Application of Doppler wind lidar observations to hurricane analysis and prediction

R. Atlas*[a], J.A. Zhang[b], G.D. Emmitt[c], L. Bucci[b], and K. Ryan[b]

[a]NOAA-Atlantic Oceanographic and Meteorological Laboratory, 4301 Rickenbacker Causeway, Miami, FL 33149; [b]NOAA-AOML and University of Miami, Cooperative Institute for Marine and Atmospheric Studies, 4600 Rickenbacker Causeway, Miami, FL 33149; [c]Simpson Weather Associates, 809 Jefferson Street, Charlottesville, VA 22902

ABSTRACT

One of the most important applications of a space-based Doppler Wind Lidar (DWL) would be to improve atmospheric analyses and weather forecasting. Since the mid-1980s, Observing System Simulation Experiments (OSSEs) have been conducted to evaluate the potential impact of space-based DWL data on numerical weather prediction (NWP). All of these OSSEs have shown significant beneficial impact on global analyses and forecasts. In more recent years, a limited number of experiments have been conducted to evaluate the potential impact of DWL data on hurricane forecasting and also to begin to evaluate the impact of real airborne DWL observations. These latest studies suggest that DWL can complement existing hurricane observations effectively and have the potential to contribute to improved hurricane track and intensity forecasting.

Keywords: DWL, OSSE, OSE, simulation experiments, hurricanes

1. INTRODUCTION

Winds are among the most important variables in the atmosphere. They transport all the other variables of the atmosphere and govern the exchange of mass, energy, and momentum between the atmosphere and the underlying ocean and land surfaces. There is a substantial opportunity to improve numerical weather prediction (NWP) by better observing the global wind field. Currently, winds make up a very small fraction of the observations that are used in data assimilation systems. Many of the winds that are available are created by tracking features in the cloud and water vapor fields. These atmospheric motion vectors are very valuable, but they are an indirect measurement and have inherent height uncertainties that make their use somewhat problematic. In contrast, Doppler Wind Lidars (DWLs) directly and very accurately measure the line-of-sight wind by observing the Doppler shift in the lidar signal returned by a volume of atmospheric scatterers. Baker et al. (2014)[1] provided an excellent description of the need for a DWL, a review of previous impact studies that used both simulated satellite and real-world aircraft-based data, and an overview of instrument concepts and their supporting technologies. Impact experiments with real data, termed Observing System Experiments (OSEs), are conducted with and without one observing system to quantify the impact of that observing system. Similar experiments with simulated data are termed Observing System Simulation Experiments (OSSEs). In OSSEs, a long forecast is taken to be the ‘‘truth’’ or nature run.

The present study complements previous space-based DWL OSSEs by examining the impact of DWL observations on hurricanes and by beginning to evaluate the impact of having an existing DWL on NOAA’s P3 Hurricane Hunter aircraft. The objectives of the airborne studies are first to determine if the DWL can provide meaningful data to complement the Tail Doppler Radar (TDR) on the P3 and then to assess the potential impact of these data on hurricane analysis and prediction.

*robert.atlas@noaa.gov; phone 1-305-361-4300; fax 1-305-361-4449.

2. METHODOLOGY

The methodology currently used for OSSEs is described in detail by Atlas (1997)[2] and consists of the following elements:

(1) A long atmospheric model integration using a very high resolution "state of the art" numerical model to provide a complete record of the assumed "true" state of the atmosphere (referred to as the "nature run" or "reference atmosphere"). Nature runs may be generated by either global or regional models or by embedding a regional model within a global nature run.

(2) Simulated conventional and space-based observations from the nature run. These observations are simulated with realistic coverages and accuracies.

(3) Control and experimental data assimilation cycles, with and without the specific observing systems that are being evaluated.

(4) Forecasts produced from the control and experimental assimilations.

3. EXAMPLES FROM OSSES TO ASSESS DWL DATA

An extensive series of OSSEs has been conducted since the mid-1980s to evaluate the potential impact of space-based DWL on NWP. All of these OSSEs have shown significant beneficial impact resulting from the assimilation of DWL data. Additional OSSEs have evaluated trade-offs in orbit altitude, laser power, coverage, and accuracy. Figure 1 presents two examples from the first global OSSEs to address hurricane forecasting. Here a significant impact on hurricane track prediction was observed. No similar negative impacts on hurricane track occurred in these experiments.

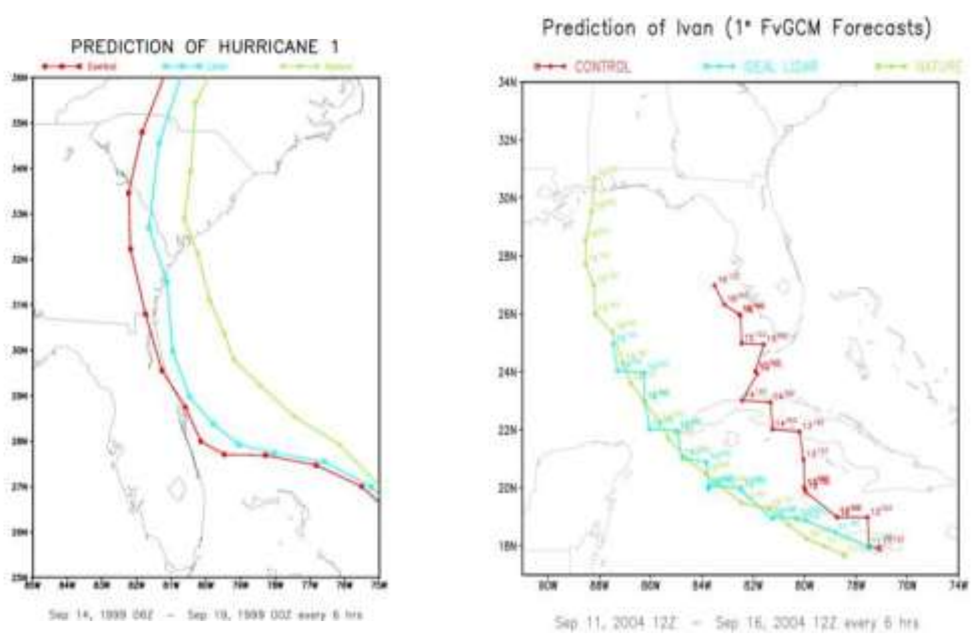

Figure 1. Illustrations of the potential impact of lidar winds in two early global OSSEs. Green: actual track from nature run. Red: forecast with all currently used data. Blue: improved forecast for same time period with simulated DWL data added.

Figure 2 shows one example from a recent OSSE using a WRF 1-km resolution nature run embedded in an ECMWF global nature run[3]. In this case, global assimilation of DWL data resulted in both improved hurricane track and intensity forecasts. Regional assimilation of DWL data in this case improved the intensity forecast substantially further, but did not improve the track forecast.

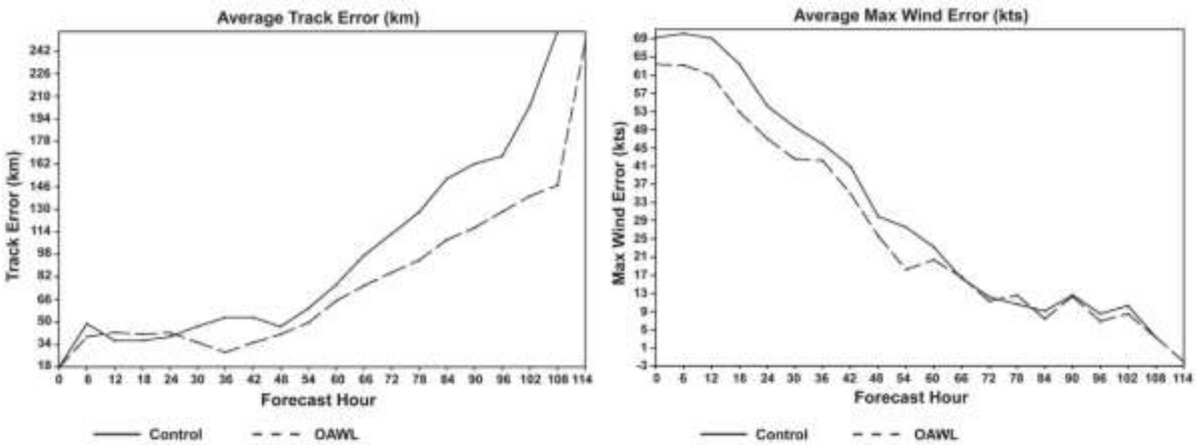

Figure 2. Impact of an Optical Autocovariance Wind Lidar (OAWL) on track and intensity forecasts in this case.

4. CURRENT WORK ON AIRBORNE DWL

The Airborne DWL (ADWL) that had been flown on a Navy NRL P3 in 2008 was installed on NOAA's P3 Orion Hurricane Hunter aircraft in 2015, as shown in figure 3. The ADWL was used to observe a limited number of tropical cyclones during the 2015 and 2016 hurricane seasons, and new flights of the ADWL into hurricanes are planned for the 2017 hurricane season. The ADWL is an airborne version of the Lockheed Martin Coherent Technologies 1.6 micron WindTracer built for the US Army.

Figure 3. DWL scanner mounted on NOAA's P3 Hurricane Hunter reconnaissance aircraft. The side-mounted scanner permits observations below, at, and above flight level.

The first successful mission for the NOAA P3 to collect DWL wind profile data was conducted in Tropical Storm (TS) Erika (2015). Erika originated from a tropical wave west of Africa on 21 August, then moved westward and became a tropical storm on 24 August. Erika remained nearly steady-state during the entire life cycle, weakening by 5 kt in the first two days and then intensifying by 10 kt (Figure 4). The P3 mission into TS Erika occurred on 26 August just before the weak intensification. During the period of P3 observations, Erika was under strong northwesterly environmental wind shear, and the convective activities mostly appeared on the downshear side (Figure 5).

The earth-relative flight track is shown in Figure 6a, which follows a standard flight pattern that is routinely used by the NOAA-Hurricane Research Division's annual operational hurricane field program. After taking into account the storm motion, the flight track is plotted in a storm-relative framework using the center fixes based on flight-level wind observations. The dropsondes released in Erika were mostly located at the center and turn points as shown in Figure 6b (red dots). We first evaluate the DWL wind profiles against the dropsonde observations. Figure 7 shows the vertical wind profiles from the DWL measurements that are collocated with the dropsondes at each dropsonde location in the storm relative framework. At the storm center, the wind speed is weak as we expect; this wind feature is captured by both the DWL and dropsondes. Both the DWL and dropsonde observations show that the surface wind speed is strongest at the right-front quadrant. The DWL data also captured the asymmetric distribution (front vs back, and left vs right) of the wind field observed by the dropsondes. This result indicates that the first ADWL wind observations in an Atlantic tropical cyclone showed excellent skill in measuring boundary layer winds.

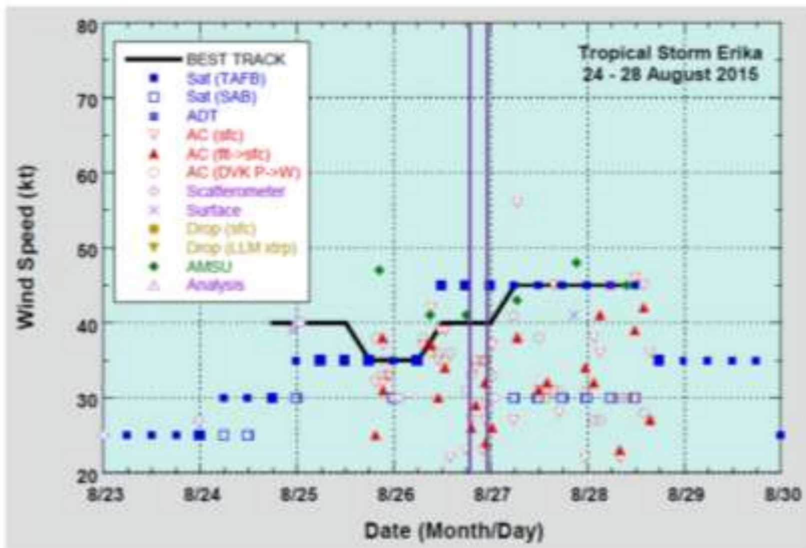

Figure 4. Plot of the storm intensity evolution of Tropical Storm Erika (2015) from the National Hurricane Center's best track. The purple lines indicate the period of DWL observations.

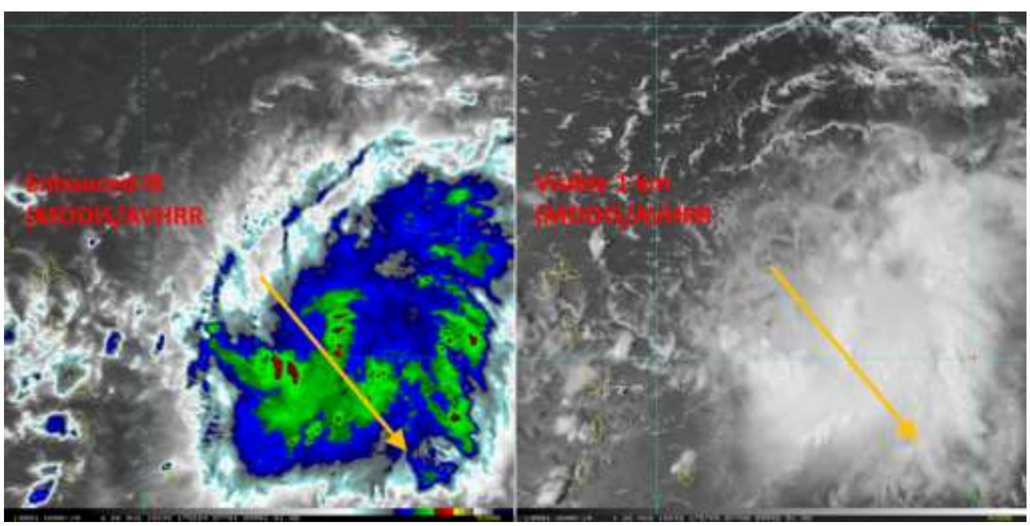

Figure 5. Satellite images from MODIS/AVHRR taken at 15-17 UTC on 26 August during the period of the DWL observations. The left panel shows the infrared (IR) image, and the right panel shows the visible image. The yellow arrow indicates the shear direction.

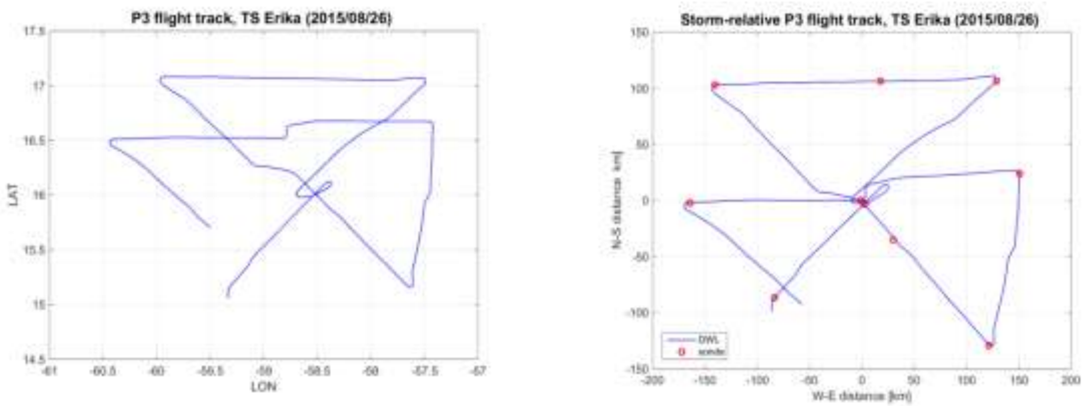

Figure 6. Flight track of the NOAA P3 for Tropical Storm Erica.

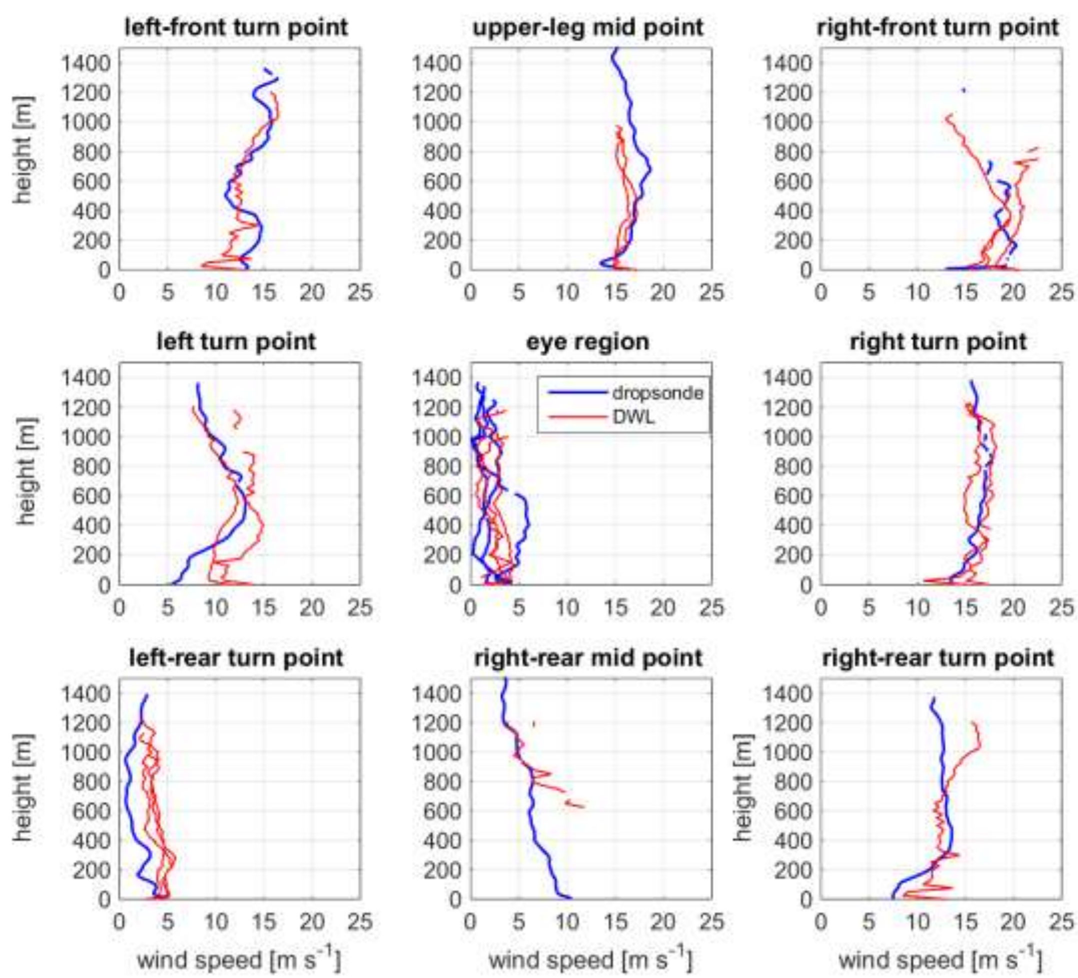

Figure 7. Plots of vertical wind profiles from the DWL (red) and dropsonde (blue) observations. The wind comparison is plotted in a storm-relative framework with the location of an observation being shown in the title of each panel.

To further evaluate the DWL wind observations, we conducted 2D analysis of the wind speeds measured by the DWL at 500 m and 1 km altitudes and compared this analysis to the Tail Doppler Radar observations (Figure 8). Note that the Doppler radar has been used to routinely measure wind speed in P3 missions with quality control before the DWL was installed on the P3. We used a piece-wise cubic spline method for the 2D wind analysis following Zhang et al. (2017)[4], which preserves original observations (i.e., along the flight track) and only interpolates data at locations where no observation was obtained. It is evident from Figure 8 that the ADWL measured wind speeds at the two levels compare well with those measured by the Doppler radar. The asymmetric distribution of the wind field measured by the Doppler radar (i.e., the strongest wind speed is on the northeast side and the weakest wind speed is on the southwest side) is captured by the ADWL. Since the Doppler radar only measures wind speed when there is precipitation, winds for almost the entire northwest quadrant were not measured well because of little precipitation there. The strong winds on the left side of the storm at ~100 m radius measured by the ADWL were not captured by the Doppler radar, as there is little rainfall or convection there (see Figure 5).

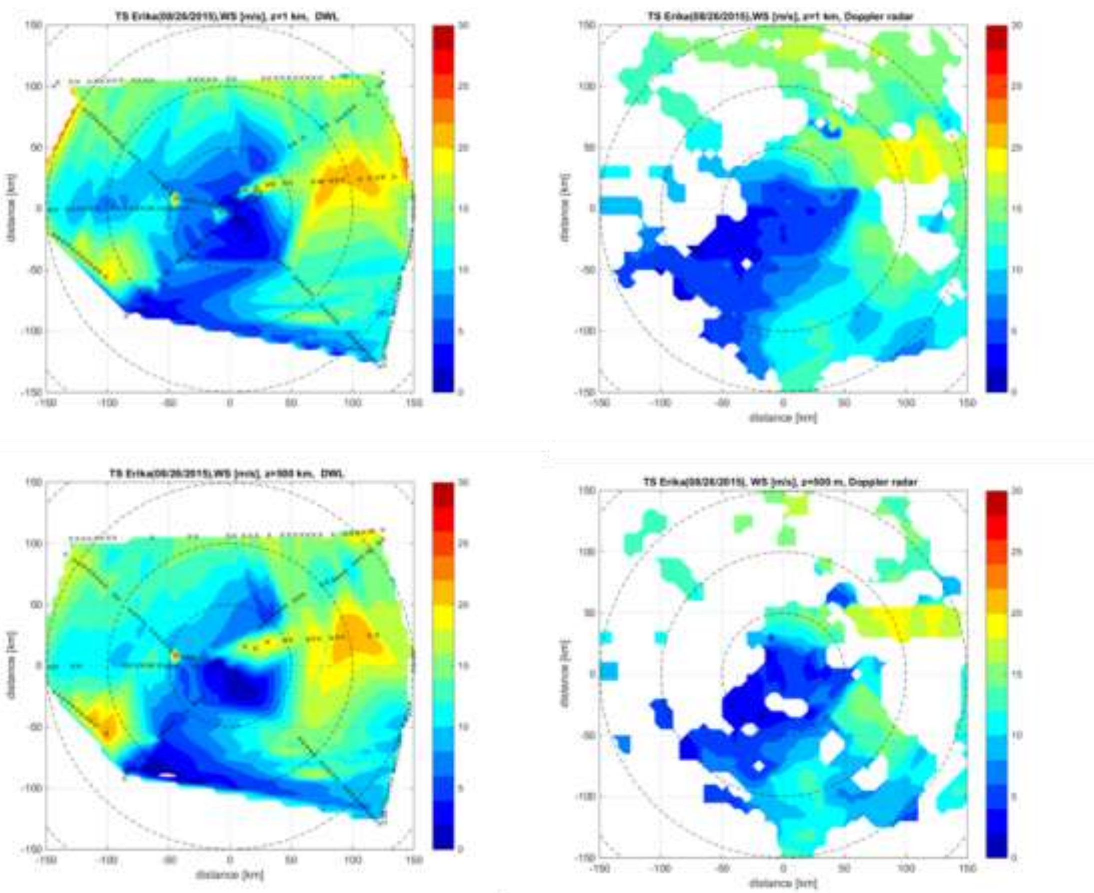

Figure 8. Plots of the wind speed at 1 km (upper panels) and 500 m (lower panels) altitudes from the DWL 2D analysis (left) and Doppler radar observations (right). The black dots in the left panels indicate locations of the DWL wind observations used in the analysis.

As mentioned earlier, the Doppler radar is also limited by its vertical resolution with the swath data only measuring winds above 500 m. On the other hand, the ADWL measures winds all the way to the surface layer. Figure 9 shows the wind speed measured by the ADWL as low as 25 m. Given the excellent data coverage of the ADWL winds, the storm-relative tangential and radial velocities can be studied. To the authors' knowledge, no previous study has shown detailed inflow layer structure in an individual tropical cyclone due to the lack of observation. Figure 10 shows the boundary layer inflow and outflow structure at four levels (25 m, 100 m, 500 m, and 1 km). It appears that the inflow is much stronger on the right side of the storm than on the left side of the storm. The strongest inflow is located along the shear direction indicated by the black arrow. This suggests that the inflow layer is deeper on the downshear side than the upshear side, which is consistent with the result of dropsonde composite analysis given by Zhang et al. (2013)[5]. The streamline pattern based on the storm-relative winds is shown in Figure 11, along with the relative vorticity for the same four levels. The closed circulation and large vorticity near the storm center suggest that Erika was able to maintain tropical storm strength despite the strong wind shear likely due to the vorticity development in the boundary layer. This hypothesis will be tested in the future using the DWL data in other cases.

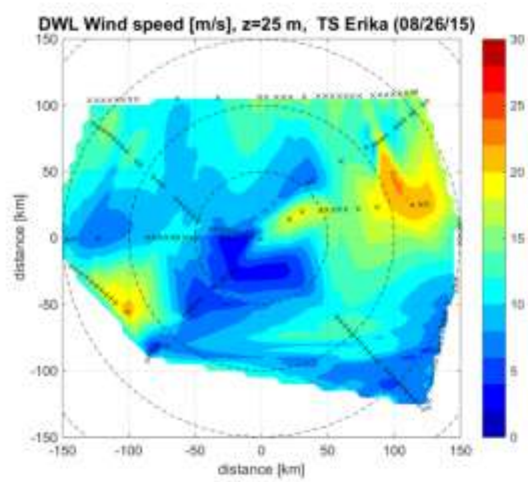

Figure 9. Plot of the wind speed measured by the DWL at 25 m in Tropical Storm Erika (2015). The black crosses are the locations of DWL winds used in the 2D analysis.

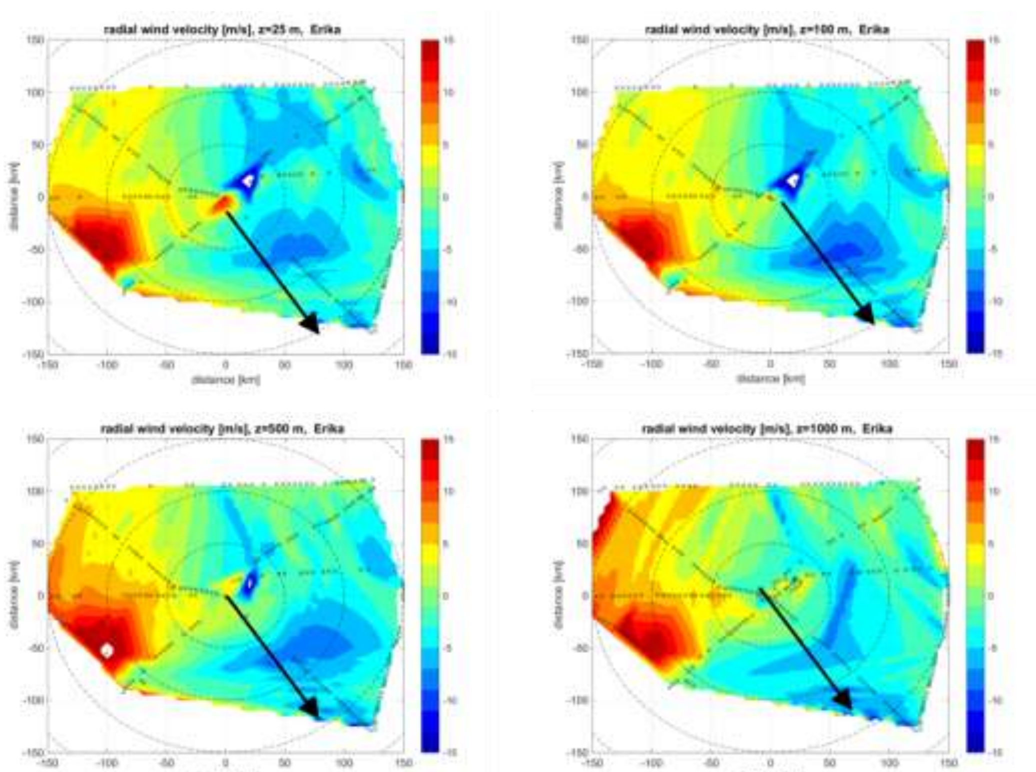

Figure 10. Plots of the radial wind velocity at 25 m, 100 m, 500 m, and 1000 m altitudes, respectively. The black crosses in each panel show the location of the DWL winds used in the 2D analysis. The black arrow represents the shear direction.

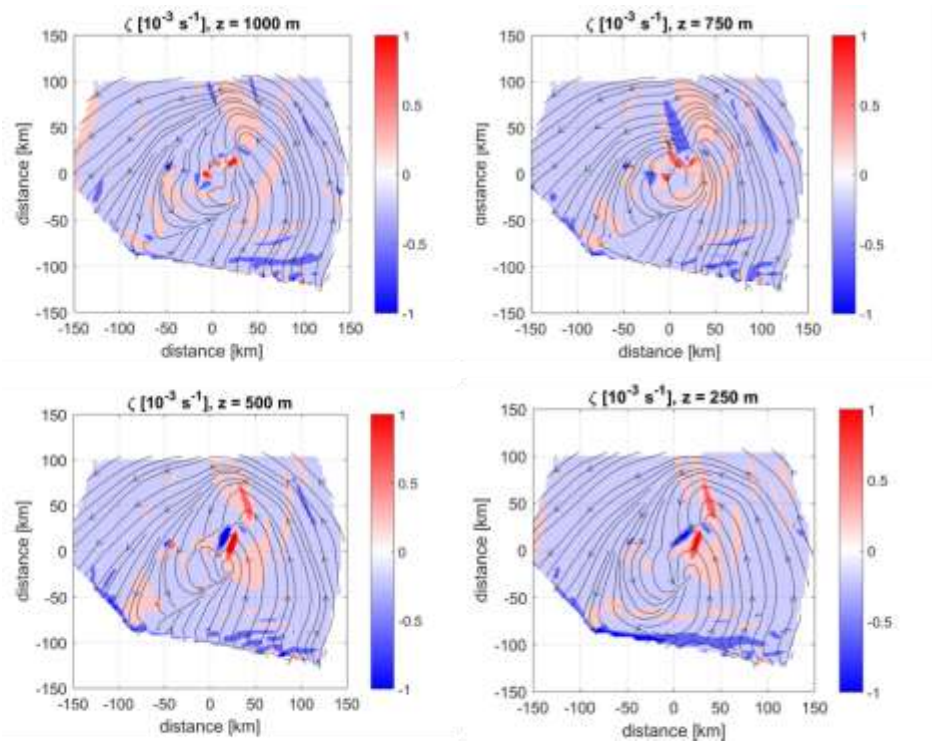

Figure 11. Plots of the relative vorticity (shading) and streamlines (contour) at 250 m, 500 m, 750 m, and 1000 m altitudes based on the DWL measured winds.

5. SUMMARY

Observing System Simulation Experiments (OSSEs), conducted using global models, have shown significant potential for space-based DWL observations to improve numerical weather prediction More recent OSSEs using both global and regional OSSEs have also demonstrated the potential to improve hurricane forecasts. In 2015, NOAA installed a DWL on its P3 Hurricane Hunter aircraft. Initial results show that the ADWL data are complementary to the P3 Tail Doppler Radar observations and are capable of filling in important gaps in our observations of tropical cyclones.

REFERENCES

[1] Baker, W. E., Atlas, R., Cardinali, C., Clement, A., Emmitt, G. D., Gentry, B. M., Hardesty, R. M., Kallen, E., Kavaya, M. J., Langland, R., Masutani, M., McCarty, W., Pierce, R. B., Pu, Z., Riishojgaard, L. P., Ryan, J., Tucker, S., Weissmann, M., and Yoe, J. G., "Lidar-measured wind profiles: The missing link in the global observing system," Bull. Amer. Meteor. Soc. 95(4), 543-564 (2014).

[2] Atlas, R., "Atmospheric observations and experiments to assess their usefulness in data assimilation," J. Meteor. Soc. Japan 75, 111-130 (1997).

[3] Atlas, R., Hoffman, R. N., Ma, Z., Emmitt, G. D., Wood, S. A., Greco, S., Tucker, S., Bucci, L., Annane, B., and Murillo, S., "Observing system simulation experiments (OSSEs) to evaluate the potential impact of an optical autocovariance wind lidar (OAWL) on numerical weather prediction," J. Atmos. Ocean. Tech. 32(9), 1593-1613 (2015).

[4] Zhang, J. A., Cione, J. J., Kalina, E. A., Uhlhorn, E. W., Hock, T., and Smith, J. A., "Observations of infrared sea surface temperature and air-sea interaction in Hurricane Edouard (2014) using GPS dropsondes," J. Atmos. Ocean. Tech. 34(6), 1333-1349 (2017).

[5] Zhang, J. A., Rogers, R. F., Reasor, P. D., Uhlhorn, E. W., and Marks, F. D., "Asymmetric hurricane boundary layer structure from dropsonde composites in relation to the environmental vertical wind shear," Mon. Wea. Rev. 141(11), 3968-3984 (2013).