The Influence of Airborne Doppler Radar Data Quality on Numerical Simulations of a Tropical Cyclone

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ABSTRACT

The impact of airborne Doppler radar data assimilation on improving numerical simulations of tropical cyclones (TCs) has been well recognized. However, the influence of radar data quality on the numerical simulation of tropical cyclones has not been given much attention. It is commonly assumed that higher quality radar data would be more beneficial to numerical simulations of TCs. This study examines the impact of the radar data quality control on assimilation of the airborne Doppler radar reflectivity and radial velocity observations in a numerical simulation of Typhoon Jangmi (2008). It is found that the quality of radar data has a strong influence on the numerical simulation of Typhoon Jangmi in terms of its track, intensity, and precipitation structures. Specifically, results suggest that a trade-off between the data quality and data coverage is necessary for different purposes in practical applications, as the higher quality data contribute to intensity forecast improvements, whereas data of lower quality but having better coverage are more beneficial to accurate track forecasting.

1. Introduction

Tropical cyclones (TCs) spend most of their lifetimes over oceans where the conventional observations are usually very sparse. At present, Doppler radar is one of the major remote sensing instruments that have the ability to provide very high spatial and temporal resolution three-dimensional observations of TCs (Marks and Houze 1987; Griffin et al. 1992; Reasor et al. 2000; Zhao et al. 2008; Murillo et al. 2011). Owing to its mobility, airborne Doppler radar is capable of sampling the detailed TC inner-core structural features at a spatial and temporal resolution of less than 1 km and 1 h, respectively (Marks and Houze 1987; Colle and Mass 2000; Reasor et al. 2000; Houze et al. 2007). Previous studies indicate that assimilating these Doppler radar observations into numerical weather prediction (NWP) models plays an important role in improving the numerical simulation and prediction of TCs (Pu et al. 2009; Xiao et al. 2009; Zhang et al. 2009). However, besides the influence of data assimilation algorithms themselves, the effectiveness of the data assimilation is often affected by the quality and coverage of the Doppler radar observations. Commonly, meteorological Doppler radar data are not only contaminated by nonweather returns such as second-trip, sidelobe clutter, ground clutter, and low signal-to-noise returns, but are also limited to the area with precipitation, resulting in fragmented data coverage. Traditionally, removing these nonmeteorological artifacts from airborne Doppler radar data is an interactive and labor-intensive process and it is not suitable for real-time radar data assimilation. With the increasing availability of TC observations from coastal and airborne Doppler radars in near–real time for scientific research

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and operational applications (Griffin et al. 1992; Sun and Crook 1997; Bielli and Roux 1999; Gao et al. 2001; Zhang et al. 2005; Zhao et al. 2008), there is a demand for automated quality control of Doppler radar data. By now, a variety of algorithms have been developed for automatic removal of clutter and nonmeteorological echoes (Steiner and Smith 2002; Zhang et al. 2004; Dixon et al. 2005; Friedrich et al. 2006; Lakshmanan et al. 2007; Gamache et al. 2008; Wolff et al. 2009). For instance, Friedrich et al. (2006) proposed a Doppler radar data quality control concept. In their studies, several quality indexes are used to represent the different levels of observed radar data quality. As for the airborne Doppler radar measurements, researchers at the Hurricane Research Division (HRD) and the National Center for Atmospheric Research (NCAR) have developed automatic quality control algorithms for the National Oceanic and Atmospheric Association (NOAA) P-3 Tail-Doppler Radar (TDR; Gamache et al. 2008) and the NCAR Electra Doppler Radar (ELDORA; Wolff et al. 2009), respectively. These improvements make real-time dual-Doppler analysis possible. However, there have been no further studies about how these different quality-controlled radar data influence the data assimilation results as well as the subsequent numerical simulations and predictions. Therefore, the objective of this paper is to evaluate the influence of NCAR ELDORA data that are processed by different levels of automated quality control procedures on the numerical simulation and prediction of Typhoon Jangmi (2008) that occurred over the northwestern Pacific Ocean in 2008. To achieve this goal, a set of numerical experiments is conducted with the Weather Research and Forecasting Model (WRF) Advanced Research version (ARW) and its three-dimensional variational data assimilation (3DVAR) system. The influence of the radar data quality on the numerical simulation and prediction of Typhoon Jangmi is examined by comparing the assimilation results with various data quality control experiments.

This paper is organized as follows. Radar data processing and quality controls are introduced in section 2. The numerical model system and experimental designs are briefly described in section 3. The impact of the data quality on the numerical simulations of Typhoon Jangmi (2008) is examined in section 4. Summary and concluding remarks are presented in section 5.

2. ELDORA radar data and quality control

The airborne Doppler radar reflectivity and radial velocity observations were obtained from the NCAR ELDORA on board the Naval Research Laboratory's (NRL) P-3 research aircrafts during The Observing System Research and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign (T-PARC 2008) and Office of Naval Research's (ONR's) Tropical Cyclone Structure (TCS-08) field experiments. The case selected for this study is Typhoon Jangmi, which occurred over the northwestern Pacific Ocean during September 2008.

Before the radar data are ingested into the numerical model, the raw data are first preprocessed by an automatic quality control procedure and then interpolated onto model grid points. In this study the automatic data quality control procedures are accomplished after editing scripts in the SOLO software package (Oye et al. 1995). By setting several different threshold values, the noise, earth surface, second-trip returns, sidelobes, and different degrees of nonmeteorological echoes are removed during the quality control process. The details of the ELDORA data quality control procedure can be found in Wolff et al. (2009). Based on the degree of quality requirements, three different data quality thresholds are used for airborne Doppler radar data quality control in this study: low, medium, and high levels. After the automatic quality control, the edited radar data are interpolated from the radar coordinate into Cartesian coordinates.

Figure 1 shows the samples of quality-controlled airborne Doppler radar reflectivity and radial velocity at the height level of 0.5 km with different data quality levels: low (Figs. 1a,d), medium (Figs. 1b,e), and high (Figs. 1c,f). Figure 1 clearly shows that there are obvious discrepancies between these different quality-controlled observations for reflectivity and radial velocity measurements. The higher the threshold level, the more data (both meteorological and nonmeteorological) are removed, resulting in smaller area data overages. After interpolating the data to model grids, the horizontal and vertical resolutions of the data are 1 and 0.5 km, respectively. For Typhoon Jamgmi (2008), data are available from the surface up to the 12-km-height level, but most of the radar data are located between altitudes of 0.5 and 10 km.

Additional quality controls are executed in the WRF 3DVAR analysis. The observations will be eliminated if the difference between the observation and the value from background (first guess field) is larger than 5 times the observational error specified in section 3.

3. Numerical experiments

The WRF ARW (Skamarock et al. 2005) and its 3DVAR system (Barker et al. 2004) are employed. The simulations are performed with two-way interactive nested domains with horizontal grid spacings of 27, 9, and 3 km at 31 vertical levels. The domain sizes are 237×187, 394×307, and 505×406 for the 27-, 9-, and 3-km domains, respectively. The WRF is initialized using the

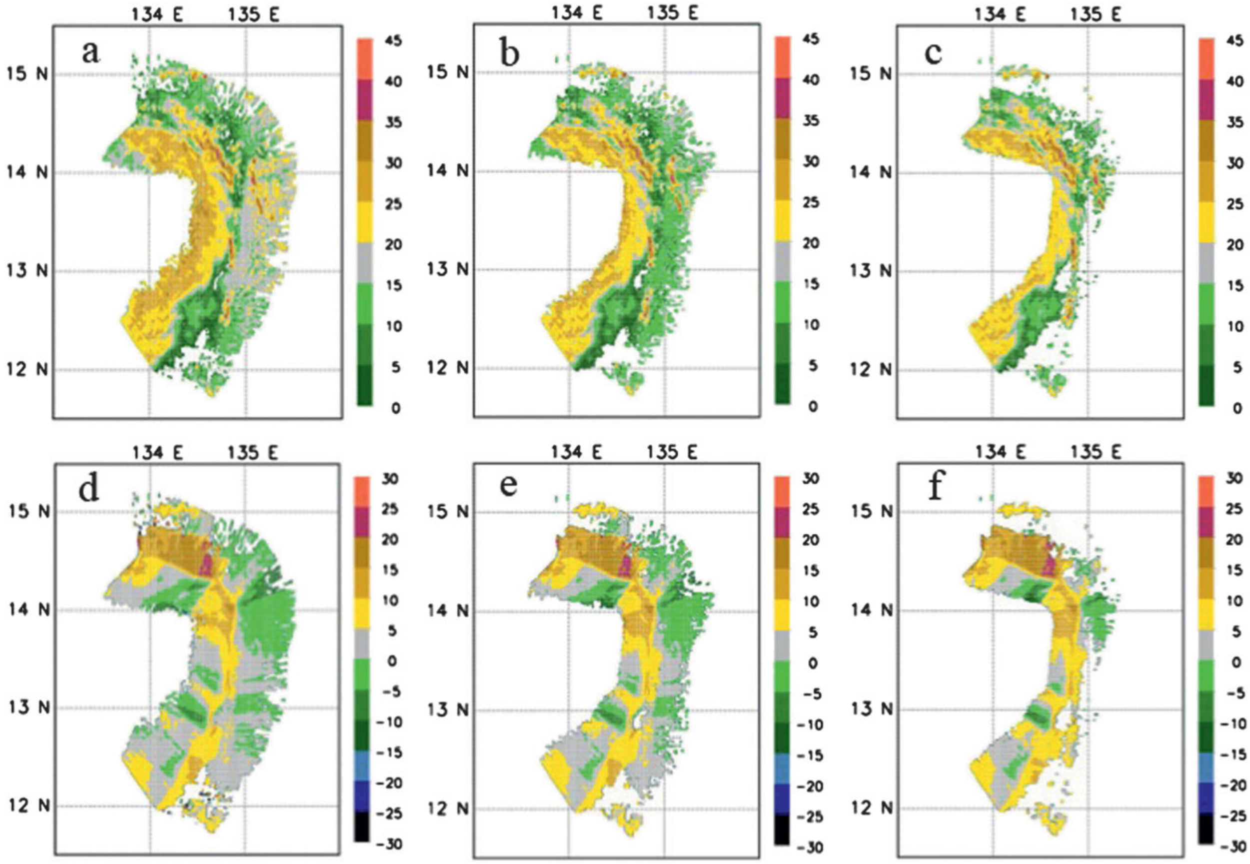


FIG. 1. (a)–(c) Radar reflectivity (dBZ) and (d)–(f) radial velocity (m s^{-1}) at 0.5-km-height level with different QC levels around 0000 UTC 25 Sep 2008: (a),(d) low, (b),(e) medium, and (c),(f) high.

National Centers for Environmental Prediction (NCEP) 1° × 1° Global Forecast System final (FNL) analysis, which also provides boundary conditions to the outer domain (27-km resolution) at 3-h intervals. The model physics options include the Purdue–Lin microphysical scheme, the Yonsei University (YSU) planetary boundary layer (PBL) scheme, the Kain–Fritsch cumulus parameterization, the longwave Rapid Radiative Transfer Model (RRTM), and the Dudhia shortwave parameterization model (see details in Skamarock et al. 2005). The cumulus parameterization is only applied on the 27- and 9-km domains.

Three data assimilation experiments are performed to examine the impact of various components of radar observations on the numerical simulation of Typhoon Jangmi:

Experiment 1—assimilation of radar reflectivity,
Experiment 2—assimilation of radar radial velocity, and
Experiment 3—assimilation of both radar reflectivity and radial velocity.

To evaluate the influence of different levels of radar data quality on the numerical simulation of Typhoon Jangmi (2008), in each experiment (experiments 1–3), three experimental configurations are conducted with the data quality set to low, medium and high levels as mentioned in section 2. Details of the experiments are summarized in Table 1.

For the control experiment, the model is initialized at 1800 UTC 24 September 2008 using NCEP FNL data;

TABLE 1. Summary of data assimilation experiments. RF represents the radar reflectivity, RV denotes the radar radial velocity, and 80%, 90%, and 99% denote the different levels of radar data quality (from low to high levels).

Expt name		Observations assimilated	Level of data quality
Expt 1	Expt 1.1	RF	Low
	Expt 1.2	RF	Medium
	Expt 1.3	RF	High
Expt 2	Expt 2.1	RV	Low
	Expt 2.2	RV	Medium
	Expt 2.3	RV	High
Expt 3	Expt 3.1	RF, RV	Low
	Expt 3.2	RF, RV	Medium
	Expt 3.3	RF, RV	High

then the WRF is integrated for a 30-h free forecast that ends at 0000 UTC 26 September 2008.

For data assimilation experiments, radar observations from one flight leg near 0000 UTC 25 September 2008 are assimilated in both 3- and 9-km grids domains. The first-guess field (background) is a 6-h model forecast starting at 1800 UTC 24 September 2008 from the control simulation. The background error covariance is generated using the so-called National Meteorological Center (NMC, now known as NCEP) method (Parrish and Derber 1992) at model grid resolutions over the same model domains. The samples used for background error statistics come from an ensemble forecasts with 20 model forecasts using different WRF physics options. To produce the increments of hydrometeors (e.g., rainwater mixing ratio) from assimilation of radar reflectivity, the total water-mixing ratio was chosen as a control variable for the background statistics (Xiao et al. 2007; Pu et al. 2009). Considering the fact that observation minus background correlation lengths for radar data are typically smaller than the scale lengths derived via the NMC method, a reduced length scale was used for the control variables in radar data assimilation.

To address the influence of the data quality on data assimilation and numerical simulations, various observational errors are used in different experiments according to the quality levels of the data assimilated in the experiments. Larger observational errors are assigned for the low-quality-level radar data, whereas smaller observational errors are specified for the high-level quality of radar data. Specifically, the observational errors of radar reflectivity (radial velocity) are assumed to 3, 2, and 1.5 dBZ (3, 2, and 1.5 m s^{-1}) for low-, medium-, and high-level quality control experiments, respectively. Through the minimization of the predefined cost function, a new analysis field is generated by the data assimilation and then the model initial conditions are replaced by the 3DVAR analyses. Boundary conditions are also updated accordingly. After that, the model is integrated with the new analysis fields and updated boundary conditions from 0000 UTC 25 September 2008 for a 24-h forecast that ends at 0000 UTC 26 September 2008.

4. Results

To examine the impact of data quality on analysis fields, Figs. 2a–c present the east–west cross section of analysis increments of temperature and water vapor through the center of Jangmi at the initial time of the experiments that assimilated radar reflectivity observations (viz., experiments 1.1, 1.2, and 1.3). There is no difference between these three experiments except for the quality of the radar reflectivity observations. Overall, the assimilation of radar

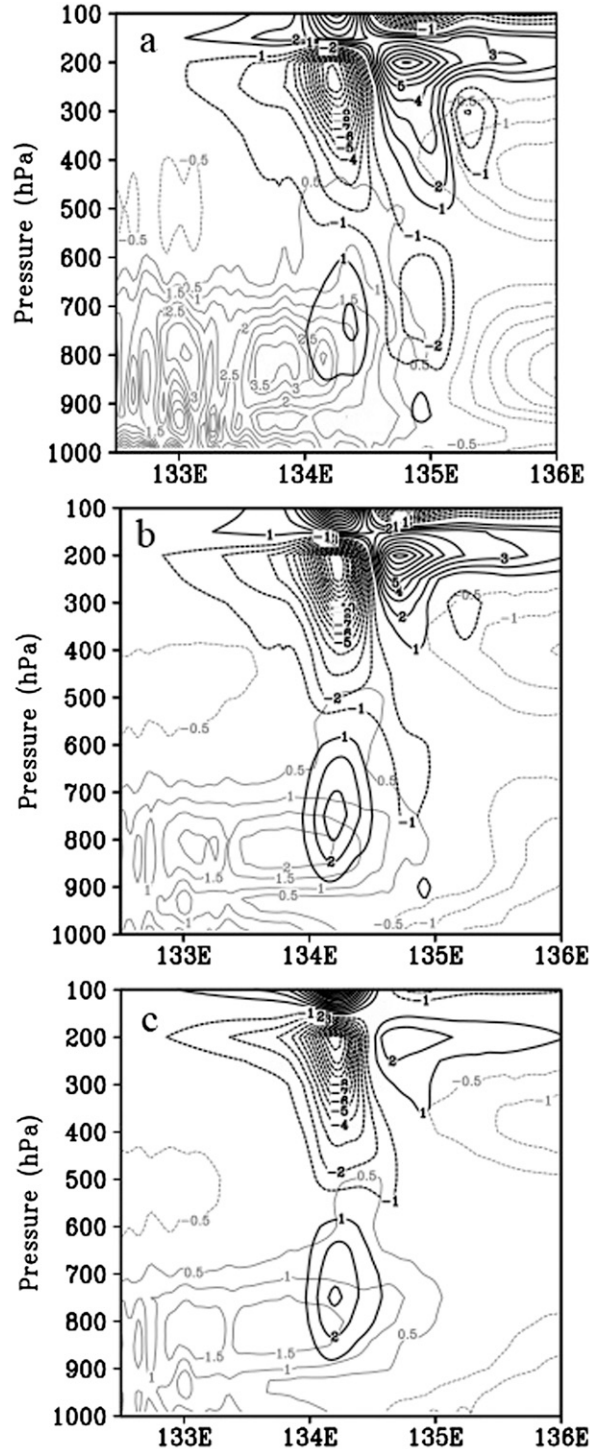


FIG. 2. East–west cross section through the center of Typhoon Jangmi for analysis increments of temperature [the black solid (dashed) lines represent positive (negative) values; K) and water vapor [the gray solid (dashed) lines represent positive (negative) values; g kg^{-1}], with assimilation of different quality-controlled radar reflectivity observations at 0000 UTC 25 Sep 2008: (a) low QC level (expt 1.1), (b) medium QC level (expt 1.2), and (c) high QC level (expt 1.3).

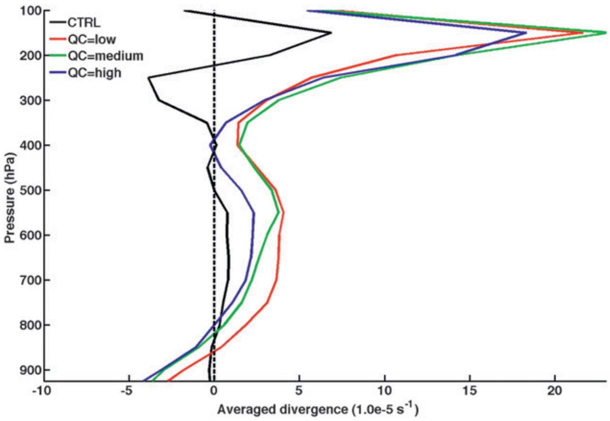


FIG. 3. Averaged divergence profiles over the area within a radius of 300 km around Jangmi's circulation center at 0000 UTC 25 Sep 2008 from the CTRL, expt 2.1 (low QC), expt 2.2 (medium QC), and expt 2.3 (high QC). The vertical axis denotes pressure levels. The horizontal axis represents the magnitudes of the divergence (10^{-5} s^{-1}).

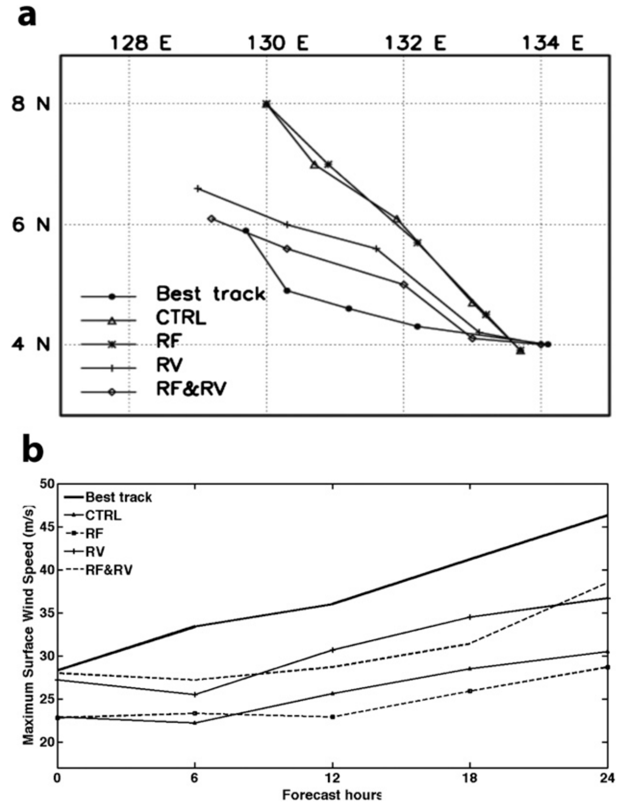


FIG. 4. Time evolution of (a) the storm track and (b) maximum surface wind (m s^{-1}) of Typhoon Jangmi from CTRL and experiments with assimilation of reflectivity only (RF), radial velocity only (RV), and both reflectivity and radial velocity (RF and RV), compared with the JTWC best-track data between 0000 UTC 25 Sep and 0000 UTC 26 Sep 2008. All experiments assimilated the data with the low QC level.

reflectivity data enhances the warm-core of Jangmi (centered near 134°E at the time) for the vertical levels below 600 hPa. However, with the different qualities of the data, the patterns of the temperature increments are different in three experiments. Specifically, with assimilation of the data at a low quality control (QC) level (experiment 1.1; see Fig. 2a), there are negative temperature increments that accompany the positive temperature increments near the vortex warm-core areas. With assimilation of the data at a medium QC level (experiment 1.2; see Fig. 2b), the negative temperature increments are much weaker than these in experiment 1.1. Assimilation of data at a high QC level (experiment 1.3; see Fig. 2c) completely eliminated the negative temperature increments near the vortex core area.

Analysis increments of the water vapor field show that the assimilation of radar reflectivity data wetted the Jangmi's vortex core area in most cases, specifically at the lower troposphere (below 600-hPa pressure level). It is believed that the moist conditions are commonly more favorable for the vortex to develop, while dry environment conditions could cause the vortex to decay (Pu and Zhang 2010). Discrepancies are seen in various experiments. Specifically, assimilation of the data at low QC levels has resulted in the largest analysis increments in the water vapor field. But, on the east side of the vortex, there are negative water vapor increments that could be evidence of the negative impact from the assimilation of lower quality of Doppler radar data (Fig. 2a). Fortunately, when the data at the high QC level were assimilated, these negative increments in the water vapor field were almost eliminated (Fig. 2c).

To illustrate the influence of the assimilation of various qualities of radar radial velocity measurements on the vortex inner-core structure, Fig. 3 shows averaged divergence profiles over the area within a radius of 300 km around Jangmi's circulation center at 0000 UTC 25 September 2008 from the control experiment (CTRL) and experiments 2.1 (low QC), 2.2 (medium QC), and 2.3 (high QC). It is obvious that assimilation of radar radial velocity enhanced the low-level convergence and upper-level divergence of Jangmi. Compared with the results from other experiments, the assimilation of radial velocity measurements at high QC level enhanced the low-level convergence the most, confirming that high quality radar measurements may be more beneficial in improving the vortex inner-core structure.

Figure 4a compares track forecasts from the control experiment and experiments 1.1, 2.1, and 3.1 against the Joint Typhoon Warning Center (JTWC) best-track data. Figure 4a shows that assimilation of both radar reflectivity and radial velocity (experiment 3.1) leads to the largest improvements in the track forecast. The impact from the assimilation of the radial velocity (experiment

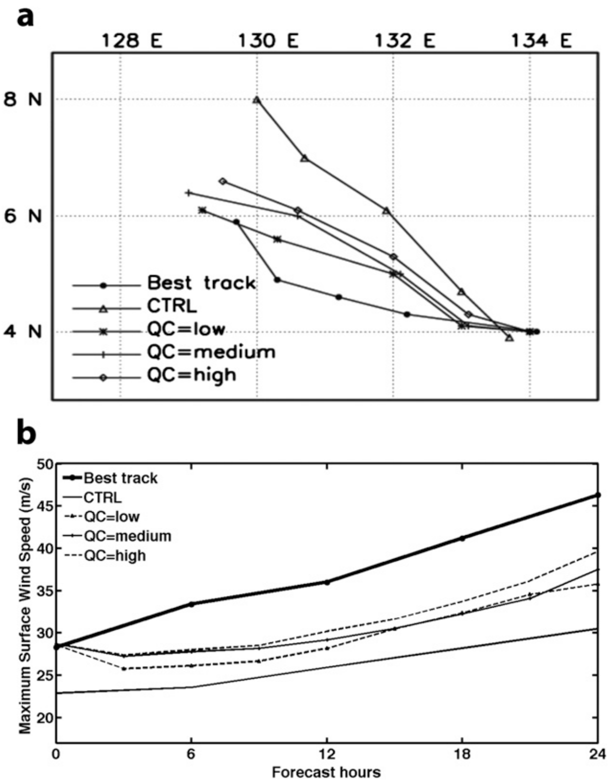


FIG. 5. Time evolution of (a) the storm track and (b) maximum surface wind (m s^{-1}) of Typhoon Jangmi from CTRL and experiments with assimilation of both the reflectivity and radial velocity under various quality levels of the data, compared with the JTWC best-track data between 0000 UTC 25 Sep and 0000 UTC 26 Sep 2008.

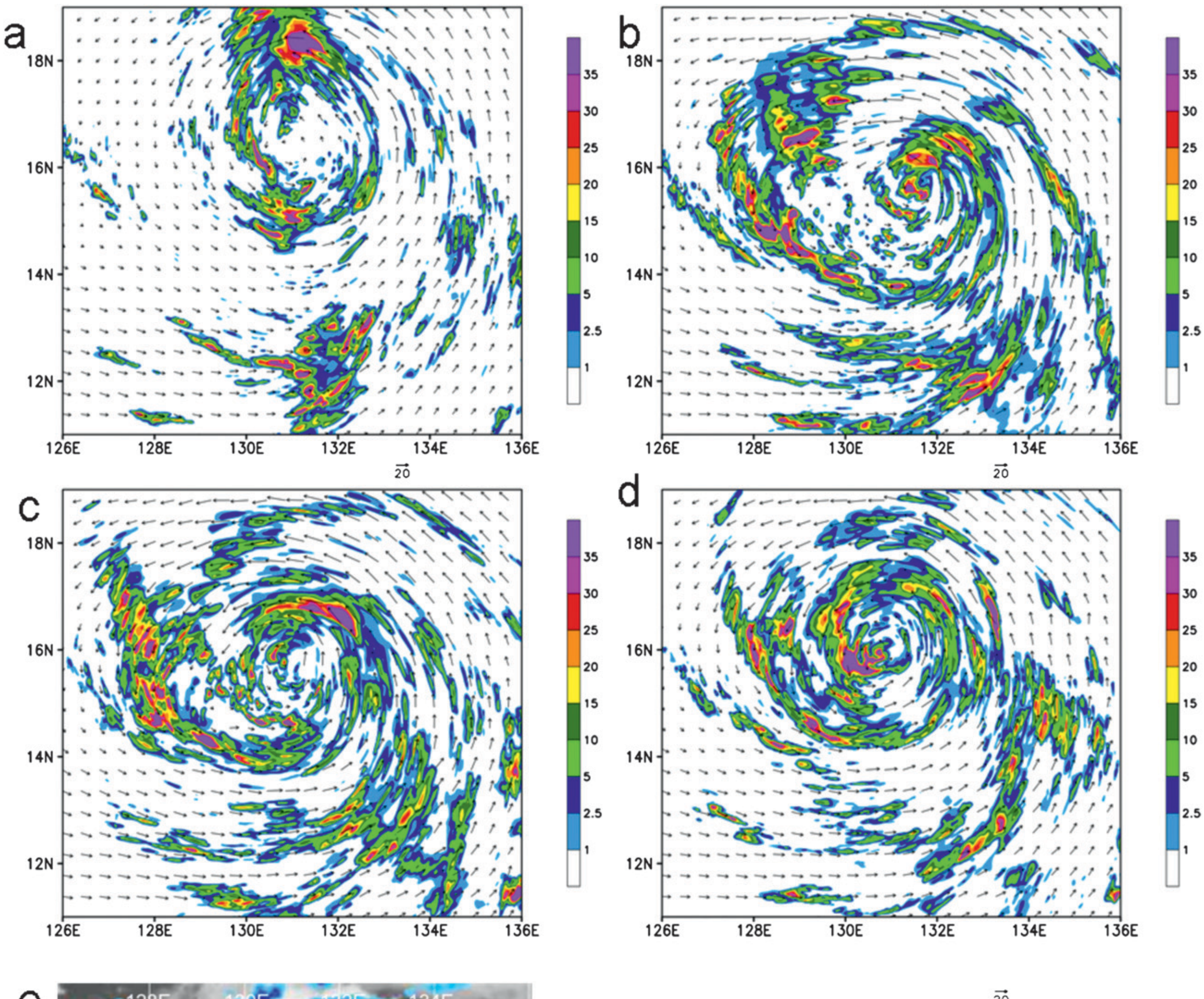
2.1) is also significant; however, the assimilation of radar reflectivity (experiment 1.1) only has a slight influence on track forecasts. Figure 4b shows the time series of the intensity forecasts. Compared with the best-track data, it is found that the assimilation of radial velocity makes significant improvements in the maximum surface wind simulation. Although the assimilation of reflectivity only has a positive influence over a short time period (in the first 9 h), the assimilation of both reflectivity and radial velocity results in the largest improvements in the intensity forecasts during both early and late phases. The overall results here are consistent with those of many previous studies (Xiao et al. 2007; Zhao and Jin 2008; Pu et al. 2009). Results from another two groups, namely experiments. 1.2, 2.2, and 3.2 and experiments 1.3, 2.3, and 3.3, yield similar conclusions.

To demonstrate the impact of the radar data quality control on the numerical simulation of Typhoon Jangmi, Fig. 5a shows the data impact of assimilating both radar reflectivity and radial velocity with various QC levels. Results indicate that, although the track forecasts are improved in all experiments after data assimilation, the assimilation of different quality-controlled radar data results in different track forecasts, especially in the last 12 h of the forecasts. Specifically, experiment 3.1 (low QC level) makes a better track forecast than do the other two data assimilation experiments. Meanwhile, the track forecast in Exp. 3.2 (medium QC level) is better than that in experiment 3.3 (high QC level). The results imply that the better data coverage may be more beneficial to the tropical cyclone track forecast than data quality.

The intensity forecasts are also compared with JTWC best-track data (Fig. 5b). The maximum surface wind speed simulation is improved in all experiments after data assimilation. Specifically, the highest quality data result in the largest improvement in the intensity forecast. Figure 6 shows the simulated hourly rain rate at 1700 UTC 25 September 2008 from the control experiment and various other experiments (Figs. 6a–d) that assimilated both reflectivity and radial velocity. It is clearly shown that the storm precipitation patterns are significantly different in various experiments. Comparing to the National Aeronautics and Space Administration (NASA) *Aqua* satellite rainfall observations (Fig. 6e), in general, data assimilation experiments reproduce more realistic structures of precipitation patterns. Specifically, the simulated storm center from experiment 3.1 (low QC level) is much closer to the JTWC best-track data than are those from the other two data assimilation experiments. The simulation from experiment 3.3 (high QC level) predicts a better-organized eyewall rainfall structure and intensity. Meanwhile, the simulated precipitation patterns to the south of the storm center near the inner-core regions are not as well predicted in experiment 3.1. These results indicate that the radar data quality has a strong influence on the intensity and precipitation predictions of Typhoon Jangmi.

5. Summary and concluding remarks

The impact of airborne Doppler radar data assimilation on improving the numerical simulations of tropical cyclones has been well recognized. However, the influence of radar data quality on the numerical simulation of tropical cyclones has not received significant attention in previous studies. This study examines the impact of the radar data quality control on the assimilation of NCAR ELDORA airborne Doppler radar reflectivity and radial velocity in numerical simulations of Typhoon Jangmi (2008) with the WRF and its 3DVAR system. Three groups of experiments are conducted with different levels of radar data quality control. It is found that assimilating different levels of quality-controlled airborne Doppler radar data into the WRF had a strong influence on the numerical simulation of Typhoon Jangmi (2008) in terms



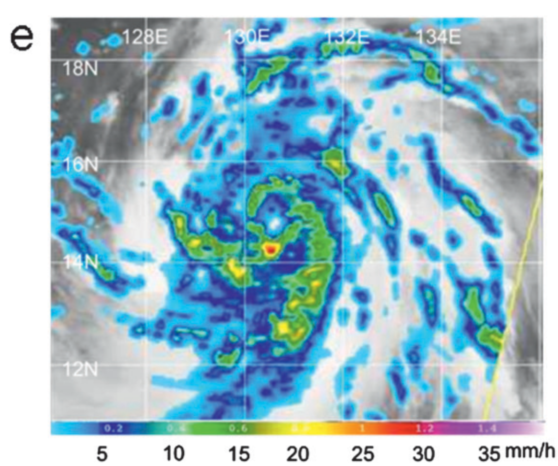


FIG. 6. The hourly rain rate (mm h^{-1}) from (a) CTRL and the experiments assimilating both reflectivity and radial velocity with different radar data qualities at 1700 UTC 25 Sep 2008: (b) low QC level (expt 3.1), (c) medium QC level (expt 3.2), and (d) high QC level (expt 3.3), compared with (e) NASA *Aqua* satellite observations at 1709 UTC 25 Sep. 2008. (Courtesy of the Naval Research Laboratory.)

of its track, intensity, and precipitation structures. Results from this study suggest that a trade-off between the radar data quality and data coverage is necessary in practical applications according to their different purposes. Although the high quality data contribute to the improved intensity forecast, lower quality data, but with better coverage, are beneficial to more accurate track forecasting. More case studies should be made in the future to help us develop more robust conclusions.

Numerical results from this study also indicate that forecast impacts from the assimilation of radar reflectivity data are smaller than those from the assimilation of radial velocity observations in almost all cases. This conclusion is similar to that from several previous studies (e.g., Xiao et al. 2007; Zhao and Jin 2008; Pu et al. 2009). However, there are some issues that should be mentioned here and addressed in future studies. First, the X-band ELDORA radar reflectivity observations are subject to significant attenuation in heavy rainfall areas. The attenuation poses an additional challenge for quality control, assimilation, and other applications (e.g., estimate rainfalls) of these reflective data (Xue et al. 2009). Earlier studies by Smyth and Illingworth (1998) have pointed out that the attenuation becomes increasingly more serious as the radar wavelength is reduced (e.g., to levels less than 10 cm). Recent studies by Park et al. (2005a,b), Snyder et al. (2010), and Lim et al. (2011) have all addressed the attenuation correction at X-band from the observation and application perspectives. They all proved that their attenuation correction algorithms have greatly improved the quality of reflectivity data. In light of their efforts, *results in this paper are limited by a lack of attenuation correction in the quality control algorithm*. Second, in the current WRF 3DVAR system, the radar reflectivity assimilation procedure is based on a warm-rain microphysical scheme that ignores ice processes. This factor could also limit the overall forecast impact from the assimilation of radar reflectivity data. Development and further improvement are necessary in future studies. Finally, advanced data assimilation methods, such as ensemble Kalman filter methods, offer the flexibility to perform the attenuation correction within the data assimilation procedure. For instance, using an ensemble square root Kalman filter, Xue et al. (2009) developed a new approach to dealing with attenuated radar reflectivity data in the data assimilation process with simulated data. Specifically, they built the attenuation correction into their data assimilation system by calculating the expected attenuation within the forward observation operators using the estimated atmospheric state. Tests with simulated reflectivity data from an X-band 3-cm wavelength radar for a supercell storm show that the attenuation correction was very effective. This work (Xue et al. 2009) sets a new direction for dealing with the observational errors and attenuation corrections in radar data assimilation. Thus, further investigation should be undertaken for the cases studied in this paper using ensemble Kalman filter methods in the near future.

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