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# Improving Hurricane Intensity Forecasting through Data Assimilation: Environmental Conditions Versus the Vortex Initialization

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## 1. Introduction

Tropical cyclones (TCs) are one of nature's most intense phenomena and one of all coastal residents' greatest fears. They threaten the maritime industry, devastate coastal regions and cause floods and erosion inland through torrential rainfall, high winds and severe storm surges. Through coastal development and growth, the United States has become more vulnerable to the impact of hurricanes now than at any time in the recent past (Pielke & Pielke, 1997). An extreme example was Hurricane Katrina during the summer of 2005. Owing to the great social and economic impact of hurricanes, it is of great importance that the track and intensity of these hurricanes can be accurately predicted many hours in advance.

Over the last two decades, computer modeling and data assimilation techniques have advanced rapidly. Along with the development of high-resolution numerical modeling and advanced data assimilation capabilities, the skill of numerical weather prediction has improved significantly. As a result of these efforts, TC track forecasts have improved substantially. However, the intensity forecast remains a great challenge in the operational and research communities. According to reports from Rogers et al. (2006) and the National Hurricane Center (NHC, <http://www.nhc.noaa.gov/verification>), the official 48 h TC track forecast error has been reduced by 45% in the past 15 years, while the intensity forecast error has decreased by only 17%. The rapid intensification of TCs has been especially poorly predicted (Tittley & Elsberry, 2000; Houze et al., 2006).

The lack of skill in numerical forecasts of TC intensity can be attributed to three factors (Rogers et al., 2006): 1) inaccurate initial conditions in the storm vortex and environment in numerical models; 2) limitations in numerical models such as imperfect physical parameterizations; and 3) inadequate understanding of the physics of TCs and their development. Among other factors, the uncertainties in hurricane initialization are some of the fundamental reasons for the limited skill in hurricane forecasts.

The processes associated with TC intensifications have been investigated in numerous previous studies (e.g., Malkus, 1958; Willoughby, 1988; Frank & Ritchie, 1999; Montgomery et al., 2006). It has been recognized that the large scale environmental conditions such as vertical wind shear, pre-existing upper level troughs, mesoscale convections, storm-scale

inner core structures, and air-sea interactions, such as the ocean surface fluxes all play important roles (e.g., Davis & Emanuel, 1988; DeMaria & Pickle, 1988; Kuo et al., 1991; Merrill & Velden, 1996; Willoughby & Black, 1996; Bosart et al., 2000; Zhu et al., 2002; Montgomery et al., 2006). Therefore, in order to improve TC forecasting, accurate specifications of each of the large scale, mesoscale, and small-scale atmospheric conditions is very important.

Since TCs form over the oceans, where conventional observations are sparse, significant progress has been made with the use of satellite and airborne in-situ and remote sensing data in TC forecasting. It has been shown that these additional observations have a positive impact on TC forecasts. For instance, the U.S. National Oceanic and Atmospheric Administration (NOAA) synoptic surveillance missions are very useful in improving individual TC track forecasts (e.g., Franklin & DeMaria, 1992; Franklin et al., 1993; Burpee et al., 1996; Aberson, 2002; Aberson et al., 2003; Aberson & Etherton, 2006). Other research programs such as the “Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region” (DOTSTAR) have also demonstrated the positive impact of the targeted observations on the track forecasts of the typhoons over the Western Pacific Ocean (Wu et al., 2007).

Along with the advancements in remote sensing techniques, the amount of usable satellite data has increased rapidly in the last two decades. Many satellite data products have become useful sources for TC analyses and forecasts (e.g., Velden et al., 1992; Leslie et al., 1998; Velden et al., 1998; Pu et al., 2002; Zhu et al., 2002; Pu & Tao, 2004; Hou et al., 2004; Wu et al., 2006; Chen, 2007; Zhang et al., 2007; Pu et al., 2008). However, due to cloud and rain effects, few observations of TC inner core regions are assimilated into the model. Satellite data assimilation has mainly contributed to the improvement in hurricane environmental conditions. Thus, even in a high-resolution model, the initial conditions may not resolve the realistic inner core structure and intensity of TCs. The use of so-called “bogus vortices” is often adopted in research numerical simulations and operational forecasting (Kurihara *et al.*, 1993; Leslie & Holland, 1995; Pu & Braun, 2001; Braun et al., 2006). Due to both the lack of conventional observations and the difficulties in using rain- and cloud-affected satellite observations, the initialization of hurricane inner core structures with realistic dynamic and thermodynamic observations has been a challenging problem in NWP. Fortunately, the amount of available Doppler radar data and recent developments in radar data assimilation have brought hopes of improving TC inner-core thermodynamic and hydrometeor conditions. Several studies (Zhao et al., 2008; Zhao & Jn, 2008; Pu et al., 2009b) have proved that radar data assimilation resulted in a significant impact on TC track and intensity forecasting.

From all the aforementioned studies, improved hurricane environmental conditions and the vortex initialization both play important roles in the accurate forecasting of hurricane rapid intensification and intensity changes. Specifically, through the assimilation of satellite, radar and in-situ aircraft observations, it has been established that the hurricane intensity forecast can be indeed improved by data assimilation. However, a general conclusion regarding how (and to what extent) environmental conditions and initial vortex structure can contribute to significant improvement in hurricane rapid intensification is yet to be established. With the results from author’s recent studies, this topic will be addressed in this current chapter.

## 2. Improving TC environmental conditions

Among all the environmental conditions that have an impact on TC intensity changes, it has been well recognized that the environmental vertical wind shear is an important factor that influences the tropical cyclone structure and development. Rogers et al. (2003) suggested that tropical cyclone convection and precipitation structures are closely related to the magnitude of environmental vertical wind shear. Merriell (1988) and Frank and Ritchie (1999) concluded that weak environmental vertical wind shear is a necessary condition for tropical cyclone deepening.

With a mesoscale community weather research and forecasting (WRF) model (Skamarock et al., 2008) and its three-dimensional variational (3DVAR) data assimilation system (Barker et al., 2004), Figure 1 compares the impact of assimilating various wind data, including these from the National Aeronautics and Space Administration (NASA) QuikSCAT satellite measured ocean surface vectors, NOAA GOES-11 rapid scan atmospheric motion vector, and aircraft dropwindsondes, on the environmental vertical wind shear for Tropical Storm Gert (2005) over the Atlantic Ocean. The significant impact of wind data assimilation on TC environmental conditions has been shown; as a result, the assimilation of aircraft dropsonde data and satellite wind data help the model to reproduce more accurate storm landfall forecasts. About 50% of the track error was reduced. The landfall time and locations are well captured by the forecasts with data assimilation (see Pu et al., 2008 for details).

A further study with Hurricane Cindy (2005) shows that the assimilation of the aforementioned wind data has a great impact on the quantitative precipitation forecast (QPF) during Cindy's evolution (Fig. 2), implying the significant effects of environmental wind shear on the mesoscale convective system associated with Cindy (See Pu et al., 2008 for details).

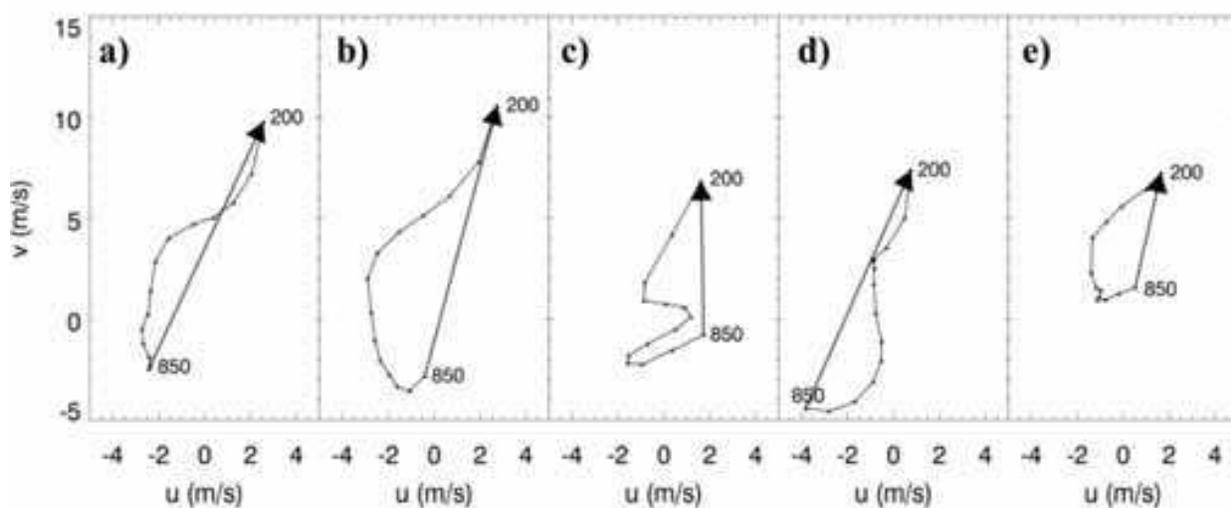


Fig. 1. The hodograph of environmental winds ( $\text{m s}^{-1}$ ) between 850 and 200 hPa in the vicinity of the vortex of tropical storm Gert (2005) at 1200 UTC 24 July 2005. Different panels represent the wind shears obtained from the experiments without the assimilation of wind data (a), and with assimilation of b) NASA QuikSCAT ocean surface vectors, c) NOAA GOES-11 rapid scan atmospheric motion vector, d) Dropwindsondes, and e) all of above wind data mentioned. [Figure from Pu et al. (2008)].

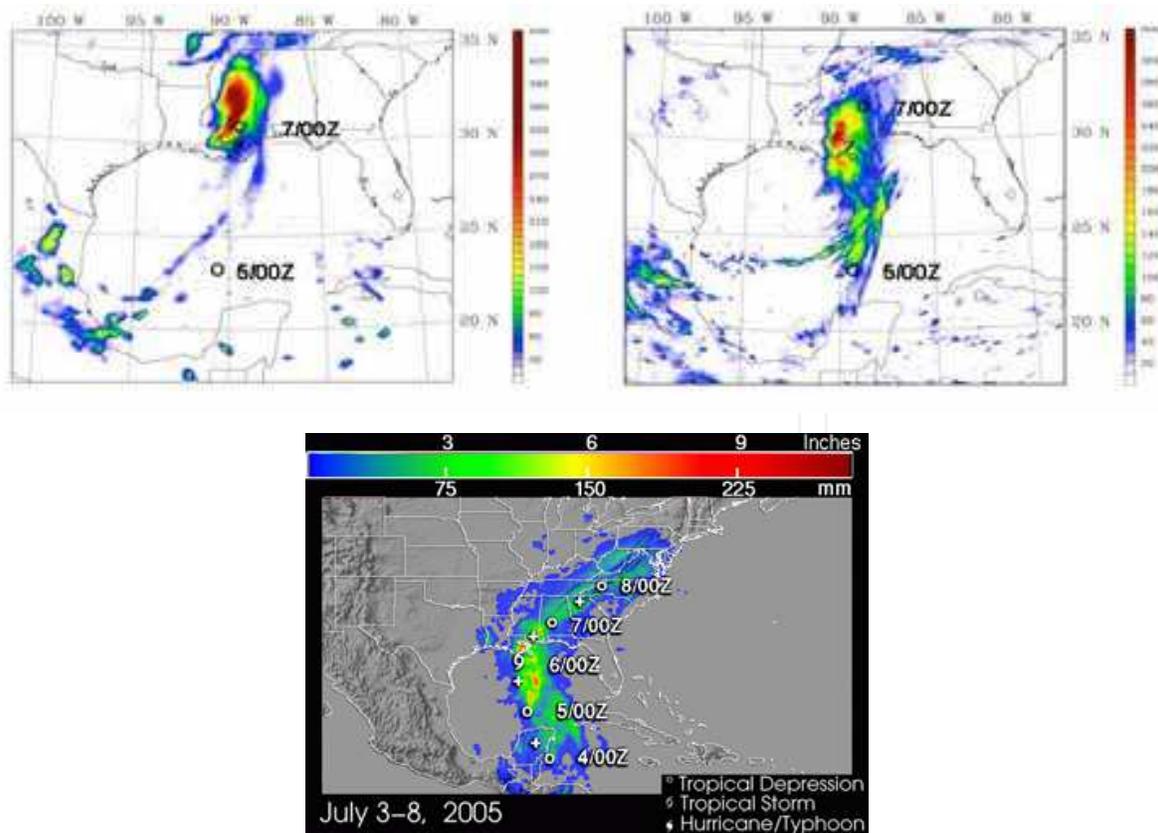


Fig. 2. The weather research and forecasting (WRF) model forecasted rainfall amount over 48 hours from Hurricane Cindy, July 5-7, 2005 (top panels) without (left) and with (right) data assimilation. The bottom panel shows the rainfall accumulation along the track during Cindy's life cycle [courtesy of NASA Tropical Rainfall Measuring Mission (TRMM) project]. Without data assimilation, the forecast shows unrealistically large amounts of rain after Cindy made landfall. It also shows that the forecast missed a large amount of rainfall that occurred before Cindy made landfall. However, the image with data assimilation more accurately portrays the rain that actually fell.

In addition to wind information, accurate atmospheric profile information was generally lacking before the Atmosphere Infrared Sounder (AIRS) was launched into orbit onboard the NASA Aqua satellite in May 2002. In order to evaluate the AIRS data impact on TCs forecast, Pu and Zhang (2010) performed a series of data assimilation experiments with the mesoscale community weather research and forecasting (WRF) model and its data assimilation system. Results show that the assimilation of the AIRS retrieved temperature and moisture profiles has a significant impact on the numerical simulations of TCs, although the overall impacts of the data on numerical simulations of TCs are very sensitive to the data quality. Specifically, it is found that the forecast of the formation of tropical storm Debby (2006, over Atlantic Ocean) is very sensitive to the assimilation of moisture profiles. Compared with the moisture profiles, temperature profiles show a larger impact on Debby's track forecasting, mainly because the wind field responds largely to the analysis increment of the temperature field. When both moisture and temperature profiles are adjusted through bias correction, the data assimilation leads to improved track and intensity forecasts for Debby (Pu & Zhang, 2010). Additional experiment with a Supertyphoon Jangmi (2008) also indicated that the AIRS data has a positive impact on the storm's track forecast of Jangmi.

### 3. Does accurate initial intensity lead to an accurate TC intensity forecast?

The aforementioned data assimilation experiments have indicated that assimilation of atmospheric temperature, wind and moisture profiles could contribute to accurate specification of TC environmental conditions in the numerical model and thus result in improved TC forecasts. In fact, with the assimilation of available satellite and in-situ data, we are often able to capture the initial intensity of TCs through assimilation of the data around the TC environment. However, the accurate initial intensity of the TC vortices does not always lead to perfect intensity forecasts.

In a recent study by Li and Pu (2008), numerical simulations focus on the early rapid intensification period of Hurricane Emily (2005) from 0600 UTC 14 July to 0600 UTC 15 July 2005, when the observed minimum central sea level pressure (MSLP) changed from 991 to 952 hPa. The WRF model initial conditions were generated using a WRF 3DVAR data assimilation system. The GOES-11 rapid scan atmospheric motion vectors, QuikSCAT ocean surface vector winds, and aircraft dropwindsonde data, collected during NASA Tropical Cloud Systems and Processes (TCSP) experiment (Halverson et al., 2007), were assimilated into the WRF model with the available conventional data in a 6 hourly cycling data

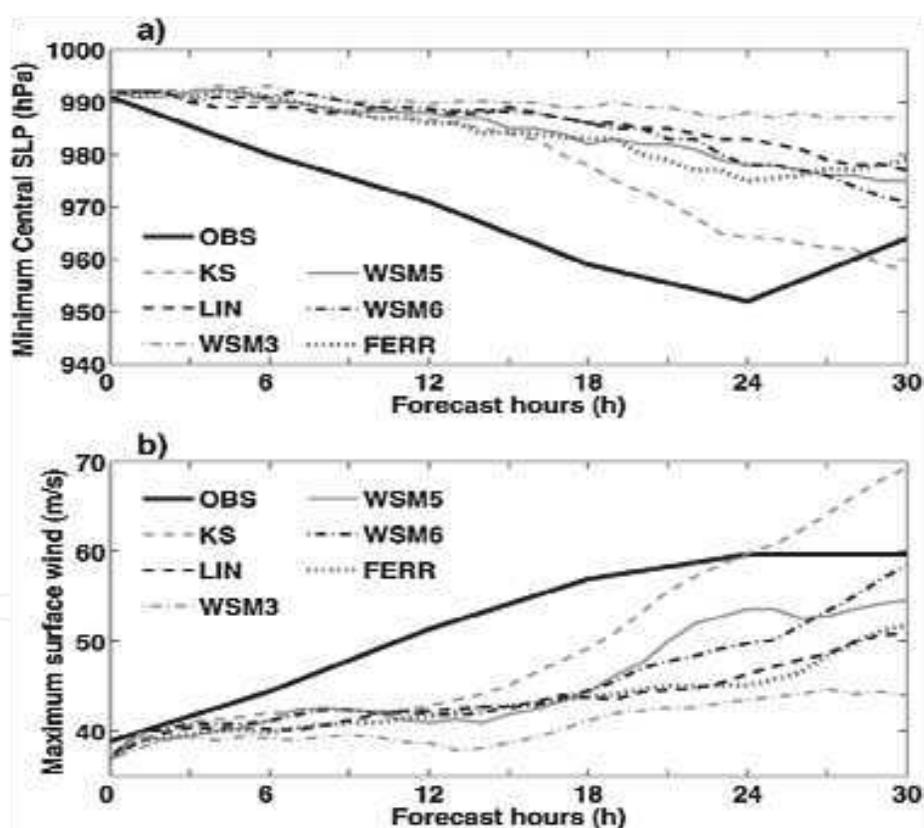


Fig. 3. Time series of a) minimum central sea level pressure (hPa) and b) maximum surface wind speed ( $\text{m s}^{-1}$ ) from the National Hurricane Center best track data (OBS) and the numerical simulations of Hurricane Emily using WRF model during 0600 UTC 14 July to 1200 UTC 15 July 2005 with different microphysical schemes: Kessler warm-rain scheme (KS); Purdue Lin scheme (LIN); WRF single moment (WSM); three-class simple ice scheme (WSM3); WSM five-class mixed phase scheme (WSM5); WSM six-class graupel scheme (WSM6); Eta Ferrier scheme (FERR). [Figure from Li and Pu (2008)].

assimilation within the 12 h assimilation window (1800 UTC 13 to 0600 UTC 14 July 2005). At the end of data assimilation, the intensity (in terms of minimum sea-level pressure and maximum wind) of the initial vortex matches the intensity specified by the National Hurricane Center's best track data. After the data assimilation, a 30-h numerical simulation was conducted at a 3 km grid spacing. Numerical simulation results show significant sensitivity of the forecast of Hurricane Emily to varying cloud microphysical schemes in WRF model. However, even with different combinations of the various physical schemes, none of the experiments were able to capture the real intensification of Hurricane Emily during the simulation period, although all of the simulations start from the same initial conditions with the same storm intensity that matches the best track intensity of the storm in terms of both minimum central sea-level pressure and maximum surface wind.

A diagnostic study (Pu et al., 2009a) is then conducted to examine the accompanying initial and forecast errors. The initial conditions and the simulated hurricane vortices are compared with flight level data acquired from the United States Air Force C-130J aircraft. Unrealistic thermal and convective structures of the storm eyewall are found in the initial conditions (Fig. 4). In addition, the simulated (forecast) eyewall does not contract rapidly enough during the model simulation. Although the possible factors that cause the failure in the intensity forecast are complicated, and the diagnostic study from Pu et al. (2009a) can only explain some of the reasons linked with this failure, overall *results from the study suggest that a more accurate representation of the hurricane vortex, especially the inner core structures in the initial conditions, is necessary for a more accurate forecast of hurricane rapid intensification* (See Pu et al., 2009a for details).

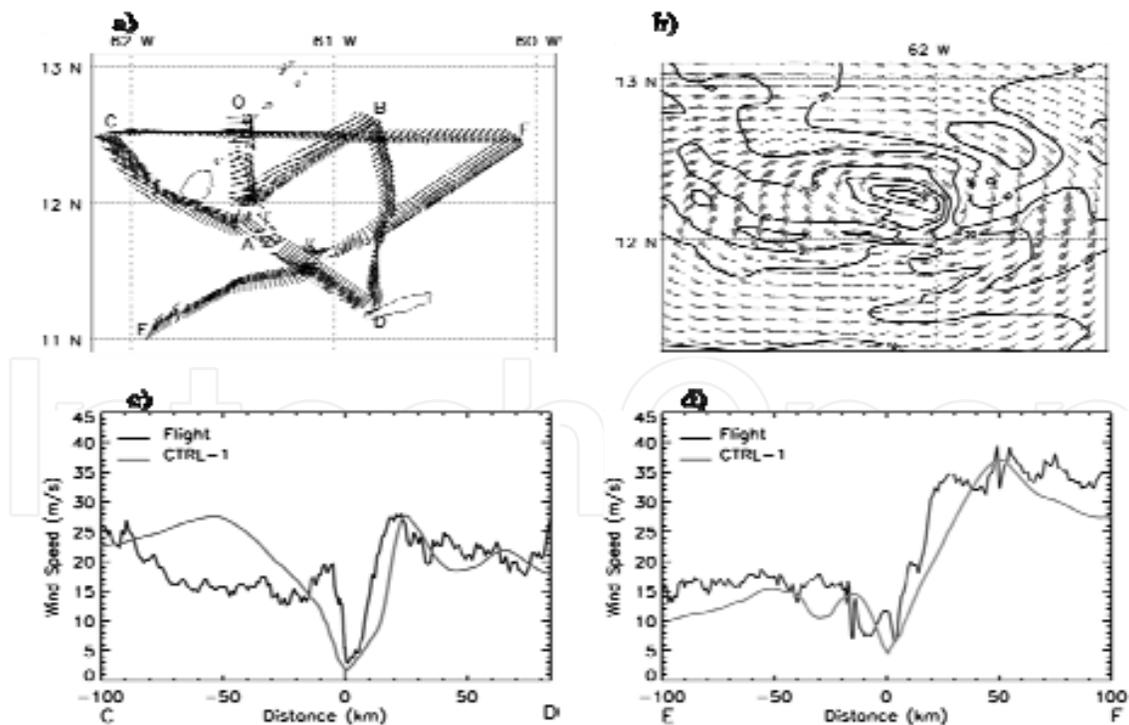


Fig. 4. Comparison of the wind structure of Hurricane Emily from a) US Air Force flight level data; b) the model initial condition at 0600 UTC 14 July 2005 at 1-km resolution (Exp. CTRL-1); and wind speed comparison from the model initial condition and the US air force flight level data at legs CD (c) and EF (d). [Figure from Pu et al. 2009a]

### 3. Impact of assimilation of the airborne Doppler radar on TC forecast

As mentioned above and in previous studies, accurate forecasts of TC structure and intensity changes are closely related to the storm inner-core thermal and dynamic structures and their evolution (Jordan 1961; Franklin et al., 1988; Kossin & Eastin, 2001; Houze et al., 2006; Rogers et al., 2006). Unfortunately, most available satellite data over the TC inner-core region are contaminated by heavy precipitation. This produces uncertainties in representing TC structures in model initial conditions. Recent operations of Doppler radar have brought opportunities to sample the thermodynamics, microphysics and dynamic characteristics of TCs (Marks 2003). With data at high spatial and temporal resolution, airborne Doppler radar can reveal detailed structural features of the TCs, and studies have demonstrated that these radar data are useful in studying hurricanes (Xiao et al., 2007; Zhao et al., 2008; Zhao & Jn 2008, Pu et al., 2009b).

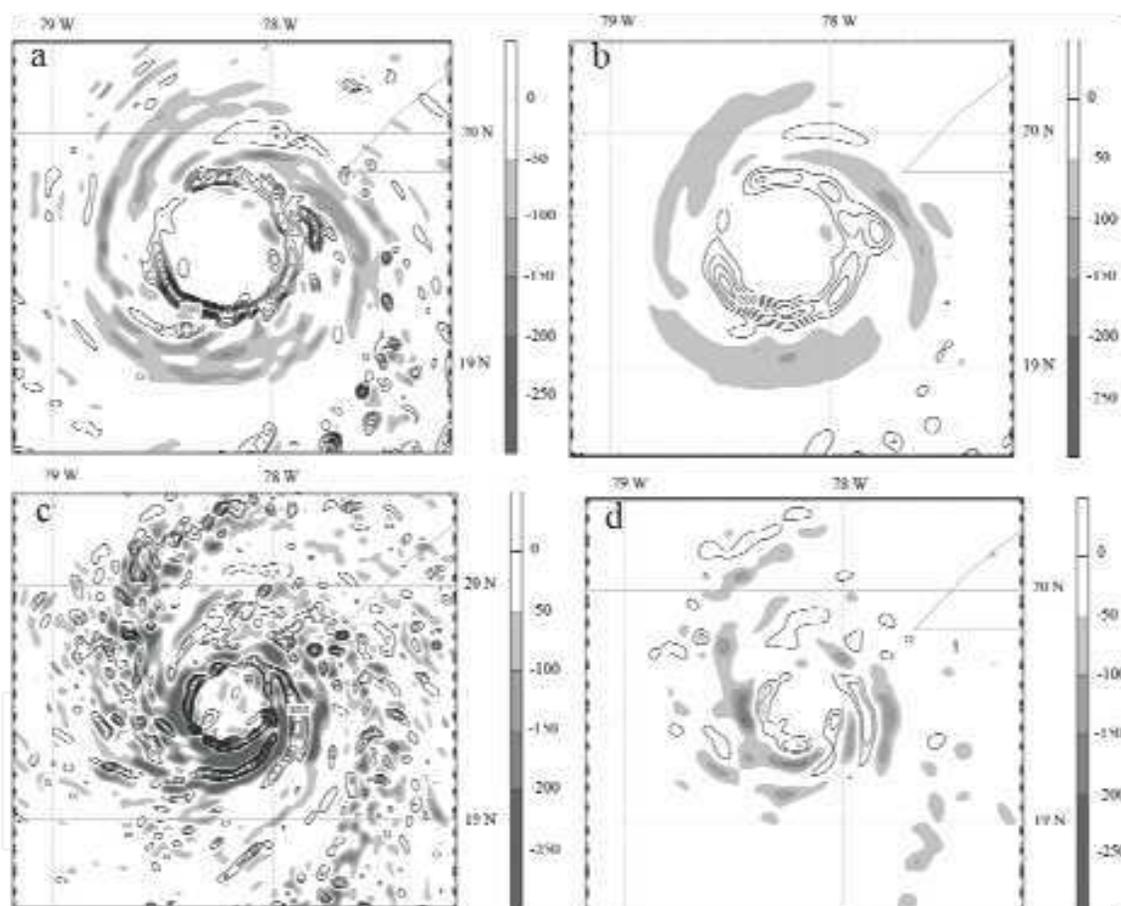


Fig. 5. Divergence fields at 250hPa (top) and 850hPa (bottom) pressure levels. The control experiment (left; without assimilation of radar data), compared with a experiment that assimilates the radar radial velocity data (right) at 0600UTC 8 July 2005. The line contours denote positive values of the divergence, while the shaded contours represent negative values. The contour interval is  $50 \times 10^{-5} \text{ s}^{-1}$ . (from Pu et al. 2009b).

With very high resolution (about 1-2 km in the horizontal and 0.5 km in the vertical direction), airborne Doppler radars mostly represent the wind, moisture, and hydrometeor structure within the hurricane eyewall. In a recent study (Pu et al., 2009b), the usefulness of

airborne Doppler radar reflectivity and radial velocity in better representing the hurricane inner core structure and improving hurricane intensity forecasts has been investigated. A series of numerical experiments is conducted for Hurricane Dennis (2005) to study its intensity changes near landfall. Both radar reflectivity and radial velocity derived wind fields are assimilated into the WRF model with its 3DVAR system. Numerical results indicate that the radar data assimilation has greatly improved the simulated structure and intensity changes of Hurricane Dennis. The hurricane landfall, intensification and weakening events during the simulation period are well captured by assimilating both radar reflectivity and radial velocity data. As shown in Figure 5, the assimilation of radar radial velocity data improved the divergence/ convergence structure over Hurricane Dennis inner-core area. Figure 6 and 7 illustrates the impact of assimilation of airborne Doppler radar data on the numerical simulation of the track intensity changes of Dennis during the simulation period; significant improvement in Dennis's track and intensity forecast is clearly evidenced.

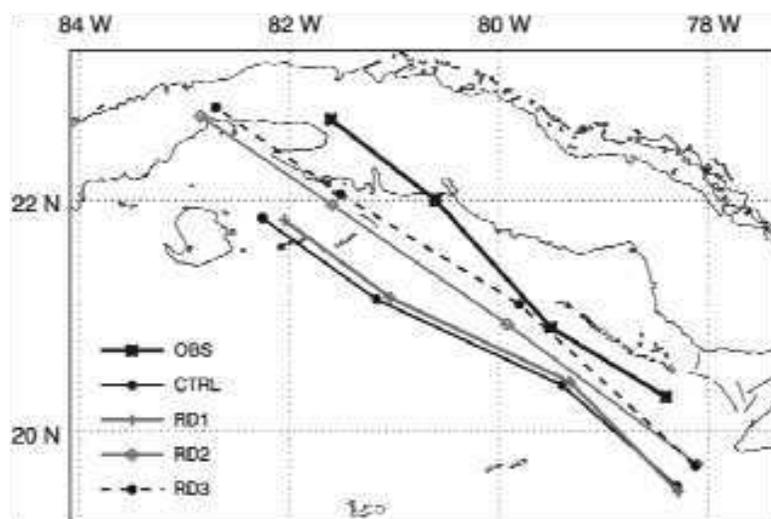


Fig. 6. Storm tracks of Hurricane Dennis (in 6-h interval) between 0600 UTC 8 and 0000 UTC 9 July 2005. National Hurricane Center best track data (OBS) compared with the experimental forecast with assimilation of radar reflectivity (RD1), radial velocity (RD2) and both radar reflectivity and radial velocity (RD3). (from Pu et al., 2009b)

#### 4. Summary and concluding remarks

Forecasting hurricane rapid intensification is a challenging problem for operational weather prediction. Our limited forecasting ability can be mainly attributed to inaccurate initial conditions. Recent studies demonstrated that improved hurricane environmental conditions and the vortex initialization both play important roles in the accurate forecasting of hurricane rapid intensification and intensity changes. Specifically, through the assimilation of satellite, radar and in-situ aircraft observations, it has been established that the hurricane intensity forecast can indeed be improved by data assimilation. However, a general conclusion regarding to how and to what extent the environmental conditions and initial vortex structure can contribute to the significant improvement of hurricane rapid intensification has not yet been established. With the results from recent studies, this book

chapter discussed the impact of accurate environmental conditions and improved vortex initialization on hurricane rapid intensification forecasts. It is obvious that both factors are very important for improving hurricane intensity forecasting. In order to improve the current limited skill of hurricane intensity forecasting, an integrated data assimilation effort with the assimilation of observations in TC environment and the inner-core region is necessary.

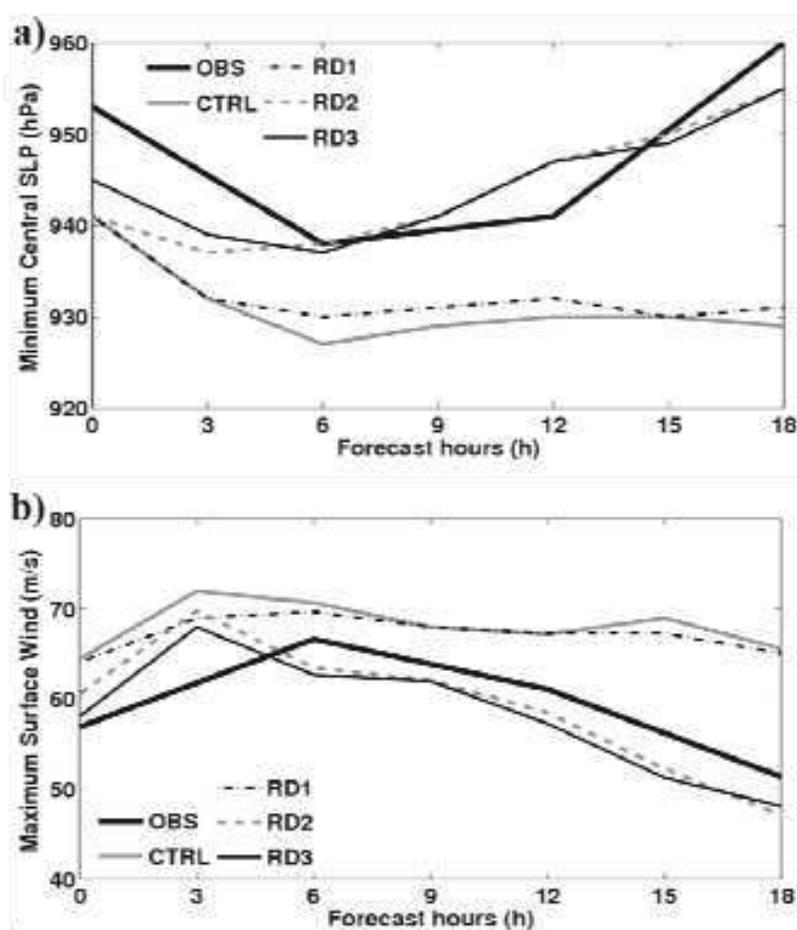


Fig. 7. Time series of observed and simulation minimum Sea Level Pressure (left) and storm track (right) between 0600 UTC 8 and 0000 UTC 9 July 2005. National Hurricane Center best track data (OBS) compared with the experimental forecast with assimilation of radar reflectivity (RD1), radial velocity (RD2) and both radar reflectivity and radial velocity (RD3). (from Pu et al., 2009b)

In addition, since uncertainties in the model initial conditions are only one of the many factors that could influence the accuracy of TC intensity forecasting, studies should also be conducted to improve computer models and our understanding of the processes that control hurricane intensity change.

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This book represents recent research on tropical cyclones and their impact, and a wide range of topics are covered. An updated global climatology is presented, including the global occurrence of tropical cyclones and the terrestrial factors that may contribute to the variability and long-term trends in their occurrence. Research also examines long term trends in tropical cyclone occurrences and intensity as related to solar activity, while other research discusses the impact climate change may have on these storms. The dynamics and structure of tropical cyclones are studied, with traditional diagnostics employed to examine these as well as more modern approaches in examining their thermodynamics. The book aptly demonstrates how new research into short-range forecasting of tropical cyclone tracks and intensities using satellite information has led to significant improvements. In looking at societal and ecological risks, and damage assessment, authors investigate the use of technology for anticipating, and later evaluating, the amount of damage that is done to human society, watersheds, and forests by land-falling storms. The economic and ecological vulnerability of coastal regions are also studied and are supported by case studies which examine the potential hazards related to the evacuation of populated areas, including medical facilities. These studies provide decision makers with a potential basis for developing improved evacuation techniques.

### **How to reference**

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