DOPPLER WIND LIDAR MEASUREMENTS SCENARIOS IN THE TROPICS

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Abstract

This study compares dynamical aspects of the assimilation of space-borne wind observations from several scenarios with two Doppler wind lidars (DWL) in space. The impact is measured with respect to ADM-Aeolus, a DWL satellite built by the European Space Agency with launch scheduled for 2009. In particular, the role of the background-error covariances in the tropics is studied in the context of “identical twin” observing system simulation experiments. The assimilation model describes the horizontal structure of potential temperature and wind fields in regions of deep tropical convection. The background-error covariances are derived from the tropical forecast errors of the ECMWF model. The difficulty with making use of balance relationships in tropical three-dimensional variational assimilation is illustrated. Results show that for large-scale tropical conditions and using reliable background-error statistics, differences among various scenarios are not large. As the background-error covariances becomes less reliable, horizontal scales become smaller and the flow becomes less zonal, importance of observing information on the wind vector increases.

INTRODUCTION

In 2009 the European Space Agency (ESA) plans to launch a space-borne Doppler Wind Lidar instrument (DWL). The mission, known as the Atmospheric Dynamic Mission, ADM-Aeolus, aims at providing the first direct observations of wind profiles from space (Stoffelen et al. 2005). A lack of direct observations of wind profile measurements over the major part of the Earth (Fig. 1) has been recognized as the main missing component of the current global observing system (e.g., Baker et al. 1995). Therefore, a positive impact of new wind profiles is expected globally. In the extratropics, wind profiles are especially relevant over the ocean storm-track regions. But a larger positive impact of assimilating new wind measurements is expected in the tropics, based on the basic dynamical arguments about the relative importance of mass- and wind-field observations (e.g., Žagar et al. 2004), as well as from the realistic assessment of the wind profiles provided by ADM (Tan et al. 2006). The ADM-Aeolus will provide measurements of the horizontal line-of-sight (LOS) wind component perpendicular to the satellite track. In the tropics, the ADM measurements are close to the zonal direction. Because of this and because of the sparse horizontal sampling of measurements, spatial structures in the analysis fields emerge mainly from background information (estimated spatial structures of error correlations in a short-term model forecast).

Even if LOS winds provide sufficient information to be beneficial in a variational data assimilation system (Stoffelen et al. 2006, Tan and Andersson 2004, Žagar 2004), it would be advantageous to have more complete information on the full wind field. With this purpose in mind, several space-borne DWL sampling scenarios were proposed in the frame of a project devoted to the Prediction Improvement for Extreme Weather (PIEW) over Europe (Marseille et al. 2007).

The goal of this paper is to study the potential impact of DWL scenarios, envisaged by PIEW, in the tropics. In particular, dynamical aspects of the multivariate variational assimilation and the role of the background-error covariances in the tropics are addressed. The added impact by another satellite measuring LOS winds is assessed for different flow conditions and by using different assumptions about the reliability of the background-error covariances for the assimilation.
Figure 1: (a) Availability of vertical wind profiles for the assimilation at the European Centre for Medium Range Weather Forecast (ECMWF) at 00 UTC, 2 August 2006. (b) Observation coverage of the globe by the ADM-Aeolus satellite during a 12-hour period. Shown are successive locations at which line-of-sight wind profile measurements are available.

METHODOLOGY

The variational analysis problem is solved for a three-equation model which represents the first baroclinic mode of the tropical atmosphere in regions of deep convection. The model describes the horizontal structure of dynamical fields which develop in response to heating. Model equations and details of the numerical approach are described in Zagar et al (2007).

Although highly simplified with respect to NWP models, the model enables realistic horizontal representation of forecast errors in the tropics and it is thus suitable for studying the dependence of assimilated horizontal structures of equatorial waves on the background information in the data assimilation system. The background-error covariance model is a multivariate model which includes the mass-wind couplings representative of equatorial inertia-gravity modes, Kelvin and mixed Rossby-gravity modes, in addition to Rossby waves (Zagar et al. 2004). Spectra of the background errors based on these waves are derived from the tropical forecast errors of the ECMWF model (Zagar et al. 2005).

Reported assimilation experiments apply "identical twin" Observing System Simulation Experiments (OSSE). In this approach, a "nature run" is performed first, creating an artificial history of the atmosphere by numerical integration of the same model used later for the assimilation. Simulated observations are generated from the nature run by adding random error (from a distribution of zero mean and variance equal to the background-error variance) to the historical values for the potential temperature field and two wind components. Hereafter, assimilation is conducted with simulated data at times and locations corresponding to the simulated patterns of DWL observations (Fig. 2). Temperature observations are assumed taken at the same locations as LOS winds. The observation operator for LOS winds interpolates the model wind to positions of DWL measurements and calculates the model equivalent of the LOS component.

Figure 2: Observing System Simulation Experiment setup.

Nature run is prepared so that its variability in terms of various equatorial motions corresponds to their relative weight in the background-error variance spectra used in the assimilation. In other words, simulated observations and the background-field errors have the same statistics which enables a detailed comparison between the value of observations and that of a reliable first-guess error information. Other type of experiments performed is denoted "poor background-error experiments" or
experiments with unreliable background-error covariances because in these cases nature simulations are not characterized by the same variance as the background errors. More details about the model setup can be found in Žagar et al. (2007).

Observations are simulated and assimilated over the whole model domain defined as the tropical channel between 33°N and 33°S. Verification of the analysis outputs is carried out within a smaller tropical belt between 20°S and 20°N.

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ADM-Aeolus and five additional DWL scenarios are studied. Other five scenarios are evaluated with respect to the analysis improvements provided by ADM. In each case scenario consists of the ADM-Aeolus track plus an additional DWL instrument of the Aeolus type (Fig. 3). The scenarios include a tandem-Aeolus with two satellites in one orbit plane with 180° phase difference, two satellites in orbits with different inclinations angles (dual-inclination scenario) and two satellites in the ADM-Aeolus orbit providing the complete wind vector (dual-perspective scenario, denoted Los2-DD). These three scenarios have been proposed by the PIEW project as combinations of two DWLs which proved most beneficial in correcting forecast failures of extreme weather events in the Northern hemisphere extra-tropics (Marseille et al. 2007). A fourth scenario included here is denoted "reduced dual-perspective scenario". This is the same as the dual-perspective scenario but with half of its meridional coverage in order to measure the importance of the meridional sampling. In addition, a fifth scenario was added lateron in this study. It combines good properties of both tandem-Aeolus and dual-perspective scenarios; that is, it provides a good coverage of the extra-tropical regions and a dual component in the tropics. This scenario is denoted the "dual-tandem" scenario. In the following result section and in the figures these six scenarios are denoted as "Aeolus", "Tandem", "Dual-incl", "Los2-DD", "Los2-D" and "Dual-tandem", respectively.

![Figure 3: Observation coverage of the globe for various scenarios during 6 hours. (a) ADM-Aeolus, (b) Tandem-Aeolus, (c) Dual-perspective, (d) Dual-tandem, (e) Dual-inclination and (f) Reduced dual-perspective scenarios. Arrows start at locations of measurements and point along the line-of-sight.](image-url)
RESULTS

Now we discuss results of assimilation for various scenarios and observations types. The impact of simulated scenarios is presented from the modelling perspective, i.e. with respect to the background-error term used to recover the missing part of the wind vector. As it will be shown, the representativity of the background errors influences the analysis results to a great extent. Relative weight between DWL observations and the background term is seen more clearly in 3D-Var. Therefore 4D-Var results are in most experiments contrasted to those based on the 3D-Var assimilation. The impact of DWL scenarios is presented for cases of (i) complex flow with many scales, (ii) large-scale mainly zonal flow and (iii) large-scale flow and assimilation using poor background-error covariances.

Idealized flows with known variance and many scales

This is the main experiment of the study and it is applying reliable background-error covariances. Nature is modelled as a mixture of equatorial waves including small-scale structures. A number of assimilations experiments is carried out. In each case the energy in the simulated nature run is dominated by the kinetic energy; potential energy contributes on average about 20% of the total energy. Contributions to the kinetic energy from the zonal and meridional winds are almost equal, since the background-error variance is characterized by the same energy partition between the two components.

In 3D-Var, the structure of analysis increments arises from observations and from the background-error term spreading the observed information horizontally. The impact of various DWL scenarios on the analysis scores for three model variables is determined by the observation coverage and by the local LOS direction with respect to the wind direction. Thus the observations taken at locations of the tandem-Aeolus scenario provide the best impact for the zonal wind while dual-perspective scenarios are superior in the meridional wind scores. Relative improvements from various scenarios with respect to Aeolus range between zero and 20% improvement (Fig. 4).

An important feature in Fig. 4 is that the assimilation system behaves as if the analysis was nearly univariate. Consequently, no added value from the dual-perspective and reduced dual-perspective scenarios in temperature and zonal wind scores reflects the fact that the spatial coverage for these scenarios is nearly the same as for Aeolus i.e. that the meridional coverage provided by Aeolus has provided sufficient information.

In 4D-Var, each observation is taken into account at its appropriate measurement time and the model is used to propagate observed information back and forth in time. In this way the missing wind component can be extracted with the help of the model equations and the background-error covariances. Furthermore, an internal model adjustment between the mass field and the wind field extracts information about the wind field from temperature observations and vice versa. In this case a difference between the impact of assimilating LOS winds alone or together with temperature become significant in the wind-field scores (Fig. 5). Recovery of the meridional wind is better with respect to 3D-Var for all scenarios, especially for those observing mainly zonal winds; both dual-inclination and dual-tandem scenarios are now superior to the dual-perspective scenarios. When both temperature
and wind observation are assimilated, the dual-inclination scenario provides on average best scores, followed by the tandem-Aeolus (for u wind) and dual-tandem (for v wind and temperature) scenarios.

**Figure 5:** As in Fig. 4, but for 4D-Var assimilation.

**Large-scale mainly zonal flow**

On average, the large-scale tropical flow is predominantly zonal and of interest for a medium and extended-range forecasting in mid-latitudes is the accurate analysis of large-scale tropical waves. Thus a DWL measuring almost the zonal wind component, as Aeolus, could be argued as a favoured option. In case of mainly-zonal flow it is expected that the tandem-Aeolus scenario would perform better than in the previous experiments with u and v components equally important. This experiment aims at quantifying the difference.

The error reduction of the first-guess field in 3D-Var is in this case between 5% and 50%, depending on the observation type and the variable verified. In general, the differences between various observation types are smaller in 4D-Var than in 3D-Var. In 4D-Var, all scenarios contain meridional winds missing in their 3D-Var results. Major improvements of the meridional wind analysis is seen in its analysis errors which reduced for additional 20% (w.r.t. the first-guess errors) in 4D-Var in comparison with 3D-Var (not shown). Improvements in 3D-Var with respect to Aeolus range from several up to about 25% for the meridional wind component and dual-perspective scenarios (Fig. 6).

However, since the meridional wind component makes a smaller part of the total flow, the relative improvement is dominated by the value added by the tandem-Aeolus scenario to the analysis of the zonal wind.

**Figure 6:** As in Fig. 4, but for large-scale tropical flows.

Compared to the 3D-Var case, where the added value of another satellite is always positive, in the 4D-Var case temperature scores become worse with more observations, especially for the tandem-Aeolus and dual-inclination scenarios (Fig. 7). Possible reasons can be found in the simplicity of our model and in the way the experiment was prepared. Our assimilation system produces analysis fields that contain significant amounts of divergence. However, the model itself does not contain a physical process that could maintain or generate the divergence. Therefore, during the model integration in 4D-Var some useful divergence information obtained from the mass data can be lost by its adjustment to the wind field and to the background-error covariances. It is also possible that observations include more geostrophically balanced information, especially in the subtropics, than is present in the
background-error covariance matrix. Such differences may explain why the dual-perspective scenario has a greater value than the dual-inclination scenario in this set of experiments.

**Figure 7**: As in Fig. 6, but for 4D-Var.

**Poor background-error covariances**

If the background-error covariances represent the errors in the first-guess fields poorly, adding another satellite results in a much greater benefit for the analysis than in the cases discussed until now. This is illustrated in Fig. 8.

Comparison of Fig. 8 with Fig. 5 and Fig. 7 shows that the improvements with respect to Aeolus can be significantly larger depending on the reliability of the background-error covariances. In case of poor covariances the added value of second DWL satellite can be larger than 40%. Both dual-perspective and dual-inclination scenarios outperform the tandem-Aeolus scenario even for the zonal wind. The reduced dual-perspective scenario provides better results for the meridional wind component than the dual-inclination and tandem-Aeolus scenarios. This reflects the value of any information provided about another wind component. Weighting each variable according to its energy content, the dual-inclination scenario represents the most optimal solution in this case as it is a compromise between the improved zonal coverage provided by tandem-Aeolus (the dual-inclination scenario also has about 15% more profiles in the tropics than other scenarios) and the need for complete wind vector information (dual-perspective).

**Figure 8**: As in Fig. 7, but for assimilation experiments using poor background-error covariances.

**CONCLUSIONS**

Although this study was motivated by the potential impact of future DWL satellites for reducing uncertainties in the tropical wind field, OSSE experiments have been done within an idealized framework. Therefore this study does not provide realistic assessments of the impact of these scenarios in full-scale state-of-the-art data assimilation system; however, the conclusions presented concerning dynamical aspects of the impact of future observing systems should be valid in any assimilation system.
For ADM-Aeolus, the reduction of analysis and forecasts error in the ECMWF model in the tropics is estimated to be of the same magnitude as that of radio-soundings (Tan and Andersson 2004). This result is in line with the dynamical arguments about the greater importance of the wind field than the mass field for 4D-Var in the tropics and it provides a strong motivation for early follow-on missions. Presented results suggest that the most optimal choice among the three PIEW scenarios is not necessarily the same one as in the case of the mid-latitudes (tandem-Aeolus, Marseille et al. 2007). Likely reasons for the difference are the structure of the tropical background-error covariances i.e. the differences in the dynamics of the tropics as compared to that of the mid-latitudes. For average tropical conditions (mainly zonal winds, large-scale structures and a small variability of the mass field) and using a reliable background-error statistics and assuming a perfect model in 4D-Var, differences among various scenarios are not large. As the background-error term for data assimilation becomes less reliable, horizontal scales smaller, cloud areas larger and the flow less zonal, the importance of having information about other wind component increases. The added values of the second DWL satellite vary between 0% and 40%, depending on the quality of the background-error covariances, the observation type and the variable verified. The dual-inclination scenario appears more valuable than two other scenarios proposed in PIEW as it represents a compromise between the spatial coverage and need for both wind components.

REFERENCES


