Hurricane Initialization Using Airborne Doppler Radar Data for WRF

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1. Introduction

Landfalling hurricanes are one of the most dangerous disasters. Accurate prediction of their track and intensity are crucial for the protection of life and property. Although progress has been made in track forecasting during the past decade, intensity forecasting remains unsatisfactory. An acknowledged deficiency in all hurricane-forecast systems, including the most advanced Weather Research and Forecasting (WRF) model, is an improper initialization of the hurricane and its surrounding environment (Davis et al. 2007). Clearly, an improved vortex initialization, using advanced data assimilation techniques, would augment the skill of short-term forecasts (< 2 days) of the critical rain and wind features of tropical cyclones as they approach land.

During the past few decades, hurricane forecasting has relied heavily on satellite observations. However, most available satellite data over the hurricane inner-core region are unfortunately contaminated by heavy precipitation and thus produce unreliable initial fields for the region. The usage of satellite data to resolve vortex inner-core structure for improving hurricane intensity forecasting is therefore limited. As hurricanes approach coastal regions, another important source of data, 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. The airborne Doppler radar observations can properly resolve hurricane inner-core features; this will certainly help improve the hurricane initialization for the hurricane intensity forecast.

In this study, we will utilize 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. We will report some results of hurricane initializations with the airborne Doppler radar data and subsequent forecasts for three cases, Hurricanes Jeanne (2004), Katrina (2005), and Rita (2005).

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 (Fig. 1).

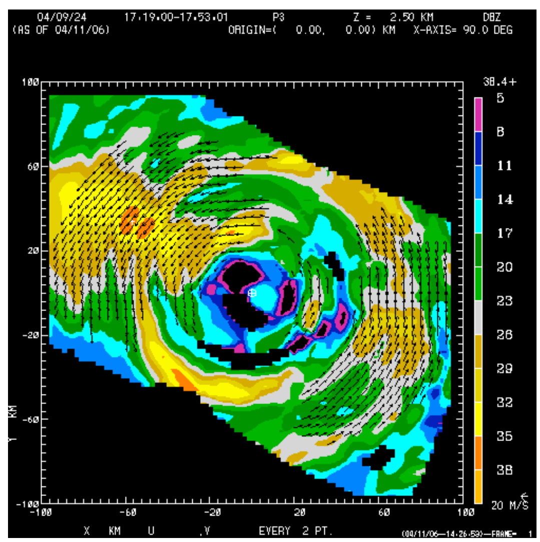

Figure 1: Airborne Doppler radar wind and reflectivity observations for Hurricane Jeanne (2004) at 1719-1753 UTC 24 September 2004. The color shading is for the radar reflectivity.

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). We collect the available ADR data for hurricanes Jeanne (2004), Katrina (2005), and Rita, 2005). For each case, the aircraft flew a series of legs through the

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hurricane, each lasting 30-40 minutes (an example is shown in Figure 2).

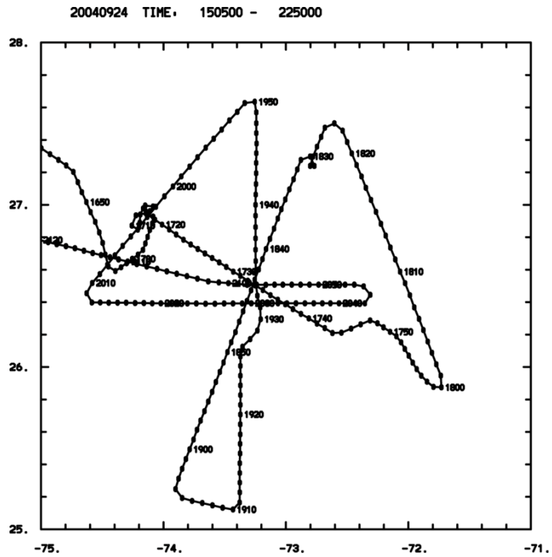

Figure 2: An example of flight tracks for hurricane Jeanne around 1800 UTC 24 September 2004

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 and 2007. 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. Brief Review of the Hurricane Cases

a. Hurricane Jeanne (2004)

Jeanne (2004) was a tropical cyclone with less than 70-kt winds before 17 September. It then gradually strengthened to a hurricane with 85-kt winds by the time it completed the loop on 23 September. The winds increased to 100-kt (category three on the Saffir/Simpson hurricane scale) by 1200 UTC on 25 September. It produced heavy rain over Guadeloupe, Puerto Rico and the Dominican Republic and caused an estimated death of more than 3000 in Haiti, from torrential rainfall flooding. Jeanne made landfall on the east coast of Florida early on 26 September.

b. Hurricane Katrina (2005)

Considering the scope of its impacts, Katrina was one of the most devastating natural disasters in the history of the United States. Katrina formed around 1200 UTC 24 August. 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.

c. Hurricane Rita (2005)

Rita was an intense hurricane that reached Category 5 strength over the central Gulf of Mexico, where it had the fourth-lowest central pressure on record in the Atlantic basin. It produced significant storm surge that devastated coastal communities in southwestern Louisiana, and its winds, rain, and tornadoes caused fatalities and a wide swath of damage from eastern Texas to Alabama. Rita had strengthened from a tropical storm to a Category 5 hurricane in less than 36 h. It remained at Category 5 strength for about 18 hours, reaching its estimated peak intensity of 155-kt by 0300 UTC 22 September.

4. Experimental Design

Four groups of experiments are designed for the selected three hurricane cases. There are two groups of experiments for Katrina, one is starting from 1800 UTC 25 September, and the other is starting from 1800 UTC 27 September. Every group of experiments includes two runs, control run (CTRL) and the run with ADR data assimilation. The detailed information of the experimental designs is described in Table 1. The initial condition of CTRL is from GFS analysis, which is interpolated to WRF grids using WRF preprocessing system (WPS). The CTRL initial conditions are also used as the first guess of data assimilation. All radar data assimilations are conducted on the 4 km resolution domain. However, forecasts are executed on the 12- and 4-km nested domains by WRF model. The same grid sizes are used for hurricane Jeanne (2004) and Katrina (2005). The coarse domain is 400x301x35, and the nested one is 451x502x35. The domain configuration for hurricane Rita is different in the central location and grid sizes that are 356x406x31 and 403x463x31 for the coarse and nested domains.

Table 1. Description of the airborne Doppler radar data assimilation experiments

	Exps	Assimilation Time	Data Duration
Jeanne	JEA	2004_09_24-18:00	17:19 - 20:47
	KA1	2005_08_25_18:00	15:13 – 19:40
	KA2	2005_08_27_18:00	16:30 – 19:52
Rita	RIT	2005_09_20_18:00	15:41 – 17:56

5. 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 analysis of Hurricane Jeanne (2004). Figure 3 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 4a and b shows the 850-mb u and v increments with ADR data assimilation, respectively. The pattern and the maximum value look reasonable, considering the observation concentrate in a small scale within the eyewall. The analysis also generates temperature increment through the balances in WRF-VAR system. Figure 4c shows 300 hPa temperature increment after ADR data assimilation for Hurricane Jeanne (2004). It shows a warmer core in the vortex analysis with the ADR data assimilation.

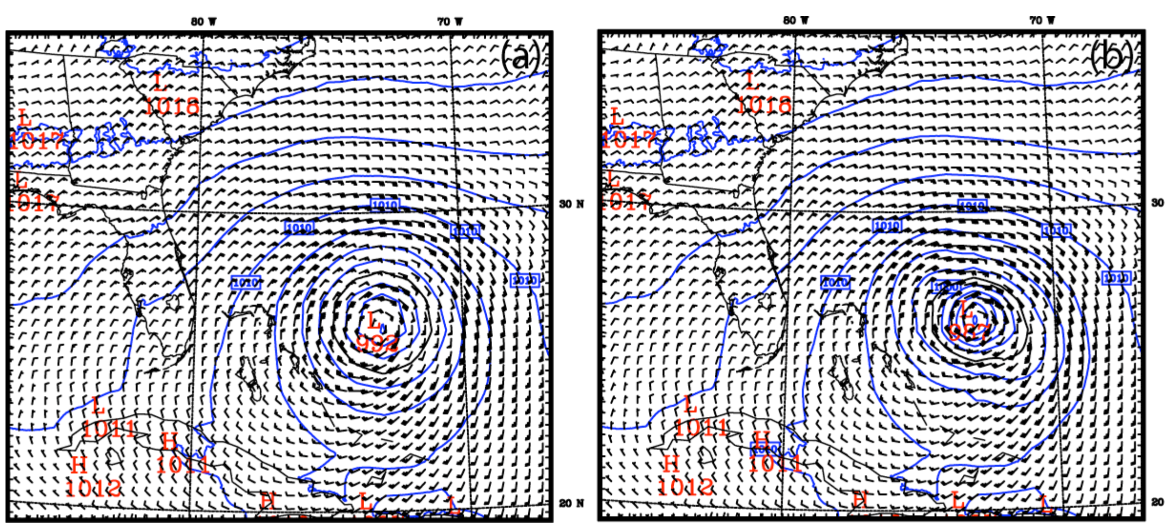

Figure. 3: Hurricane Jeanne's (2004) 850 hPa wind barbs (a full barb represents 5 m/s) and sea level pressure at 1800 UTC 24 September 2004: (a) before and (b) after ADR data assimilation

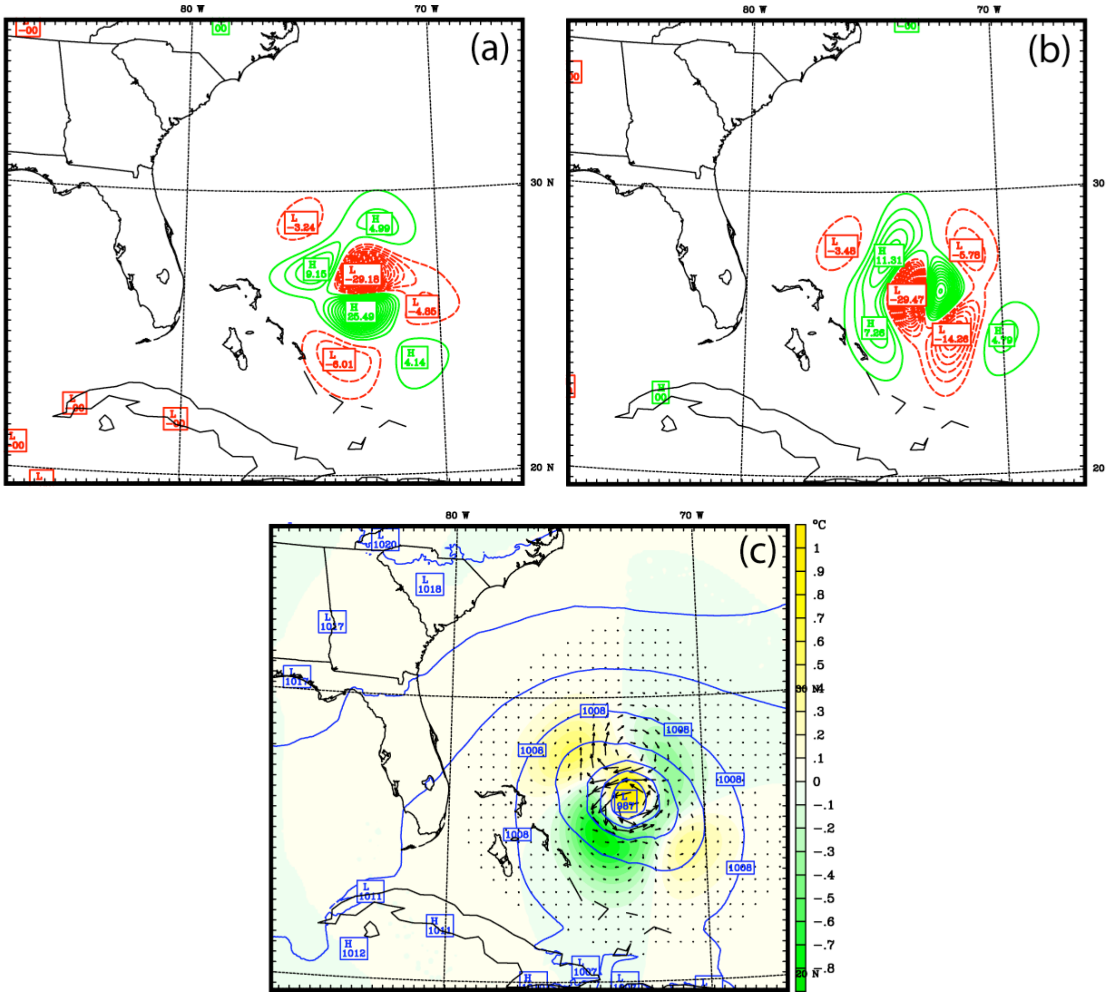

Figure 4: Increments of the ADR data assimilation experiment for Hurricane Jeanne (2004): (a) u increments, (b) v increments at 850 hPa, and (c) T increments at 300 hPa

b. Track and Intensity Forecasts of hurricane Jeanne (2004)

In order to evaluate the impact of ADR data assimilation on the forecast of Hurricane Jeanne (2004), we designed four experiments. They are CTRL (which uses GFS analysis), GTS (which assimilates only Global Technique System data), RVALL (which assimilates all available ADR wind data around 1800 UTC 24 September 2004 within a 6-h assimilation window), and GTSRV (which assimilates both GTS and ADR wind data together).

Figure 5 shows the track forecasts and their errors (in km) compared with the best track of Hurricane Jeanne (2004). The WRF forecast initialized from GFS has track errors around or above 100 km, with a track error of 171 km at 48 h. All data assimilation experiments drop the errors below 100 km, with the mean track errors of 70.6, 56.5, and 60.5 km for the experiments GTS, RVALL, and GTSRV, respectively.

As is apparent from Figure 6, the addition of the radar observations is crucial for the improvement of hurricane intensity. We can see both the CSLP and MSW are improved greatly after assimilating ADR wind data. The initial CSLP is dropped 8 hPa, and initial MSW is enhanced 18 m/s by assimilating ADR wind data comparing with CTRL and GTS. The mean errors of CSLP at 48 h are 28.135, 26.2, 15.195, and 15.920 hPa for CTRL, GTS, RVALL, and GTSRV, respectively, which demonstrate the improvement in the intensity forecasts resulting from the ADR data assimilation. Furthermore, the effect of these additional data persists for at least 24 h. This time scale is longer than is typically found for the incorporation of Doppler radar data for convection forecasting and may be attributed to the relatively long intrinsic period of this hurricane vortex (several hours versus tens of minutes). 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 one day into the forecast. The 3DVAR method is relatively inexpensive computationally and can easily be run in real time. Because we used only data available in real time, it appears that a significant improvement of short-range intensity forecasts is possible with radar data assimilation.

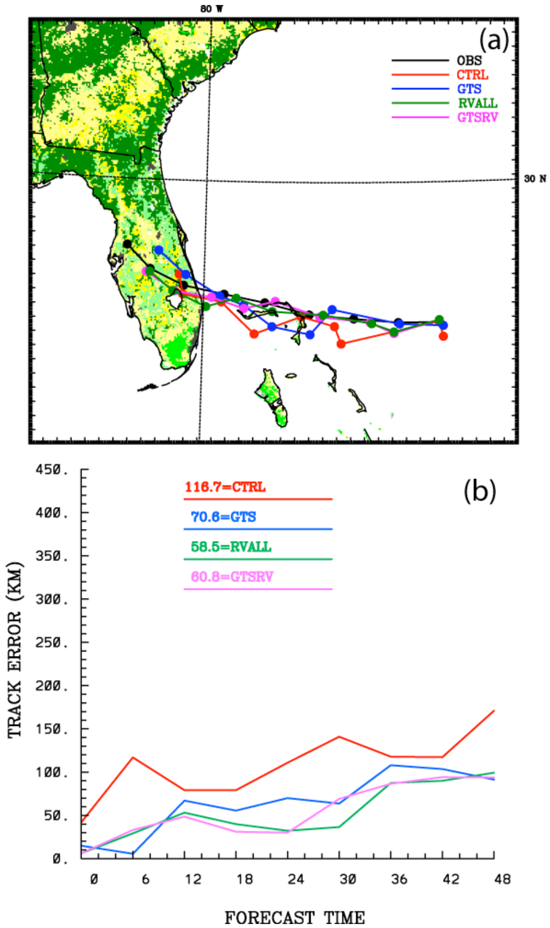

Figure 5: The predicted 48-h (a) tracks and (b) track errors of Hurricane Jeanne (2004) from 1800 UTC 24 to 1800 UTC 26 September 2004

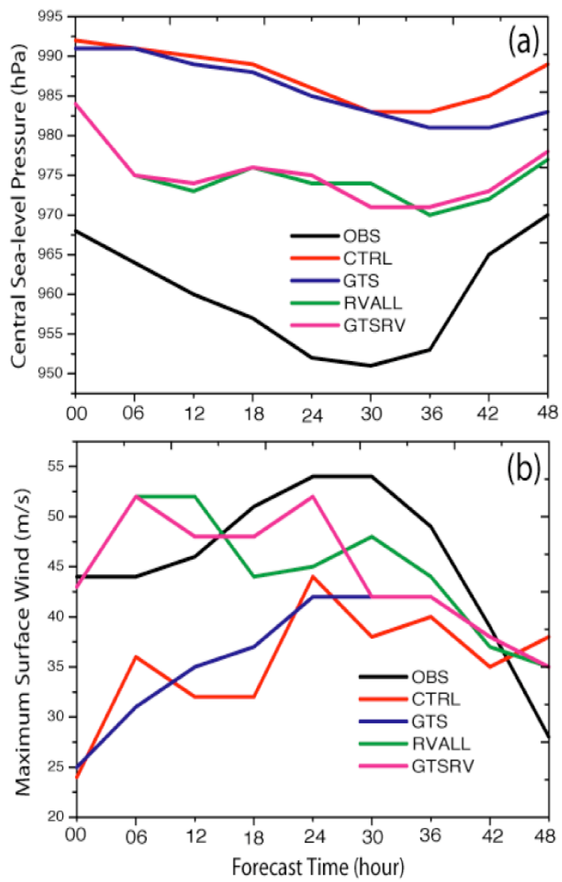

Figure 6: The predicted CSLP (hPa) and MSW (m/s) of Hurricane Jeanne (2004) from 1800 UTC 24 to 1800 UTC 26 September 2004

c. Hurricanes Katrina and Rita (2005)

Since the improvement of 48-h intensity forecast obviously presents in hurricane Jeanne (2004), we extend our evaluation of ADR data assimilation to Hurricanes Katrina and Rita (2005). There are two times of flight for Hurricane Katrina, around 1800 UTC on 25 as well as 27 August 2005, respectively. Statistically, we found that the positive impacts of ADR data assimilation by WRF 3D-Var are shown in all 48-h forecast of the hurricane intensity for each case (Fig. 7). The forecast errors of CTRL in almost all pair of experiments are larger than those with radar data assimilation. The improvement is presented at every forecast time, with only two exceptions for KA2 at 42 and 48 h. Calculation of the mean errors of CSLP for these 3 sets of experiments shows CTRL has 30.74, but with radar data assimilation drops to 24.54 hPa. Assimilating radar data statistically reduces CSLP forecast error of more than 6 hPa. Figure 8 shows the difference of forecast error between CTRL and with radar data assimilation for each case. It clearly demonstrates positive impacts on forecast of intensity within 48 hours in every case. Again there is only two exceptions for KA2 at 42 and 48 h.

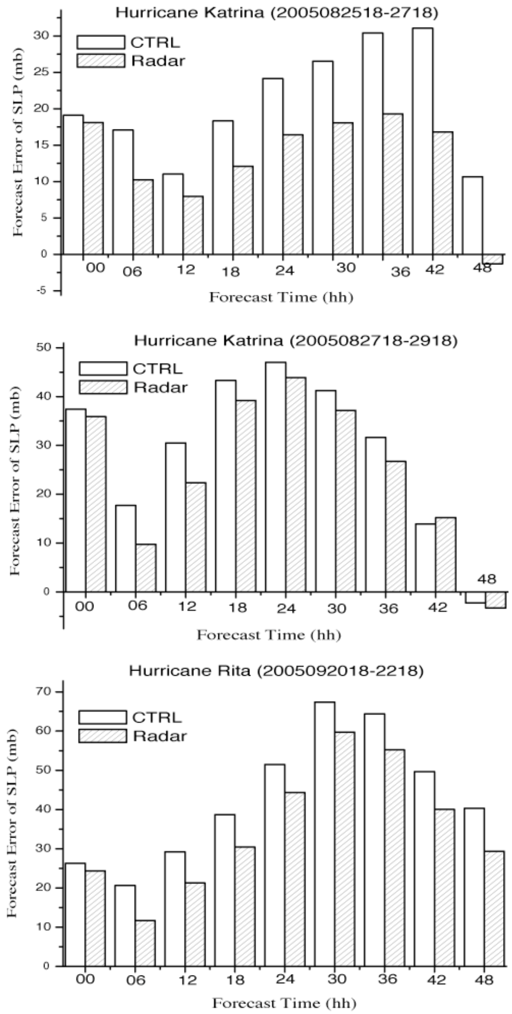

Figure 7: Forecasted hurricane intensity errors for each case (The white bar represents CTRL, and the gray bar is the one with assimilating ADR data)

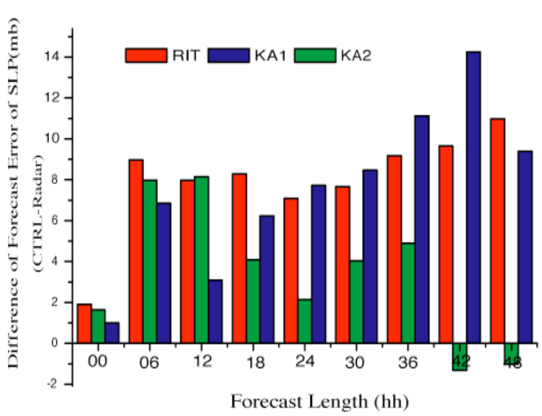

Figure 8: The difference of predicted intensity errors between CTRL and with radar data assimilation

6. 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 Jeanne (2004), Katrina and Rita (2005). Four groups of experiments for the three hurricanes are carried out. Positive impacts are found with the ADR data assimilation for hurricanes. 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. The vortex warm core structure can also be enhanced with ADR data assimilation.
- With the enhanced hurricane initialization, the subsequent forecasts of hurricane track are improved. Although the track is mostly influenced by thelarge-scale flow feature, a better definition of vortex after assimilating ADR data should contribute further to the improvement of track forecasts.
- The significance of our experimental results is that the forecast of storm intensity, a notoriously difficult parameter to predict, is improved with ADR data assimilation using 3DVAR alone, without use of a synthetic vortex. The improvement of hurricane intensity forecasting lasts for at least one day into the forecast. 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, especially for Hurricanes Katrina and Rita (2005). In addition, we will explore further how the improvement of the initial vortex structure and intensity leads to better forecasts of storm intensity changes for Hurricane Katrina and Rita (2005). These diagnostic results and their explanations will be reported in the future.

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