Doppler Wind Lidar (DWL) Technology is Ready to be Demonstrated in Space

Provided by

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1. What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

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) determined that global wind profiles are "essential for operational weather forecasting on all scales and at all latitudes" (WMO 1996, Chapter 13, Page 295). This is because the wind field plays a unique dynamical role in forcing the mass field to adjust to it at all scales in the tropics, and at small scales in the extratropics (Baker et al. 1995).

In its previous decadal survey report on Earth Science and Applications from Space (National Research Council--NRC 2007), the NRC recommended a global wind mission, and the NRC Weather Panel, in the same report, determined that a DWL in low-Earth orbit (LEO) could make a *transformational* impact on global tropospheric and stratospheric analyses. More recently, a WMO (2012) workshop found the current global observing systems to be heavily skewed toward measuring atmospheric mass rather than wind, especially for the satellite instruments, even though the average influence of wind observations is higher, on both an individual instrument and a "per observation" basis as may be seen in Fig. 1 (Källén et al. 2010). In this illustration, the forecast error impact is presented for the total number of observations of each type, as well as the error contribution per observation for the ECMWF data assimilation system. The conventional observing system is well balanced in terms of mass and wind observations, while the satellite observing system is dominated by mass observations. If, however, the impact factor is divided by the number of observations, ***the individual space-based wind observations are more influential than the space-based mass observations***.

The overall value of weather forecasting to the US economy has been estimated to be ***$200 million per year for each hour of useful forecast range*** (Riishojgaard 2008). The Joint Center for Satellite Data Assimilation has found that the typical extension in the useful forecast range has been roughly two hours with the initial operational implementation of data from major new instruments (i.e., AIRS, IASI, COSMIC). Forecast impact experiments at ECMWF with DWL airborne campaign measurements and with recent DWL OSSES (Riishojgaard et al. 2012; Atlas et al. 2015), provide evidence that extending the useful forecast range by two hours with data from a space-based DWL is a conservative estimate.

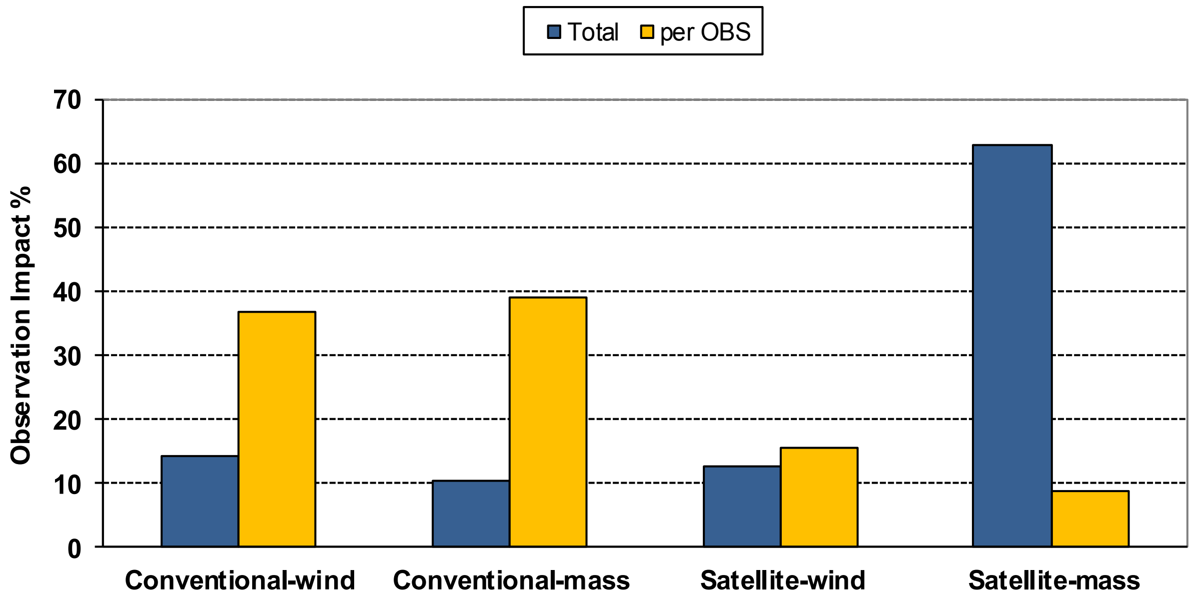

Fig. 1. The contribution of existing mass vs. wind observations in reducing the 24-h forecast error, expressed as observation impact (%), in terms of the total number of observations and on a per-observation basis for the ECMWF data assimilation system.

In addition to the routine improvements in operational weather forecasting, range-resolved wind data from a space-based DWL would provide a large number of societal benefits including: 1) atmospheric and climate science, e.g., transport of aerosols, moisture, pollution, CO2/CH4 sources and sinks; 2) aircraft and shipping operations; 3) agriculture; 4) energy infrastructure demand and risk assessment; 5) air quality forecasts; 6) military operations; 7) homeland security; 8) dispersion forecasts for nuclear, biological, chemical releases; and 8) forecasting extreme weather events.

Major land-falling hurricanes clearly fall into the extreme weather category. While hurricane forecasts have been steadily improving, substantial error and uncertainty still exist. The environmental steering that influences tropical cyclone motion is correlated with the storm's initial intensity. Airborne DWL research (Pu, Zhang and Emmitt 2010) and numerical model studies (Atlas et al. 2007; Atlas and Emmitt, 2008) have shown the importance of accurately representing the interaction of the storm's circulation with its environment. The difficulty in forecasting tropical cyclone intensity relates to the complex kinematic (e.g., via vertical wind shear) and thermodynamic (e.g., via moisture exchange) interaction between the surrounding environment and the storm, the air-sea fluxes beneath the storm and the impact of atmospheric aerosols on tropical convection. Due to the large-scale coverage and altitude-resolved data products, a space-based DWL is an ideal observing system for providing wind profiles in the clear-air environment outside of the cyclone, thus improving knowledge of the large scale environment, critical to making accurate tropical cyclone track and intensity forecasts.

Beyond providing a wealth of new wind data, a space-based DWL will improve atmospheric motion vectors (AMVs) computed using passive techniques by accurately specifying the height of AMVs, their greatest source of error (Folger and Weissmann 2014; Di Michele et al. 2013), and by validating their velocity estimates.

Accurate, altitude-resolved measurements of the global wind field will also support major advances in the understanding of several key climate change issues. The most comprehensive tool available to analyze climatic trends is the reanalysis technique (Uppala et al. 2005; Simmons et al. 2010). An intercomparison of first-generation 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. 2 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 with Kistler et al. (2001) but the same spatial pattern is found.

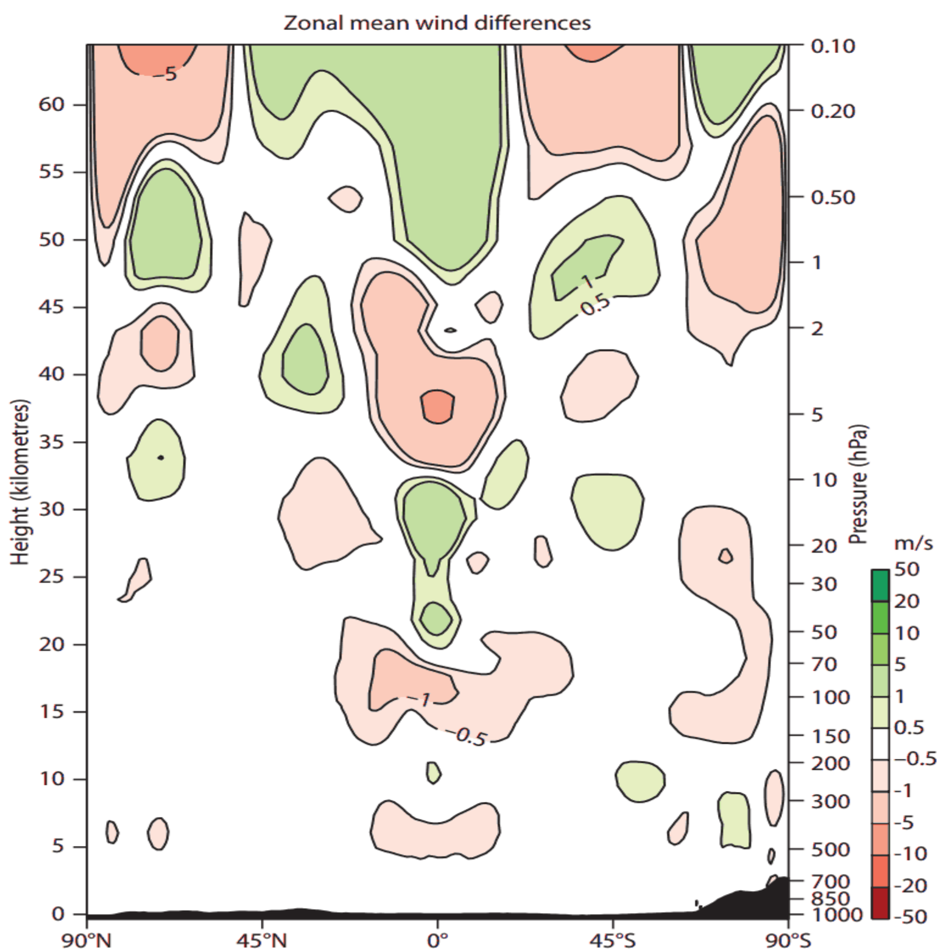

Fig. 2. Shown is the zonally averaged latitude–height cross section of zonal mean wind differences (m s^{-1}) between ERA-40 and ERA-Interim for the time period 1989–2001.

2. Why are these challenge/questions timely to address now especially with respect to readiness?

Recent technology advances that include improved structural materials, higher laser efficiency and output power, and more robust optical coatings, have allowed Doppler lidar technology to reach a maturity level needed to make the required wind measurements from space (Baker et al. 2014). NASA has invested in various DWL technology approaches including: 1) coherent detection (Kavaya et al. 2014); 2) direct detection with Fabry-Perot (FP) etalons (Gentry et al. 2000; ESA 2008; Reitebuch et al. 2009; Dong et al. 2010); 3) direct detection using a modified Mach-Zehnder interferometer (Grund and Tucker 2011; Bruneau et al. 2013), and 4) single-wavelength full direct detection (ESA 2008; LeRille et al. 2012; Reitebuch 2012). ESA's Aeolus mission (ESA 2008; Endemann 2006; LeRille et al. 2012) uses the latter approach, featuring a double-edge FP etalon for the molecular returns and a fringe-imaging Fizeau spectrometer for the aerosol returns. The Aeolus development effort has significantly reduced the risk for a future winds mission by addressing many technical and theoretical challenges associated with space-based wind measurements, as well as demonstrating instrument performance during a series of airborne campaigns (e.g., Marksteiner et al. 2011; Reitebuch et al. 2013). Most recently a joint airborne campaign sponsored by NASA, ESA, and DLR was performed with four wind lidars on two aircraft – the NASA DC-8 and the DLR Falcon – in May 2015 with coordinated flights over the North Atlantic, Greenland and Iceland in preparation for Aeolus validation and supporting PolarWinds objectives (Emmitt et al. 2014).

Moreover, since the NRC (2007) report, there have been several other airborne demonstrations of various DWL approaches (Weissmann et al. 2012; Pu, Zhang, and Emmitt 2010; Kavaya et al. 2014; Reitebuch et al. 2013; Tucker et al. 2015). In addition, numerous technical problems such as laser damage for the 355 nm UV wavelength have been addressed during Aeolus development (see references above). Perhaps most importantly, the CALIPSO atmospheric aerosol lidar mission (Winker et al. 2010), is currently over nine years into its three year mission (on orbit operations since 2006), demonstrating that laser lifetime, reliability and system performance are possible for space-based lidar systems. Furthermore, CALIPSO measures range-resolved aerosols and clouds and calibrates on each orbit using molecular return, providing a measurement demonstration of the signals underlying a combined DWL molecular/aerosol DWL approach.

In a previous input to the NRC (Hardesty 2005), we advocated a hybrid DWL approach which utilized a coherent detection lidar for wind measurements in the low-to-mid troposphere and a direct detection lidar to sample the upper troposphere and lower stratosphere. Subsequent analysis at the NASA/GSFC Instrument Design Laboratory showed that, while providing full tropospheric coverage, an approach requiring two different lasers and two different receivers carries substantial risk and, therefore, high cost. New, technologically-feasible, single-laser DWL mission approaches with potentially high science impact include a coherent lidar aerosol/cloud focused-mission (Kavaya et al. 2014), an Aeolus-type mission (see above), and an Optical Autocovariance Wind Lidar (OAWL) type receiver for aerosol or molecular returns (Grund and Tucker 2011; Bruneau et al. 2013). The technology in each of these approaches has matured in recent years and DWL mission designs are simpler today than a decade ago which is critical to reducing complexity which, in turn, drives risk and, therefore, cost.

3. Why are space-based observations fundamental to addressing these challenges/questions?

As noted in NASA's 2014 Science Plan (NASA 2014), from space we can observe and track changes on a global scale, connecting causes to effects, and we can study regional changes in their global context. The challenges discussed above clearly require global wind measurements provided by at least one DWL in

LEO. Accurately depicting the environmental steering currents for major land-falling hurricanes, for example, can only be done from space.

ESA's Aeolus mission, expected to launch in mid-2017, will deploy the first space-based DWL with an expected lifetime of three years. The resulting data will enable the science community to gain valuable experience in assimilating DWL measurements in conjunction with other conventional and space-based measurements for weather forecasting, climate studies, and other applications. At this time, however, ESA has no plans for a follow-on DWL mission. It is imperative that the U.S. take advantage of its investments in DWL technology and the investments and experience from the ADM-Aeolus mission to deploy a U.S. spaced-based DWL as soon as possible in order to provide the Nation with the benefits discussed above. Prior to such a space mission, it is also important to continue investing in the improvement and demonstration of space-ready technology, especially in the areas of component space-qualification, airborne deployment and demonstration, and data analysis and assimilation.

(Please note: References are available on request.)