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Impact of airborne Doppler wind lidar profiles on numerical simulations of a tropical cyclone

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[1] During the THORPEX Pacific Asian Regional Campaign (TPARC) field experiment in 2008, an airborne Doppler wind lidar (DWL) was onboard the U.S. Naval Research Laboratory's P-3 research flight. It was the first time the DWL was used for a tropical cyclone mission. This paper presents the first results demonstrating the impact of airborne DWL measurements on the numerical simulation of Typhoon Nuri (2008) in its formation phase. With an advanced research version of the weather research and forecasting (WRF) model and its data assimilation systems, numerical results show the DWL data have a positive impact on numerical simulations of Typhoon Nuri in terms of its formation, track and intensity. Dropsondes released in the areas where the DWL was operating show good agreement for measured winds. Compared with the three-dimensional variational method, a four-dimensional variational data assimilation system is deemed to be more promising for assimilating the DWL data.

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1. Introduction

[2] Due to a lack of conventional observations over the open ocean, forecasting tropical cyclone (TC) formation and intensification is one of the great challenges in modern Numerical Weather Prediction (NWP). In order to better understand the dynamics and physical processes that control the formation and intensification of TCs, and also to explore the effectiveness of observing systems in improving the predictability of TCs and many other weather phenomena, there have been many field programs conducted over the Atlantic and Western Pacific areas [e.g., *Houze et al.*, 2006; *Elsberry and Harr*, 2008] in recent years.

[3] Among the many observations necessary for detecting TC structures, those of the wind are the most vital. Many previous studies have demonstrated that the assimilation of wind data in NWP models has resulted in improved numerical simulations and forecasts of TCs [e.g., *Velden et al.*, 1998; *Pu et al.*, 2008]. Unfortunately, considering the rapid structural variability of TCs during their formation and intensification, the availability of wind data is quite limited. Satellite wind data, such as those from GOES rapid scan [*Velden et al.*, 2005] are mainly available in the upper levels of the troposphere. QuickSCAT ocean surface vector winds are only available near the ocean surface. Despite the large uncertainties of satellite winds over the TC vortex areas, the available data are not enough to sample the complex structure of a TC during its formation and intensification. Aircraft dropsonding provides one useful platform with which to detect wind profiles near the hurricane. However, most of the soundings are usually quite scattered and mainly in the lower levels of the troposphere. Thus, there has been the pressing need for detecting the wind profiles near TCs and their environment.

[4] During August and September 2008, a multinational field campaign commenced in the Western Pacific tropical basin. Under the umbrella of the Observing-System Research and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign (TPARC), the Tropical Cyclone Structure Program (TCS08, sponsored by U.S. Office of Naval Research [*Elsberry and Harr*, 2008]) investigated the tropical cyclone formation and structural changes. During the TPARC/TCS08 field experiment, several observing systems were involved, including the following: U.S. Air Force 53rd Weather Squadron C-130J reconnaissance aircraft; NRL P-3 aircraft and the German DLR Falcon; and the Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR). With comprehensive instrumentation on-board, the TPARC/TCS08 field missions also offer a unique opportunity for evaluating the effectiveness of observing systems for improving the predictability of tropical cyclones.

[5] Among the considerable instrumentation used during TPARC/TCS08, one particular instrument was an airborne Doppler wind lidar (DWL), which was onboard on NRL P-3 research flight. It was the first time the airborne DWL was used for a tropical cyclone mission. With the ability to sample wind profiles at 50 m resolution vertically and 1 km horizontally, the airborne DWL provides high-resolution wind profiles for tropical cyclone studies.

[6] As a first evaluation, this paper demonstrates the impact of the airborne Doppler wind lidar (DWL) data on a numerical simulation of Typhoon Nuri. We first compared the data with available dropsonding data and then assimilated the data into the WRF model. Different methods used to assimilate the DWL data are also evaluated.

2. Characteristics of the DWL Data and Comparison With Dropsondes

[7] Typhoon Nuri (2008) was the first tropical system ever sampled by the airborne DWL. The mission occurred during 2330 UTC 16 August to 0200 UTC 17 August 2008 around Nuri when it was still a tropical disturbance. Afterwards, Nuri was designated as a tropical depression at

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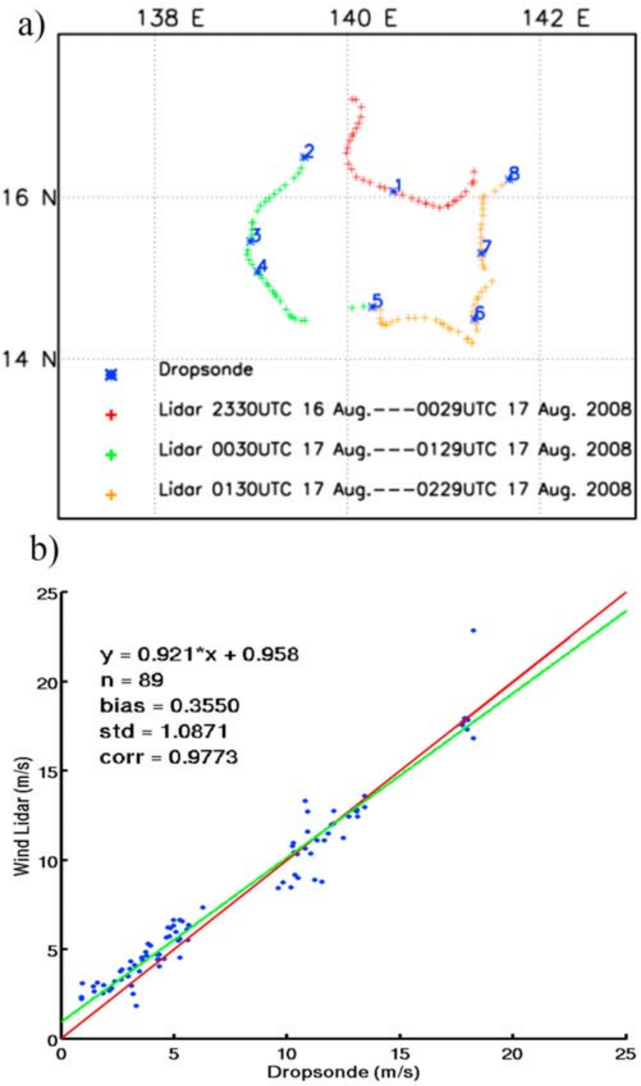

Figure 1. (a) TPARC/TCS08 Doppler wind lidar (DWL) observational locations along the NRL P-3 flight track. Different colors show the observational locations at different times. The dropsonding observational locations that coincide with DWL observations are marked in blue. (b) Wind speed scatter plot of dropsondes and DWL measurements.

1200UTC 17 August 2008 by the Joint Typhoon Warning Center (JTWC). The Japan Meteorological Agency named Nuri as a tropical storm the next day (18 August 2008) and it reached typhoon status late on 18 August 2008. Considering the available data, the main emphasis of this study is to examine the impact of the assimilation of DWL observations on the numerical simulation of the formation and development of Typhoon Nuri.

[8] Figure 1a shows the flight track and data locations for DWL wind profiles during a three-hour interval. The locations of dropsondes released in the same area and co-located with DWL data are also marked on Figure 1a. The DWL wind profiles had a 50 m vertical and 1 km horizontal resolution. Most of profiles extended from near the surface to a 2000 m height level.

[9] In order to assess the quality of the DWL data, the DWL wind profiles are compared with the dropsonde data collected in the same flight. To make a fair comparison, only the dropsonde data that match the location (both horizontally and vertically) and time of the DWL observations are first used for the statistics. Figure 1b shows that the DWL observations significantly agree with the dropsonde winds. The correlation between the two observations is nearly 98%.

[10] Wind profiles at each individual location of the dropsonde and DWL are also compared. Figure 2 shows two arbitrary samples. Although at some levels the DWL winds diverge from the dropsondes for about 1 m/s, both soundings tend to agree quite well. Despite the different error ranges from the two types of measurements, time and vertical sample resolution also contribute to the small differences between the two soundings.

3. Assimilation Experiments and Data Impacts

3.1. Experimental Design

[11] An advanced research version of the weather research and forecasting (WRF-ARW) model is employed for this study. The model is based on an Eulerian solver for the fully compressible nonhydrostatic equations, cast in flux conservation form, using a mass (hydrostatic pressure) vertical coordinate. It carries multiple physical options for cumulus, microphysics, planetary boundary layer (PBL) and radiation processes. Details of the model are provided by *Skamarock*

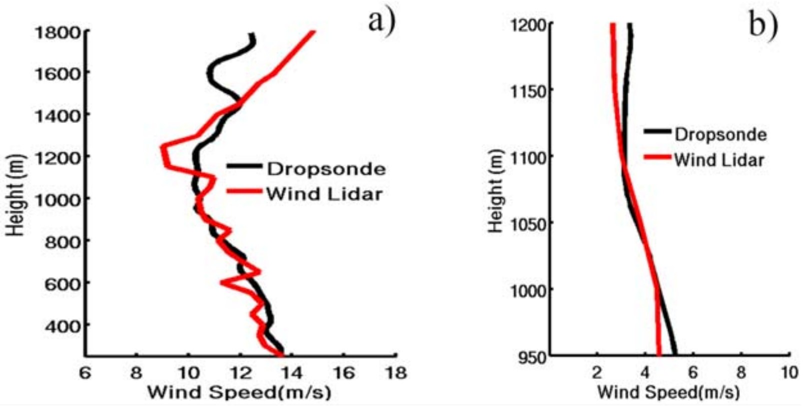

Figure 2. Comparison of wind speed profiles between dropsondes (black) and DWL measurements (red) at locations (a) 7 and (b) 5 as marked in Figure 1a.

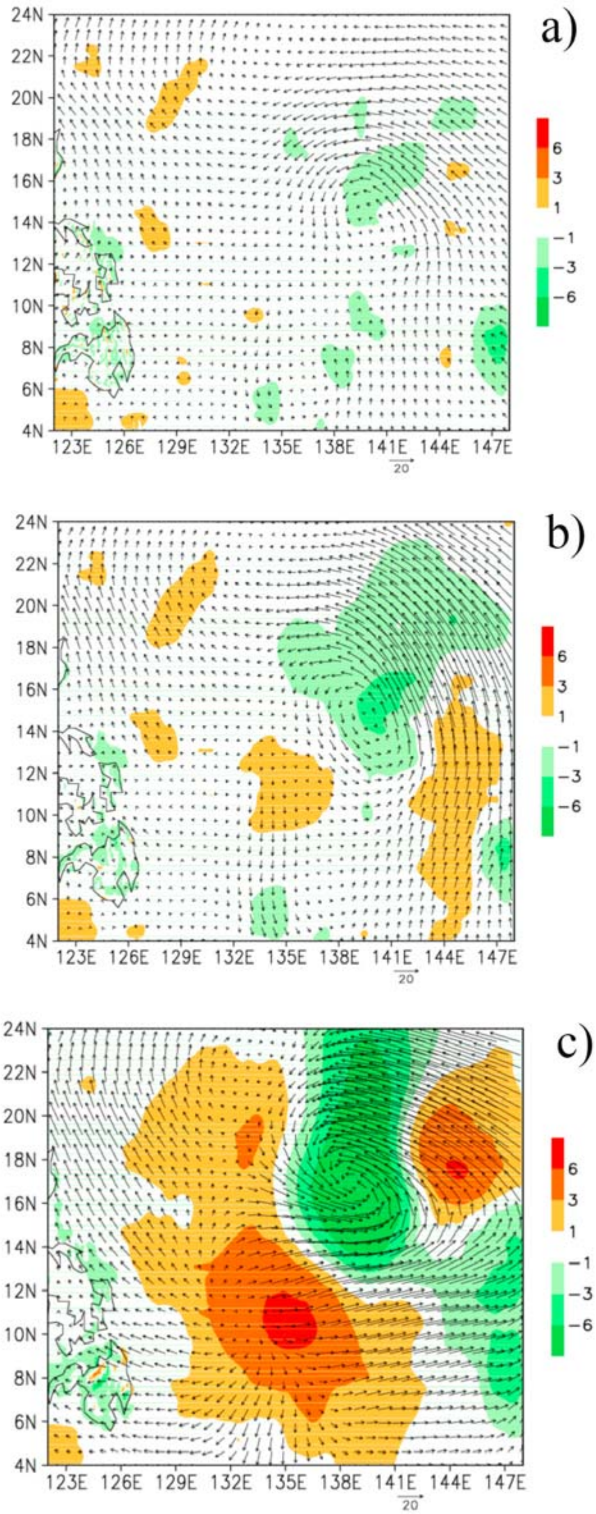

Figure 3. (a) The divergence field (unit: 10^{-5} s^{-1}, shaded contours) and wind vectors at 850 hPa pressure level for the guess field ("No data" or without data assimilation) at 0000 UTC 17 August 2008. (b) The divergence field in CTRL experiment, and analysis increments of wind vectors denoted by the differences between the analysis and first guess fields at 850 h Pa pressure level at 0000 UTC 17 August 2008. (c) Same as Figure 3b except 3DVAR assimilation of DWL data.

et al. [2005]. Along with the WRF-ARW, a three-dimensional variational data assimilation (3DVAR) system [*Barker et al.*, 2004] and a four-dimensional variational data assimilation (4DVAR) system [*Huang et al.*, 2009] were developed to facilitate the data assimilation in order to form initial conditions for the model forecasts.

[12] Version 3 of the WRF model is used for the experiments in this study. Physics options include the Betts-Miller-Janjic cumulus parameterization, Thompson microphysics scheme, the Yonsei University (YSU) planetary boundary layer parameterization, and the Rapid Radiative Transfer Model longwave and Dudhia shortwave atmospheric radiation schemes (detailed description of these physical schemes is provided by *Skamarock et al.* [2005]). A two-way interactive, two-level nested grid technique is employed to achieve the multi-scale forecast. The outer domain resolution has 27-km grid spacing and the inner domain resolution is 9-km. The model vertical structure is comprised of 31 σ levels with the top of the model set at 50 hPa, where $\sigma = (p_h - p_{ht})/(p_{hs} - p_{ht})$ while p_h is the hydrostatic component of the pressure, and p_{hs} and p_{ht} refer to values of the pressure along the surface and top boundaries, respectively. The σ levels are placed close together in the low-levels (below 500hPa) and are relatively coarsely spaced above.

[13] For the 3DVAR and 4DVAR data experiments, the background error covariance matrix was estimated using the so-called "NMC" method [*Parrish and Derber*, 1992; *Barker et al.*, 2004]. The observational error covariance matrix O_{DWL} was treated as a diagonal matrix with statistically determined variances of 4 m^2s^{-2}. Routine quality control was conducted before the data assimilation. Fortunately, all DWL data (a total of 49 profiles after data thinning) passed the default quality control set in WRF 3DVAR and 4DVAR.

[14] For the experiments, the data from National Centers for Environmental Prediction (NCEP) global final analysis (FNL) on a 1.0 × 1.0 degree grid were used to provide boundary conditions for numerical simulations. Instead of directly using the NCEP FNL analysis for the first guess in the 3DVAR and 4DVAR experiments, a WRF simulation, initialized by the WRF standard initialization process package using the NCEP FNL analysis, was first integrated 6-h to provide a first guess field ("No Data") for all data assimilation experiments. The control experiment (CTRL) assimilates available conventional observations (very sparse, no data around Nuri) and aforementioned dropsonde data with 3DVAR method. The other two experiments are conducted to assimilate the DWL profiles using 3DVAR and 4DVAR systems. All data assimilation experiments are performed for the two domains separately. However, all the forecasts are run using both domains. All figures present results from the 9-km grid spacing domain.

[15] A cycling 3DVAR approach is employed to conduct three consecutive 1-h data assimilations from 0000 UTC 17 August to 0200 UTC 17 August 2008 for both CTRL and DWL assimilation with 3DVAR. *Pu et al.* [2008] demonstrated that a cycling data assimilation experiment is advantageous over a common 3 or 6 h cut off window in 3DVAR. For the 4DVAR experiment, a three-hour assimilation is set and all data are assimilated in the window. From the end of data assimilation, forecasts are then run through 46 h to 0000 UTC 19 August 2008 when Nuri becomes a mature Typhoon.

3.2. Results: Data Impacts

[16] Results from data assimilation experiments show that the DWL wind profiles improved the numerical simulation of Nuri. Their forecast impacts were greater than these from conventional and dropsonde data (Figures 3–5). Ample evidence was found in the wind field. Figure 3 shows sample results from the 3DVAR experiment that indicated that the DWL wind has resulted in enhanced convergence flow during the data assimilation cycles. Figure 4 shows the divergence field averaged over the area with a radius of 250 km around the center of circulation at 0600 UTC 17 August 2008, which was 4-h forecast after the data assimilation. It is obvious that the assimilation of DWL data enhanced the low level convergence and upper level divergence of Nuri during its development from a tropical disturbance to a tropical depression. In addition, compared with 3DVAR, the 4DVAR method causes the model to produce stronger lower level convergences and upper level divergences.

[17] Figure 5a demonstrates the data impact on the intensity forecast of Nuri, showing assimilations of the DWL data have resulted in stronger TC forecasts, with the simulated TC intensities are closer to the intensity of Nuri as taken from the JTWC best track. The forecast tracks are also compared with JCWT best track data (Figure 5b). It is apparent that the assimilation of DWL profiles mitigated the northern bias of the simulated storm track for Nuri. The track error has also been reduced. Compared with the 3DVAR method, the 4DVAR data assimilation resulted in a much better track as the overall track errors are reduced significantly (Figure 5c).

4. Concluding Remarks

[18] The airborne DWL instrument onboard the NRL P-3 was first operated during the TPARC/TCS08 field experiment for tropical cyclone studies. Results from this paper show a positive impact of the Airborne Doppler lidar data on the numerical simulation of Typhoon Nuri in terms of its formation, track and intensity. Dropsondes released in the same area where the Doppler lidar was operating show good agreement for measured winds. Compared with a 3DVAR data assimilation method, a 4DVAR system is deemed to be more promising for future DWL data assimilations.

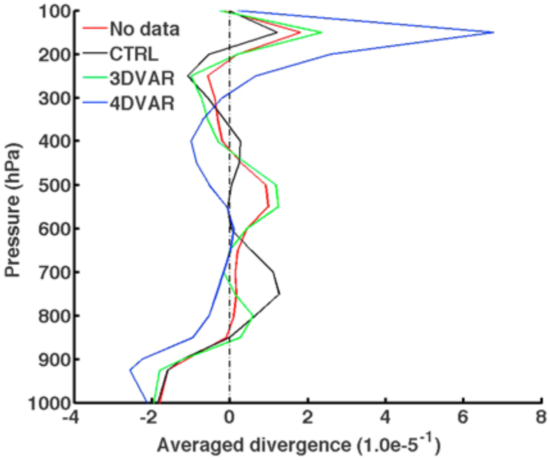

Figure 4. Averaged divergence profiles over the area with radius of 250 km around Nuri's circulation center at 0600 UTC 17 August 2008. The vertical axis denotes pressure levels. The horizontal axis represents the magnitudes of the divergence (10^{-5} s^{-1}).

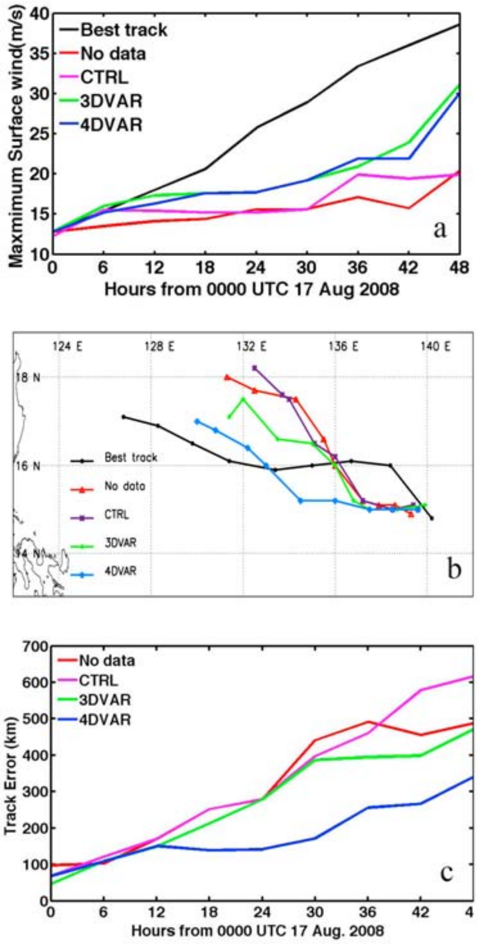

Figure 5. (a) The maximum surface wind, (b) Nuri's track and (c) track errors from 0000UTC 17 August 2008 to 0000UTC 19 August 2008. The forecasts with (green curves for 3DVAR and blue curves for 4DVAR) and without ("no data" in red curve and "CTRL" in purple curve) assimilation of DWL winds are compared with the JTWC best track data (black curves in Figures 5a and 5b). DWL data are assimilated for the period of 0000 UTC – 0200 UTC 17 August 2008 in both the 3DVAR and 4DVAR experiments.

[19] Studies from this paper present a first evaluation of the impact of DWL data on tropical cyclone forecasts in a research community model. A more comprehensive evaluation of the impact of the data on operational tropical cyclone forecasts is needed in the future using operational models, while integrating the DWL data with all conventional and satellite data available. In addition, since the conventional and dropsonde data are very sparse in this study, more realistic comparisons of forecasting impacts from the DWL and dropsonde measurements still await future field experiments when more data become available.

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