Impacts of Airborne Doppler Radar Data Assimilation on the Forecasts of Hurricane Katrina (2005)

Qingnong Xiao*[1], Xiaoyan Zhang[1], Christopher Davis[1], John Tuttle[1], Greg Holland[1], Pat Fitzpatrick[2]

1. *Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research, Boulder, Colorado*
2. *GeoResources Institute, Mississippi State University, Stennis Space Center, Mississippi*

1. Introduction

One* of the important facts that prohibit improvement of hurricane intensity forecasting is unsatisfactory initialization of small-scale inner-core vortex structure (Davis et al. 2008). Most available satellite data over the hurricane inner-core region are unfortunately contaminated by heavy precipitation and thus produce unreliable data for the vortex initialization. However, the airborne Doppler radar observations can properly resolve these inner-core features. As hurricanes approach coastal regions, Doppler radar observations are now available in real time from reconnaissance aircraft (Marks 2003) and from the extensive network of coastal radars. These data are currently being used primarily in the form of images for qualitative interpretation by forecasters. The technology already exists to make use of these data in advanced data assimilation procedures. This will certainly help improve the hurricane initialization for the hurricane intensity forecast.

In this study, we utilized the high-resolution non-hydrostatic Weather Research and Forecast (WRF) model (Skamarock et al. 2005) and its variational data assimilation system (WRF-Var; Barker et al. 2004; Skamarock et al. 2005) to assimilate airborne Doppler radar observations from NOAA P-3 reconnaissance aircraft. Numerical experiments were conducted to perform hurricane initialization with the airborne Doppler radar data and subsequent forecasts for Hurricane Katrina (2005). It is demonstrated that assimilation of airborne Doppler radar data can enhance the definition of hurricane inner core structures. The forecast skill of the storm's track, intensity and structure are therefore improved with the initialization using Airborne Doppler radar data.

2. Airborne Doppler Radar Dataset and Assimilation Methodology

a. Dataset

Airborne Doppler Radar (ADR) data have been collected in tropical cyclones since 1982 (Marks, 2003). The data have a very high resolution, about 1-2 km in horizontal and 0.5 km in vertical direction. They mostly represent some inner wind, and moisture and hydrometeor structures within the eyewall. Figure 1 shows the radar wind and reflectivity observations at 2.5 km for Hurricane Katrina at 1630-1713 UTC, 1738-1814 UTC and 1952-2025 UTC 27 August 2005.

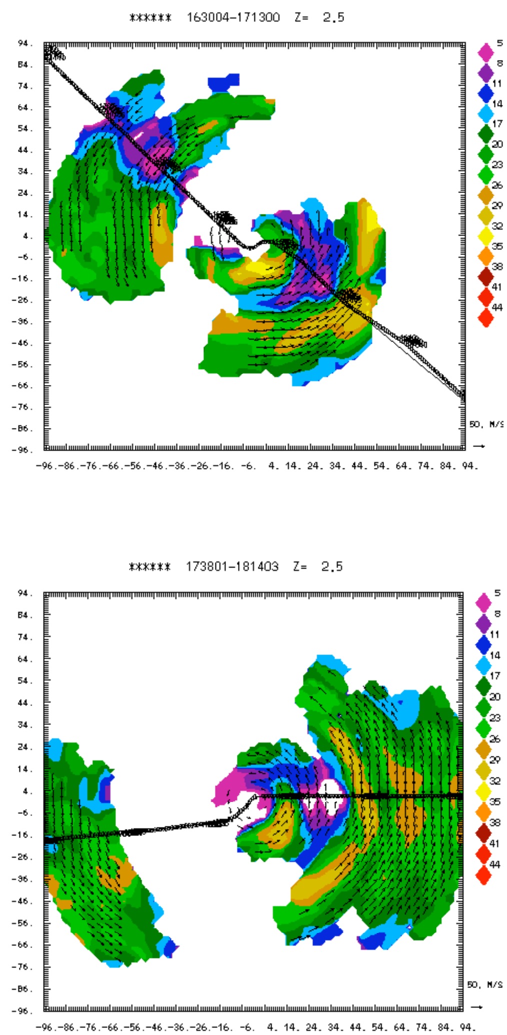

Figure 1: Airborne Doppler radar wind and reflectivity observations for Hurricane Katrina at 1630-1713 UTC (top) and 1738-1814 UTC (bottom) 27 August 2005. The color shading is for the radar reflectivity with the scales on the right.

* Corresponding to Qingnong Xiao (hsiao@ucar.edu)

The ADR data used in this research have been quality controlled by NOAA Hurricane Research Division (HRD). The ADR wind data that we start with are the automatic real-time Doppler winds fields and reflectivity retrieved from the tail radar observations of the NOAA P-3s (Gamache et. al. 2004). For Hurricane Katrina (2005), the aircraft flew a series of legs through the hurricane, each lasting 30-40 minutes (Figure 1).

b. Assimilation Methodology

The WRF three-dimensional variational data assimilation system, WRF 3D-Var (Barker et al. 2004), is used in this research. WRF 3D-Var uses the multivariate incremental formulation (Courtier 1994), producing a multivariate incremental analysis in model space. The minimization is performed in preconditioned control variable space**.** The preconditioned control variables are streamfunction, unbalanced velocity potential, unbalanced temperature, pseudo relative humidity, and unbalanced surface pressure. Error correlations between control variables are neglected except for a constraint on mass and winds, whereby geostrophic or cyclostrophic balance can be enforced. A statistical regression is used to ensure that the balanced pressure is used only where appropriate. The National Meteorological Center (NMC) method (Parrish and Derber 1992) is applied to generate the background error covariances using the one-month WRF forecasts on a 12-km grid over the Gulf of Mexico area in September 2004.

The Doppler radar data assimilations in WRF 3D-Var were described in Xiao et al. (2005; 2007) and Xiao and Sun (2007). Its capability in rainfall forecast was verified in KMA operational (Xiao et al. 2008). For the airborne Doppler winds, the data from NOAA/HRD are already gridded wind components. Assimilation of the winds is straight a way, similar to the assimilation of conventional sounding winds. In order to assimilate the reflectivity data, WRF 3D-Var introduced a partitioning procedure for the moisture and water hydrometeor increments using the warm-rain scheme of Dudhia (1989). The warm rain process includes condensation of water vapor into cloud (P_{CON}), accretion of cloud by rain (P_{RA}), automatic conversion of cloud to rain (P_{RC}), and evaporation of rain to water vapor (P_{RE}). The warm rain parameterization builds a relation among rainwater, cloud water, moisture and temperature. When rainwater information (from reflectivity) enters into the minimization iteration procedure, the forward warm rain process and its backward adjoint distribute this information to the increments of other variables (under the constraint of the warm rain scheme. Once the 3D-Var system produces q_c and q_r increments, the assimilation of reflectivity is straightforward. The operator of directly assimilating the radar reflectivity can refer to Xiao et al. (2007) and Xiao and Sun (2007.)

3. Overview of Hurricane Katrina (2005) and Experimental Design

a. Hurricane Katrina (2005)

Katrina was one of the most devastating natural disasters in the history of the United States. Katrina formed around 1200 UTC 24 August 2005. It was estimated to have reached hurricane status near 2100 UTC 25 August. It nearly doubled in size on 27 August, and strengthened from a low-end Category 3 hurricane to a Category 5 in less than 12 h, reaching an intensity of-145 kt by 1200 UTC 28 August. Katrina attained its peak intensity of 150-kt at 1800 UTC 28 August about 170 n mi southeast of the mouth of the Mississippi River.

b. Experimental Design

The hurricane initialization with airborne Doppler radar data assimilation was conducted at 1800 UTC 27 August 2005. Three experiments were carried out. CTRL has the initial condition from GFS analysis, which is interpolated to WRF grids using WRF preprocessing system (WPS). The CTRL initial conditions were also used as the first guess of data assimilation. The experiment GTS assimilates all conventional data. The experiment GTSRV assimilates GTS data plus radar winds. The domain configuration contains three domains with the resolutions of 12, 4, and 1.33 km. The two inner domains are moving nested domains. GTS data are assimilated in all three domains, but radar data assimilation is conducted on the two inner domains. Numerical forecast started from 1800 UTC 27 August 2005 after the initialization.

4. Results

a. Impact of ADR Winds on Hurricane Structure

First of all, we examined the impact of the ADR wind assimilation on the vortex structure. Figure 2a and b is the sea level pressure (SLP) and 850-mb wind vectors before and after ADR data assimilation. We can easily see the cyclonic circulation is strengthened and its central SLP is decreased in the experiment assimilating the ADR data. Figure 3a and b shows the surface wind velocities and vectors before and after the ADR data assimilation, respectively. It looks more reasonable in the pattern of the wind distribution and the maximum wind velocity after ADR data assimilation. Similar to the observations, a strong vortex circulation concentrates in a small scale within the eye-wall, whereas the GFS analysis has a broader vortex circulation.

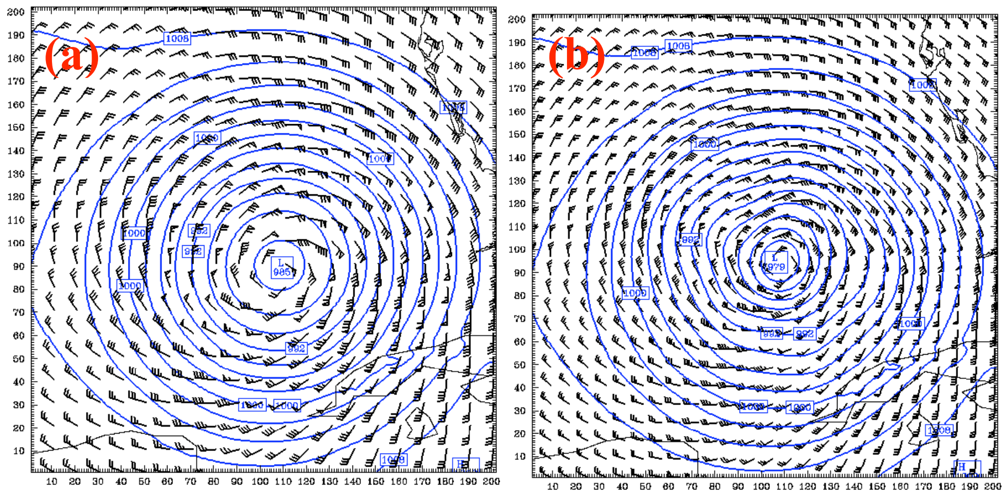

Figure. 2: Hurricane Katrina's (2005) 850 hPa wind barbs (a full barb represents 5 m/s) and sea level pressure at 1800 UTC 27 August 2005: (a) before and (b) after ADR data assimilation

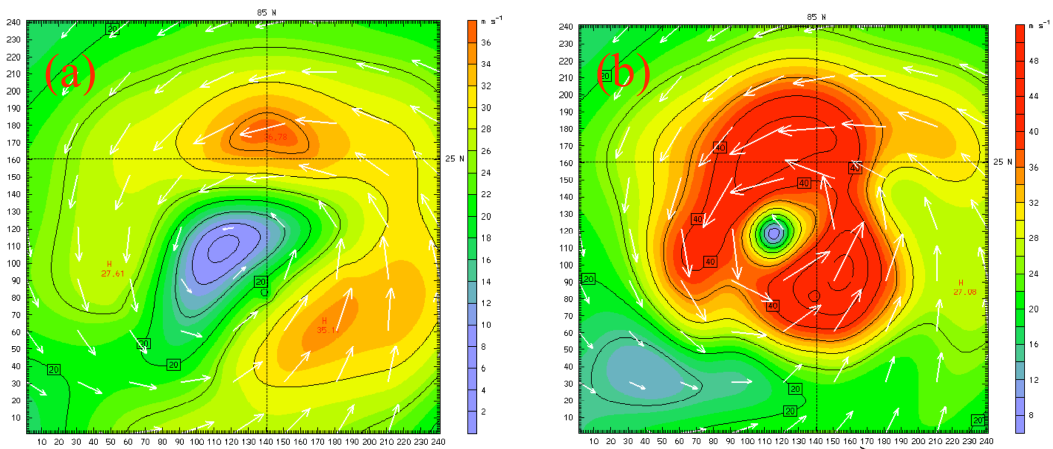

Figure 3: Hurricane Katrina's (2005) surface wind velocities and vectors at 1800 UTC 27 August 2005: (a) before, and (b) after ADR data assimilation

b. Intensity Forecasts

The track forecasts from all experiments are good, and therefore omitted in the presentation. Figure 4 shows 48h intensity forecasts of the three experiments for Katrina (2005) started from 1800 UTC 27 August 2005. The observed hurricane intensity is also shown in the figure for comparison. As is apparent from the figure, the addition of the radar observations is crucial for the improvement of hurricane intensity. We can see both the CSLP and MSW are significantly improved after assimilating ADR wind data. The initial CSLP is dropped 8 hPa, and initial MSW is enhanced 32 kt by assimilating ADR wind data comparing with CTRL and GTS. The errors of CSLP before 36h and MSW before 30h are reduced, indicating the improvement in the intensity forecasts resulting from the ADR data assimilation. These results indicate hurricane intensity forecast has much more to do with the inner core structure of the vortex. The significance of the above result is that the forecast of storm intensity, a notoriously difficult parameter to predict, is improved with ADR data assimilation using 3DVAR without use of a synthetic vortex, and the improvement lasts for at least 30 hours into the forecast. The 3DVAR method is relatively inexpensive computationally and can easily be run in real time. It appears that a significant improvement of short-range intensity forecasts is possible with radar data assimilation.

We also found that the prediction of maximum intensity of Katrina (2005) was delayed about 12- 18 hours. This time lag is in all experiments, indicating that we should further tune the WRF model setup to get better intensity forecast. From the viewpoint of data impact, the ADR data has positive impact on the hurricane intensity in this study.

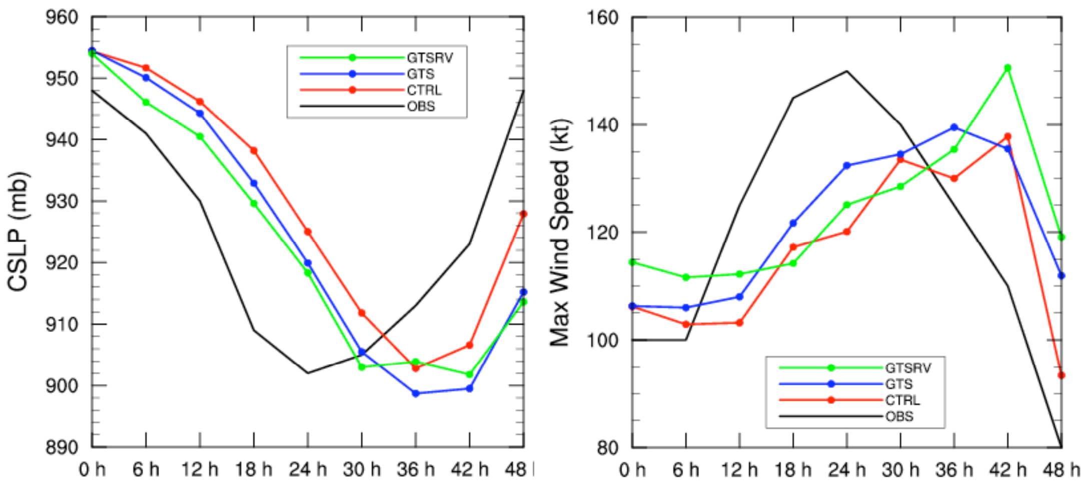

Figure 4: The predicted CSLP (hPa) and MSW (m/s) of Hurricane Katrina (2005) from 1800 UTC 27 to 1800 UTC 29 August 2005

5. Summary and Conclusions

While a hurricane track is sensitive to synoptic-scale flow features (>1000 km scale), hurricane intensity forecast has much more to do with the initialization of inner core structure of the vortex. Usually a vortex bogussing is necessary for most of the hurricane forecasting models. With the advance of the remote sensing technology using Doppler radars, the observations from airborne Doppler radars onboard NOAA reconnaissance aircraft provide valuable information of hurricane wind and hydrometeor structures. Assimilation of the information to hurricane initial conditions can enhance the hurricane vortex structures and therefore can improve the hurricane intensity forecast. In this study, we evaluate the ADR data on the initializations and subsequent forecasts for Hurricanes Katrina (2005). Positive impacts are found with the ADR data assimilation for hurricane intensity forecast. Main findings are as follows:

- Assimilation of ADR data can enhance hurricane structure. The GFS analysis usually has weak hurricane vortex circulation. Assimilation of ADR winds improves the vortex circulation; the hurricane vortex becomes stronger than GFS analysis and closer to observations.
- With the enhanced hurricane vortex, the subsequent forecasts of hurricane intensity are improved with ADR data assimilation using 3DVAR alone, without use of a synthetic vortex. The 3DVAR method is relatively inexpensive computationally and can easily be run in real time.

While encouraging, more diagnosis and explanation of the results are needed. In addition, we also conducted experiments with reflectivity assimilation using WRF 3D-Var. The WRF 4D-Var has developed recently, and we have some preliminary results for the case using 4D-Var. Analysis of the results are under way, and will be reported in the near future.

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Reference

Barker D. M., W. Huang, Y.-R. Guo, A. J. Bourgeois, and Q. N. Xiao, 2004: A three-dimensional variational data assimilation system for MM5: Implementation and initial results. *Mon. Wea. Rev.*, **132**, 897–914.

Courtier, P., J.-N. Thépaut, and A. Hollingsworth, 1994: A strategy for operational implementation of 4D-Var, using an incremental approach. *Quart. J. Roy. Meteor. Soc.,* **120**, 1367–1387.

Davis, C., Wei Wang, Y. Chen, K. Corbosiero, Jimy Dudhia, Greg Holland, Joe Klemp, John Michalakes, Richard Rotunno, Chris Snyder, Qingnong Xiao, Mark DeMaria and Shuyi Chen, 2008: Prediction of Landfalling Hurricanes with the Advanced Hurricane WRF Model. *Mon. Wea. Rev*., in press.

Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *J. Atmos. Sci*., **46**, 3077-3107

Gamache John F., J. S. Griffin, Jr., P. P. Dodge, and N. F. Griffin, 2004: Automatic Doppler analysis of three-dimensional wind fields in hurricane eyewalls**.** *26th Conference on Hurricanes and Tropical Meteorology, Miami, FL.*, May 2-7, 2004.

Marks, Frank D., Jr., 2003: State of the science: Radar view of tropical cyclones. Radar and atmospheric science: A collection of essays in honor of David Atlas. Wakimoto and Srivastava, Eds, *Meteorological Monographs*, **52**, AMS, MA, 33-74.

Parrish D. F., and J. C. Derber, 1992: The National Meteorological Center's spectral statistical-interpolation analysis system. *Mon. Wea. Rev.*, **120**, 1747–1763.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang and J. G. Powers, 2005: A Description of the Advanced Research WRF Version 2. NCAR Technical Note TN-468+STR. 88 pp.

Xiao, Q., Y.-H. Kuo, J. Sun, W.-C. Lee, Eunha Lim, Y.-R. Guo and D. M. Barker, 2005: Assimilation of Doppler radar observations with a regional 3DVAR system: Impact of Doppler velocities on forecasts of a heavy rainfall case. *J. Appl. Met*., **44**, 768-788.

Xiao, Q., Y.-H. Kuo, J. Sun, W.-C. Lee, D. M. Barker, and Eunha Lim, 2007: An approach of radar reflectivity assimilation and its assessment with the inland QPF of Typhoon Rusa (2002) at landfall. *J. Appl. Meteor. Climat.*, **46**, 14-22.

Xiao, Q., and J. Sun, 2007: Multiple radar data assimilation and short-range QPF of a squall line observed during IHOP_2002. *Mon. Wea. Rev.*, **135**, 3381-3404.

Xiao, Q., Eunha Lim, Duk-Jin Won, Juanzhen Sun, Wen-Chau Lee, Mi-Seon Lee, Woo-Jin Lee, Joo-Young Cho, Y.-H. Kuo, D. M. Barker, D.-K. Lee, and Hee-Sang Lee, 2008: Doppler radar data assimilation in KMA's operational forecasting. *Bull. Amer. Met. Soc.*, **89**, 39-43.