Global Wind Profiles will Advance Cross-Cutting Earth Science

Provided by

Dr. Michael Hardesty, CIRES/University of Colorado and NOAA; Dr. Robert Atlas, NOAA/OAR/AOML; Dr. Wayman Baker, NOAA/NWS/NCEP (retired); Dr. Dave Emmitt, Simpson Weather Associates; Dr. Ron Gelaro, NASA/GSFC/GMAO; Mr. Bruce Gentry, NASA/GSFC/MAP; Dr. Rolf Langland, DoD/NRL; Mr. John Pereira, NOAA/OPPA; Dr. Oliver Reitebuch, DLR; Dr. Lars Peter Riishojgaard, WMO; Dr. Vijay Tallapragada, NOAA/NWS/NCEP; Dr. Sara Tucker, Ball Aerospace and Technologies Corporation (BATC); and Dr. Carl Weimer, BATC

Introduction and Background

As we stated in our previous White Paper submission to the NRC in 2015, measurement of the three-dimensional global wind field is a frontier that must be crossed to significantly improve the initial conditions for numerical weather forecasts (Baker et al. 2014). The World Meteorological Organization (WMO) has recently reaffirmed that "wind profiles at all levels outside the main populated areas" is the #1 priority for global NWP (WMO 2014, http://www.wmo.int/pages/prog/www/OSY/SOG/SoG-Global-NWP.pdf .

Typically, measurement of the global wind field is associated with the above NWP application and would clearly advance Earth System Science Theme II – Weather and Air Quality: Minutes to Subseasonal. But, measurements from a space-based DWL would also advance understanding in Theme I – Global Hydrological Cycles and Water Resources and in Theme IV – Climate Variability and Change: Seasonal to Centennial. In this White Paper we will lay out the rationale for wind profile measurements for advancing understanding in each of these themes.

Although wind information from a number of sources is available for assimilation into numerical analysis and forecast models, the lack of global wind profiles represents a significant deficiency in the current observing system. Doppler wind lidar (DWL) measurements, complemented by existing and potential future wind observations such as atmospheric motion vectors (AMVs) from advanced sounding systems (e.g., Maschhoff et al. 2015, see http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3249&context=smallsat), will provide the missing link for wind observations. Since the 2007 Decadal Survey, the DWL community has achieved substantial progress in advancing DWL technologies, field testing them on the ground and in aircraft, evaluating the data obtained, and assessing their potential for improving understanding in the three Earth Science themes listed above. In validation of the 2007 Decadal Survey's support of DWL for 3-D global winds, NASA has invested significantly in both coherent detection DWL (at LaRC) and direct detection DWL (at GSFC and at Ball Aerospace) over the past nine years. While both technologies may have a role in addressing the need for global winds, in Section 4 we will highlight a promising technology developed at Ball Aerospace over the past several years (Grund and Tucker 2011; Bruneau et al. 2013). While there has a been a long history of deriving AMVs with passive techniques, and the approach discussed in Maschhoff et al. 2015 is very promising, a space-based DWL stands alone in being able to provide direct wind measurements. This is especially important in the tropics where passive techniques cannot infer the divergent component of the wind. In addition, DWL measurements will be able to anchor AMVs and mitigate some of their other shortcomings (i.e., height assignment error).

Below is the specific information requested in the RFI.

1. A clear description of the Science and Application target, its importance to the Theme as evidenced in previous reports or community roadmaps, and how, by addressing it, understanding in one or more of the above-mentioned Decadal Survey Themes is advanced.

The Science and Application target is significantly improved analysis of the 3-D global wind field and subsequent forecast and reanalysis applications. Every day, millions of global temperature and humidity profile measurements are obtained *in-situ* and remotely. In stark contrast, wind profile measurements are available only from radiosonde launch sites and via aircraft ascent/descent near major commercial airports, located primarily over the US, Europe and Asia. Additional wind data are also provided by the generation of AMVs, aircraft at flight level, and from scatterometers. Vast regions over the oceans, in the Southern Hemisphere and in the tropics have little or no wind profile information. This imbalance in data coverage of the Global Observing System (GOS), especially for the satellite components, is a key concern of the World Meteorological Organization (WMO 2012b). This imbalance, readily seen in **Fig. 1,** is currently the main limiting factor, not only for the skill of weather and air quality forecasts (**Theme II**), but also for the use of re-analysis data to support climate monitoring (**Theme IV**), weather and climate process studies (**Themes II and IV**), and the accurate depiction of the transport of water vapor in the global hydrological cycle (**Theme I**). The only way to mitigate the gap in the GOS is to measure wind profiles globally from space and assimilate them to improve the entire analysis/reanalysis/forecast system.

Because of the sparsity of wind profiles, we are confident that the assimilation of DWL wind measurements will have a major impact on the above Earth Science themes. This confidence is substantiated by: 1) OSSE studies conducted for the ADM-Aeolus mission (Stoffelen et al. 2006; Tan et al. 2007), 2) DWL OSSE study results reported in Riishojgaard et al. (2012) and Atlas et al. (2015) 3) Observing System Experiments (OSEs) with actual wind observations (Horanyi et al. 2014a), and 4) a Forecast Sensitivity to Observations (FSO--Baker 2000) analysis applied to the NASA GEOS-5 data assimilation system and illustrated in **Fig. 2**. The figure shows that the global contribution to forecast skill due to wind observations is about two thirds of that due to radiances (top left), despite the fact that six times as many radiances are assimilated as wind observations (bottom left). The disproportionate impact of wind observations is even more dramatic in the tropics, where the contribution made by wind data exceeds that made by radiances (top right) despite the roughly nine times more radiances than wind observations assimilated in this region (bottom right) due to the lack of radiosondes in the tropics.

The sharp contrast in data coverage manifests itself in significant differences in atmospheric analyses produced by NWP centers (i.e., ECMWF and NCEP) as discussed in Langland and Maue (2012) and Baker et al. (2014) and shown in **Fig. 3**. Over regions such as Europe, the US, and East Asia that are well covered by radiosonde, aircraft, and land surface observations, the differences between ECMWF and NCEP analyses of upper tropospheric winds are relatively small, with correspondingly small analysis uncertainty. In contrast, over regions where the analyses rely primarily on satellite radiance data, the differences tend to be larger. **Figure 3**, for example, shows large uncertainties in the analyzed 300 hPa wind speed over much of the tropics, southern mid-latitudes, and North Pacific basin. The analysis uncertainty is also smaller over the North Atlantic than over the North Pacific due to better coverage by aircraft observations. The differences in wind analyses between NWP centers explain, in part, the differences in their forecasts of the track and intensity of hurricanes and winter storms, in air quality forecasts, in the transport of chemical constituents, etc. on short-to-medium-range timescales (**Theme II**).

The most comprehensive tool available to analyze climate trends is the reanalysis technique (Uppala et al. 2005; Simmons et al. 2010). The differences in wind field analyses just discussed not only create uncertainty in NWP applications and products, they also make uncertainties between reanalyses unacceptably large for climate monitoring. An intercomparison of first-generation NCEP reanalyses (Kistler et al. 2001, not shown here) clearly demonstrated that even a basic quantity such as zonally averaged, time-mean zonal winds is not well constrained by the present observing system. In the tropical upper troposphere and the lower stratosphere, the difference between zonal winds obtained from independent reanalysis efforts is of the same order as the characteristic time variability of this quantity. This does not necessarily imply that the reanalysis technique is inadequate but rather points to the fact that additional wind information is needed to make reanalyses more consistent. More recent reanalysis results still show the same features. For example, **Fig. 4** shows the zonal wind difference between the most recent reanalysis from ECMWF Re-Analysis (ERA-Interim; see Simmons et al. 2010; Dee et al. 2011) and the second-generation 40-year ECMWF Re-Analysis (ERA-40;

Uppala et al. 2005) for the overlapping time period 1989–2001. The differences are smaller than noted in Kistler et al. (2001), but the same spatial pattern is found. A space-based DWL will reduce the uncertainty present in today's reanalyses and, therefore, advance our ability to accurately monitor climate trends (**Theme IV**).

The Grand Challenge of the NASA Energy and Water cycle Study (NEWS), established in 2003, is "to document and enable improved, observationally-based, predictions of energy and water cycle consequences of Earth system variability and change" (http://nasa-news.org) with the ". . . ultimate goal to achieve a breakthrough improvement in the nation's energy and water cycle prediction capability". But, the uncertainties in the analyzed wind field and derived quantities discussed above are impeding advances in some of the key questions posed when NEWS was established and are still present, as noted in the recent 2014 NEWS 10 Year Progress Report (http://news.cisc.gmu.edu/doc/pdf/NEWS-10%20Yr%20Progress%20Report-June%2020%202014%20.pdf). For example, "Where are the biggest errors and uncertainties in the cycles—precipitation, soil moisture, evaporation, horizontal transport, runoff, etc.?" To obtain accurate estimates of the horizontal transport over data sparse regions, wind profiles must be measured by a satellite DWL and assimilated. Similarly, to address the NEWS question: "How will water cycle dynamics change in the future?" global wind profiles must be measured and assimilated (**Theme I**).

2. An explanation of the utility of the measured geophysical variable(s) to achieving the science and application target.

Our confidence is high for DWL-measured winds to achieve the science and application target of a significantly improved analysis of the 3-D global wind field and similarly for the subsequent forecast and reanalysis applications. This confidence is substantiated by the OSSE studies cited above (Stoffelen et al. 2006, Tan et al. 2007; Riishojgaard et al. 2012; Atlas et al. 2015), the OSE study conducted by Horanyi et al. (2014a), and the FSO analysis (Baker 2000) applied to the NASA GEOS-5 data assimilation system and highlighted in **Fig.2**. The key findings of these studies are 1) ADM-Aeolus will have a significant impact on NWP quality if the wind observations fulfill the accuracy requirements (Stoffelen et al. 2006; Tan et al. 2007; Horanyi et al. 2014a). 2) The addition of the simulated lidar wind observations leads to a statistically significant increase in the Anomaly Correlation score at day five of approximately 1.5 points and 2 points in the northern and southern hemispheres, respectively (Riishjogaard et al. 2012). For comparison purposes, the overall rate of progress of NWP skill over the last 10 – 20 years has generally ranged from 0.5 to 1 point annually, due to a combination of factors: Better observations, improvements to model and data assimilation methodology through scientific advances, and increased spatial and temporal resolution due to more powerful computers. Typically, a contribution that can be attributed to a specific new observing system is generally modest. In that context, the magnitude of the impact of the DWL is exceedingly rare. 3) Both global and regional OSSEs demonstrate significant potential for lidar wind profile observations from space to improve global NWP and hurricane track and intensity prediction (Atlas et al. 2015). 4) As highlighted in **Fig. 2** utilizing the FSO technique (Baker 2000) for the NASA GEOS-5 data assimilation system and summarized above, the global contribution to forecast skill due to wind observations is about two thirds of that due to radiances, despite the fact that six times as many radiances are assimilated as wind observations. The disproportionate impact of wind observations is even more dramatic in the tropics, where the contribution made by wind data exceeds that made by radiances despite the roughly nine times more radiances than wind observations assimilated in this region due to the lack of radiosondes in the tropics.

3. The key requirements on the quality (i.e. the performance and coverage specifications) of the measurement(s) needed for achieving the science and application target.

To ensure the science and application target is achieved, we have adopted a measurement requirement for an EV-I mission of a minimum of 1200 radiosonde-like DWL wind profiles every 24 hours, based on the goal to effectively double the radiosonde network, but with more uniform coverage provided by an orbiting DWL. The coverage could be further improved for a Decadal Survey mission by sampling the atmosphere on both sides of the spacecraft, by deploying multiple DWL instruments, and/or by leveraging international collaboration, as discussed further below.

For a wind speed precision requirement for an EV-I mission, which would also be applicable for a Decadal Survey mission, we adopted a horizontal line of sight precision requirement of 3 msec^{-1} based on the WMO data requirements document (WMO 2012a). This document lists consensus requirements of world-wide operational NWP centers, based on over 20 years of experimentation and intercomparison of data assimilation and analysis results. Additional background on the requirements can be found in the official reports from the WMO Impact Workshops (e.g., WMO 2012b). The 3 msec^{-1} value is considered by WMO to be the "breakthrough" level, defined as the level at which a major forecast impact is expected. Another important requirement is the wind speed bias accuracy requirement. Based on ECMWF OSEs with varying amounts of bias (Isaksen 2013; Horanyi et al. 2014b), we have established the wind speed bias requirement to be 0.5 msec^{-1}. Also for an EV-I mission, we adopted minimum wind profile spatial scale requirements of 100 km horizontal and 1 km vertical resolutions which are also based on the WMO requirements. These requirements would also be appropriate for a Decadal Survey mission.

4. The likelihood of affordably achieving the required measurement(s) in the decadal timeframe given the heritage and maturity of current and near-future instruments and data algorithms, and the potential for leveraging similar or complementary measurements, especially from international partners.

There is a high likelihood of a successful space-based wind lidar mission completed within the next decade that demonstrates improvement in weather forecast skill (i.e., ESA ADM-Aeolus mission; NASA EV-I mission), and refines what will be needed for a 3-D Winds Decadal Survey mission. CALIPSO has demonstrated ten years of continuous lidar measurements of clouds and aerosols, proving that reliable long-term atmospheric lidar measurements are possible using the Nd:YAG based laser technology; the same technology used to map the Earth, Moon, Mars, and Mercury. The high likelihood of success is also the result of extensive studies of different technologies and methodologies that have been vetted through OSSEs, Instrument Design Lab (IDL) studies, and through significant technology investments made by ESTO in the US and by ESA for ADM-Aeolus over the last decades. This also assumes that focused investments will continue to be made to help reduce technology risk. That focus should be on risk associated with: UV laser systems, multi-look approaches to provide vector winds, and in receiver technologies that can resolve the Doppler shifts from both aerosol and molecular scattering to provide measurements throughout the full troposphere and lower stratosphere. Aircraft demonstrations continue to play an important role for testing instrument prototypes, algorithm development, and perform studies that explore the scientific impact of wind measurements as well as help in refining the requirements for a full space mission to achieve global results. To initiate a Decadal Survey mission within the next decade, an early space demonstration needs to be performed that can act as a stepping stone proving some of the technologies in space, reducing the risk to a full mission, and proving that the approach shows adequate maturity to move forward. This could be done on the ISS, on a sounding rocket, or as a secondary payload to reduce the cost. Once successful, the risks in development will be significantly reduced, preparing the path towards a 3-D Winds Decadal Survey mission.

This disciplined approach towards retiring risk associated with advanced technologies has been applied in the development of the Optical Autocovariance Wind Lidar (OAWL). With a core design derived from CALIPSO and using Nd:YAG laser technology (1064 nm and 532 nm) combined with a unique, efficient interferometric approach to resolve Doppler induced frequency shifts, the OAWL approach was conceived as a realistic method for measuring winds from space. The measurement technique has been demonstrated via ground validation and aircraft testing. Its measurement impact for space implementation was shown to be positive via an OSSE (Atlas et al. 2015), and its technology approach vetted for cost and implementation realism by both the NASA IDL and the industry partner for the CALIPSO lidar. The ATHENA-OAWL submission to the Earth-Venture Instrument #2 AO proposed that an aerosol only version of OAWL, using only visible (532 nm) with two look angles could be cost-effectively implemented on the ISS at an acceptable risk. The proposal was ranked as having low cost risk and high scientific impact, but still requiring more technology development and flight validation. That work was then funded by NASA ESD and will be completed in 2016. Additional investments have been made in creating a single low-risk receiver approach to measuring both aerosol and Rayleigh Doppler winds, but more development will need to be performed. NASA has also invested in advancing to TRL 6 the UV laser technology based on Nd:YAG, a development being performed by the company that built the CALIPSO and ICESat II lasers. These significant investments and development efforts have laid the ground work for success in the next decade.

The OSSEs have identified another important aspect of space-based winds measurements: that weather forecasts will strongly benefit from more global coverage than a single space-based lidar can provide. While there are methods to significantly increase the performance of space-based lidars by the use of much larger receiver apertures and higher power lasers, these are at a relatively low maturity. A better approach would be to implement multiple satellites in different inclinations. To spread the cost and risk, international collaborations could be sought. One potential partner for global wind measurements is the European Space Agency. In mid-2017, the first DWL in space, the ESA ADM-Aeolus mission (ESA 2008; LeRille et al. 2012; Reitebuch 2012a), is expected to be launched. ADM-Aeolus, is a single-wavelength full direct detection instrument operating at 355 nm. ADM-Aeolus measures the wind field with a single look permitting only line-of-sight (LOS) wind data to be obtained and assimilated for NWP and other applications. Although modern data assimilation systems can effectively use LOS data, 4D-Var for example, the forecast impact will not be as large as by assimilating horizontal vector winds as highlighted in a recent impact study with actual wind observations (Horanyi et al. 2014a). In this study, "comparisons between zonal HLOS and full vector wind observations have shown a global average forecast impact loss in zonal HLOS (for the zonal wind and temperature parameters) of 35% up to the 2-day forecast which decreases to 20% loss from day 2 to 5 forecasts. This relatively small impact loss is very promising for the benefit of the Aeolus mission." This finding reaffirms the ESA decision to go with just the LOS ADM-AEOLUS configuration. But, it also confirms the expected additional improvement with the vector wind and reaffirms the decision to employ a two-look configuration in the ATHENA-OAWL proposal maximizing forecast impact.

NASA's support of ESA's ADM-Aeolus' calibration and validation via aircraft underflights and data assimilation will help to build collaboration between the US and Europe on space-based wind measurements. Collaboration on wind observations is also possible with the Japanese Aerospace Exploration Agency (JAXA), which also has investigated potential space-based wind measurement concepts.

Summary

The key points in this White Paper are summarized below:

1 The WMO has recently reaffirmed that "wind profiles at all levels outside the main populated areas" is the #1 priority for global NWP (WMO 2014, http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html#SOG).

2. Because of the sparsity of wind profiles, the assimilation of DWL wind measurements will have a major impact on the following Earth Science themes: Weather and Air Quality Forecasts (**Theme II**), Global Hydrological Cycles and Water Resources (**Theme I**) , and Climate Variability and Change (**Theme IV**).

3. Confidence that a DWL will have a major impact on Earth Science is based on: 1) OSSE studies conducted for the ADM-Aeolus mission (Stoffelen et al. 2006; Tan et al. 2007), 2) DWL OSSE study results reported in Riishojgaard et al. (2012) and Atlas et al. (2015), 3) the OSE study conducted by Horanyi et al. (2014a), and 4) a Forecast Sensitivity to Observations (FSO--Baker 2000) analysis applied to the NASA GEOS-5 data assimilation system.

4. Given recent advances and demonstrations of technology through NASA investment, a space-based DWL that can achieve the measurement goals is doable and affordable. The instrument would be synergistic with AMV approaches. DWL also offers the potential for international collaboration with Europe and Japan.

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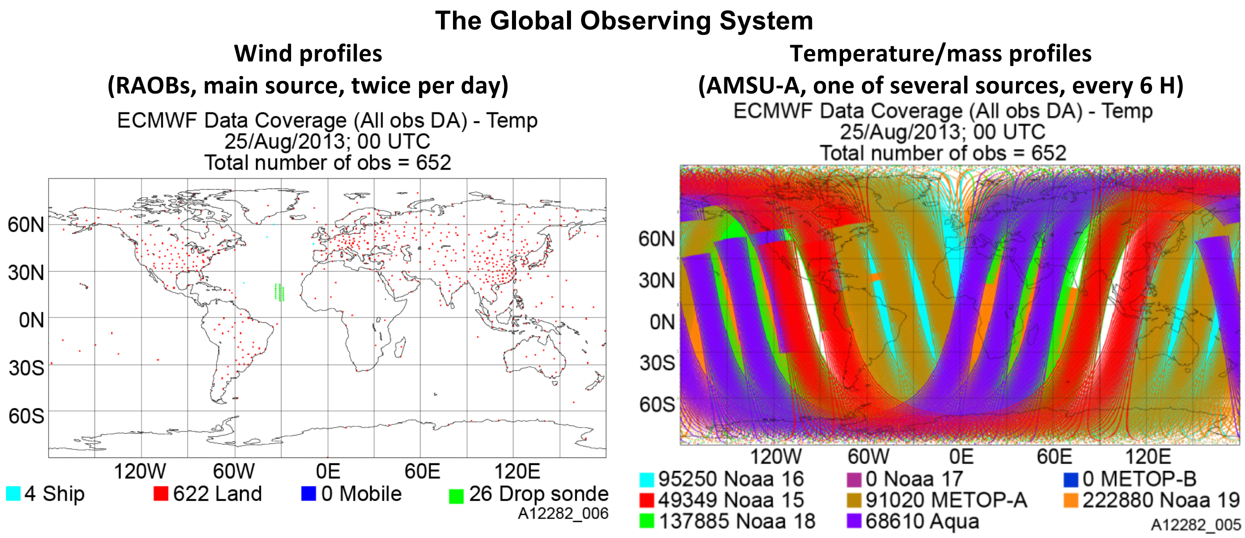

Fig. 1. The Global Observing System highlighting the abundance of atmospheric mass measurements and the shortage of wind profiles.

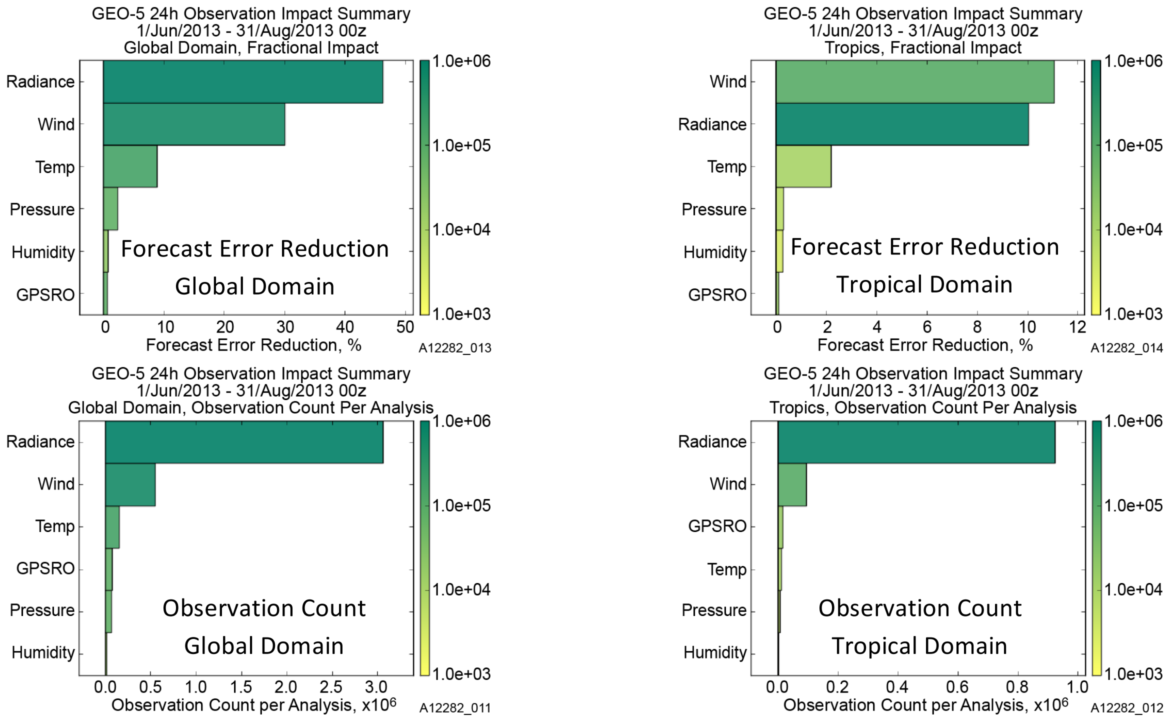

Fig.2. Wind observations disproportionately affect forecast error reduction. Shown is the average 24-h forecast error reduction (top row) and observation count (bottom row) for data types assimilated in NASA GEOS-5 during the period 1 June – 31 Aug 2013, for the global domain (left column) and tropics only (right column). Impact is measured in terms of the reduction in the global moist energy error norm from the surface to 150 hPa. The observation count refers to the average number of each data type assimilated during each 6-h assimilation window during the period.

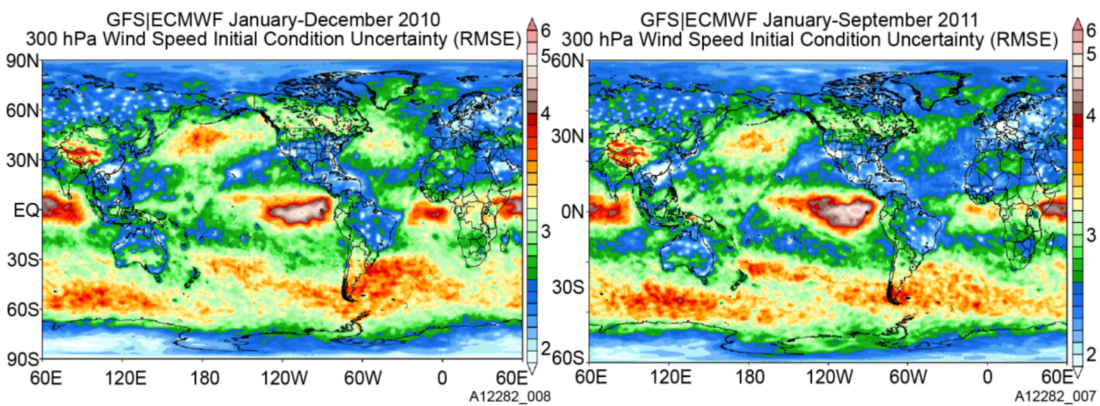

Fig. 3. Root Mean Square (RMS) differences (m/s) in 300 hPa wind speed analyses produced by ECMWF and the NCEP GFS demonstrate large uncertainties in wind speed analyses in regions with limited radiosonde measurements: LEFT: January – December 2010; RIGHT: January – September 2011. Includes all daily analyses provided at 0000 UTC and 1200 UTC.

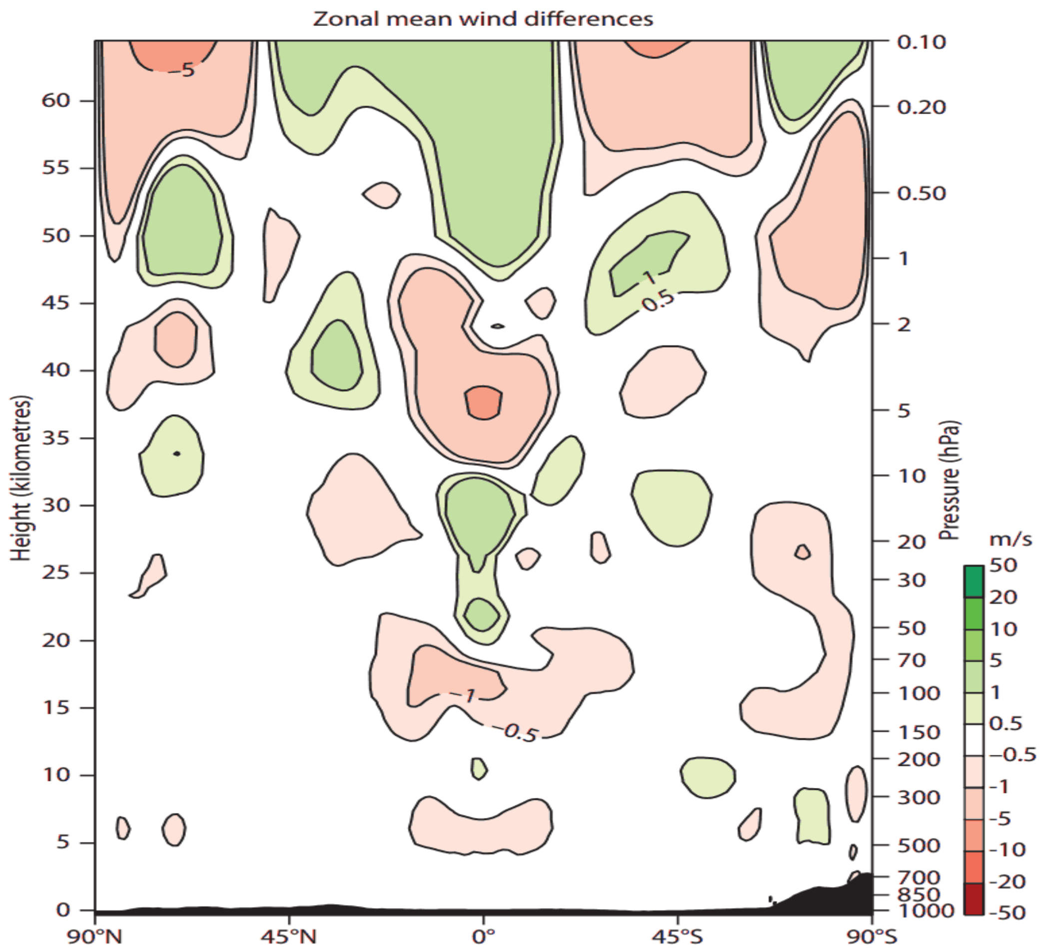

Fig. 4. Shown is the zonally averaged latitude–height cross section of zonal mean wind differences ($m\ s^{-1}$) between ERA-40 and ERA-Interim for the time period 1989–2001.