Diagnosis of the Initial and Forecast Errors in the Numerical Simulation of the Rapid Intensification of Hurricane Emily (2005)

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ABSTRACT

A diagnostic study is conducted to examine the initial and forecast errors in a short-range numerical simulation of Hurricane Emily's (2005) early rapid intensification. The initial conditions and the simulated hurricane vortices using high-resolution grids (1 and 3 km), generated from the Advanced Research version of the Weather Research and Forecasting (ARW) model and its three-dimensional variational data assimilation (3DVAR) systems, are compared with the flight-level data acquired from the U.S. Air Force C-130J aircraft data.

Numerical simulation results show that the model fails at predicting the actual rapid intensification of the hurricane, although the initial intensity of the vortex matches the observed intensity. Comparing the model results with aircraft flight-level data, unrealistic thermal and convective structures of the storm eyewall are found in the initial conditions. In addition, the simulated eyewall does not contract rapidly enough during the model simulation. Increasing the model's horizontal resolution from 3 to 1 km can help the model to produce a deeper storm and also a more realistic eye structure. However, even at 1 km the model is still not able to fully resolve the inner-core structures.

To provide additional insight, a set of mesoscale reanalyses is generated through the assimilation of available satellite and aircraft dropsonde data into the ARW model throughout the whole simulation period at a 6-h interval. It is found that the short-range numerical simulation of the hurricane has been greatly improved by the mesoscale reanalysis; the data assimilation helps the model to reproduce stronger wind, thermal, and convective structures of the storm, and a more realistic eyewall contraction and eye structure.

Results from this 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.

1. Introduction

Over the past two decades, tropical cyclone (TC) track forecasts have been improved greatly. However, intensity forecasts have only improved slightly (Willoughby 2007; Houze et al. 2006). According to Rogers et al. (2007), the lack of skill in numerical forecasts of TC intensity can be attributed to three factors: 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 all the factors that influence the accuracy of TC forecasts, many studies suggested that the deficiencies in model initial conditions are a major factor that leads to inaccurate forecasts of TC intensity. Mesoscale structures of TCs and environmental conditions are often erroneously represented in numerical models due to a lack of conventional data over the ocean (Kurihara et al. 1993; Shi et al. 1996). It has been proven that the accurate specification of the hurricane initial vortex is very important to hurricane track and intensity forecasts (e.g., Kurihara et al. 1993, Pu and Braun 2001). The assimilation of available satellite and in situ data has also been helpful for the numerical simulations of hurricanes. Krishnamurti et al. (1998) assimilated satellite outgoing longwave radiation data and Special Sensor Microwave Imager (SSM/I) rainfall data into the initial conditions of Hurricane Opal (1995). They showed that these data improved the intensity forecast by changing the structure of the specific humidity, surface

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moisture flux, and diabatic heating around the storm core. Leidner et al. (2003) found that the initial wind field around the center of Hurricane Lili (1996) was improved with the assimilation of National Aeronautics and Space Administration (NASA) Scatterometer (NSCAT) ocean surface wind vectors. The improved wind field caused stronger updrafts, enhanced the warm-core structure, produced more moisture at low levels in the storm vortex, and generated a better intensity forecast. Kamineni et al. (2006) showed that assimilating the dropsonde data and the moisture profiles from the airborne lidar Atmospheric Sensing Experiment system resulted in increased specific humidity and enhanced evaporation and precipitation. These changes caused a stronger convergence of mass and moisture fluxes and contributed to the improved intensity forecast of Hurricane Erin (2001). A recent study by Pu et al. (2008) shows the positive impacts of assimilation of aircraft dropsonde and satellite wind data on the numerical simulation of two tropical storms near landfall.

Other studies showed that the errors in TC intensity forecasts come from imperfect numerical model systems. It has been recognized that the different cumulus, planetary boundary layer (PBL), and microphysical parameterization schemes in the numerical models can significantly influence the intensity forecasts of TCs (Karyampudi et al. 1998; Braun and Tao 2000; Zhu and Zhang 2006; McFarquhar et al. 2006). For instance, Zhu and Zhang (2006) showed a pronounced sensitivity of the simulated intensity and inner-core structure of Hurricane Bonnie (1998) to various cloud microphysical processes in the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5). Braun and Tao (2000) showed that different PBL schemes in the MM5 caused a difference of 16 hPa in the minimum central sea level pressure (CSLP) and 15 m s^{-1} in maximum surface wind (MSW) forecasts of Hurricane Bob (1991). Davis and Bosart (2002) investigated the dynamics that govern the intensification and track of Tropical Cyclone Diana (1984) by varying the model cumulus parameterization, boundary layer treatment, sea surface temperature (SST), and horizontal grid spacing. They confirmed the importance of the model physical schemes to the intensity forecast.

In addition to the model physical processes, Houze et al. (2006) suggested that the intensity variations of TCs are closely associated with their internal structures. They demonstrated that the intensity change of Hurricane Rita (2005) was well predicted because of the successful forecast of the storm's eyewall structure and its variation.

Studies have also demonstrated that the use of a fine horizontal resolution in the numerical simulations can help with TC intensity forecasting (Bosart et al. 2000; Houze et al. 2006; Willoughby 2007). Davis and Bosart (2002) compared numerical simulations of TC Diana (1984) with the MM5 at horizontal resolutions of 27, 9, and 3 km. They showed that the intensity forecast from the simulation at 3-km resolution is closer to the observations than that from the other simulations, partly because the simulation generated more realistic structures of the updrafts and the convective downdrafts. Another study by Chen et al. (2007) indicated that only the numerical simulation with a horizontal resolution of 1.67 km is able to produce a reasonable inner-core structure for Hurricane Floyd (1999), while the simulations at the 5- and 15-km grids are unable to do so. Davis et al. (2006) compared the simulated landfalling Atlantic tropical cyclones in 2004 and 2005 using the Weather Research and Forecasting (WRF) model at 12-, 4-, and 1.33-km resolutions. They showed that the intensity forecasts of tropical cyclones have been greatly improved by increasing the horizontal resolution from 12 to 4 km. At 12-km resolution, the model-simulated vortex is too large and the rainband structures are unrealistic. However, the increase in model resolution to 4 km has significantly improved the rainband structures. Further increasing the model resolution from 4 to 1.33 km caused the simulation to capture the rapid intensification of Hurricane Katrina (2005) quite well.

Overall, previous studies have shown that accurate initial conditions, improved model physics parameterizations, and high resolution are the main factors that influence the accuracy of hurricane intensity forecasts. Therefore, given an advanced numerical model at high resolution, the accurate forecast of hurricane intensity will rely strongly on the accuracy of the model initial conditions. However, in most of the real cases, due to the sparse and generally coarse data available over the hurricane vortex regions, the initial conditions for hurricane forecasting are commonly conducted at a coarse resolution without specifying the detailed dynamic and thermodynamic structures of the hurricane vortices. In this situation, even given the accurate initial intensity of the storm and the advanced parameterization schemes of the numerical model, the model could still fail to predict the accurate rate of intensification of the hurricane. Previous studies by Li and Pu (2008, 2009) presented a case of this type. The sensitivity of the numerical simulations of the rapid intensification of Hurricane Emily (2005) to various cloud microphysical schemes, PBL processes, and cumulus schemes has been investigated. Results indicated that the contributions from these physical processes can only partially explain the rapid intensification of Hurricane Emily. Of all the experiments with various physical schemes, none were

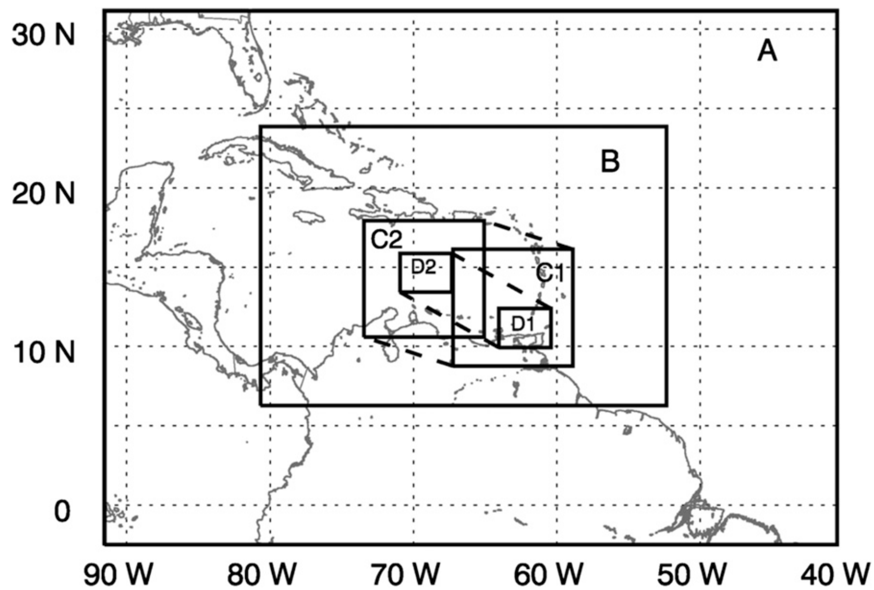


FIG. 1. The locations of the model domains for numerical simulations of Hurricane Emily (2005). Domain A is the 27-km grid, and domains B and C are the nested 9- and 3-km grids, respectively. Domain C moved from C1 to C2 at 15 h. Domain D is the 1-km grid. It was moved 4 times (from D1 to D2) to keep the storm near the center of the domain.

able to capture the observed rapid intensification of Hurricane Emily during the simulation period. In this study, we attempt to further understand the possible factors that may result in the failure of the simulated hurricane's rapid intensification. Specifically, we will compare the numerical simulation results with available U.S. Air Force aircraft flight-level data to diagnose the errors in both the initial conditions and model forecasts.

The paper is organized as follows. Section 2 describes the numerical simulation results of Hurricane Emily, the observational data, and the mesoscale reanalysis results. Section 3 analyzes the problems in the model initial conditions. Section 4 discusses the problems in the model simulations and also examines the impacts of the horizontal resolution on the numerical simulation results. A summary and conclusions are presented in section 5.

2. Simulation and mesoscale reanalysis results

a. Results from previous numerical simulation of Hurricane Emily

Hurricane Emily (2005) formed on 10 July and dissipated on 21 July 2005. It crossed the Yucatan Peninsula and made landfall in northeastern Mexico. With MSWs of 72 m s^{-1} and a minimum CSLP of 929 hPa, Emily is the strongest and the longest-lived hurricane ever in the month of July in the Atlantic basin (Franklin and Brown 2006).

In a previous study by Li and Pu (2008), numerical simulations were conducted during the early rapid intensification period of Hurricane Emily from 0600 UTC 14 July to 0600 UTC 15 July 2005 when the observed minimum CSLP changed from 991 to 952 hPa. During this 24-h period, Emily intensified rapidly from a tropical storm to a category-4 hurricane on the Saffir–Simpson hurricane scale with an extreme deepening rate of about 2 hPa h^{-1}. With the Advanced Research version of the WRF (ARW) model (Skamarock et al. 2005) in grids nested at a high resolution of 3 km (Fig. 1), the sensitivity of the numerical simulations of Emily to various cloud microphysical and PBL schemes in the WRF model has been investigated. Results indicated that the numerical simulations of the early rapid intensification of Hurricane Emily are very sensitive to the choice of cloud microphysics and PBL schemes in the ARW model. Specifically, with different cloud microphysical schemes, the simulated minimum CSLP varies by up to 29 hPa. The use of various PBL schemes has resulted in differences in the simulated minimum CSLP of up to 19 hPa during the 30-h forecast period (Fig. 2). However, *of all the experiments with the various physical schemes, none of the experiments was 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 observed intensity of the storm in terms of both minimum CSLP and MSW*.

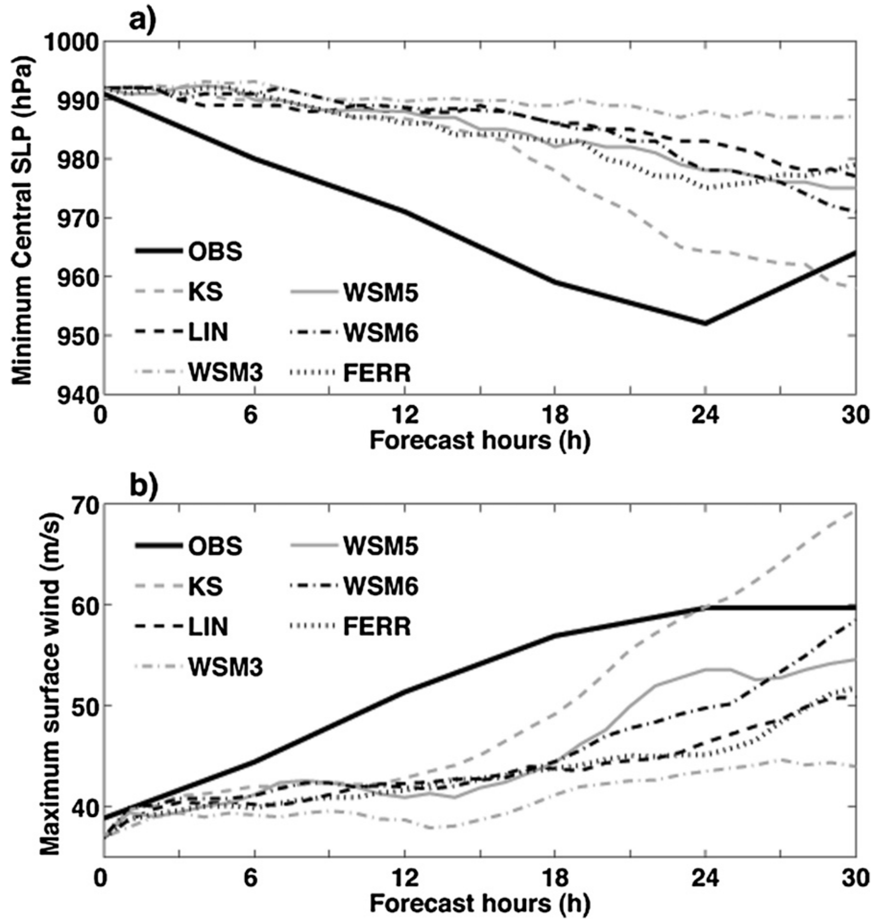


FIG. 2. Time series of the (a) minimum CSLP (hPa) and (b) maximum surface wind speed (m s^{-1}) from the NHC best-track data (OBS) and the numerical simulations of Hurricane Emily during 0600 UTC 14 Jul–1200 UTC 15 Jul 2005 with different microphysical schemes: the Kessler warm-rain scheme (KS), the Purdue Lin scheme (LIN), WSM three-class simple ice scheme (WSM3), the WSM five-class mixed-phase scheme (WSM5), the WSM six-class graupel scheme (WAM6); and the Eta Ferrier scheme (FERR) (see Li and Pu 2008).

Before performing the numerical experiments presented in Li and Pu (2008), a series of numerical experiments was conducted to examine the sensitivity of the numerical simulation of Hurricane Emily's (2005) early rapid intensification to the cumulus parameterizations in the ARW model at different horizontal resolutions (9- and 3-km grids). Results indicate that the numerical simulations are very sensitive to the choices of cumulus schemes at 9-km grid spacings. However, at 3-km resolution, the cumulus schemes do not result in any difference in the storm intensity and track forecasts (Li and Pu 2009). While the results from Li and Pu (2008, 2009) clarified the factors that influence hurricane intensity forecasts, the main reason that all of the simulation experiments did not capture the observed intensification rate of Hurricane Emily is still not sufficiently clear. An additional numerical simulation at 1-km grid resolution has also been conducted in Li and Pu (2008). The results indicate that the higher resolution is somewhat helpful but still does not reproduce the observed intensity of the hurricane. As a follow-up of the previous studies, in this paper we will conduct a diagnostic study to further investigate why the numerical simulations fail to reproduce the observed intensification rate of Hurricane Emily. Specifically, our emphasis will be on the evaluation of the realism of the hurricane vortex structures in the initial conditions and forecasts.

b. Description of the model and observational data

Among all numerical simulations in Li and Pu (2008), a simulation with the WRF single-moment six-class (WSM6) microphysical scheme produced a better forecast of storm intensity *with a* more *realistic* storm structure. In this study, the WSM6 numerical simulation

TABLE 1. The dimensions, grid spacings, and time steps for the model domains.

Domain	Dimensions ($x \times y \times z$)	Grid spacing (km)	Time step (s)
A	$190 \times 140 \times 31$	27	120
B	$340 \times 220 \times 31$	9	40
C	$300 \times 270 \times 31$	3	13
D	$390 \times 270 \times 31$	1	4

at 3-km resolution is adopted as a control run (CTRL-3) to examine the problems causing the forecast failure. The simulation at 1 km (CTRL-1) is also included in the diagnostic study for comparison.

Following Li and Pu (2008), a two-way interactive and nested domain technique is employed in all numerical simulations. As shown in Fig. 1 and Table 1, the outer domains, A and B, are at horizontal resolutions of 27 and 9 km. The inner domains C (3-km grid spacing) and D (1-km grid spacing) are moved to keep the storm near the center of the domain (from C1 to C2 and D1 to D2, as shown in Fig. 2). In addition to the WSM6 microphysical scheme, model physics options include the following: Rapid Radiative Transfer Model (RRTM) longwave radiation, Dudhia shortwave radiation, Grell–Devenyi ensemble cumulus, and Yonsei University (YSU) PBL. The cumulus scheme is only used for outer domains A and B.

As mentioned in Li and Pu (2008), the model initial conditions in both experiments CTRL-3 and CTRL-1 are obtained by assimilating the *Geostationary Operational Environmental Satellite-11* (*GOES-11*) rapid-scan atmospheric motion vectors (AMVs), NASA Quick Scatterometer (QuikSCAT) ocean surface vector wind, and available National Oceanic and Atmospheric Administration (NOAA) G-IV/P-3 aircraft dropsonde data every 6 h within a 12-h assimilation window (1800 UTC 13 July–0600 UTC 14 July 2005) at outer domains A and B using the ARW three-dimensional variational data assimilation (3DVAR) system (Barker et al. 2004). The initial conditions from domains C and D are interpolated from their mother domains, B and C, respectively.

To evaluate the degree of realism in the hurricane vortex structure in the initial conditions and forecasts, the numerical simulations will be compared with the available observations. As these available satellite and dropsonde data from the NOAA P-3 and G-IV have already been assimilated into the ARW model to help establish the initial conditions [see details in Li and Pu (2008)], it is more reasonable to find other datasets with which to evaluate the realism of the initial conditions from the data assimilation. For this purpose, we use twice-daily, high-resolution (10-s interval) observations of temperature,

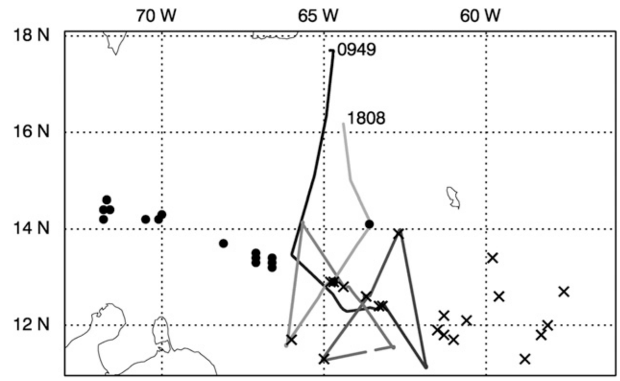


FIG. 3. The USAF C-130J flight track from 2140 UTC 14 Jul to 0804 UTC 15 Jul 2005, with the locations of dropsondes (plus signs: 14 Jul; solid circles: 15 Jul 2005).

dewpoint temperature, horizontal wind speed and direction, and vertical velocity from the U.S. Air Force (USAF) C-130J aircraft. These observations sampled the vortex structure of Hurricane Emily, and were not used during the previous study in Li and Pu (2008). But, for this reason, the data provide us a very good opportunity to evaluate the possible defects in the model initial conditions. Figure 3 shows a sample of the USAF flight track for Emily during 2140 UTC 14 July–0804 UTC 15 July 2005 with the locations of dropsondes indicated.

c. Mesoscale reanalysis during the simulation period

Since none of the previous simulations captured the observed intensification rate (Fig. 2) of Hurricane Emily, we were curious whether mesoscale analysis could capture the observed intensification. Taking advantage of the available satellite and in situ data, a set of mesoscale reanalyses (experiment DA-3) is generated through the assimilation of available satellite and aircraft dropsonde data into the ARW model throughout the whole simulation period. Specifically, this set of reanalyses is built with a setup similar to that in experiment CTRL-3 except that available *GOES-11* AMVs, QuikSCAT ocean surface vectors, and dropsonde data were assimilated into the model's 27- and 9-km domains every 6 h during the whole simulation period (0600 UTC 14 July–0600 UTC 15 July 2005). The analysis results were then interpolated to the nested 3-km grid spacing and the forecasts at 3-km resolution were executed intermediately between every two analyses. The experiment DA-1 is conducted using the same method as in DA-3 but forecasts are conducted at a higher horizontal resolution of 1 km. Table 2 lists the numerical experiments, their horizontal resolutions and the corresponding data assimilation periods. Table 3 shows the total

TABLE 2. List of the numerical experiments and the data assimilation period in the experiments.

Expt	Horizontal resolution (km)	Data assimilation period
CTRL-1	1	1800 UTC 13 Jul–0600 UTC 14 Jul 2005
CTRL-3	3	1800 UTC 13 Jul–0600 UTC 14 Jul 2005
DA-1	1	1800 UTC 13 Jul–0600 UTC 15 Jul 2005
DA-3	3	1800 UTC 13 Jul–0600 UTC 15 Jul 2005

number of each type of data assimilated in each analysis cycle during 0600 UTC 14 July–1200 UTC 15 July 2005.

Figure 4 compares the time series of the storm intensity from the National Hurricane Center (NHC) best-track data, the numerical results from DA-1 and DA-3, and the model forecast from CTRL-1 and CTRL-3 at 1- and 3-km resolutions. Clearly, *significant improvements in the simulated storm intensity are obtained in both reanalysis results from DA-1 and DA-3*. During Emily's rapid intensification period in the first 24 h (0600 UTC 14 July–0600 UTC 15 July), the observed storm intensifies from category 1 to category 4 with a 39-hPa drop in minimum CSLP (or 21 m s^{-1} increase in MSW). Within the same period, the simulated storm intensity deepened only by 13 hPa in minimum CSLP (or 12 m s^{-1} in MSW) in CTRL-3, while in the reanalysis from DA-3, the storm intensified by 29 hPa in minimum CSLP (20 m s^{-1} in MSW). Therefore, at 0600 UTC 15 July 2005, the storm intensity (in terms of the minimum CSLP) in CTRL-3 is 26 hPa (11 m s^{-1}) weaker than the observed one, while the simulated storm in DA-3 is only 10 hPa (2 m s^{-1}) weaker than the observation at the same time. The increase in the model horizontal resolution has resulted in greater intensities and faster intensification rates. In most of the cases, the simulated storm at 1-km horizontal resolution from CTRL-1 is about 0–5 hPa (or 0–4 m s^{-1}) stronger than that from CTRL-3. The storm intensity in DA-1 is 0–4 hPa (0–6 m s^{-1}) deeper than that in DA-3. Therefore, at 0600 UTC 15 July 2005, the simulated minimum CSLP from DA-1 is only 7 hPa-shallower than the observed one, while at the same time the minimum CSLP from CTRL-1 is 24 hPa shallower than the observation.

Figure 5 shows the storm track at 6-h intervals from the NHC best-track data, the reanalyses from DA-1 and DA-3, and the model forecasts from CTRL-1 and CTRL-3. Overall, the storm tracks from all of the simulations are very close to each other. Specifically, most of the simulated tracks have a northwest bias in the first 12 h of simulation, and a northeast bias in the last 18 h of simulation. A moderate improvement in the track simulation is produced by data assimilation in the last 12 h of simulation. At the end of the simulations, the track error is 73 km for DA-1, which is 44 km smaller than the track error from CTRL-3, 20 km smaller than that from CTRL-1, and 24 km smaller than that from DA-3.

The above results show that the reanalysis has greatly improved the intensity prediction for Hurricane Emily, but, why did the numerical model fail in the intensification forecast in CTRL-1 and CTRL-3? Particularly, what are the specific reasons that the reanalysis DA-1 and DA-3 improved the intensity prediction? The flight-level data from the USAF WC-130J aircraft provide horizontal structures for temperature, dewpoint, and lower-tropospheric wind around Hurricane Emily's core region. Together with the vertical profiles of temperature and dewpoint observed by dropwindsondes, a good opportunity is provided to explore the above two questions. In the following two sections, the initial conditions and model simulations will be compared with the flight-level and dropsonde data.

3. Diagnosis of errors in initial conditions

We first compared the numerical simulation results at 1 km with the aircraft flight track data since the resolution of the flight track data is close to 1 km.

Figure 6 compares the horizontal wind structure at 810 hPa with observations along the aircraft flight track from 0345 to 0622 UTC 14 (EFCDBAO in Fig. 6a), and that from the model initial conditions at 0600 UTC 14 July 2005. Quantitative comparisons of the wind speeds through the storm vortices between the model initial conditions and observations are given in Figs. 6c and 6d. From Fig. 6a, the observed wind shows a strong asymmetry with the strongest wind of 40 m s^{-1} in the

TABLE 3. List of the data assimilated in DA-3 and DA-1.

Assimilation time	Data type	No. of observations assimilated
1200 UTC 14 Jul 2005	QuikSCAT	1153
	GOES-11 AMVs	3423
	Dropsondes	12
1800 UTC 14 Jul 2005	*GOES-11*AMVs	3116
	Dropsondes	17
0000 UTC 15 Jul 2005	QuikSCAT	1467
	GOES-11 AMVs	3655
	Dropsondes	21
0600 UTC 15 Jul 2005	*GOES-11* AMVs	3321
	Dropsondes	15

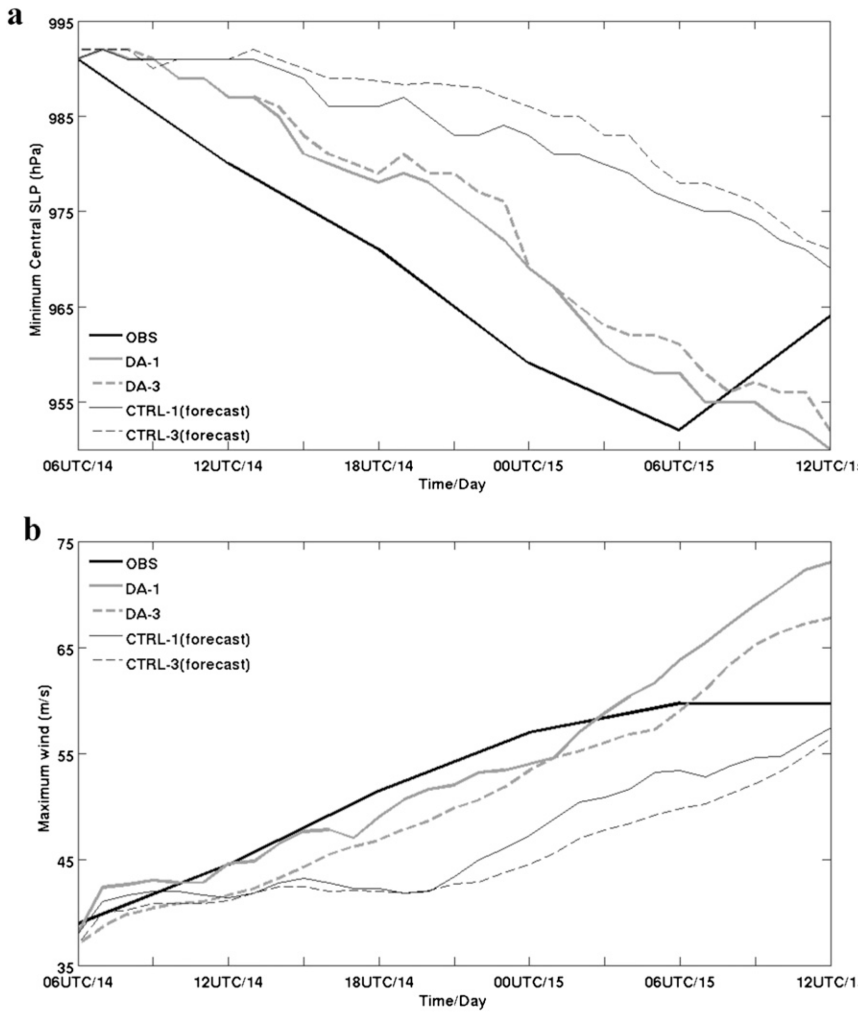


FIG. 4. Time series of the (a) minimum CSLP(hPa) and (b) maximum surface wind speed (m s^{-1}) from the NHC best-track data (OBS) and the numerical simulations of Hurricane Emily during 0600 UTC 14 Jul–1200 UTC 15 Jul 2005.

northeast quadrant but weaker wind (maximum speed of 18 m s^{-1}) in the southwest quadrant, while the maximum wind speed is 27 m s^{-1} in the southeast quadrant and 20 m s^{-1} in the northwest quadrant. As shown in Fig. 6b, the model initial conditions provide a similar asymmetric wind structure around the storm vortex, as was observed. The strongest wind is 37 m s^{-1} in the northeast quadrant, 15 m s^{-1} in the southwest quadrant, and 27 m s^{-1} in the other quadrants. These wind speeds in the model initial vortex are very close to those of the observations. This result indicates that the wind field is relatively realistic in the model initial conditions.

Figure 7 compares the temperature and dewpoint temperature (Fig. 7a) and the vertical velocity (Fig. 7b) around 810 hPa observed during flight leg CD with the corresponding field through the vortex (along the line CCDD in Fig. 6b) in the model initial conditions. Realistic temperature and moisture in the storm eye are found in the model initial conditions. Specifically, the observed storm eye has a warm center with a temperature of about 20°C, and a low dewpoint temperature of 12°C. The model initial conditions agree very clearly with these observed features. This similarity corresponds to the fact that the initial intensity of the storm in the model is close to that of the observations (Fig. 4). However, there are some unrealistic features in the thermal structure of the model initial conditions. In particular, the flight-level data show that temperature and dewpoint fields over the storm eye and eyewall are nearly symmetric, but the initial conditions display an unrealistic asymmetric thermal structure over both the storm eye and eyewall. For example, the observed warm and dry regions over the storm core from the flight-level data are located within −50 to 50 km of the storm center. But, in the model initial

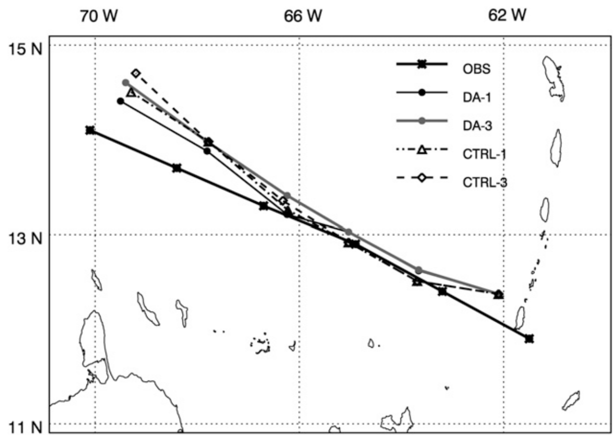


FIG. 5. Storm tracks of Emily from the NHC bes-track data and model simulations from 0600 UTC 14 Jul to 1200 UTC 15 Jul 2005 (6-h intervals). The storm moved from southeast to northwest during the time period.

conditions, the warm and dry region over the storm core exists in an area within −20 to 50 km of the storm center. In addition, the observed eyewall (indicated by the saturated region in Fig. 7a) extends beyond 50 km from the storm center on both sides. However, the eyewall in the model initial conditions covers a large area from −80 to −20 km from the storm center in the southwest quadrant and a very narrow region from 50 to 57 km from the storm center in the northeast quadrant.

The observed and simulated vertical velocities are both weak (Fig. 7b). The observed vertical velocity maximum is 2.6 m s^{-1} in the eyewall and 1.9 m s^{-1} in the model initial condition. The maximum downward motion observed during the aircraft flight is stronger than −3 m s^{-1}, while the downward motions are weaker than −1 m s^{-1} in the model initial conditions. In addition, the vertical velocity field in the model initial conditions indicates a lack of convection in the northeast quadrant, which corresponds to the narrow model eyewall (Fig. 7a). The lack of convection is also consistent with the dry air in the northeast quadrant within 20–50 km from the center, which is another symptom of the asymmetric eye and eyewall in the initial conditions.

4. Diagnosis of the forecast errors

a. *Storm structure at 0500 UTC 15 July 2005*

Figure 8 shows the horizontal wind fields at 700 hPa from the flight-level data along legs CD (0235–0338 UTC) and AB (0425–0541 UTC) on 15 July 2005 (Fig. 8a), the model forecast in CTRL-1 (Fig. 8b), and the reanalysis in DA-1 (Fig. 8c) at 0500 UTC 15 July 2005. Figure 9 compares the observed wind speed along legs AB and CD with the corresponding wind fields through the simulated vortex (along lines AABB and CCDD in Figs. 8b and 8c) in DA-1 and CTRL-1. Observations show the expected asymmetric wind field at 700 hPa for the storm moving toward the northwest. The strongest wind of 65 m s^{-1} occurs in the northeast quadrant of the vortex and the weakest wind (42 m s^{-1}) is in the southwest quadrant (Fig. 9a). In the southeast and northwest quadrants, the maximum winds are 56 m s^{-1} (Fig. 9b). The radius of maximum wind (RMW) from the flight-level data is 12 km (Fig. 9a). Both CTRL-1 and DA-1 captured the strong wind asymmetry from the southwest to northeast quadrant and the nearly symmetric wind structure in the northwest to southeast quadrant (Figs. 8b and 8c). However, the maximum wind speed in CTRL-1 is 14 m s^{-1} lower than that of the observations. The RMW is 36 km, which is 24 km larger than observed (Fig. 9a). Compared with CTRL-1, DA-1 produces better wind structure and a more realistic maximum wind speed. The RMW is only 18 km, which is also closer to the observed RMW. This result shows that the reanalysis has improved the horizontal wind structure of Hurricane Emily.

Figure 10 compares the temperature and dewpoint (Fig. 10a) and vertical velocity (Fig. 10b) at 700 hPa observed in flight leg AB with the corresponding model forecast fields along the simulated storm center from CTRL-1 and DA-1 at 0500 UTC 15 July 2005. From Fig. 10a, the observed storm has a warm eye with a maximum temperature of 21°C and a low dewpoint of 5°C. The width of the warm core is about 35 km. However, in CTRL-1, the simulated maximum temperature in the storm eye is 15°C and the dewpoint is 5°C warmer than in the observations, implying the simulated storm eye is weaker, with less warming and drying than is observed at 700 hPa. The width of the warm core in CTRL-1 is 40 km, about 10 km wider than that of the observations. In DA-1, the thermal structure over the storm eye region has been greatly improved with a more realistic warm temperature center of 21°C and a dewpoint of 6.5°C. However, similar to CTRL-1, DA-1 also produces a wider warm core than is observed. Significant improvement in the thermal field has been obtained in the reanalysis DA-1. Compared with CTRL-1, DA-1 also produces a stronger warm core.

The observations show strong updrafts and downdrafts in the eyewall within 20-km radius (Fig. 10b). An extreme updraft of about 9.2 m s^{-1} and a downdraft of −10 m s^{-1} are observed in the southwest quadrant of the vortex. Corresponding to the larger eye produced by the model forecasts, the strongest convection in CTRL-1 is located in the region near 30–50-km radius (Fig. 10a). In addition, the maximum updraft is only 5.8 m s^{-1} and the extreme downdraft is only −1.8 m s^{-1}. The weak eyewall convection and warm core agree well with the weak

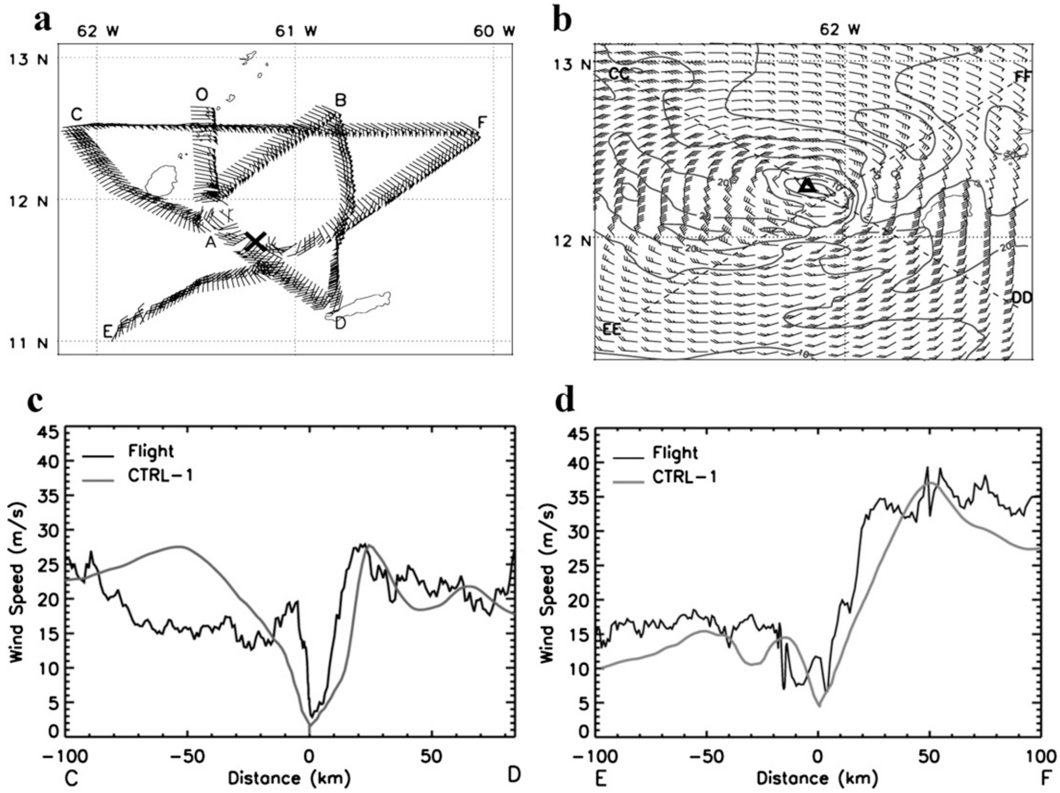


FIG. 6. The horizontal wind structure at 810 hPa: (a) along the aircraft flight track from 0345 to 0622 UTC 14 Jul and (b) from the model initial conditions at 0600 UTC 14 Jul 2005. The observed center position of Emily from the best-track data is marked as a cross sign in (a) and the simulated hurricane center is marked as a triangular sign in (b). The contour interval for wind speed is 5 m s^{-1} in (b). Comparison of the wind speeds from the USAF flight-level data along legs (c) CD and (d) EF, with the corresponded wind speeds in the model initial conditions along the lines CCDD and EEFF, respectively.

convection in the model initial conditions; the forecasted eyewall developed very slowly. In contrast, with data assimilation, significant improvements in the storm convection and eyewall are found. Specifically, the extreme speeds of the updraft and downdraft are 8.8 and -3.6 m s^{-1}, respectively, which are much closer to the observed values.

Figure 11 compares the soundings between the model simulation and dropsondes in the eye of Emily at 0543 UTC and the northeast eyewall of Emily at 0453 UTC

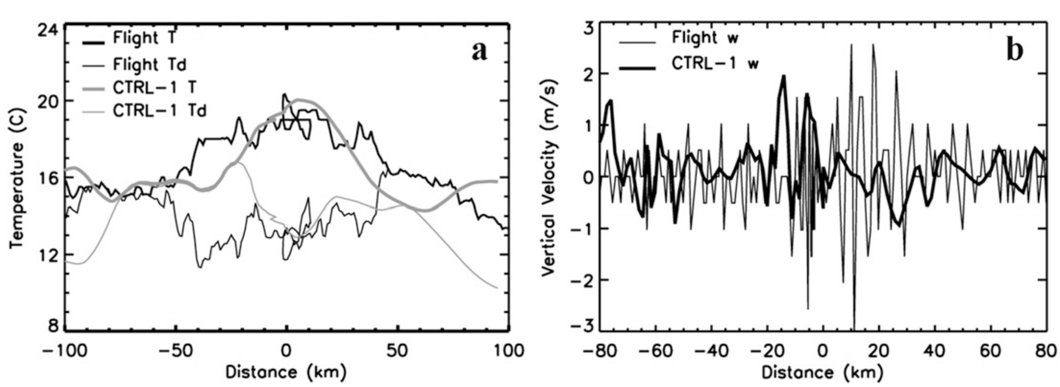
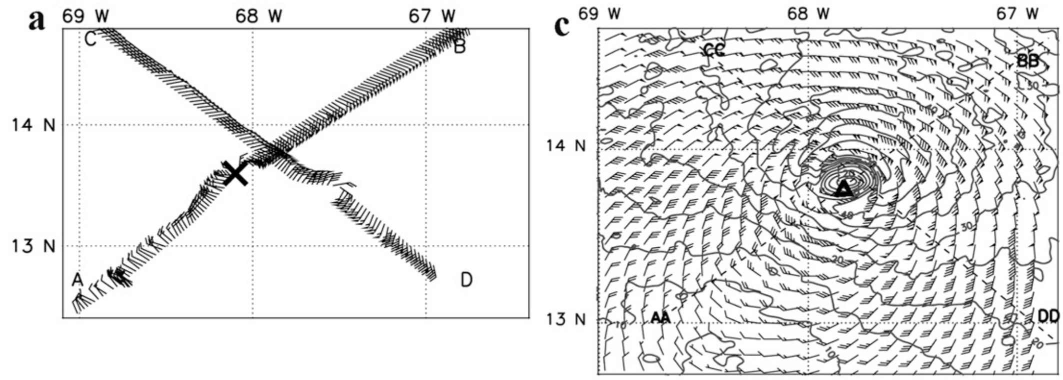


FIG. 7. Comparison of the (a) temperature and dewpoint temperature and (b) vertical velocity structures at the vortex core regions of Hurricane Emily. USAF flight-level data (along leg CD in Fig. 6a) are compared with the corresponding fields in the model initial conditions (along the line CCDD in Fig. 6b).



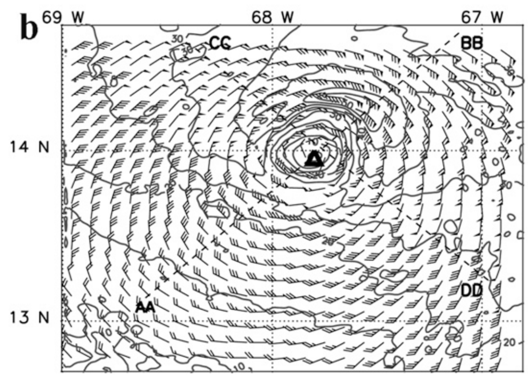


FIG. 8. (a) Wind structures of Hurricane Emily from USAF flight-level data compared with those from (b) CTRL-1 and (c) DA-1 at 0500 UTC 15 Jul 2005. The contour intervals for the wind speeds are 5 ms^{-1} in (b) and (c). The cross sign indicates Emily's center location from the best-track data in (a). The simulated hurricane center location is marked by a triangular sign in (b) and (c).

15 July 2005. Owing to the assimilation of the dropsonde data into the model, DA-1 produces a more accurate vertical structure of the storm eye than CTRL-1 does. Specifically, DA-1 reproduces a well-mixed boundary layer from the surface to 920 hPa (Fig. 11a). This feature is somewhat similar to the observations. Meanwhile, dewpoint and temperature profiles near the surface and at 700 hPa are also closer to the observations. However, the temperature between 900 and 700 hPa in DA-1 is much warmer than in the observations. In contrast, CTRL-1 produces a much colder storm eye. As shown in Fig. 11b, both DA-1 and CTRL-1 produce eyewall soundings at the northeast quadrant of the storm vortex, very close to that of the observations.

Overall, the above results show that the model forecast (CTRL-1) produces a weaker storm than was observed with respect to the vertical motion, warm core, and horizontal wind at 0500 UTC 15 July 2005. The weak convection provided in the model initial conditions may be partly responsible for this weak storm structure and the slow intensification rate in CTRL-1. With assimilation of satellite wind data and dropsonde thermal data,

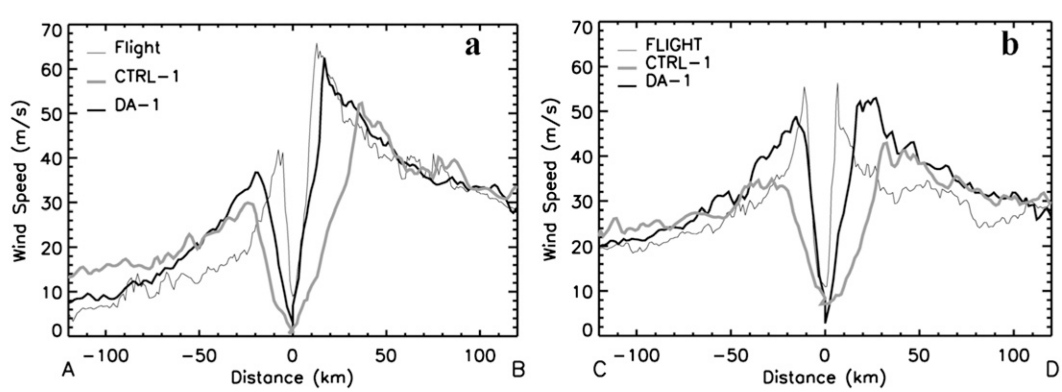


FIG. 9. Comparison of the wind speed in the observed and simulated Hurricane Emily. USAF flight-level data from flight legs (a) AB and (b) CD are compared with the simulated wind speeds along lines AABB and CCDD (see Figs. 8b and 8c), respectively.

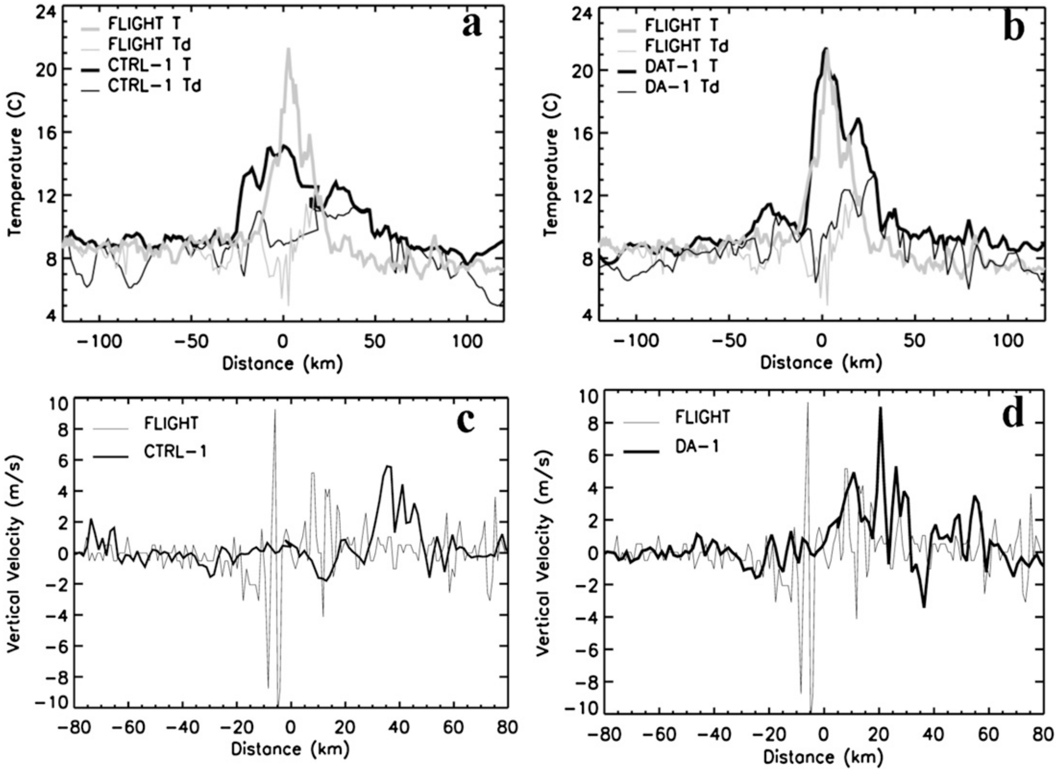


FIG. 10. Comparisons of (a),(b) temperature and dewpoint temperature and (c),(d) vertical velocity in the observed and simulated vortex core regions along leg AB for the USAF flight level data (see Fig. 8a) and along the line AABB (see Figs. 8b and 8c) for the model simulations from CTRL-1 and DA-1.

the reanalysis (DA-1) has greatly improved the intensification rate by producing the stronger eyewall convection, warm-core structure, and horizontal wind fields.

b. Eyewall contraction

During tropical cyclone development, the storm usually intensifies as the RMW contracts. Willoughby (1990) analyzed 900 radial profiles from the aircraft observations measured for 19 Atlantic tropical cyclones and suggested that this convectively driven contracting of the storm eyewall could be the primary symptom of hurricane intensification. As the eyewall moves inward, partial conservation of the angular momentum means higher tangential winds, and more moisture and energy are extracted from the ocean surface and transported into the storm eyewall.

The flight-level data indicate that Emily experienced a significant eyewall contraction during the rapid intensification period. Figure 12a shows the wind speeds from the observations at 810 hPa between 0345 and 0422 UTC 14 July, at 700 hPa between 1653 and 1744 UTC 14 July, and at 700 hPa between 0440 and 0511 UTC 15 July 2005. Shown are the results from the flight-level data (Fig. 12a), and the model forecast from CTRL-1 (Fig. 12b) and from DA-1 (Fig. 12c) at 0600 UTC 14 July at 810 hPa, at 1800 UTC 14 July at 700 hPa, and at 0500 UTC 15 July at 700 hPa. As seen in Fig. 12a, the observed maximum wind is 39 m s^{-1} at 810 hPa with an RMW of about 50 km between 0345 and 0422 UTC 14 July. About 12 h later the eyewall contracts and the RMW decreases to 16 km with a maximum wind of 52 m s^{-1}. After another 12 h the storm develops a very small eye with an RMW of about 12 km and the storm maximum relative wind increases to 65 m s^{-1}.

Numerical simulations (CTRL-1) have also generated the eyewall contraction of Emily as the storm deepens. At 0600 UTC 14 July, the model-simulated maximum wind is 37 m s^{-1}, about 2 m s^{-1} lower than the observed one, while the RMW (50 km) is about the same as in the observations. After 12 h, the maximum wind increases to 42 m s^{-1} (about 10 m s^{-1} weaker than the observations), while the RMW shrinks to 40 km (which is 24 km wider than in the observations). At 0500 UTC 15 July, the maximum wind increases to 52 m s^{-1}, 13 m s^{-1} lower than in the observations and the RMW further shrinks into 36 km, but still a factor of 3 wider than in the observations.

The DA-1 (Fig. 12c) has greatly improved the wind field and the simulated eyewall contraction. At 0600 UTC

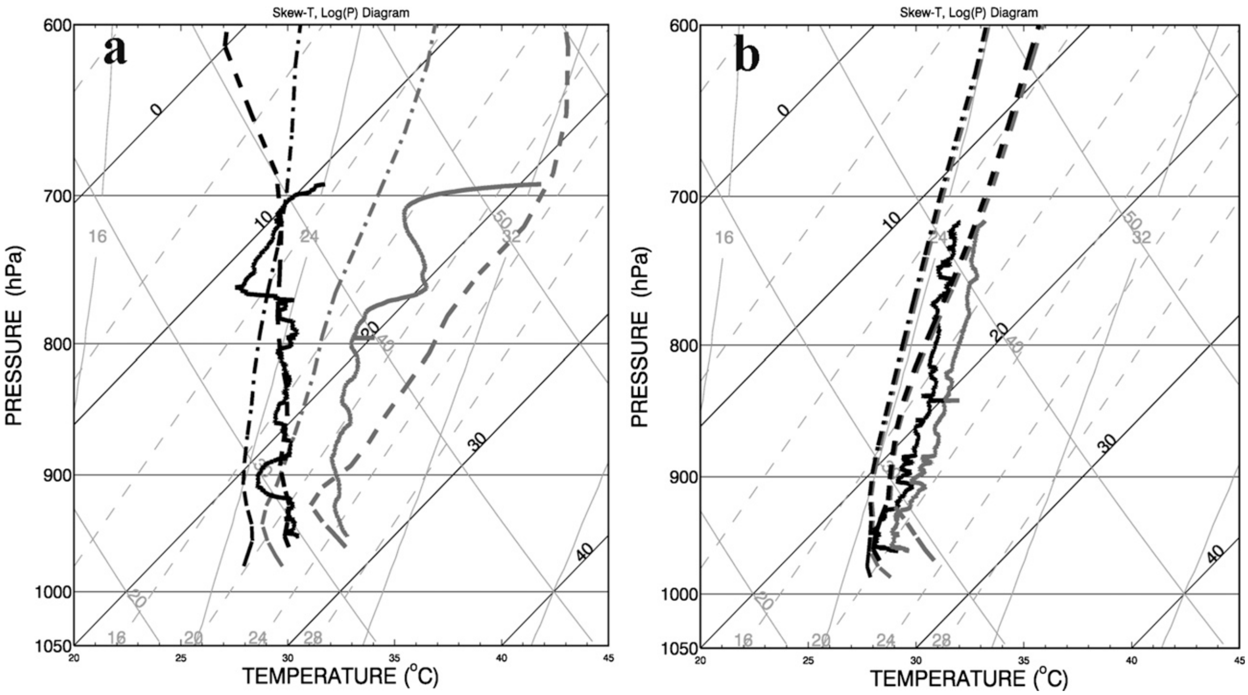


FIG. 11. Comparison of soundings from the numerical experiments at 0500 UTC 15 Jul with (a) the dropsonde near the storm eye (13.6°N, 68.1°W) at 0503 UTC 15 Jul and (b) the dropsonde in the northeast eyewall (13.8°N, 67.9°W) at 0508 UTC 15 Jul 20055. Temperature data from dropsondes, DA-1, and CTRL-1 are in solid, dash–dot, and dash gray curves, respectively. Dewpoint data from dropsondes, DA-1, and CTRL-1 are in solid, dash–dot, and dash black curves, respectively.

14 July, the model wind field is the same as that in CTRL-1 since the same initial conditions are used in both experiments. After 12 h, the maximum wind increases to 44 m s^{-1} with an RMW of 26 km. Compared with CTRL-1, the maximum wind in DA-1 is 2 m s^{-1} and the RMW is 14 km closer to the observations. At 0500 UTC 15 July, the maximum wind increases to 63 m s^{-1}, which is only 2 m s^{-1} lower than in the observations and 11 m s^{-1} larger than in CTRL-1. At the same time, the RMW in DA-1 further shrinks to 18 km, which is only 6 km larger than in the observations, and 18 km smaller than that in CTRL-1.

Overall, the above results indicate that the numerical model is able to reproduce the eyewall contraction process although the simulated eye and RMW are much larger than in the observations. This slow eyewall contraction corresponds to the slow intensification of the hurricane in the numerical simulation. In addition, data assimilation has resulted in a better representation of the wind field and eyewall contraction although the RMW is still larger than the observations and a somewhat larger eye is produced.

c. *Resolution issue*

In this section, we further compare the simulations at a coarser resolution of 3 km (CTRL-3 and DA-3) with the results at a finer resolution of 1 km (CTRL-1 and DA-1). As shown in Fig. 4, the simulations at 1-km resolution (CTRL-1 and DA-1) produce deeper intensities than those at 3-km resolution (CTRL-3 and DA-3). This result generally agrees with the results in previous studies that increasing the horizontal resolution can help to produce better intensities and structures in simulations of tropical cyclones (Davis and Bosart 2002; Davis et al. 2006).

To gain a deeper insight into the impacts of the model resolution on the simulated storm structure, Fig. 13 compares the simulated horizontal wind field between CTRL-3 and DA-3. Figure 14 compares the temperature and dewpoint, and the vertical velocity from CTRL-3 and DA-3 at 0500 UTC 15 July 2005 with the flight-level data. To make a fair comparison, the flight data (at about 1-km resolution) are filtered in the 3-km resolution to match the resolution of the model simulations in CTRL-3 and DA-3.

As shown in Fig. 13, the strongest wind in the CTRL-3 appears in the northeast quadrant and the weakest wind appears in the southwest quadrant; this is similar to the results at 1-km resolution (Fig. 8). However, the simulated wind speeds at 3-km resolution are weaker than those at 1-km resolution. Compared with the results at 3-km resolution (Fig. 14a), the simulations at 1-km

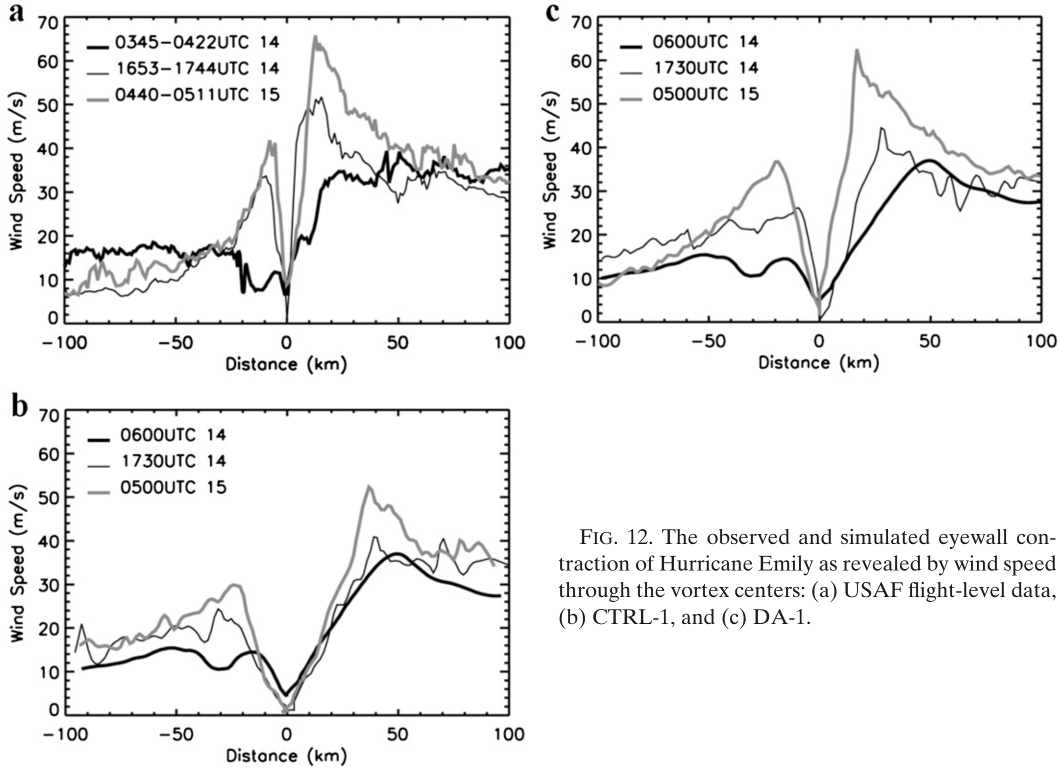


FIG. 12. The observed and simulated eyewall contraction of Hurricane Emily as revealed by wind speed through the vortex centers: (a) USAF flight-level data, (b) CTRL-1, and (c) DA-1.

resolution produce more realistic thermal structures (Fig. 10). Specifically, an increase in resolution from 3 to 1 km helps the model produce a stronger warm core for Hurricane Emily. The temperatures in the storm eyes in both DA-3 and CTRL-3 are 1°C further from those observed than are those in DA-1 and CTRL-1. The dewpoints in the storm eyes produced by DA-3 and CTRL-3 are about 2°–3°C further from those observed than are those from DA-1 and CTRL-1.

Increasing the resolution from 3 to 1 km also improves the vertical motion structure in the storm eyewall (cf. Figs. 14b and 10b). In CTRL-3, the extreme vertical motion is of 4.8 m s^{-1} for upward motion and of -1.9 m s^{-1} for downward motion, which are 1 m s^{-1} weaker than those in CTRL-1. In DA-3, the extreme vertical velocity is 5 m s^{-1} for updraft and -1.4 m s^{-1} for downdrafts. Compared with DA-3, DA-1 has improved the maximum updraft by 3.8 m s^{-1} and the downdraft by -2.2 m s^{-1}.

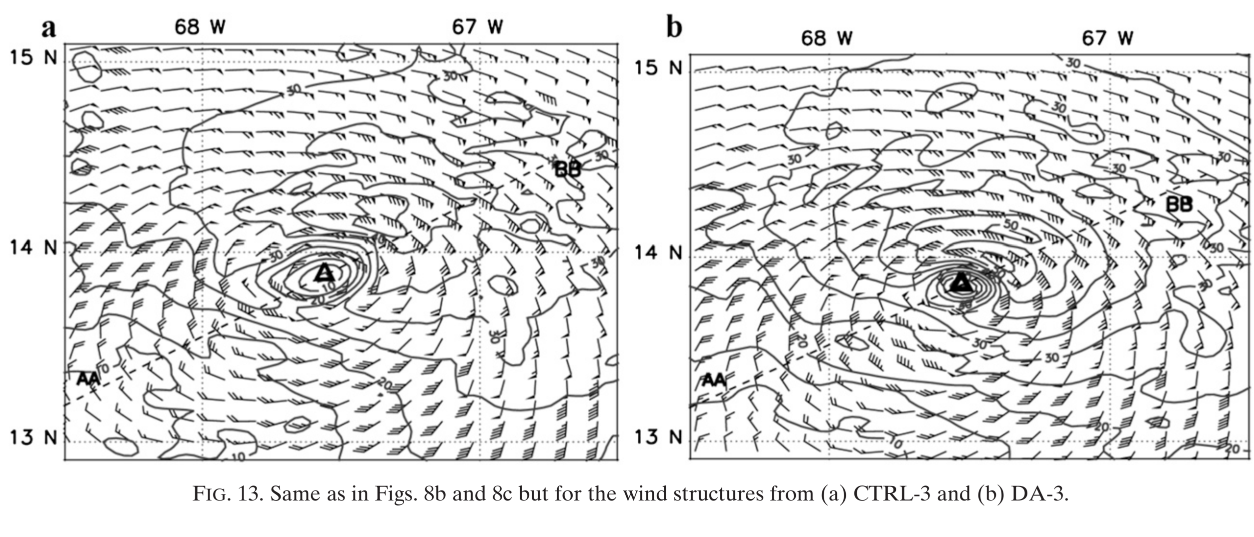


FIG. 13. Same as in Figs. 8b and 8c but for the wind structures from (a) CTRL-3 and (b) DA-3.

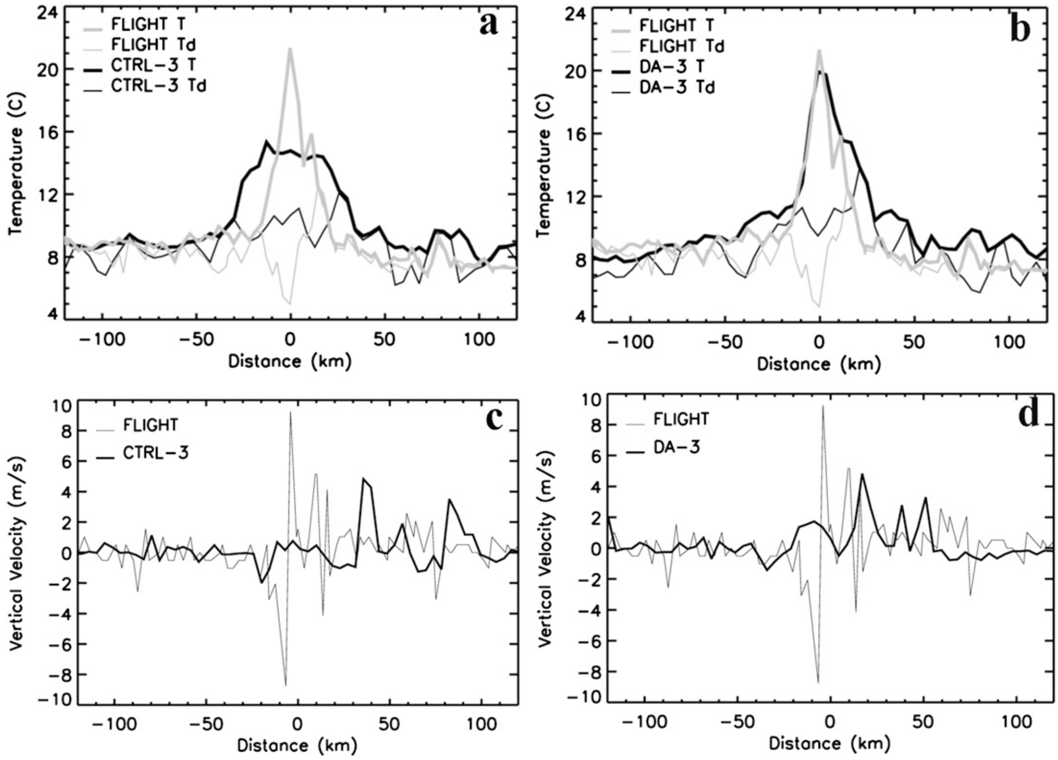


FIG. 14. Same as in Fig. 10 but for CTRL-3 and DA-3 and along the line AABB (in Fig. 13).

The simulations of eyewall contraction in both the CTRL and DA experiments have also been improved by increasing the horizontal resolution from 3 to 1 km. As shown in Fig. 15a, the RMW in CTRL-3 decreases from 50 km at 0600 UTC 14 July, to 42 km at 1730 UTC 14 July, and to 38 km at 0500 UTC 15 July 2005. It is a little slower than the 50-, 40-, and 36-km decreases in CTRL-1 at the corresponding times. In DA-3 (Fig. 15b), the RMW decreases from 50 km at 0600 UTC 14 July, to 28 km at 1730 UTC 14 July, and to 24 km at 0500 UTC 15 July 2005. It is slower than the 50-, 26-, and 18-km decreases in DA-1 (Fig. 12c), especially in the last 12 h from 1730 UTC 14 July to 0500 UTC 15 July 2005.

The above results indicate that increasing the horizontal resolution can help to produce better intensity forecasts with more realistic storm structures. However, the resolution itself only exerts a limited influence, although it can help to produce a stronger wind field, vertical motion, and a warm core. Compared with the observations, all simulations have produced a larger storm eye (Figs. 9b and 15b), implying that even 1 km may still be somewhat too coarse to fully resolve the storm inner-core structures.

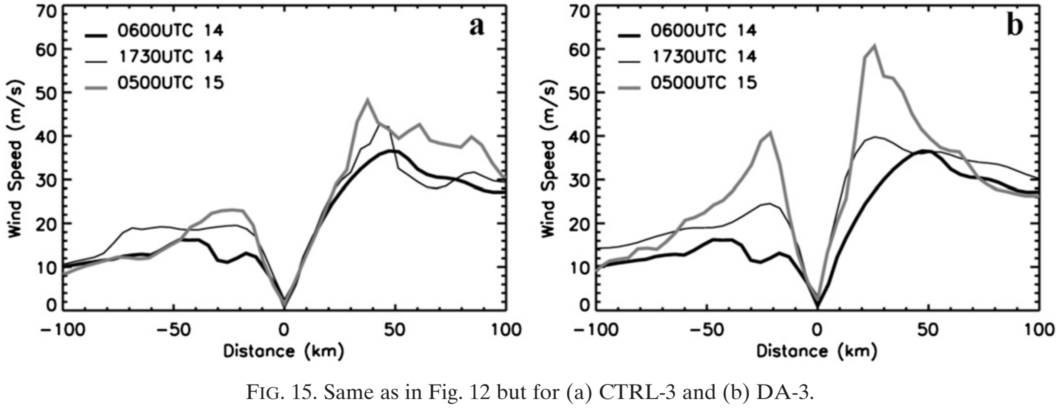


FIG. 15. Same as in Fig. 12 but for (a) CTRL-3 and (b) DA-3.

5. Summary and discussion

A diagnostic study is conducted to examine the initial and forecast errors in a short-range numerical simulation of Hurricane Emily's (2005) early rapid intensification. The initial conditions and the simulated hurricane vortices are compared with the flight-level data acquired from a U.S. Air Force C-130J aircraft. Our results show the following:

- Compared with the flight-level data, weaker vertical motion and unrealistic vortex asymmetric structure are found in the model initial conditions. Consequently, weaker eyewall convection, a warm core, and horizontal winds are observed along with the slower intensification rate in the model forecasts in CTRL-1 and CTRL-3.
- While the model forecasts fail to reproduce the rapid intensification of Hurricane Emily, the reanalysis has greatly improved the simulation of Emily's rapid intensification during the whole simulation period by assimilating all available satellite and dropsonde data into the model fields every 6 h. Owing to the improvements from data assimilation, the reanalysis results produce stronger eyewall convection fields, more intense warm cores, enhanced horizontal wind fields, and much more rapid intensification rates for Hurricane Emily.
- Eyewall contraction is an important mechanism for Hurricane Emily's rapid intensification. However, the eyewall contracts too slowly in both model forecasts, CTRL-3 and CTRL-1. In contrast, because of the data assimilation, both DA-3 and DA-1 reproduce a much smaller storm eye and more rapid eyewall contraction. This improvement corresponds to the faster intensification rates and better intensity predictions in DA-3 and DA-1.
- The model horizontal resolution has a significant influence on the simulated storm structure. With higher resolution, the model produces more realistic wind, thermal, and convective structures for the storm's inner core. However, for this specific case study, even at 1 km the model is still not able to fully resolve the storm's inner-core structures.

Although the possible factors that cause the failure in the intensity forecast are complicated, and the diagnostic study from this paper can only explain some of the reasons linked with this failure, the overall results from this study suggest that better representations of the storm vortex, especially the inner-core structures in the initial conditions and during the forecasts, are very important in improving the hurricane intensity forecasting. In addition, the improvements from the reanalysis in this study not only indicate that data assimilation is helpful for improving short-range hurricane intensity forecasts, but also imply that the improvement in the model physical processes is also necessary because of the following: while we assimilate the data into the numerical model every 6 h, we also exert strong constraints (or forcings) to correct the errors from the model forecasts.

It should be noted that the data assimilation experiments performed in this study are at coarser resolutions (27- and 9-km grid spacings) owing to facts that 1) the satellite (*GOES-11* AMVs and QuikSCAT) data were available only at coarser resolution and 2) the aircraft flight-level data were not assimilated into the ARW model. This case, however, represents the most common situations in current operational and research practices. Diagnostic results from this study clearly indicate that the data assimilation at coarser resolution is not enough to provide accurate hurricane vortex structures that are very important in producing improved hurricane intensity forecasts.

Future work will be conducted in studying the sensitivities of the detailed vortex inner-core thermal and dynamical structures on the hurricane intensity forecast. Data assimilation efforts will be directed at higher resolutions to better represent the vortex structure of the hurricane, including the use of the WRF four-dimensional variational data assimilation (4DVAR; Zhang et al. 2008) to assimilate the flight-level and radar data when the system becomes mature. In addition, improving the model dynamic and physical processes to better forecast the hurricane's inner-core structure will be another important area to explore.

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