ADM-AEOLUS WIND RETRIEVAL ALGORITHMS FOR NWP

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Abstract

With a launch anticipated around end-2009, ESA's mission ADM-Aeolus aims at providing meteorologically representative wind profiles, meeting the needs of user communities in operational numerical weather prediction (NWP) and more general atmospheric science.

This paper provides an update on the ongoing scientific and technical development of the wind retrieval algorithms that constitute the ADM-Aeolus Level-2B processor. Using the NWP-SAF approach, ESA and ECMWF are making the processor source code available to the meteorological community for use as either 1) a standalone executable in a general scientific environment, or 2) a callable subroutine integrated within a data assimilation system. The approach provides maximum flexibility for NWP centres to customize the wind retrievals to their own needs.

Simulated retrievals, demonstrating accuracy of around 2 ms^{-1}, have been reported previously. A further example shown here illustrates the ongoing effort to validate the algorithms and their upstream inputs for increasingly complicated atmospheric scenes. Such examples inform preparations for the so-called Level-2C product which will be generated via assimilation of Aeolus L2B data at ECMWF.

INTRODUCTION

The Atmospheric Dynamics Mission ADM-Aeolus is the fourth of ESA's Earth Explorer Missions (ESA 1999, Stoffelen et al. 2005, ESA 2008). Scheduled for launch around end-2009, and with a projected lifetime of three years, its objective is to demonstrate the capability to measure wind profiles from space using a Doppler wind lidar (DWL). The need for such data, with high accuracy and good resolution, has been identified as a priority for the global observing system (WMO 2004).

This paper provides an update on the ADM-Aeolus Level-2B (L2B) wind retrieval algorithms (Tan et al. 2008). The purpose of these algorithms is to obtain representative and accurate winds suitable for use in numerical weather prediction (NWP). Level-1B wind retrievals are not suitable for use in NWP for a number of reasons, the principal one being that L1B algorithms do not account explicitly for temperature and pressure effects on the response of the molecular (Rayleigh) channel of the instrument (Dabas et al. 2008) – by contrast the L2B algorithms use NWP information to take these effects into account. The design of the L2B algorithms takes account of the technical capabilities and constraints of the instrument, e.g. with respect to vertical and horizontal sampling, instrument pointing stability and zero-wind calibration. Quality control and product confidence indicators are important parameters that are provided with the wind retrievals. In broken cloud scenes, the L2B algorithms derive separate wind retrievals for cloudy and clear air; this is done through selective averaging of measurement-scale data, subsequent to a simple scene classification step. The details of the selective averaging remain an area for future scientific development, with scope to generalize the existing scene classification in order to identify layers of clear air above clouds, cloud-top layers, layers in and below thin clouds, and layers with sufficient aerosol in lower parts of the atmosphere. (The term "measurement" is used for instrument data on horizontal scales of 1-10 km, and "observation" for data aggregated to horizontal scales of 50 km).

ADM-AEOLUS VIEWING CHARACTERISTICS

The schematic in Figure 1 shows the Aeolus DWL instrument viewing from a low-altitude (~400 km) polar orbit in the direction perpendicular to the satellite track. Measurements are made in two channels: Rayleigh for molecular returns and Mie for particulate (aerosol and cloud) returns.

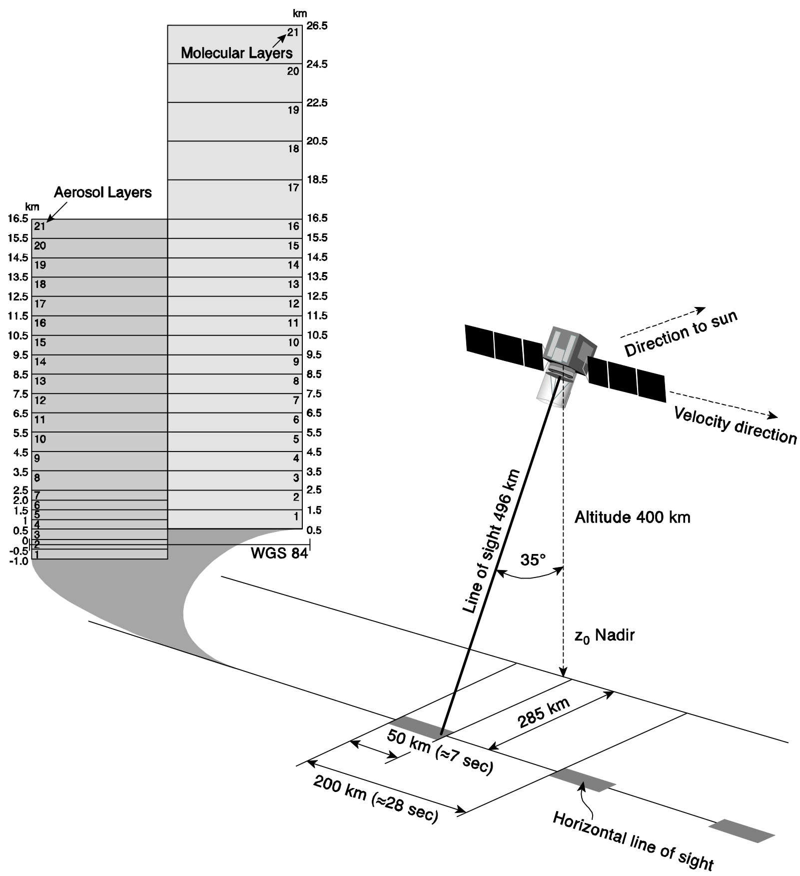

***Figure 1*. ADM-Aeolus line-of-sight viewing geometry and proposed vertical distribution of the range bins.**

The polar orbit (dawn-dusk, 1800 local time ascending node) facilitates the global coverage that is required, providing data also over the oceans which are currently poorly observed. The DWL will provide layer-averaged wind measurements and observations in 24 layers with configurable vertical distributions that can be modified in flight. The current baseline configuration will provide 1000 m vertical resolution through most of the atmosphere (from 2 to 16 km), 500 m below 2 km, and 2000 m from 16 to 26 km. The observation-scale wind retrievals involve 50 km along-track averaging, and are separated by 150 km data gaps (Figure 1) – this ensures minimal error correlation between consecutive observations (Stoffelen et al. 2005a) and maximizes the information content subject to constraints on instrument energy consumption. There is information on the horizontal line-of-sight

(HLOS) wind component only (line-of-sight velocity divided by the cosine of the local elevation angle ~53^o), which is close to east-west except at high latitudes. Level-2C products provide additionally the unobserved wind component as inferred statistically within a data assimilation process. For an introduction to the observation operators needed to assimilate Level-2B data, see Tan (2007). The benefits of assimilating simulated HLOS observations have been assessed in the context of data assimilation ensembles and are supported by information content diagnostics (Tan et al. 2007).

The Aeolus mission payload is a single DWL instrument – a high spectral resolution lidar operating in the ultraviolet (wavelength λ_0=355 nm). The range-gated Doppler shifts Δf of the returned (elastic backscatter) atmospheric signals provide profile information on wind velocity along the instrument's line-of-sight v_{LOS},

$$\Delta f = -2 v_{LOS} / \lambda_o . \tag{1}$$

Further, the signal amplitudes provide information on a) particle layers and their optical properties, and b) product confidence data, including error quantifiers, for the wind and particle information.

The accuracy of the Aeolus wind measurements/observations will depend primarily on the intensity of the backscattered laser light, which in the Mie channel depends on the presence and optical thickness of clouds, and on the aerosol backscatter (function of size distribution and number concentration), while in the Rayleigh channel it depends on the density of air and transmission through overlying cloud/aerosol. The expected yield and accuracy of Aeolus winds has been studied through detailed simulation, based on model clouds and climatological aerosol distributions (Tan and Andersson 2005).

WIND RETRIEVAL ALGORITHMS AND THE ADM-AEOLUS LEVEL-2B PROCESSOR

ADM-Aeolus is primarily a research and demonstration mission. Flexible data processing tools are being developed for use in the operational ground segment and by the meteorological community. These include algorithms to retrieve accurate and representative wind profiles, suitable for assimilation in numerical weather prediction (Tan *et al.* 2008). These algorithms have been coded in a package known as the ADM-Aeolus Level-2B Processor software, which is being made freely available to the meteorological research community. The software has been designed to be portable, and specifically to run in four different contexts: 1) Real-time processing at NWP centres with an interest to assimilate ADM-Aeolus winds within their own forecasting systems; 2) Operational processing at ECMWF to produce wind retrievals for delivery to ESA shortly after real time; 3) Re-processing at ESA for situations in which delays in data delivery prevent processing within the ECMWF operational schedule, and to accommodate future algorithm improvements and upgrades; and 4) as a standalone processor in a typical research environment.

The wind retrieval algorithms within the ADM-Aeolus Level-2B (L2B) Processor software form an integral part of the Aeolus data processing chain, not least because the mission's official Level-2B products will be generated at ECMWF using these algorithms. Tan *et al.* (2008) describe the overall architecture of the software and give mathematical details of the algorithms (see also Dabas *et al.* 2008). Based on the calibrated measurements (L1B) as inputs, L2B retrieval algorithms apply the modifications, corrections and additions required to obtain accurate and representative HLOS winds suitable for assimilation by NWP systems, as well as the appropriate quality control flags and uncertainty estimates. As mentioned in the Introduction, Level-1B (L1B) wind retrievals are not suitable for use in NWP for a number of reasons, the principal one being that L1B algorithms do not account explicitly for temperature and pressure effects on the response of the molecular (Rayleigh) channel of the instrument (Dabas *et al.* 2008). The L2B algorithms use NWP information to take these effects into account, and also account for cross-talk between the Mie and Rayleigh channels.

The L2B processor classifies the atmospheric scene into cloudy and clear regions, and in partially cloudy scenes it then derives separate wind retrievals for cloudy and clear air. The current scene classification algorithm is based on a simple thresholding of the scattering ratio reported in L1B data (which are the primary instrumental input to the L2B retrieval). It is envisaged that other scene classifications will be developed during the lifetime of the mission and so the Level-2B algorithms have been designed to provide a flexible framework to allow alternative options for classification and weighting of measurement-scale (1-10 km) data into aggregated, observation-scale (50 km) wind profiles for assimilation. The design makes it possible to address various scientific challenges, including the production of representative winds in highly inhomogeneous atmospheric conditions, such as strong wind shear, broken clouds, and aerosol layers. Because the Aeolus instrument provides separate measurements in Rayleigh and Mie channels, representing molecular (clear air) and particulate (aerosol and clouds) backscatter respectively, the combining of information from the two channels offers possibilities to detect and flag difficult, inhomogeneous conditions.

SIMULATED RETRIEVALS

Tan *et al.* (2008) showed the functionality of a baseline version of the ADM-Aeolus Level-2B software. Their selected example demonstrated the ability of the L2B retrieval software to identify clear from cloudy areas in an idealized scenario, to group the measurement range-gates accordingly, and to make L2B wind retrievals with error quantifiers less than 2 ms^{-1}. In this section we examine a scenario that is much more realistic in terms of wind and backscatter heterogeneity; this is one of several scenarios currently being used to validate the operational L1B and L2B processors.

The scenario consists of five consecutive basic repeat cycles (BRCs) in which the true scattering ratio is taken from measurements obtained during the LITE mission (Winker 1994) and the true HLOS wind is taken from co-located ECMWF analyses. In Figure 2, the upper panel shows the true scattering ratio used as input to the Aeolus End-to-End simulator (E2S v2.05) while the lower panel shows the scattering ratio retrieved by the Level-1B processor (v1.07). Both pieces of software have been developed in the frame of the satellite prime contract and they provide the input to the Level-2B processor (v 1.3). The horizontal discontinuities in scattering ratio merely reflect the 150 km gaps between consecutive BRCs (recall Figure 1). In Figure 2, a layer of high cloud is visible around 17 km in both panels. However, the finite spatial resolution of the Aeolus instrument is recognizable in the lower panel, with a consequent loss of horizontal and vertical structure and degraded contrast. Nearer the ground, the L1B retrieved scattering ratio exhibits some spurious periodicity over the BRCs, this has led to the identification and rectification of some coding bugs (variables not being re-set). It is worth remembering that the L1B processor does not always retrieve the scattering ratio (Figure 2, lower panel, area shaded white around 16 km); this could be a more common occurrence in other scenes, e.g. if the instrument is unable to penetrate thick cloud.

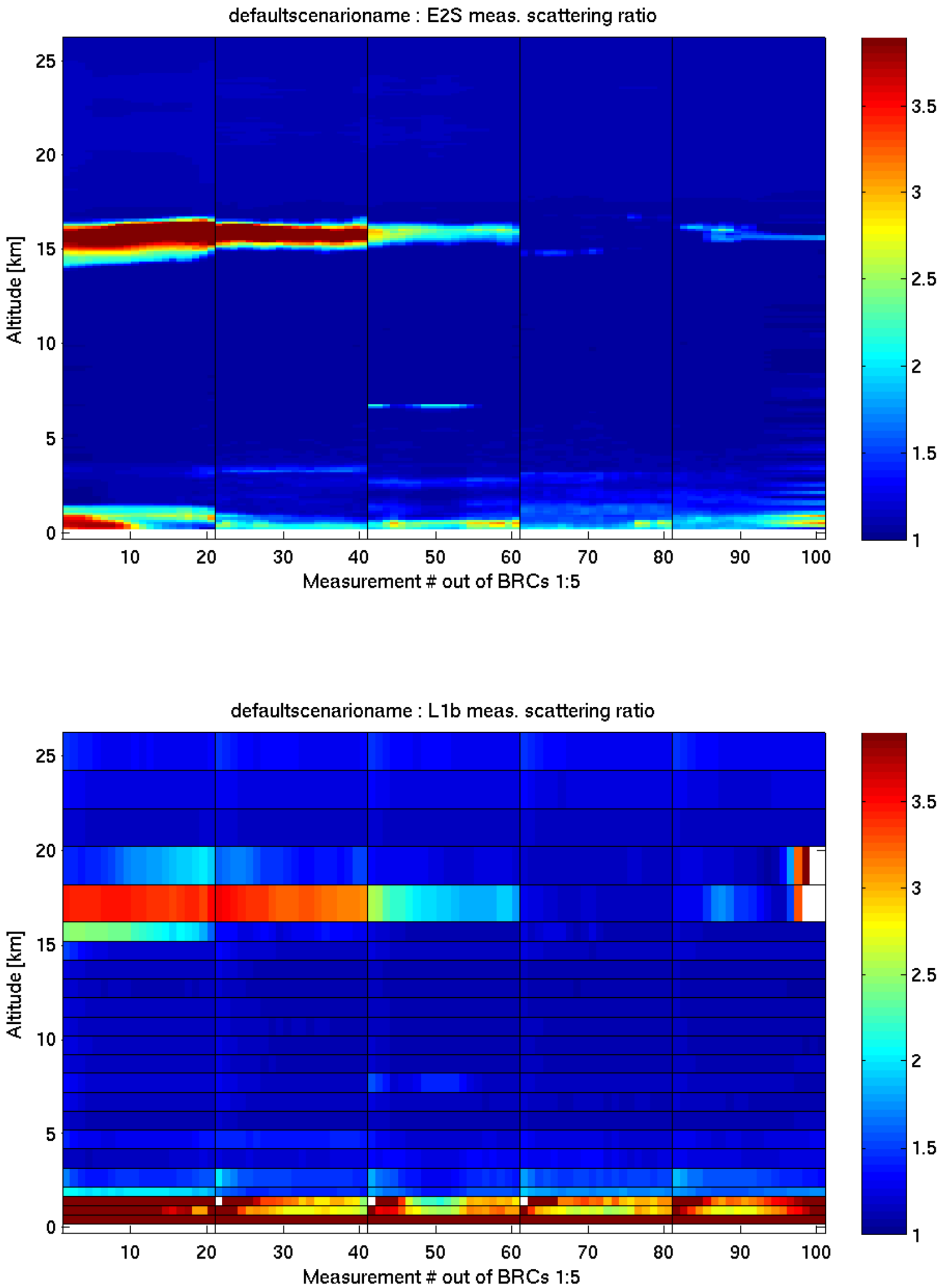

Figure 2. **Scattering ratio for Aeolus simulations based on LITE-period data. Upper panel: E2S input (high resolution truth), lower panel: L1B retrieval at instrument measurement resolution.**

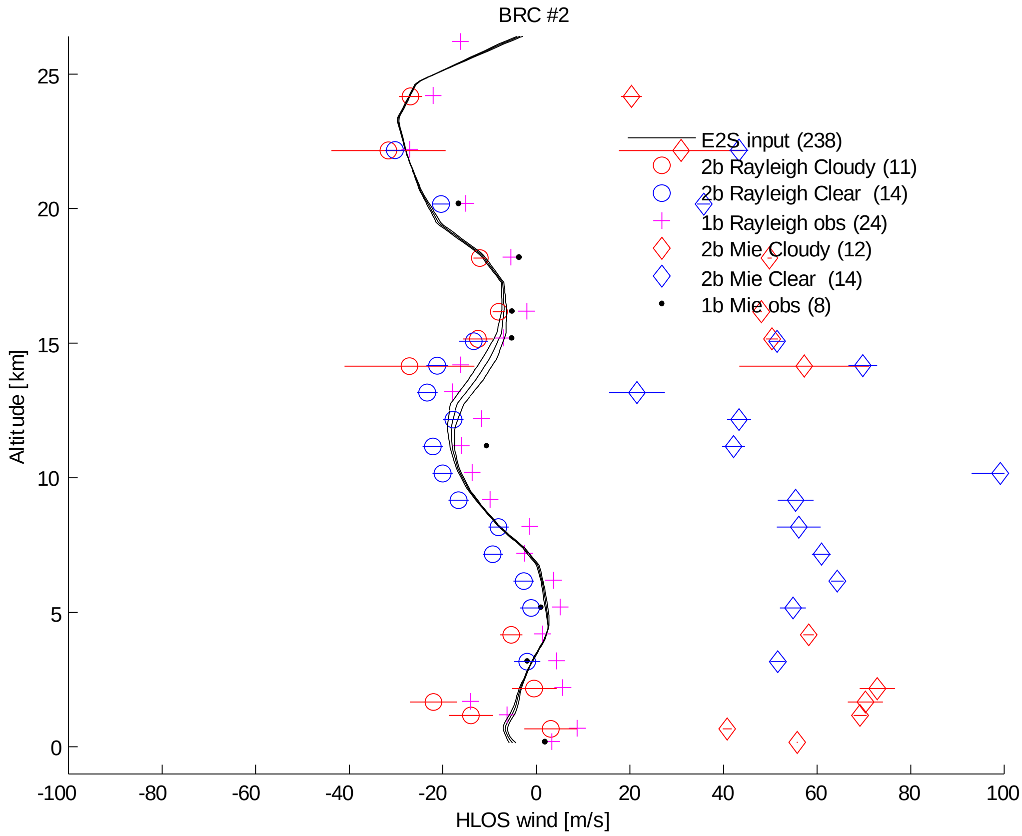

***Figure 3*. True wind profile (E2S input) and simulated retrievals (see legend). The large offset of the L2B Mie retrievals (diamonds) has been traced to a systematic error in the L1B data used as input to the L2B processor.**

The true wind for this scenario is shown as the solid lines in Figure 3 (the central line is the horizontal average for the BRC, the outer two lines include one standard deviation of the horizontal variability). In this example, L2B Rayleigh channel retrievals from clear air are confirmed as being reasonably accurate (blue circles). Some residual errors remain, which are probably associated with a re-definition of the ground wind processing performed in the L1B processor. A substantial bias in L2B Mie channel retrievals (red diamonds) has been traced to a systematic error in the internal reference data supplied in the L1B product. Preliminary investigations with an updated version of the L1B processor suggest that the error has been fixed.

CONCLUSIONS

The ADM-Aeolus is primarily a research and demonstration mission that will provide many opportunities for assessing the benefits of space-based wind profile information, and for defining the steps towards future operational DWL missions. The vertically-resolved wind information is expected to be particularly valuable for determining atmospheric motion on sub-synoptic scales and in the Tropics, i.e. the regimes for which temperature data and conventional mass/wind balance relationships are inadequate for determining the atmospheric state.

Given the experimental nature of the mission, it has been recognized that data processing needs to have sufficient flexibility to explore the full potential of the mission data. The L2B wind retrieval algorithms discussed by Tan *et al.* (2008) are likely to evolve during the mission. The evolution is expected to be relatively minor, but of course any changes will be thoroughly documented. The L2B processor software has been designed to be portable, and specifically to run in four different contexts: 1) Real-time processing at NWP centres with an interest to assimilate ADM-Aeolus winds within their own forecasting systems; 2) Operational processing at the ECMWF to produce wind retrievals for delivery to ESA shortly after real time; 3) Re-processing at ESA for situations in which delays in data delivery prevent processing within the ECMWF operational schedule, and to accommodate future algorithm improvements and upgrades; and 4) as a standalone processor in a typical research environment.

The L2B processor provides a flexible framework for classification and weighting of measurement-scale (1-10 km) data into aggregated, observation-scale (50 km) wind profiles for assimilation. The main remaining scientific challenge is to produce representative winds in inhomogeneous atmospheric conditions, such as strong wind shear, broken clouds, and aerosol layers. The Aeolus instrument provides separate measurements in Rayleigh and Mie channels, representing molecular (clear air) and particulate (aerosol and clouds) backscatter, respectively. The combining of information in the two channels offers possibilities to detect and flag difficult, inhomogeneous conditions.

The functionality of a baseline version of the L2B processor has been demonstrated in terms of classification and wind retrieval (Tan *et al.* 2008). The corresponding computed error estimates of the retrieved winds have been validated for an idealized scenario. The example scenario presented in this paper is much more realistic in terms of wind and backscatter heterogeneity and is one of a set that is currently being used to validate the operational L1B and L2B processors. The validation exercise has resulted in improvements to the L1B processor.

Another imminent step is to apply the algorithms to real data obtained from an airborne Aeolus instrument demonstrator (Durand *et al*. 2006). Further refinement of the processor will continue even after launch of the satellite, in particular as based on results from the commissioning phase immediately after launch.

The L2B software is portable to a range of computers. It is being made freely available to the meteorological research community via contact points at ESA and/or ECMWF. Operational Aeolus products will be available from ESA/ESRIN.

The research into data assimilation stimulated by preparations for Aeolus data is expected to continue throughout the mission lifetime and beyond. Improved specification of background error covariances remains a key issue (Žagar 2004, Riishojgaard *et al*. 2004, Stoffelen *et al*. 2005b, Žagar *et al*. 2005), particularly in Tropics.

It is easy to envisage other applications of Aeolus data, in particular to improve interpretation and use of other satellite data. This could include, but is not limited to, more accurate height assignment of atmospheric motion vectors (e.g. Velden *et al.* 2005) and better detection of cloud-affected radiances (English *et al.* 1999). Aeolus cloud and aerosol information (the so-called Level-2A products, Flamant *et al.* 2008) is expected to contribute to long-term databases complementing data from the Calipso and EarthCARE missions (Winker *et al.* 2003, ESA 2004). Other expectations from Aeolus extend beyond the mission lifetime to potential operational missions. The participation of others is encouraged in order to realize the full potential of the mission.

REFERENCES

Dabas, A., M.-L. Denneulin, P. Flamant, C. Loth, A. Garnier and A. Dolfi-Bouteyre, 2008: Correcting winds measured with a Rayleigh Doppler lidar from pressure and temperature effects. *Tellus*, **60A,** pp 206—215.

Durand, Y., E. Chinal, M. Endemann, R. Meynart, O. Reitebuch and R. Treichel, 2006: ALADIN Airborne Demonstrator: a Doppler Wind Lidar to prepare ESA´s Aeolus Explorer Mission. *Proceedings SPIE Optics and Photonics*, **6296**, pp 13-17 August 2006, San Diego.

English, S. J., J. R. Eyre and J. A. Smith, 1999: A cloud-detection scheme for use with satellite sounding radiances in the context of data assimilation for numerical weather prediction. *Q. J. R. Meteorol. Soc.* **125,** pp 2539—2378.

ESA, 1999: The four candidate Earth Explorer core missions - Atmospheric Dynamics Mission. *ESA Report for Mission Selection*, **ESA SP-1233(4),** 145 pp.

ESA, 2004: The six candidate Earth Explorer core missions - Earth Clouds, Aerosols and Radiation Explorer. *ESA Report for Mission Selection*, **ESA SP-1279(1),** 60 pp.

ESA, 2008: The Atmospheric Dynamics Mission Science Report, in press.

Flamant, P., J. Cuesta, M.-L. Denneulin, A. Dabas and D. Huber, 2008: ADM-Aeolus retrieval algorithms for aerosol and cloud products. *Tellus*, **60A,** pp 273—286.

Riishøjgaard, L. P., R. Atlas and G. D. Emmitt, 2004: The Impact of Doppler Lidar Wind Observations on a Single-Level Meteorological Analysis. *J. Appl. Meteor.*, **43,** pp 810—820.

Stoffelen, A., J. Pailleux, E. Källén, J. M. Vaughan, L Isaksen, P. Flamant, W. Wergen, E. Andersson, H. Schyberg, A. Culoma, R. Meynart, M. Endemann and P. Ingmann, 2005a: The atmospheric dynamics mission for global wind measurement. *Bull. Amer. Meteorol. Soc.*, **86,** pp 73—87.

Stoffelen, A., G-J. Marseille, E. Andersson and D. G. H. Tan, 2005b: Comment on "The Impact of DWL Observations on a Single-Level Meteorological Analysis" by L. P. Riishøjgaard, R. Atlas, and G. D. Emmitt. *J. Appl. Meteorol.*, **44,** pp 1276—1277.

Tan, D.G.H. and E. Andersson, 2005: Simulation of the yield and accuracy of wind profile measurements from the Atmospheric Dynamics Mission (ADM-Aeolus). *Q. J. R. Meteorol. Soc.*, **131,** pp 1737—1757.

Tan, D.G.H., 2007: Expectations from ADM-Aeolus. Proc. ECMWF Seminar on Recent Developments in the Use of Satellite Observations in NWP, available from: ECMWF, Reading, UK, pp 349—363.

Tan, D.G.H., E. Andersson, M. Fisher and L. Isaksen, 2007: Observing-system impact assessment using a data assimilation ensemble technique: application to the ADM-Aeolus wind profiling mission. *Q. J. R. Meteorol. Soc.*, **133,** pp 381—390.

Tan, D.G.H., E. Andersson, J. de Kloe, G.-J. Marseille, A. Stoffelen, P. Poli, M.-L. Denneulin, A. Dabas, D. Huber, O. Reitebuch, P. Flamant, O. Le Rille and H. Nett, 2008: The ADM-Aeolus wind retrieval algorithms. *Tellus*, **60A,** pp 191—205.

Velden, C., J. Daniels, D. Stettner, D. Santek, J. Key, J. Dunion, K. Holmlund, G. Dengel, W. Bresky and P. Menzel, 2005: Recent innovations in deriving tropospheric winds from meteorological satellites. *Bull. Amer. Meteorol. Soc.*, **86,** pp 205—223.

Winker, D.M., R.H. Couch and M.P. McCormick, 1996: An overview of LITE: NASA's Lidar in-space Technology Experiment. *Proceedings IEEE*, **84**, pp 164—180.

Winker, D.M., J.R. Pelon and M.P. McCormick, 2003: The CALIPSO mission: spaceborne lidar for observation of aerosols and clouds. *Proceedings SPIE*, **4893**, 1—11.

WMO 2004: Proceedings of the 3rd WMO Workshop on "The Impact of Various Observing Systems on Numerical Weather Prediction", Alpbach, Austria, 9—12 March 2004, Eds. H. Böttger, P. Menzel and J. Pailleux. *WMO/TD* No. **1228**, 324 pp.

Žagar, N., 2004: Assimilation of equatorial waves by line of sight wind observations. *J. Atm. Sci.*, **61,** 1877—1893.

Žagar, N., E. Andersson and M. Fisher, 2005: Balanced tropical data assimilation based on study of equatorial waves in ECMWF short-range forecast errors. *Q. J. R. Meteorol. Soc.*, **131,** 987—1011.