While tropical cyclone (TC) track forecasts have improved significantly over the past 15 yr, intensity forecasts have improved only slightly over the same period. Rogers et al. (2006) noted that the official 48-h TC track forecast errors have decreased by nearly 45% while the official TC intensity forecast errors have decreased by only 17%. One of the major reasons for the slow pace in improvement of intensity forecasts may be deficiencies in the collection and assimilation of real-time inner-core data into numerical weather prediction (NWP) models. These data will serve to better characterize the TC intensity and structures in the model initial fields.

Tropical cyclone observing systems have considerably improved over the past decades. Radars, both airborne and land based (fixed and mobile), have proved useful tools for observing and
understanding TC structure and development. Early radar observations of TCs, first made in the mid-1940s (e.g., Wexler 1947), revealed mesoscale features of TCs, such as a nearly clear eye, a circular eyewall composed of deep cumulus convection, and asymmetric structures of the eyewall. Since then radar has been playing a more and more important role in TC studies, especially with significant technology advances in airborne Doppler radar on National Oceanic and Atmospheric Administration's (NOAA's) research aircraft and the Weather Surveillance Radar-1988 Doppler (WSR-88D) radar network (Marks 2003). Many algorithms have been developed (Gamache et al. 1995; Roux and Marks 1996; Lee and Marks 2000; Lee et al. 2000; Harasti et al. 2004; Lee et al. 2006) to retrieve TC structures from radar observations collected over more than three decades (Black et al. 1972; Bluestein and Marks 1987; Marks and Houze 1987; Roux and Viltard 1995; Black et al. 1996; Reasor et al. 2000; Lee et al. 2003; Aberson et al. 2006; Knupp et al. 2006). These studies showed that radar data combined with other in situ observations have led to improved understanding of finescale three-dimensional structures in the vicinity of the TC inner core, the outer precipitation band structure, and the boundary layer wind distributions. Assimilation of these data into NWP models would allow for better initialization of TC intensity and fine structure. However, studies of this kind have been rarely reported in the past years. It still remains a challenge to assimilate the new information gained through radar observations for better analysis, initialization, prediction, and verification of TCs.

Resolution of mesoscale NWP models has increased significantly (2–4 km) in recent years to resolve in detail the inner-core structure (Yau et al. 2004; Braun et al. 2006). This recent development combined with advances in TC observations presents both a new challenge and an opportunity (e.g., Rogers et al. 2006). The availability in real-time full-volume, full-resolution (level II) radar data (Crum et al. 2003) and the important improvements in data assimilation techniques have also paved the way for radar data assimilation. Research efforts have been made in the last decade with an attempt to extract and assimilate meteorological information from Doppler radar observations into NWP models to improve the model capability of forecasting severe weather events (Shapiro et al. 1995, 2003; Qiu and Xu 1996; Sun 2004, 2005; Sun and Crook 1997, 1998; Xu et al. 1995, 2001a,b; Gao et al. 1999; Wu et al. 2000; Weygandt et al. 2002a,b; Snyder and Zhang 2003; Xiao et al. 2005). While these studies were done mostly for isolated thunderstorms and mesoscale convective systems, it should be feasible and practical to apply these techniques to TC structure and intensity analyses and predictions.

At the Naval Research Laboratory (NRL), a high-resolution data assimilation system is under development to assimilate high-resolution data, especially those from Doppler radars, into the Navy’s Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS*—a registered trademark of the Naval Research Laboratory; Hodur 1997) to improve the model’s capability and accuracy in predictions of hazardous weather. A variational approach developed by Xu et al. (2001b) is used in this system to retrieve the three-dimensional wind fields and the thermodynamic perturbations associated with the retrieved winds from radar observations of radial velocity from one or more radars in the storm area. These retrieved fields are then assimilated into the COAMPS model to improve the mesoscale and storm-scale dynamical and thermodynamic features in the model initial fields. Results from our previous study of a squall line case (Zhao et al. 2006) showed a major impact of radar wind data assimilations on storm predictions. Recently, the system has been enhanced with new capabilities to assimilate radar reflectivity data along with radar radial velocity observations to improve the characterization of both the dynamical and microphysical structures of storms in model initial conditions. This development was motivated by the fact that radar reflectivity data have better data coverage and more data sources (e.g., those from non-Doppler radars) than the radial velocity observations. Temperature and water vapor are also modified during the reflectivity data assimilation to maintain the consistency and balance among the model fields. Several storm cases have been selected to test the radar data assimilation system. Tropical cyclones, as a special type of severe storms, are included in these case studies.
The objective of this study is to examine the capability of improving TC structure and intensity forecasts by assimilating land-based Doppler radar observations into a mesoscale NWP model. One particular issue we want to address in this study is how and to what extent the radar data improve the characterization of the finescale dynamical and microphysical structures around and inside TC inner core in the model analysis and the forecast fields, especially during periods in which the storms undergo significant structure and intensity changes (e.g., rapid intensifying at the beginning of TC development or quick weakening at landfall). Given the fact that hurricanes cannot be observed by land-based radars until they are close to landfall, the improved hurricane intensity and structure forecasts that we attempt to achieve in this study may not be able to provide a 48-h lead time that is usually needed for issuing prelandfall warnings. However, the improved forecasts can still provide valuable mesoscale guidance for preparation, damage mitigation, and recovery efforts for inland flooding and strong surface winds during landfall and postlandfall periods (Marks et al. 1998), especially in cases where a hurricane and the associated severe weather remain stationary for a period of time after landfall. Most importantly, results from this study about the capability of improving hurricane intensity and structure forecasts using radar data assimilation can be applied to airborne and spaceborne radar data when they are becoming an integral part of hurricane studies. These data provide a broad coverage of hurricanes at various stages, including phases of rapid intensity changes.

The landfall of Hurricane Isabel on the east coast of the United States in 2003 is selected as a focus of this study. The hurricane landfall process was fully observed by fine WSR-88D radars in the Next Generation Weather Radar (NEXRAD) network in the hurricane landfall region. Data from these five radars during the landfall period were collected. The radar data assimilation system developed at NRL is employed to retrieve the storm dynamical and microphysical structures and assimilate the retrieved information into COAMPS.

**DATA ASSIMILATION ALGORITHMS AND PROCEDURES.** The radar data assimilation system used for this study consists of the following two components: radar radial velocity data assimilation and radar reflectivity data assimilation. The algorithm used in this study for radar radial velocity data assimilation is the three-and-half-dimensional variational (3.5DVAR) system developed by Xu et al. (2001a,b) and Gu et al. (2001). It retrieves the three-dimensional winds \((u, v, w)\) needed for initializing the model from radar observations of Doppler radial velocity in a variational framework by using model dynamical equations as constraints. It also retrieves thermodynamic perturbations based on the retrieved winds to provide additional dynamical balances among the model initial fields. Usually, data from a single radar are not enough to cover large storm systems such as hurricanes. The 3.5DVAR system, however, has been enhanced with the capability of using data from one or more radars in the storm region to increase the data coverage and improve the accuracy of retrievals. This feature makes the system more suitable than the single radar analysis system for data assimilation for storms with large spatial sizes. Radial velocity folding (or aliasing) is also a common and challenging issue in Doppler radial velocity assimilation for hurricanes. The radar data used for this study are from the WSR-88D network with a typical unambiguous (Nyquist) velocity of about 27 m s\(^{-1}\). This number is much smaller than the maximum wind speed frequently observed in hurricanes and causes velocity folding in large areas of high wind speed inside the storms. The 3.5DVAR system has an automated dealiasing algorithm that uses model forecasts as first guesses for unfolding Doppler radial velocity data before they are assimilated into an NWP model. Details of the 3.5DVAR system and its data quality control algorithms can be found in Zhao et al. (2006).

A three-dimensional variational (3DVAR) approach is used for assimilating radar reflectivity data into the model to initialize the three-dimensional microphysical fields. Unlike the radial velocity data assimilation that uses the radar observations directly in the observational space, the reflectivity data assimilation requires that the reflectivity data from all available radars be preinterpolated onto the model grid points. A three-dimensional radar reflectivity mosaic system has been developed by Zhao et al. (2004) at NRL for this purpose. This system processes the full-volume, full-resolution (level II) reflectivity data from one or more radars in an area of interest after data quality controls and then interpolates the data to a common three-dimensional grid. This system is globally relocatable with the flexibility to use any three-dimensional grids and domain sizes defined by users. In this study, we interpolate radar reflectivity data onto the COAMPS grids. Three-dimensional microphysical fields are then retrieved from the gridded reflectivity data. A detailed description of this procedure is given in the appendix.
Our previous study (Zhao et al. 2006) showed that the results from the hourly cycled data assimilation procedure had larger and smoother improvements than those from the one-time (single cycle) data assimilation. Based on this finding, the data assimilation system is designed to start several hours before the analysis time. After that, the data assimilations are performed hourly to update the model fields. Hourly model forecasts are also launched from each hourly updated initial condition to provide background fields for the next hourly data assimilation cycle. This procedure continues until the last hourly data assimilation is performed at the analysis time ($t=0\,\text{h}$). In each hourly data assimilation, three time levels of radar radial velocity data about 5 min apart from each other and centered at the hour are used for wind and thermodynamical perturbation retrieval, and one time level of reflectivity data at the hour is used for microphysical retrieval. After the final hourly data assimilation, the model is launched for a free forecast. This hourly cycled data assimilation procedure takes the advantage of the frequent update rate of radar observations.

**RESULTS FROM HURRICANE ISABEL (2003).** Hurricane Isabel (2003) at landfall. Hurricane Isabel was a long-lived hurricane that attained Saffir–Simpson category 5 at 1800 UTC 11 September. It was a category 2 hurricane when it made landfall near Drum Inlet, North Carolina, between 1600 and 1700 UTC 18 September 2003. At the time of landfall, Hurricane Isabel had a maximum wind speed of about 45 m s$^{-1}$ with several rainbands stretching out from the hurricane center. It weakened quickly after landfall and lost hurricane characteristics at about 0600 UTC 19 September to become a tropical storm. Several observational studies have been conducted to understand the dynamical and microphysical structures of the intense storms (Montgomery et al. 2006; Aberson et al. 2006). Figure 1 gives the hurricane track from 0000 UTC 18 September to 0300 UTC 19 September (www.nhc.noaa.gov/2003isabel.shtml) and the locations of the five WSR-88D radars. The hurricane eye passed the WSR-88D radar at Morehead City, North Carolina, very closely (about 50–60 km) right after landfall. This provided a rare opportunity to continuously observe the storms from inside the hurricane by a land-based radar. These radar data are valuable for data assimilation and model forecast verification. Because of the rapid changes in hurricane intensity and structures during and after landfall, it is very difficult for the model to accurately predict the wind speed and precipitation over land, which is critical for damage mitigation. Therefore, this case is considered to be an ideal case for studying the impact of radar data on TC intensity and structure forecasts.

**Experiment design.** The COAMPS model is used to provide background fields for the analyses and also as the test bed for the data assimilation. COAMPS is an operational, globally relocatable, multiple nested non-hydrostatic model suitable for weather predictions at spatial and temporal scales of 1–100 km for 0–72 h. Figure 1 gives the domain of the innermost (third) nested grid with a horizontal resolution of 3 km.

The COAMPS model was “cold” started (without previous data assimilation cycles) at 0000 UTC 18 September to spinup for 12 h. The model was then “warm” started again at 1200 UTC. One hour later, as the hurricane moved close to the radar stations, the hourly cycled radar data assimilation started. Four radar data assimilation cycles were performed at 1300, 1400, 1500, and 1600 UTC. After the last data assimilation cycle at 1600 UTC, the COAMPS model was warm started to make a 24-h forecast that covers both the landfall and the postlandfall periods.

To investigate the impact of radar reflectivity and Doppler radial velocity data on model forecasts individually, two experiments were conducted: one with radar reflectivity data assimilation only (Exp-Ref) and the other with radial velocity data assimilation only (Exp-Vr). The impact from assimilating these

![Fig. 1. The inner frame shows the COAMPS simulation domain with 3-km resolution. The observed Hurricane Isabel location is marked every 1–3 h from 0000 UTC 18 to 0300 UTC 19 Sep. The locations of the five radar stations are shown by the black dots and the ranges of radar data coverage are indicated by solid circles for radial velocity and dashed for reflectivity.](image-url)
two datasets at the same time was also evaluated in another experiment (Exp-All). Results from these experiments were compared with the control run (CNTL), which did not assimilate any radar data. For quick reference, these experiments are listed in Table 1.

**Impact on analyses.** The impact from assimilating radar reflectivity and radial velocity data are examined first in the hurricane analysis fields. Figures 2a and 2b give the horizontal cross sections of total precipitation mixing ratio (TPMR) at 3 km above the surface from CNTL and the Exp-Ref experiment at the end of the data assimilation period (1600 UTC), respectively. Here TPMR is defined as the sum of rain \((q_r)\), snow \((q_s)\), and graupel \((q_g)\), which are the fields to be assimilated into the model. Since the emphasis here is to evaluate the data assimilation impact on the TC intensity and structure analysis, and for easy comparison, the radar reflectivity fields derived from these hydrometeors from CNTL and Exp-Ref are also displayed in Figs. 2c and 2d. The observed radar reflectivity at the same level and same time is given in Fig. 2e. Without assimilating any radar data, the model forecast TPMR field (Fig. 2a) shows no organization in the storm area and it is difficult to even define the accurate position of the hurricane center, whereas after four cycles of hourly reflectivity data assimilation, the precipitation area is organized into band-like structures to the southwest of the hurricane center (Fig. 2b) and is located much closer to the observed radar reflectivity (Fig. 2e) than those in Fig. 2a. The hurricane eye and eyewall structures can now be defined in Fig. 2b. The observed mesoscale finger-shaped region of reflectivity inside the eyewall is also captured in the analysis. The high TPMR values to the northeast of the center remain unchanged in the analysis due to lack of radar observations in that area. Similarly, a comparison between the derived radar reflectivity fields from the CNTL and Exp-Ref tests also suggests the positive impact of reflectivity assimilation on organizing precipitation bands and defining the eyewall structure (Figs. 2c, and 2d).

To show the changes in the vertical structures resulting from reflectivity assimilation, vertical cross sections of TPMR and CNTL and Exp-Ref through the hurricane eye (along line PQ in Fig. 2b at the latitude of 34.7°N) are given in Figs. 3a and 3b. It is obvious that the CNTL run predicts a large amount of precipitation (with a maximum value of about 2.5 g kg\(^{-1}\)) near 6 km while radar observations show strong reflectivity areas near the surface near the center (which is also close to the radar station at Morehead City, North Carolina; Fig. 3e). With the reflectivity data assimilation, the maximum TPMR regions near the hurricane center have been shifted downward to the surface. Another outstanding contrast between Figs. 3a and 3b is the magnitude of TPMR. The maximum value TPMR in the eyewall is reduced to between 0.6 and 0.8 g kg\(^{-1}\) after the reflectivity assimilation cycles. There is a similar impact on the derived radar reflectivity fields from the reflectivity assimilation (Figs. 3c, and 3d). In regions far from the hurricane center, the corrections are also notable, though not as remarkable as those near the hurricane center because of the missing radar data at the bottom of the storms due to the long distances from the radar stations. Exp-Vr also changes the storm microphysical structures (not shown). However, compared to those from Exp-Ref, these changes are much smaller.

Significant changes in the magnitude and distribution of wind speed also resulted from the radial velocity data assimilation. These changes can be seen clearly by comparing the wind fields at 2 km above the surface from CNTL (Fig. 4a) and Exp-Vr (Fig. 4b). The hurricane inner core is organized into a much tighter structure after the radial velocity data assimilation. Also, the maximum wind speed at this level increases by about 5–10 m s\(^{-1}\) and the area of wind speed exceeding 50 m s\(^{-1}\) expands substantially in Exp-Vr. The surface wind field is also modified. Although the magnitude of the surface wind speed is only moderately greater (~5 m s\(^{-1}\)), the structure of the inner core in Exp-Vr (Fig. 5b) is much improved relative to that in CNTL (Fig. 5a). Both runs display asymmetry in the surface wind distribution with the high wind speed on the right side of the hurricane track, in a general agreement with the observed surface wind composite (Fig. 5c) constructed using various data sources (Powell et al. 1998), but the more compact inner-core structure in Exp-Vr compares much better with the observations than that in CNTL. The reader is cautioned that the observed surface wind composite (e.g., Fig. 5c) shows the average of observed winds for

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
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<tbody>
<tr>
<td>CNTL</td>
<td>No radar data assimilation</td>
</tr>
<tr>
<td>Exp-Ref</td>
<td>Radar reflectivity data assimilation only</td>
</tr>
<tr>
<td>Exp-Vr</td>
<td>Radar radial velocity data assimilation only</td>
</tr>
<tr>
<td>Exp-All</td>
<td>Radar reflectivity and radial velocity data assimilated at the same time</td>
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TABLE 1. Description of the radar data assimilation experiments.
a 3-h period around the landfall time, whereas the analyses from our experiments depict the wind fields at 1600 UTC. Of note is that both tests underestimate the hurricane intensity. Possible reasons are under investigation at NRL (e.g., Jin et al. 2007), but this is out of the scope of the current study.

The vertical cross section along line PQ (see Fig. 2b) is also constructed for the horizontal wind

![Fig. 2. (a) Horizontal cross section of TPMR (g kg\(^{-1}\)) at 3 km above the surface from the COAMPS CNTL run valid for 1600 UTC 18 Sep; (b) as in (a), except for the retrieved field from radar reflectivity observations from the Exp-Ref experiment. The thin black line indicates the location of the vertical cross section shown in Fig. 3; (c) As in (a), except for the calculated radar reflectivity fields (dB); (d) as in (b), except for the calculated radar reflectivity fields; (e) Observed radar reflectivity (dB) at the same level and valid for the same time as in (a).]
fields to illustrate the impact of the radial velocity assimilation on the hurricane's vertical structure. The wind speed in Exp-Vr increases by 5 m s\(^{-1}\) on both the east and west sides of the eye (Fig. 6a versus Fig. 6b).

Corresponding to the tighter inner-core structure in Exp-Vr seen in the horizontal cross sections, there is also a large gradient in wind speed across the eyewall on the east side (see Fig. 6b), and the vertical tilting

![Fig. 3. As in Fig. 2, except for a vertical cross section along 34.7°N through the hurricane eye (along line PQ in Fig. 2b).](image-url)
of the eyewall on the west side in CNTL (see Fig. 6a) is reduced to a large extent in Exp-Vr. The storm has been intensified by the data assimilation to near the strength of a category 2 hurricane. The radar reflectivity data assimilation changes the wind structures in the analysis fields only slightly and the wind fields from Exp-Ref are not discussed here.

Impact on forecasts. After the last data assimilation cycle at 1600 UTC, a 24-h forecast was launched from each experiment, which means that the CNTL run simply continued from the previous run, whereas the other three experiments (see Table 1) started from the analysis fields as the initial conditions for the subsequent 24-h forecasts. The surface wind speed and sea level pressure (SLP) from the 2-h forecasts are given in Fig. 7, while Fig. 8 shows the predicted composite radar reflectivity (the maximum radar reflectivity in a column) fields and the horizontal wind speed at 2.0 km above the surface at the same time. For comparison, the observed composite radar reflectivity and the horizontal wind speed retrieved using the 3.5DVAR algorithm at the same level and at the same time are given in Fig. 9. Correlation coefficients (Corr) and root-mean-square errors (rmse) between the predicted composite reflectivity and the observed field are calculated for each of these four experiments and shown in Figs. 8a–d. These statistical scores are calculated at model grid points inside the study domain.

As in the CNTL forecast over the previous hours, CNTL continues to underpredict the hurricane intensity indicated by the horizontal wind speeds at and above the surface and the minimal SLP (Fig. 7a). The radar reflectivity forecasts from CNTL (Fig. 8a), however, are much higher compared to the observed fields in Fig. 9. The overprediction of the reflectivity fields of CNTL is effectively corrected by the reflectivity data assimilation in Exp-Ref so that the reflectivity forecasts in Exp-Ref are significantly adjusted in magnitude toward the observations with an rmse reduction of 2.52 dBZ (Fig. 8b). The improvement in the inner-core structures and the rainbands from Exp-Ref, however, is not apparent. It is found that improvements in the hurricane wind structures by the reflectivity data assimilation are basically negligible (Fig. 7b). If these two facts above are related to each other, one could expect that the organization of rainbands in hurricanes is mainly controlled by dynamical processes, as suggested by earlier studies (e.g., Willoughby 1978). This has also been indicated here by the radial velocity data assimilation experiment.

The forecasts from Exp-Vr show remarkable improvements in the intensity and structure of the hurricane manifest in the well-organized hurricane eye with stronger horizontal gradients in SLP and higher wind speed at and above the surface (see Fig. 7c). Compared with the observed minimal SLP of 957 hPa at 1800 UTC (see Fig. 13), the minimal SLP of 964 hPa from Exp-Vr is about 14 hPa better than the minimal SLP of 978 hPa from CNTL (Fig. 7a). The rainbands in the Exp-Vr forecasts (Fig. 8c) appear to be much better organized and closer to the observations near the eyewall than those in CNTL and Exp-Ref. The magnitudes of the predicted radar reflectivity of these rainbands, however, do not change much from those in the CNTL forecasts, especially in the outer rainbands, as seen from the Corr and rmse numbers in Figs. 8a and 8c. Most of the data assimilation impact from Exp-Ref and Exp-Vr are preserved in the combined data assimilation forecasts, the Exp-All.
experiment, in which the wind structures (Fig. 7d) are basically similar to those from Exp-Vr while the predicted radar reflectivity of the rainbands (Fig. 8d) is much improved, with an rmse reduction of 4.96 dBZ and a Corr increase of 0.21. Exp-All has overall the best results, compared to Exp-Ref and Exp-Vr. However, if one considers the contributions from reflectivity and radial velocity data assimilations separately, the impacts from the radial velocity data are stronger and more important than those from the reflectivity data because the radial velocity data assimilation not only changes the whole dynamical structures of the hurricane but also reorganizes the rainbands.

The radar data assimilation moves the predicted hurricane center closer to the observed location (Fig. 7). The improvement in the TC location is most evident from the forecasts of Exp-Vr, and Exp-All retains the improved locations. Although track forecast improvements were not the primary objective of this study, the results strongly imply that improvements in the intensity and structure forecasts may also improve the track prediction. In this study, we examine only several hours of the hurricane center locations after landfall, and the improvement in hurricane track prediction is not significant. Further studies for more than one case with longer forecast durations using airborne Doppler radar data assimilation will be needed to assess the potential for improving track predictions.

Additionally, the impact of radar data assimilation on the wind forecasts can be examined by calculating the Doppler radial velocities from the model forecast three-dimensional winds \((u, v, w)\) at radar observa-
FIG. 7. Surface wind speed (m s$^{-1}$, shaded) and sea level pressure (hPa, contoured at 2 hPa) from the model forecasts at 2 h after the data assimilation (valid for 1800 UTC) from (a) CNTL, (b) Exp-Ref, (c) Exp-Vr, and (d) Exp-All. The hurricane symbol indicates the approximate location of the observed hurricane center.

tional grid points and then comparing them with observed radar radial velocity. Figure 10 gives the calculated Doppler radial velocities from the wind forecasts of CNTL and Exp-Vr (which has the best wind forecast improvements) along with the observations from the Morehead City radar at the lowest radar elevation angle (0.48°). Correlation coefficients between the predicted Doppler radial velocities and the observations are calculated for both CNTL and Exp-Vr for all five forecast hours and given in Fig. 10. These scores are calculated at radar observational grid points on a radar conical surface. The radial velocity data assimilation in Exp-Vr not only improves the magnitude of the calculated radial velocity in the forecasts but also changes the locations of both the maximum and minimum radial velocity and moves them closer to the observations. Correlations between the Exp-Vr radial velocity and that observed are about 6%–7% higher than between CNTL and that observed at the first 1 h after the data assimilation. The improvement in the correlation persists through the first 5 h (see Fig. 10). This means that both the intensity and the distribution (and hence the hurricane center location) of the wind circulations from Exp-Vr forecasts have been improved. Verifications have been done for all 14 radar elevation angles (from 0.48° to 19.5°), and the results (not shown here) illustrate improvements through all these levels. It is also found that the improvement increases as the radar elevation angle goes up. It should be pointed out that this comparison is done on radar scan surfaces with positive elevation angles. Therefore, this is a forecast verification of three-dimensional winds rather than just horizontal winds, particularly at higher radar elevation angles.

To study the impact of radar data assimilation on the prediction of inland flooding during and after the hurricane landfall, forecasts of 24-h accumulated precipitation (valid at 1200 UTC 19 September) from CNTL and Exp-All are examined and given
Fig. 8. As in Fig. 7, except for composite reflectivity (dBZ, shaded) and horizontal wind speed (m s$^{-1}$, contoured at 5 m s$^{-1}$ intervals) at 2 km above the surface. Corr and rmse of composite reflectivity forecasts verified against the observations (shown in Fig. 9) are also calculated and shown for each experiment.

in Figs. 11a and 11b, respectively, along with observations shown in Fig. 11c. Equitable threat scores (EQTS) of the precipitation forecasts are calculated as a function of precipitation amounts for these two experiments and given in Fig. 12. The 24-h precipitation observations are obtained from the National Centers for Environmental Prediction (NCEP) Stage IV precipitation analyses (Baldwin and Mitchell 1996; Lin and Mitchell 2005). Exp-All improves precipitation forecasts for all precipitation amounts, with the largest improvement for the precipitation amounts of 25–50 mm. This largest improvement in precipitation forecasts mainly occurs along the path of the inner-core region during the hurricane landfall, where significant improvements in hurricane dynamical structures by radar data assimilation have been observed. The precipitation band along the border of North Carolina and South Carolina (mainly produced by the hurricane spiral rainbands), however, was not well predicted.

Fig. 9. Observed composite reflectivity (dBZ, shaded) at 1800 UTC and retrieved horizontal wind speed (m s$^{-1}$, contoured at 5 m s$^{-1}$ intervals) retrieved from the radar observations at 2 km above the surface.
Fig. 10. Radial velocity (m s⁻¹) computed from the model forecasts of three-dimensional winds displayed at the Morehead city WSR-88D radar with an elevation angle of 0.48° compared with the radar observations from 1 to 5 h after the data assimilation. (left) The results from the CNTL run, (middle) from the Exp-Vr run, and (right) the observations. The correlations shown in the figures are calculated between the forecast radial velocity and the observed.
Fig. 12. Equitable threat scores of the 24-h accumulated precipitation forecasts from CNTL and Exp-All (shown in Figs. 11a and 11b, respectively) verified against NCEP Stage IV precipitation analyses (shown in Fig. 11c) at 1200 UTC 19 Sep 2003.

Fig. 13. Time series of surface maximum wind speed and the hurricane central SLP from the model forecasts verified against the NHC best track data.

by Exp-All. The reason is not clear and further investigation is needed.

Finally, Fig. 13 displays the predicted maximum surface winds and hurricane minimum SLP verified against the National Hurricane Center (NHC) best-track data for the time period before the major portion of the storm moved away from the study domain. Because the results from Exp-Ref and Exp-All are very close to those from CNTL and Exp-Vr, respectively, they are omitted in Fig. 13. There are substantial improvements in the hurricane intensity forecast from the radial velocity data assimilation, with a maximum surface wind speed increase of about 5 m s\(^{-1}\) and a minimum SLP decrease of about 14 hPa. It is also found that the improvements become smaller after 5 h of forecast. This could be due to the rapid change in hurricane structures and intensity during and after the landfall, which may quickly reduce the impact of radar data assimilation.
SUMMARY. In this study, we examine the capability of improving hurricane intensity and structure analyses and forecasts by assimilating radar observations into a mesoscale NWP model. Hurricane Isabel at landfall near Drum Inlet of North Carolina on 18 September 2003 was selected for this study. Radar observations of reflectivity and Doppler radial velocity from five WSR-88D radars in the landfall area during the hurricane landfall period were collected and assimilated into COAMPS using a variational approach. Four experiments have been conducted: the control run, the run with reflectivity assimilation only, the run with radial velocity assimilation only, and the run with combined reflectivity and radial velocity assimilation. In the data assimilation experiments, four hourly data assimilation cycles were carried out before a 24-h forecast was launched at 1600 UTC. The analyses and forecasts from these experiments have been analyzed and verified against radar observations, NCEP Stage IV precipitation analyses, and NHC best-track data to assess the values of the assimilated radar data for hurricane predictions. The following are highlights of this study:

1) The reflectivity data assimilation algorithm successfully retrieves the three-dimensional precipitation fields from radar observations and assimilates them into the model initial fields. It effectively corrects the overpredicted intensity and coverage of the rainbands by the control run. The impact on the hurricane intensity (i.e., wind speed) and dynamical structures (i.e., inner core), however, is marginal.

2) The radial velocity data assimilation, on the other hand, exhibits a remarkable impact on the analyses and forecasts of hurricane intensity and dynamical structures. It not only changes the three-dimensional dynamical structures but also reorganizes the rainbands of the hurricane. This test demonstrates the improvement of model dynamical fields directly from assimilating radial velocity data. Compared to the reflectivity data assimilation (Exp-Ref), the radial velocity data assimilation (Exp-Vr) appears more important for hurricane intensity and structure forecasts.

3) Overall, Exp-All provides the best forecasts among all of the experiments because it combines the major benefits from both reflectivity and radial velocity data assimilations. The encouraging indication from this experiment is that the two types of data complement each other in the processes of improving model initial fields and forecasts.

4) The hurricane center locations in the forecasts from Exp-Vr and Exp-All are also improved. While this may not be a significant issue for the prediction of hurricane location changes during just a few hours of landfall, it suggests that radar data assimilation may also have a positive impact on hurricane track predictions. Further studies should be conducted using airborne Doppler radar data to investigate the impact of radar data assimilation on hurricane track forecasts over a longer period.

5) The radar data assimilation shows an overall improvement in 24-h precipitation forecasts. Precipitation forecasts along the path of the inner-core region during the hurricane landfall are improved the most. This could be related to the improved dynamical structures in the inner-core region due to the radial velocity data assimilation.

This study illustrates both the impacts of radar data on hurricane intensity and structure prediction and the effectiveness of the data assimilation procedures employed in this study. The improved forecasts can provide valuable mesoscale guidance for preparation, damage mitigation, and recovery efforts for inland flooding and strong surface winds during landfall and postlandfall periods. This study demonstrates an important synergy between observations/analyses and forecasts in understanding the dynamical and physical processes inside the storms during and after landfall. Furthermore, this study indicates the potential for improving hurricane intensity and structure forecasts using radar data assimilation when more airborne and spaceborne radar data are becoming available for hurricane studies. It should be noted that the results from this study are from one case study only and quite preliminary because radar data assimilation for hurricane intensity and structure forecasts is a relatively new research area. Many technical and scientific challenges remain. Further studies will be needed in the future for hurricanes at various stages so that a more complete and better understanding of the impacts of radar data assimilation on hurricane predictions can be achieved.

ACKNOWLEDGMENTS. The authors would like to thank Dr. Qin Xu of the National Severe Storms Laboratory for insightful discussions of this study. Thanks also go to scientists of the Naval Research Laboratory, Mr. John Cook, Mr. Mike Frost, Dr. James Doyle, Dr. Rich Hodur, and Dr. William Thompson for their help and support for this work. Discussions with Dr. Paul Harasti of the University...
After the radar reflectivity data have been interpolated onto model grid points, the model microphysical fields are then updated using the information from the observed radar reflectivity. The first step is to compute the radar reflectivity of the background fields $Z_b$ via the relation

$$Z_b = 10 \times \log \left( a \, M_{rh}^{b} + a \, M_{sh}^{b} + a \, M_{hh}^{b} \right),$$  \hspace{1cm} (A1)$$

where $Z_b$ is expressed in units of dBZ. Here, $M_{rh}$, $M_{sh}$, and $M_{hh}$ represent the rain, snow, and hail liquid water content from the background fields, respectively, expressed in units of g m$^{-3}$, and $a$, $a$, $b$, $b$, and $b$ are empirical constants determined by Douglas (1964)$^{1}$ by curve fitting the observed variables to this general analytic relationship between the reflectivity factor and liquid water content. Please also see Zhao et al. (2006, p. 508) for the values of these constants. It should be mentioned that the real values of these parameters may vary from case to case, depending on the real droplet size distributions inside the storms. Errors may have been generated in the estimation of $Z_b$ from using the empirical constants. These errors are included in the background error covariance. Because the S- and C-band radars utilized for this research are not sensitive to the detection of cloud liquid water droplets and cloud ice crystals, these hydrometeor types are not included in (A1). We assume that the relationships for rain and hail reported by Douglas are also approximately valid for drizzle and graupel, respectively. This assumption is partially supported by Hagen and Yuter (2003) who determined a reflectivity–liquid water content relationship for drizzle and rain that is very similar to the relationship for rain given by Douglas (1964). Equation (A1) is also used in converting the model hydrometeor fields into radar reflectivity for forecast verification.

The radar reflectivity analysis $Z_a$ is then obtained by minimizing the cost function

$$J_z = \left[ w_z (Z_a - Z_o)^2 \right] + \left[ w_o (Z_o - Z_o) \right],$$  \hspace{1cm} (A2)$$

where $Z_a$, $Z_o$, and $Z_o$ are state vectors of $Z_a$, $Z_o$, and $Z_o$, respectively, $Z_o$ is the observed radar reflectivity, $[\, ]$ denotes summation over all model grid points, and $w_z$ and $w_o$ are the weights given by the inverses of the background and observation error variances, respectively. No additional attenuation correction is done beyond the built-in automated attenuation correction for the level II data. Fortunately, the data we used for this case study are from S-band radars and the observed radar reflectivity in most areas of the storms is less than 45 dBZ (see Fig. 9). Therefore, the errors caused by attenuation should be relatively small and are accounted for in the observational error covariance. In this study, we assume that the observational error variance is 1 (dBZ)$^2$, and therefore $w_i = 1.0$ (dBZ)$^{-2}$; $w_o$ is computed adaptively (without tuning) to normalize and balance the cost function in the same way as described in the appendix of Zhao et al. (2006). A combination of equations given by Keeler and Passarelli (1990) and Keeler and Ellis (2000) demonstrate that the instrumentation error component of the observational error variance of weather echo power (and reflectivity) is indeed $\sim 1$ (dB)$^2$; however, other non-Gaussian contributors to the observational variance, such as attenuation and the contamination from nonmeteorological targets, as well as the representativeness error component (Daley 1991), are difficult to quantify and are thus a subject for future research. The assumed observation error variance is much smaller than the background error variance (typical value $\sim 100$ (dBZ)$^2$); therefore, the analysis performed by minimizing the cost function in (A2) basically nudges the analysis toward the observations.

After the above analysis step, a gain factor is computed from the reflectivity increment,

$$c = 10^{\frac{(Z_o-Z_a)}{10}}.$$  \hspace{1cm} (A3)$$

Then, the model hydrometeor fields are updated using the following equations:

$$M_{rh} = c^{M_{rh}} \hspace{1cm} (A4)$$

$$M_{sh} = c^{M_{sh}} \hspace{1cm} (A5)$$

$$M_{hh} = c^{M_{hh}}.$$  \hspace{1cm} (A6)$$

By using (A4)–(A6), we assume that the hydrometeor fields in the analyses have the same spatial distri-

\hspace{1cm} $^{1}$ Also summarized in Battan (1973, p. 88).
value of mixing ratio of rain below the melting level precipitation. In this case, we first add a very small points where the observed reflectivity indicates the presence of precipitation but the model predicts no precipitation and snow above to the background fields. Then, the above procedures are performed to update the background fields.

REFERENCES


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