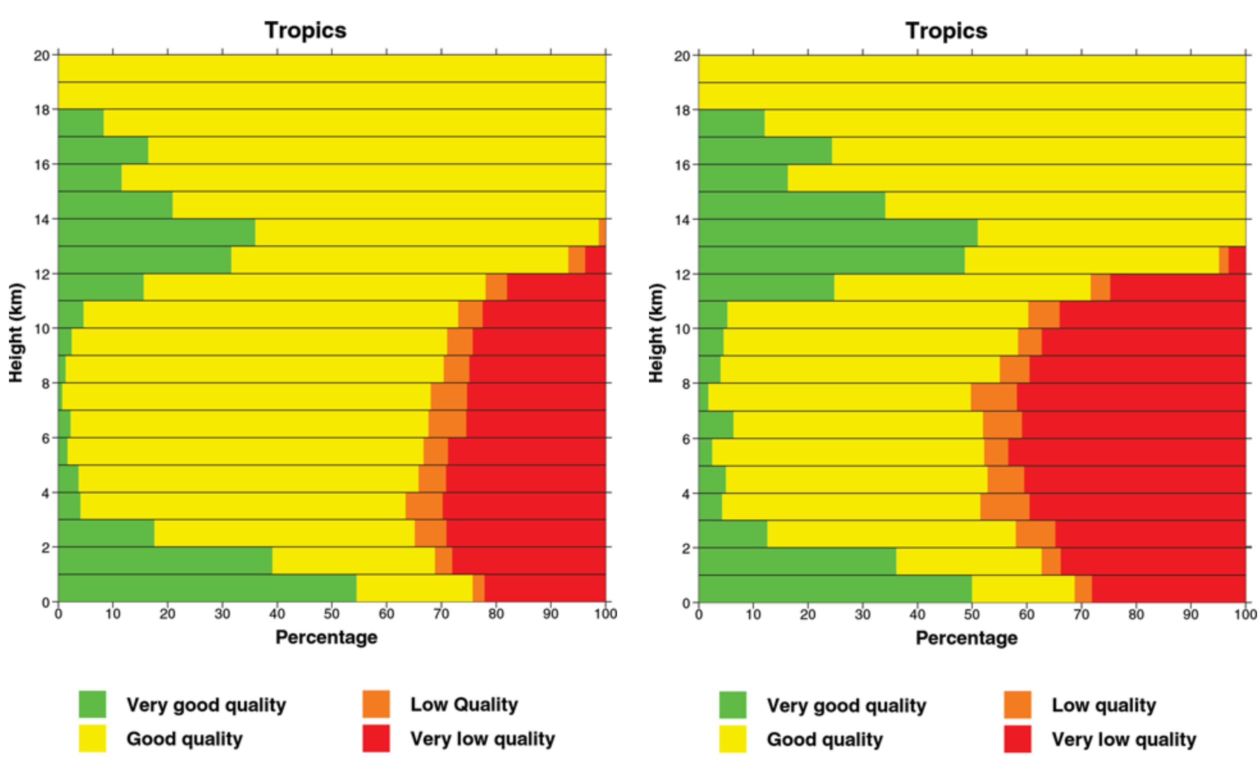

FIG. 8. Simulated performance classification of the *ADM-Aeolus* DWL in the tropical region below 20° latitude (a) for all profiles, and (b) only for the data points at each level with the 20% strongest humidity flux. Classification is as in Fig. 4. The detectability of the near-surface humidity flux is somewhat reduced but better than 60% in the Tropics (Stoffelen and Marseille 1998).

et al. 2000), which demonstrated a positive impact of simulated single-LOS winds. This confirms that the matching of multiple azimuth "looks" in one geographical area is not required for data assimilation. However, two independent wind components may be desirable in certain flow configurations (Riishojgaard et al. 2004).

At very small scales (e.g., the footprint of a DWL), and in extreme cases such as thunderstorms, the vertical component of the wind may be quite substantial and the assumption to neglect vertical motion is strictly not valid in such situations. However, current NWP models cannot represent these small scales, and as such the vertical motion is regarded as an unwanted component of the measurement and is treated as part of the so-called spatial representativeness error (Lorenc et al. 1992).

Over data-sparse areas the 2–3 m s^{-1} accuracy requirement is expected to be sufficient to provide a beneficial impact on meteorological analyses; the requirement is comparable with the typical first-guess error. This requirement is significant because experience in meteorological data assimilation shows that observations with an accuracy that is poorer than the first guess often fail to have a significant beneficial impact on NWP. In summary, Table 1 provides an overview on the *ADM-Aeolus* requirements.

The expected meteorological impact in the Tropics is the most certain, and, from a climatological point of view, is also the most useful. Moreover, to improve atmospheric analysis beyond the Tropics, and more particularly NWP in Europe, the above requirements have been carefully chosen to be able to demonstrate the beneficial impact of DWL winds at midlatitudes (ESA 1999).

ADM-AEOLUS DOPPLER WIND LIDAR DESCRIPTION.

Measurement principle. *ADM-Aeolus* will use a single LOS perpendicular to the flight direction (Fig. 1). The spaceborne lidar will emit a spectrally narrow laser pulse directed at a 35° slant angle toward the atmosphere. Laser light of a 355-nm wavelength is scattered in the atmosphere by molecules (Rayleigh–Brillouin scattering) and by small aerosol and cloud particles (Mie scattering) that move with the wind. A very small fraction of such scattering is backscattered toward the spacecraft. The scattered light has a different frequency than the light that is emitted by the laser because of the Doppler effect. Due to the scatterer's relative movement in the direction of observation, a frequency shift δf occurs, given by

$$\delta f = -2V/\lambda, \quad (1)$$

where V, the LOS velocity between the transmitter and scatterers, is due to three contributions—spacecraft motion, Earth rotation, and wind flow—and λ is the laser-transmitted wavelength. The Doppler frequency shift due to the platform moving at 7 km s^{-1} is cancelled as much as possible by looking at 90° from the direction of travel and, moreover, can be corrected. Figure 9 shows schematically the wavelength distribution of the light signal.

The wide-bandwidth Rayleigh–Brillouin scattering spectrum, equivalent to ~600 m s^{-1} full width at half maximum (FWHM), is nearly of Gaussian form at shorter wavelengths. A Doppler Gaussian shape applies strictly at low pressures where correlations between the motions of gas molecules can be disregarded. At higher pressures, close to one atmosphere, the molecular velocity correlations arise due to

TABLE 1. Observational requirements of the Atmospheric Dynamics Mission.

Key parameters	Observational requirements PBL	Troposphere	Stratosphere
Vertical domain (km)	0–2	2–16	16–20
Vertical resolution (km)	0.5	1	2
Horizontal domain		Global	
No. of profiles (h^{-1})		>100	
Profile separation (km)		>200	
Horizontal integration length (km)		50	
Horizontal subsample length (km)		0.7–50	
Accuracy (HLOS component) (m s^{-1})	1	2	3
Zero-wind bias (m s^{-1})		0.1	
Wind speed slope error (%)		0.5	
Data reliability (%)		95	
Data availability (h)		3	
Length of observational dataset (yr)		3	

the propagation of pressure waves through the scattering medium, and result in the Rayleigh–Brillouin spectrum. This effect is taken into account in the evaluation of the lidar performance. The two contributions, from aerosols and molecules, are centred at the same frequency and superimposed:

1) narrow-bandwidth aerosol (Mie) scattering typically equivalent to a ~10 m s^{-1} width or less (in practice, the line width is largely due to the laser line width), and
2) broadband molecular (Rayleigh–Brillouin) scattering with an equivalent width (FWHM) of ~600 m s^{-1}.

In addition, there will be a broadband, semicontinuous background of reflected sunlight. The relative magnitude of the first two components is expressed by the scattering ratio (the ratio between the total scattering and molecular scattering) and is largely determined by the laser wavelength according to a λ^{-4} dependence for molecules and λ^{-a} for particles, where the exponent "a" varies from 0 to 3, depending on the particle size and wavelength. The scattering ratio is given by $(1 + C\lambda^{-a+4})$, where C is a constant. Typically, in the midtroposphere at 10 μm (in the infrared), aerosol (Mie) scattering is strongest, whereas at 355 nm (in the ultraviolet) the molecular (Rayleigh–Brillouin) scattering predominates and the scattering ratio is close to unity (except in clouds). Aerosol scattering is highly variable (several orders of magnitude) depending on the previous history of the air mass and is usually very strong within the planetary boundary layer and at high levels in the atmosphere, for example, thin and incipient cirrus clouds. Molecular scattering that is related to temperature and pressure varies more slowly and predictably through the atmosphere (roughly a factor 3 from the surface up to the tropopause level). At the lidar receiver the light signal from the atmosphere: $S(R) = K R^{-2} \beta(R) T^2$ [R is the range from spacecraft, K is an instrumental constant, β is the backscatter coefficient, and T is the atmospheric transmission] is sampled serially in time (for $R = ct/2$) in 20 successive range gates (ΔR), which determine the height resolution in the atmosphere, where typically ΔR equals 0.25–1 km.

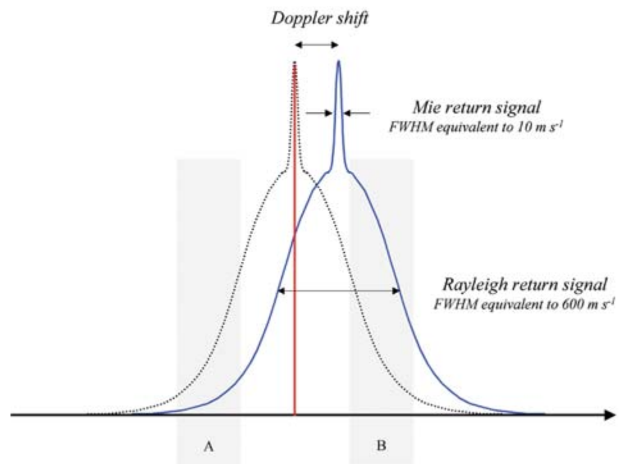

FIG. 9. Schematic spectrum (blue) of the light collected by a lidar in the UV near-visible region showing the scattering from aerosols (Mie return) and molecules (Rayleigh–Brillouin return). The received spectrum is shifted with respect to the emitted laser light (red line). The dotted curve represents a not-shifted spectrum (zero wind speed). The molecular return signal is broad due to thermal motion. The particular return signal is narrow for the particles that are heavier than molecules, and both are in collisional (kinetic energy) equilibrium. Also shown the position of the receiver's spectral filters A and B used for the double-edged detection technique.

ADM-Aeolus *design*. In early proposals dedicated to wind measurements from space the National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA) considered CO_2 laser technology, with heterodyne detection and a conical scan at ~45° from nadir to sample the atmospheric wind field. This basic concept was proposed for both the WINDSAT (Huffaker 1978; Osmundson 1981) and Laser Atmospheric Wind Sounder (LAWS; Baker 1995) projects. The CO_2 laser technique was considered as mature at that time, but the necessary accuracy for LOS measurements resulted in demanding requirements for a large CO_2 laser system, a large scanning telescope, and a lag-angle compensation unit. More recently, a multiple perspective CO_2 Doppler lidar has been studied in France by Centre Nationale d'Etudes Spatiales (CNES; CNES 1988) in the framework of the Bilan Energetique du System Tropical (BEST; or Tropical System Energy Budget). In BEST, the scanning requirement was made simpler using four (or even only two) fixed LOSs set at 90° from one another and 45° from nadir. More recently, NASA considered a system based on heterodyne detection at shorter wavelengths with a 2.1-μm solid-state laser. None of these projects proceeded beyond the feasibility level (phase A) or consolidated (phase B) study. It is worth noting that the CO_2 technology and a conical scan are currently used in the airborne WIND instrument developed in French–German cooperation (Werner et al. 2001). Wind infrared Doppler lidar (WIND) has been involved successfully in international field campaigns since its completion in 1999 (Reitebuch et al. 2001).

In parallel with these studies, ESA has been considering the feasibility of a space-based Doppler wind lidar. These activities have resulted in the selection of a high-performance Doppler wind lidar based on direct detection implementing interferometric techniques at the receiver level. This technique had been developed 30 yr ago (Benedetti-Michelangeli et al. 1972) and has been used routinely since then at 532 nm (Chanin et al. 1989). For eye safety reasons a UV wavelength is preferable. As a result, such a system, with pulsed laser operating at 355-nm wavelength would utilize both Rayleigh–Brillouin scattering from molecules and Mie scattering from thin cloud and aerosol particles.

The direct-detection UV concept at 355 nm, utilizing both aerosol and molecular scattering, was selected as the best compromise in terms of performance, especially for its robustness in terms of its lack of aerosols and the consequent impact on performance. This concept can provide compliant wind measurements up to high altitudes (20 km and above) for an operational mission, which is basically independent of the aerosol content. The technical and programmatic risks were evaluated as acceptable, and finally the mission based on the present instrument concept promises to be fully compliant with the requirements as discussed in the section, "Meteorological impact of wind profile measurements."

An intercomparison and validation study was conducted in the framework of the ESA campaign called "VALID." During 2 weeks in 1999, several ground-based lidars, a 72-MHz radar, and radiosondes have been operated simultaneously. The measurements have been compared with the ECMWF analysis (Delaval et al. 2000). The results presented during the Granada, Spain, meeting in 1999 were convincing enough to go ahead with the present mission.

The *ADM-Aeolus* laser source is based on a single-mode, 150-mJ, 100-Hz pulse/repetition frequency, diode-pumped and frequency-tripled (355 nm) Nd-YAG laser (see Table 2).

A 1.5-m-diameter Cassegrain afocal telescope is proposed as transceiver (for both transmitting and receiving). An isothermal and lightweight design will be used for the telescopic mirrors and structure, yielding the required optical quality and stability without additional focusing or alignment mechanisms.

The combination of two receivers—one for the Mie spectrum and one for the Rayleigh–Brillouin spectrum—thus provides an optimal performance over the whole altitude range. The Mie receiver is a Fizeau spectrometer, combined with a charge-coupled device (CCD) detector. This spectrometer has been validated in the framework of the ESA Technology Research Programme. The Rayleigh receiver is planned as a double Fabry–Perot etalon. Both aerosol (Mie) and molecular (Rayleigh–Brillouin) scattering will be examined simultaneously. The central part of the spectrum is filtered out and directed toward the Mie analyzer. The Fizeau fringe is superimposed on some Rayleigh residual light and atmospheric radiance, which provide an additional noise background. Computational analysis determines the center of the Mie fringe, and, after appropriate frequency calibration, the Doppler shift.

The broadband Rayleigh–Brillouin (molecular) scattering is analyzed by the dual-filter or double-edged technique (see Fig. 9). Two filters formed by the double Fabry–Perot etalon are positioned on either side of the laser wavelength in order to perform a differential measurement of the scat-

Table 2. Technical parameters of the spaceborne *ADM-Aeolus* Doppler wind lidar.

Parameters	Value
Satellite	
Altitude	400 km
Orbit	Sun synchronous, 6–18 h
Mass	1200 kg
Single LOS	At 90° from platform direction of travel
Nadir slant angle	35°
Instrument	
Wavelength (3rd harmonic)	355 nm, single mode
Pulse energy	150 mJ in 30 ns
Repetition rate	100 Hz in burst mode
Burst operation	7 s on, 5-s warm-up, 16 s off
Signal format (postprocessing)	
Altitude range above surface (for Mie and Rayleigh channel)	−1 to +30 km (extendable)
Vertical resolution	0.25–5 km (adjustable)

tered light. Because the line shape is Gaussian it can be described by two parameters. Two measurements within the Rayleigh–Brillouin spectrum are therefore sufficient to provide the line center and, thus, the Doppler frequency shift and wind speed.

In addition, because *ADM-Aeolus* is a high spectral resolution lidar the signal strengths in the Rayleigh and Mie channels can be used to derive secondary products like aerosol and cloud optical properties.

The high-sensitivity CCD detectors accumulate batches of 15 or 50 return signals on the chip. These accumulated signals are downlinked for quality control and further averaging in the processing station. The full observation of 700 shots is typically taken over 7 s, followed by a quiet period of about 21 s. In this 7-s-measurement period the satellite will have traveled approximately 50 km and thus the wind fields will have been effectively averaged over this distance in the propagation direction. The vertical height resolution is determined by techniques of time gating the return signal. At low levels a resolution of 0.5 km is required, extending to 1 km in the troposphere and to 2 km above a 16-km altitude. Extensive studies of system performance by both scientific laboratories and industry in the framework of preparatory studies had been carried out (Courtier et al. 1992; Delaval et al. 2000; ESA 1989, 1999; Lorenc et al. 1992; Marseille and Stoffelen 2003; Marseille et al. 2000; Vaughan et al. 1999; Stoffelen and Marseille 1998). Overall system analysis, with budgeting for a wide range of potential errors sources, shows performance within the required specification.

ADM-Aeolus will provide about 3000 globally distributed wind profiles per day, above thick clouds or down to the surface in clear air, at typically 200-km separation along the satellite track. The 200-km separation is compliant with synoptic analysis (see the section titled "Meteorological impact of wind profile measurements"). Wind information in thin clouds or at the top of thick clouds is also attainable; information on other elements such as cloud and aerosols can be extracted as well. A near-real-time delivery of data to the main NWP centers is anticipated.

After the detailed design of the hardware, integration and testing of the major building blocks, as well as satellite and instrument integration and testing, the launch is planned to be in late 2007.

Ground-based and airborne measurement campaigns are underway to obtain realistic atmospheric situations for use in algorithm development, and to allow the final selection of instrument parameters for optimised in-orbit measurement performance.

SUMMARY AND CONCLUDING REMARKS.

The *Atmospheric Dynamics Mission (ADM-Aeolus)*, is currently being developed by the European Space Agency within its Living Planet Programme. The *ADM-Aeolus* will demonstrate the capability of a spaceborne Doppler wind lidar to accurately measure wind profiles in the troposphere and the lower stratosphere (0–27 km). The mission thus contributes to resolving one of the main identified deficiencies of the current Global Observing System. From the backscattered frequency-shifted laser light it will be possible to obtain about 3000 globally distributed profiles of horizontal line-of-sight winds daily, and with good vertical resolution. The accuracy of *ADM-Aeolus* winds, in most cloud-free regions and above thick clouds, is expected to be comparable to that of radiosonde wind measurements.

The *ADM-Aeolus* laser will emit a narrow linewidth pulse directed at a 35° slant angle toward the atmosphere. Atmospheric scattering of light in the chosen wavelength (355 nm) is due to both molecular (Rayleigh–Brillouin) and aerosol (Mie) scattering, providing a sufficient return signal emanating from layers throughout the troposphere and the lower stratosphere. The strength of the return signal, and, thus, the quality of the derived wind, will depend on the cloudiness and also, in the lower troposphere, on the aerosol loading. In overcast situations high-quality wind observations will be obtained down to the cloud top. The mission also provides ancillary information on the aerosol concentration and cloud-top height.

The *ADM-Aeolus* wind profiles will find wide application in NWP and climate studies, improving the accuracy of numerical weather forecasting, advancing our understanding of tropical dynamics, and processes relevant to climate variability and climate modeling. With a target launch date in 2007, work has already been instigated preparing for the future real-time assimilation of *ADM-Aeolus* wind data into operational NWP models. The midlatitude focus is on those regions where forecast performance is known to be particularly sensitive to the accuracy of initial conditions. In particular, a beneficial impact on the prediction of severe storm events is expected and further investigated. For the Tropics, the focus of current investigations is on defining the appropriate mass–wind relationships for effective assimilation of the *ADM-Aeolus* wind data in state-of-the-art data assimilation systems (e.g., Žagar et al. 2004a,b; Žagar 2004).

During its projected 3-yr lifetime the *ADM-Aeolus* will demonstrate the feasibility of global wind field measurement from space. Based on the results that are obtained with *ADM-Aeolus*, future operational missions may be built, fully exploiting the concept of spaceborne Doppler wind lidars.

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