Verification of a High-Resolution Model Forecast Using Airborne Doppler Radar Analysis during the Rapid Intensification of Hurricane Guillermo

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ABSTRACT

The NOAA Hurricane Research Division (HRD) P-3 aircraft provided airborne radar observations during the period of rapid intensification of Hurricane Guillermo on 2 August 1997. The inner core structure and evolution of Hurricane Guillermo (1997) over a 120 km by 120 km square area, centered on the storm, was observed by the P-3 aircraft during 10 flight legs at half-hour intervals during a 6-h period from 1800 UTC 2 August to 0000 UTC 3 August 1997. A high-resolution short-term model forecast initialized at 1800 UTC 2 August 1997 was made using the fifth-generation Pennsylvania State University–NCAR nonhydrostatic, two-way interactive, movable, triply nested grid Mesoscale Model (MM5). The weak vortex at the initial time in the NCEP analysis was replaced by a tropical storm–like vortex generated by a 4D variational data assimilation (4D-Var) vortex initialization experiment. The modeled Guillermo followed the observed track with less than a 12-km track error at any time during the 6-h forecast period. The modeled eye is smaller than the observed eye and the modeled vortex is more upright than shown by the radar analysis. The minimum pressure, maximum wind (intensity), and radial profile of tangential winds are close to the radar analysis after 2–3 h of model spinup. A spectral decomposition further reveals that (i) large differences between the model simulation and radar analysis of the asymmetric features are mostly caused by azimuthal phase errors; (ii) the wavenumber 1 component dominates the asymmetric features and remains stationary within the inner core region, as is also observed by airborne Doppler radar; and (iii) although being significantly different from radar analysis, the azimuthal phase of the wavenumber 1 component of modeled reflectivity does not vary greatly with time as the radar data suggest.

1. Introduction

Advances in radar technology allow oceanic hurricanes to be observed at very high resolutions. Airborne Doppler radars can observe hurricane near-core evolution at a spatial resolution of less than a few kilometers. Many interesting inner-core structural features have been observed by airborne Doppler radars, such as (i) concentric and/or double eyewalls, (ii) an outward sloping with height of the maximum of the tangential wind, (iii) a deep layer of radial inflow in the lower troposphere, (iv) discrete convective-scale bubbles of more intense upward motion, superimposed on the rising branch of the secondary circulation, and (v) convective-scale downdrafts located throughout and below the core of maximum precipitation in the eyewall (Marks and Houze 1984, 1987; Reasor et al. 2000; to cite a few). Temporal evolutions of these features are found to relate to the intensity change of tropical storms.

Numerical simulations of hurricanes have also shown considerable progress over the past 20–30 yr (Anthes 1972; Jones 1977; Liu et al. 1997; Zou and Xiao 2000; Zou et al. 2001; to cite a few). Many general features of a hurricane, such as the eye, eyewall, spiral rainband, and other typical inner-core structures, are reproducible with a high-resolution mesoscale model. Often, modeled reflectivity distribution compares favorably with radar analysis of a real hurricane. Only a snapshot of radar reflectivity, instead of the temporal evolution of reflectivity, is usually compared between model simulations and radar analysis. Thus, verification of a model simulation with radar-observed inner-core structures and their hourly temporal evolutions is still rare in the literature.

Temporal evolution of eye size, eyewall, low-level inflow, outward sloping maximum of symmetric tangential wind, as
well as the shape, the radial extent, and the azimuthal phase of rainbands, is case dependent and is closely related to intensity changes. Therefore, to assess the model performance in simulating hurricane evolution and to elucidate the problems associated with hurricane intensity forecasts, model simulations must be related to the inner-core structural details as illuminated by Doppler radar. This paper presents a detailed comparison between model-simulated and radar-observed rainbands and flow fields during a 6-h period of rapid intensification (an increase of maximum of at least 15.4 m s\(^{-1}\) in a 24-h period; Reasor et al. 2009) of Hurricane Guillermo (1997) on 2 August 1997.

Rapid intensification poses a significant threat to ships and a growing number of coastal communities. Because of the complexity of interaction between scales within tropical cyclones (TCs) and their important role in a storm’s rapid intensification, the TC intensity problem remains among the major unsolved scientific problems. Guillermo is selected for this study on rapid intensification because of the lack of complexity in the large-scale environment as implied by the storm motion and the relatively simple TC structure (Reasor et al. 2009).

High-resolution numerical experiments are first conducted to explicitly simulate the inner-core structures of Hurricane Guillermo (1997) using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) nonhydrostatic, two-way interactive, movable, triply nested grid Mesoscale Model (MM5). The 6-h model simulation corresponds to a time period when Hurricane Guillermo experienced a rapid deepening and evolved from a category 3 to a category 4 hurricane. National Oceanic and Atmospheric Administration (NOAA) Hurricane Research Division (HRD) P-3 aircraft provided airborne radar observations on 10 flight legs over much of the inner-core region (within 60 km of the eye) within this time period. This paper is organized as follows: section 2 provides a brief overview of Hurricane Guillermo (1997), available airborne radar observations, and the radar analysis methodology. Section 3 describes the basic features of MM5, model design, and an improvement made to the construction of an initial vortex using a four-dimensional variational data assimilation (4D-Var) vortex initialization scheme. Section 4 presents and compares some features of model-simulated and radar-observed Hurricane Guillermo (1997), mainly in low-wavenumber space. A summary and conclusions are given in the final section.

2. Overview of Hurricane Guillermo, airborne radar observations, and radar analysis methodology

Hurricane Guillermo (1997) was one of the strongest storms in the eastern Pacific Ocean. It started from a tropical wave that was first formed off the coast of Africa on 16 July 1997, which then moved westward for 10 days without further strengthening. By 27 July, it reached the Pacific coast of Mexico. With an increase in—and favorable organization of—convection in the following days, the tropical wave strengthened steadily, becoming a depression on 30 July, a tropical storm on 31 July, and a category 1 hurricane on 1 August. A period of rapid intensification occurred from approximately 0600 UTC 2 August to 1200 UTC 3 August. During this rapid intensification time, Guillermo moved west-northwestward over 29°–30°C sea surface temperature (SST). After the rapid intensification period, Guillermo fluctuated a little in strength during the following 2 days while continually moving across the eastern Pacific. On 5 August, Guillermo reached category 5 intensity with 44 m s\(^{-1}\) maximum winds and a minimum pressure of 919 hPa. Thereafter, the storm weakened, becoming a tropical storm on 8 August 1997.

A vortex motion and evolution experiment was conducted on 2 August involving the NOAA HRD P-3 aircraft. Airborne radar observations within a 120 × 120 km\(^2\) box, centered on Hurricane Guillermo (1997), were made from 10 flight legs. Table 1 lists the observing times, the central sea level pressure (SLP), and the location of the storm at the time of each flight leg. Radar data from 10 flight legs covered a 5-h time period from 1900 to 2400 UTC 2 August 1997. It is seen that Hurricane Guillermo (1997) experienced a continual deepening during this time period. The average deepening rate is as high as 2 hPa h\(^{-1}\).

The airborne Doppler radar measured the reflectivity and Doppler radial winds of Hurricane Guillermo. The along-beam resolution was 150 m, the along-track spacing between consecutive scans was 1.6–1.8 km, and the beamwidth is 1.9°. Having made appropriate navigational corrections and removed spurious echoes (e.g., sea
The Pennsylvania State University–NCAR nonhydrostatic, two-way interactive, movable, triply nested grid 3D mesoscale model (see Dudhia 1993; Grell et al. 1994) is used in this study. The coarse mesh (domain A) is fixed, has a horizontal resolution of 36 km (domain size: 4968 × 3888 km²), and employs the global analysis for both the model state and lateral boundary conditions at the forecast initial time. The synoptic scales thus come mainly from the global analyses within which Guillermo evolves. The size of domain A is 4968 × 3888 km². The intermediate mesh (domain B; domain size: 1296 × 1296 km²) moves with Hurricane Guillermo every 2 h and is used to simulate the hurricane-scale flows at 12-km horizontal resolution. The fine mesh (domain C) moves every hour, following the center of Guillermo. The fine mesh (domain C; domain size: 432 × 432 km²) with a grid size of 4 km is designed to resolve explicitly the central core and spiral rainbands of the storm. Coarse meshes (domains A and B) provide the fine mesh (domain C) with time-dependent lateral boundary conditions. The same 27 vertical layers are used for all three domains. For verification purposes, the model output is mapped onto the height levels of the radar data and the radar analysis is interpolated to the horizontal grid points used in the model.

The Grell cumulus parameterization scheme and the Tao–Simpson cloud microphysics (Tao and Simpson 1993) scheme were used simultaneously to simulate the evolution of the large-scale flows over the coarse meshes (Zhang and Fritsch 1988; Molinari and Dudek 1992). Only the Tao–Simpson cloud microphysics scheme is used over the finest-mesh domain. The Tao–Simpson cloud microphysics scheme contains prognostic equations for rainwater, cloud water, and graupel, which allows the model radar reflectivity to be estimated based on the 3D distributions of all three hydrometeor variables. Other model physics include the Blackadar (1979) PBL parameterization scheme and a cloud–radiation interaction scheme (Dudhia 1993).

The model forecast is initialized at 1800 UTC 2 August 1997 with the National Centers for Environmental Prediction (NCEP) 2.5° (latitude–longitude) resolution analysis. The central SLP at 1800 UTC August 2 from NCEP analysis is 1009 hPa, which is about 50 hPa higher than the National Hurricane Center (NHC) observed intensity. The NCEP analysis also fails to place the vortex at the observed location of the storm. A 4D-Var vortex initialization experiment is thus carried out on the mesh B domain to generate an initial tropical storm–like vortex having Hurricane Guillermo’s observed location, intensity, and size. Fujita’s formula is used to construct a more realistic artificial SLP. The central SLP (958 hPa), the outmost closed isobar (1010 hPa), and the radius of the outmost closed isobar (150 nm), required by Fujita’s formula, are from the best track dataset. The assimilation window is a half-hour (i.e., from 1800 to 1830 UTC). The designated SLPs are assimilated at 3-min intervals within a half-hour time window. Details of the 4D-Var vortex initialization scheme were described in Zou and Xiao (2000) and Park and Zou (2004). As an improvement to the 4D-Var vortex initialization scheme, the Geophysical Fluid Dynamics Laboratory (GFDL) vortex-removal scheme (Kurihara et al. 1993) is employed to remove the analysis vortex in the NCEP SLP analysis. The initial vortex generated on domain B is then interpolated to the finest-mesh C. The advantages of using a 4D-Var approach to insert a bogus vortex are twofold: (i) it produces an initial vortex in which all model variables satisfy the model dynamics and physics within the
half-hour assimilation window; and (ii) 4D observations such as airborne radar data can be assimilated simultaneously with the bogus vortex (results from radar data assimilation will be reported in a separate paper). Since the vortex initialization is carried out at 12-km resolution and the model forecast is made with triply nested grids (36-, 12-, and 4-km resolutions), model spinup may still be expected.

4. Forecast verification with airborne radar analysis
   a. Track and intensity

   A reasonably accurate track prediction is important for intensity forecasts so that the model-simulated Guillermo will be located in the same large-scale environment as the observed storm. The observed Hurricane Guillermo moved mainly westward with only a slight northward tilt (see Table 1). The modeled Hurricane Guillermo moves slightly slower than the observed, with a small southward bias. From 1800 UTC 2 August to 0000 UTC 3 August 1997, the observed Hurricane Guillermo traveled about a 110-km distance, mostly westward. The model forecast track error is less than 12 km at the times of all flight legs (Table 1). No serious spinup is found in the track prediction.

   For the intensity forecast, the model forecast experienced a 3-h spinup time. After this short spinup time, the modeled hurricane intensity agrees reasonably well with the radar analysis. Figure 1 compares the model forecast with the central SLP and the maximum surface wind observed by Doppler radar from 2130 UTC 2 August to 0000 UTC 3 August 1997 on flight legs 5–10. The observing times of two subsequent flight legs during this time period are separated by a half-hour. The modeled central SLP is slightly lower than the observations (Fig. 1a). However, by 0000 UTC 3 August 1997 (360-min forecast time), the model-predicted central SLP (946 hPa) is very close to the best analysis value (947 hPa).

   As described in section 2, the maximum surface wind speed at the initial time is not specified in the initial vortex. Although weaker than the observed winds at the initial time, the maximum surface wind speed quickly strengthened, reaching the observed intensity of 66.8 m s$^{-1}$ in 2 h. The maximum surface wind from the model forecast, varying between 65 and 70 m s$^{-1}$ from 2130 UTC 2 August to 0000 UTC 3 August 1997, is in good agreement with the radar analysis (Fig. 1b).

   b. Tangential and radial winds

   Figure 2 shows the radial profiles of the azimuthal mean tangential wind ($\bar{u}$) calculated from model forecast and radar data on legs 5–10 (from 2130 UTC 2 August to 0000 UTC 3 August 1997) at 1-, 3-, and 5-km altitudes. It is noticed that the radial structure of the azimuthal mean tangential wind from radar analysis does not vary greatly from one time to another during rapid intensification. It is found that the radial variation of the tangential wind speed $u(r)$ outside the radius of maximum wind ($R_{\text{max}}$) from both the model simulation and radar analysis can be approximated by the following empirical formula:

   \[
   \bar{u}(r) = u_{\text{max}} \left( \frac{R_{\text{max}}}{r} \right)^{x}. \tag{1}
   \]

   For example, the model-simulated profile at 1 km (see Fig. 2) can be represented by (1) with $x = 0.64$, and that from radar analysis can also be represented by (1) with $x = 0.58$. These values of the exponent in (1) are close to the values found in the literature (where $x = 0.62 \pm 0.18$; Anthes 1982).
It is seen from Fig. 2 that the modeled hurricane has a smaller radius of maximum azimuthal mean tangential wind. This turns out to be true at all vertical levels. Figure 3 shows the maximum azimuthal mean tangential wind and the radius of maximum azimuthal mean tangential wind on flight legs 5 and 9. The modeled maximum tangential wind is very close to the radar analysis in the midtroposphere, but stronger in the lower and upper troposphere than that observed by the radar. The radius of maximum wind is nearly constant with height from the surface to about 7–8 km (about 20 km in model forecast and 28 km in radar data), and increases with height in the upper troposphere. If we approximate the radial variation of the tangential wind inside the radius of maximum wind by rigid body rotation, \( u(r) = \omega r \), where \( \omega \) is the angular speed, we find that the angular speed (i.e., the slope of the radial profile of the tangential wind) of the hurricane in the model simulation is larger than the observed value in the core region. Using data at 5 km, the estimated rotational time \( (2\pi R_{\text{max}}/u_{\text{max}}) \) of the modeled hurricane is approximately 0.22 h, which is much smaller than the value (0.31 h) derived from radar data.

The cross sections of the mean tangential wind and radial wind components, from the model simulation and radar analysis on legs 5 and 9, are shown in Fig. 4. The model vortex is more upright than that revealed in the radar analyses. In addition to the difference in eye size, the strong convergent flow near the surface seen in the model forecast is very weakly revealed in radar data, if at all. The outflow slopes are also weaker in radar analysis. The inflow and outflow differences are because the radar is not observing the boundary layer (<1 km) and because of the lack of hydrometeors for the radar to measure wind in the upper level (>12 km). The radar analysis method, which includes a weak constraint on the second derivatives of all the 3D wind components being zero, filters the wind fields greatly and could weaken the winds (see section 2).

To gain further insight into the differences between the asymmetric features in the modeled hurricane and the real hurricane, an azimuthal spectral analysis is carried out. Kinetic energies calculated from the horizontal wind in the model forecast and the radar analysis as well as those contributed by symmetric and asymmetric components (sum of wavenumbers 1 and 2) at 9-, 5-, and 1-km altitudes are shown in Table 2. It is seen from both the model simulation and the radar analysis that most of the kinetic energy (>80%) within hurricanes comes from the tangential circulation. No more than 20% of the kinetic energy is accounted for by asymmetric components. Most of the asymmetric energy is accounted for by wavenumbers 1 and 2.

Figure 5 shows the tangential and radial winds at 5-km altitude for wavenumbers 1 and 2 at 2330 UTC 2 August (leg 9). The modeled flow field for wavenumber 1, within the core of the storm, is about 180° out

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**Fig. 2.** Radial profiles of tangential wind at 1-, 3-, and 5-km altitudes from model forecast (solid) and radar observations (dashed) on flight legs 5–10.
of phase with the flow described by radar data. In other words, an inflow (outflow) region in the model simulation corresponds to an outflow (inflow) region in radar data at this time. We also notice that the azimuthal phase difference between model forecast and radar analysis reduces with the increase of the distance from the storm center. The radial variation of wavenumber 1 features is quite small except for a discontinuous jump at the radius of maximum wind. Wavenumber 2 features from the radar analysis circle from larger radii into the radius of maximum wind cyclonically in the eyewall. However, the wavenumber 2 features from the model simulation are characterized by two distinct flow regimes, one near the radius of maximum wind and the other at larger radii. The modeled flow field for wavenumber 2 has a larger phase error at the radius of maximum wind than outside the radius of maximum wind.

Radial variations of the azimuthal phase of asymmetric features within a hurricane described above can be seen more clearly in Fig. 6, which presents the radial variations of the initial azimuthal phase for wavenumbers 1 and 2 of both the tangential wind and the radial wind. Based on the definition of the azimuthal angle, an increase of azimuthal phase of a wave with decreasing radial distance corresponds to a cyclonic rotation of the wave features into smaller radii. It is confirmed that wavenumber 1 has a nearly constant initial azimuthal phase for both the model-simulated and radar-observed hurricanes (Figs. 6a,c). The phase difference of wavenumber 1 between the model forecast and radar data is nearly 180° in the eye core. In the eyewall region, the phase difference of wavenumber 1 becomes very small. Compared to the radar data, the initial azimuthal phase of wavenumber 2 of the modeled tangential wind increases much faster with the decrease of radius, resulting in an increase of phase difference of tangential wind to about 160° at the radius of maximum wind. Although the radial variation of the initial azimuthal phase of radial wind for wavenumber 2 in the eye is quite different from

![Graphs showing radial variations of maximum azimuthal mean tangential wind and radius of maximum azimuthal mean tangential wind on legs 5 and 9.](image-url)
that of the radar-derived wind, the amplitude of wavenumber 2 in the eye is very small (see Figs. 6c–f).

To demonstrate how much phase error could contribute to the total differences between model forecast and radar data, an experiment is carried out to see how the model asymmetric features compare with the radar-observed asymmetry if azimuthal phase errors were removed from wavenumbers 1 and 2. Figures 5c and 5f
show the distributions of wavenumbers 1 and 2 after the correction of azimuthal phase error, respectively. The reconstructed asymmetric flow fields (Figs. 5c,f) compared much more favorably to the radar analysis (Figs. 5b, 6e) than the original model fields (Figs. 5a,d). The inflow and outflow regions of the reconstructed fields are fairly consistent with the radar-observed flow pattern.

c. Reflectivity

In addition to wind, airborne radar provides reflectivity measurements with high spatial (less than 4 km) and temporal (less than a half-hour) resolutions. Radar reflectivity is a variable that is sensitive to the hydrometeor variables, whose structural and intensity changes are closely related to hurricane intensity. For model verification and data assimilation, an explicit relationship that allows the reflectivity to be calculated from the state variables of NWP models is required. The mathematical formulation used for evaluating modeled reflectivity is provided in the appendix.

Figure 7 shows the horizontal distributions of reflectivity at 3-km altitude at 2330 UTC 2 August 1997 from the radar analysis and model forecast over an area of 360 km $\times$ 360 km. The high-resolution (4 km) short-term (5.5 h) model forecast reproduced the observed hurricane structure reasonably well, including eye, eyewall, and rainbands. The azimuthal phase of the modeled rainbands matches well with that of the radar-observed rainbands outside the radius of maximum wind. However, there are several noticeable differences that are worth mentioning. First, the modeled reflectivity field is smoother at high-reflectivity values and more discontinuous at low-reflectivity values. The former is due to the still coarser resolution of model grids than that of radar data and the latter is probably a result of using the forward model for calculating model reflectivity. Second, the maximum values of the reflectivity characterizing heavy rainbands are more than 10 dBZ larger than the radar-observed reflectivity values. Third, most regions of the observed hurricane are covered by reflectivity above 15 dBZ but areas with reflectivity greater than 6 dBZ covered a lesser portion of the modeled hurricane than that above 15 dBZ. Finally, the azimuthal phase of the rainband at the radius of maximum wind does not match the azimuthal phase of the radar-observed rainband. The higher reflectivities in model simulation may result from the model producing too many larger droplets, or equivalently that the $L$ parameter in the reflectivity observation operator is too small [see (A1)–(A3)].

Horizontal distributions of vertical mean reflectivity from 2 to 4 km and their temporal variations are given in Fig. 8. The two most noticeable features in Fig. 8 are (i) the azimuthal phase of wavenumber 1 changes very little with time while the observed and modeled Hurricane Guillermo experienced continuous deepening; and (ii) the modeled reflectivity field has a large azimuthal phase error ($\approx 60^\circ$) of wavenumber 1 when compared with the radar data.

Wavenumber 1 is found to dominate the asymmetric features within the inner-core region that were observed by the airborne radar. Figure 9 presents the amplitude variation of both wavenumber 1 and 2 components of the vertical mean reflectivity from radar analysis and model forecast at 2330 UTC 2 August 1997 (corresponding to the
observing time of flight leg 9). Within the 60-km radius covered by airborne radar data, wavenumber 1 dominates. The radial profiles of amplitudes of wavenumbers 1 and 2 over a larger radial distance can be examined from the model forecast.

Azimuthal phase differences also contribute greatly to the reflectivity errors of the model forecast. This is quantitatively confirmed in Fig. 10, which presents the RMS errors of the asymmetric components of reflectivity between the radar data and the model forecast at all altitudes both before and after the phase correction. The RMS differences are largest near the radius of maximum wind and in the midtroposphere (about 6 km) and upper troposphere (about 9 km) (Fig. 10a). RMS differences as large as 5–11 dBZ are seen in most areas. A significant reduction of the RMS error is achieved through phase correction (Fig. 10b). RMS differences are reduced to no more than 5 dBZ after phase correction except between 50- and 60-km radial distance in the lower troposphere.

We have thus demonstrated that errors in the modeled asymmetric features are mostly due to phase errors as well as the size of the model-simulated hurricane eye. The present study suggests that assimilation of radar data is challenging in the following sense: model-produced hurricane structures often do not match radar-observed structures and/or structural evolution at the scales observed by airborne radar. As such, the radar-observed inflow regions could correspond to outflows in the model due to the azimuthal phase errors of the modeled
asymmetric flow at a particular location. If the modeled asymmetric features are not rotating at the same speed as those observed, a fitting between model and observation at earlier times will not result in a closer fit at future times. In other words, the model will have a short memory of those radar data incorporated into the model.

5. Summary and conclusions

The inner-core structures and their evolutions observed by airborne radar within 60-km radial distance during a 6-h period of rapid intensification of Hurricane Guillermo (1997) on 2 August are examined and compared with a model forecast produced by the Pennsylvania State University–NCAR nonhydrostatic, two-way interactive, movable, triply nested grid (36–12–4 km) Mesoscale Model (MM5). The Grell cumulus parameterization scheme and the Tao–Simpson cloud microphysics scheme were used simultaneously to simulate the evolution of the large-scale flows over the coarse domains. The intense storm itself is explicitly resolved over the fine-mesh domain using a grid size of 4 km without using any cumulus parameterization scheme.
The weak vortex in the NCEP analysis is first removed using the GFDL vortex-removal scheme (Kurihara et al. 1993). Then, a radial profile of SLP is specified using Fujita’s (1952) equation in which the radius of maximum sea level pressure gradient is calculated from the radius of the 34-kt wind of Hurricane Guillermo at the initial time of model integration using the linear regression model developed by Park and Zou (2004). Finally, a 4D-Var experiment is carried out on domain B (12-km resolution) to obtain the vortex fields of other model variables from assimilating the specified surface pressure field. The NCEP analysis, with its analysis vortex removed, serves as the initial guess field for the 4D-Var experiment. The initial vortex generated on domain B is then interpolated to the finest-mesh C (4-km resolution).

The modeled hurricane followed closely the observed track of Hurricane Guillermo. The maximum track error of the model forecast is less than 12 km from the hourly model output. However, the model forecast also reproduced the observed hourly deepening rate when, after a few hours of model spinup, Hurricane Guillermo evolved from a category 3 (initialized at 1800 UTC 2 August 1977) to a category 4 at the end of 6 h of model integration. The inner-core structures and the evolution of the modeled hurricane in the later 3 h are then compared with airborne radar analysis resulting from data collected on six flight legs over much of the inner-core region. The model-predicted radial profile of tangential winds outside of the radius of maximum radar wind approximates reasonably well those observed by the airborne radar. Model forecasts also reproduced the general features of hurricanes, such as eye, eyewall, and rainbands. However, the modeled radius of maximum wind is too small.

During the rapid intensification period of Hurricane Guillermo on 2 August, both model and radar data show that the asymmetric flow within a 60-km distance from the storm center is dominated by wavenumber 1. The wavenumber 1 features do not change greatly with time, characterizing a nearly constant azimuthal phase. On the contrary, wavenumber 2 activity changes greatly with time. The maximum amplitude of wavenumber 2 is beyond the region observed by the airborne radar. However, significant differences are found between the model forecast and the radar analysis. It was shown that most of the errors in model-generated asymmetric features of wind and reflectivity are due to the azimuthal phase error.

The present study suggests that a numerical model must simulate the observed radial profile of the tangential wind, especially the maximum wind and the radius of the maximum wind (or equivalently the rotation speed of the hurricane), with reasonable accuracy for it to possibly capture reasonably well the temporal evolution of the spatial distribution of asymmetric flow and rainband structures. Only then can radar data assimilation be more effective. Efforts were made to develop an innovative vortex initialization method using airborne radar data and results will be presented in a separate paper.

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APPENDIX

Observation Operator for Reflectivity

Hydrometeor distributions in the atmosphere can be described by measurements of the drop size distribution \( N(D) \)—here \( N(D) \) is the number of drops per millimeter diameter interval per cubic meter of space. Measurements of the drop size distribution suggest the following drop size distribution (Stoelinga 2005):

\[
N(D) = N_0 e^{-\Lambda D},
\]  
(A1)

where \( N_0 \) is a constant intercept parameter (\( N_0 = 8 \times 10^3 \text{ mm}^{-2} \text{ mm}^{-1} \), \( 2 \times 10^4 \text{ mm}^{-2} \text{ mm}^{-1} \), and \( 4 \times 10^3 \text{ mm}^{-3} \text{ mm}^{-1} \) for rainwater, snow, and graupel, respectively) and \( \Lambda \) is the slope factor that can be calculated from the hydrometeor mixing ratio using

\[
\Lambda = \left( \frac{\pi N_0 \rho_{\text{hydrometeor}}}{\rho_d q_{\text{hydrometeor}}} \right)^{1/4}.
\]  
(A2)

In (A2), \( q_{\text{hydrometeor}} \) represents either the mixing ratio of rainwater \( q_r \), the mixing ratio of snow \( q_s \), or the mixing ratio of graupel \( q_g \) when any of them is present. Out of all the hydrometeor variables, rainwater contributes most to the radar reflectivity. The density \( \rho_{\text{hydrometeor}} \) equals \( \rho_r = 10^3 \text{ kg m}^{-3}, \rho_s = 10^2 \text{ kg m}^{-3}, \) and \( \rho_g = 4 \times 10^2 \text{ kg m}^{-3} \) for rainwater, snow, and graupel, respectively.

FIG. 8. Wavenumber 1 component of the vertical mean reflectivity from 2- to 6-km altitudes from (a)–(d) radar observations and (e)–(h) model forecast on flight legs 7–10 (from left to right).

FIG. 9. Amplitude of wavenumber 1 and 2 components of the vertical mean reflectivity (dBZ) from radar observations (dashed) and model forecast (solid) at 2330 UTC 2 Aug 1997. The number 2 on the two lines indicates wavenumber 2.
When radar transmits a pulse of energy, the energy is directed into space by the radar antenna at the speed of light, forming an expanding shell of energy with increasing distance from the radar location. If intercepted by a water droplet (e.g., raindrop, snowflake, and graupel), this intercepted radiated power is reradiated (not equally) in all directions. The amount of energy reradiated by the water droplet depends on the property of the droplet. Some of the reradiated energy is returned to the radar location and is measured by the radar. Based on these measurements, a quantity called radar reflectivity factor ($z$) is derived, providing a measure of the efficiency of water droplets in a unit sample volume intercepting and returning radio energy. Since raindrops, snowflakes, and graupel are either approximately spherical or can be approximated by an equivalent sphere and are much smaller in size (diameter $D \leq 5$ mm) than the wavelength ($\lambda$) of the radar-transmitted radio waves ($\lambda \approx 1-30$ cm), the returned energy scattered back to the radar can be approximated as Rayleigh scattering, a much simpler form of the more general complete solution (Mie scattering) describing the distribution and intensity of scattered energy. Using the relationship between reflectivity and the droplet size distribution in the Rayleigh region, reflectivity for three different hydrometeor variables can be expressed uniformly as follows (Doviak and Zrnic 1993; Smith 1984; Fovell and Ogura 1988):

$$z_{\text{hydrometeor}} = \left( \frac{\rho_{\text{hydrometeor}}}{\rho_r} \right)^2 \alpha_{\text{frozen}} \int_0^\infty N(D) D^6 dD,$$

(A3)

where $\alpha_{\text{frozen}} = 0.224$ for frozen hydrometeor (snow or graupel) and $\alpha_{\text{frozen}} = 1$ for rainwater. Substituting the drop size distribution (A1) into (A2), we obtain a relationship between radar reflectivity and a particular hydrometeor variable (i.e., rainwater, snow, and graupel):

$$z_{\text{hydrometeor}} = \alpha_{\text{frozen}} \int_0^\infty N_0 e^{-\Lambda D} D^6 dD$$

$$= N_0 \frac{6!}{\Lambda^6} \left( \frac{\rho_{\text{hydrometeor}}}{\rho_r} \right)^2 \alpha_{\text{frozen}}.$$

(A4)

The reflectivity ($z$) is additive, that is, the total reflectivity at a grid point is the sum of the reflectivities associated with different hydrometeor mixing ratios at that grid point, that is,

$$z = z_{\text{rainwater}} + z_{\text{snow}} + z_{\text{graupel}}.$$  

(A5)

Since the value of $z$ varies by 10 orders of magnitude, the following logarithmic radar reflectivity factor $Z$ is often used:
The unit for $Z$ is dBZ, meaning a decibel relative to a reflectivity of 1 (mm)$^6$ m$^{-3}$. It is pointed out that the logarithmic radar reflectivity factor $Z$ is not additive.

Using (A2)–(A6), the model reflectivity factor $Z$ (dBZ) can be calculated from the rainwater mixing ratio ($q_r$), snow mixing ratio ($q_s$), graupel mixing ratio ($q_g$), and density of dry air (kg m$^{-3}$); the latter is determined by the virtual temperature ($T_v$) and pressure ($p$) through the equation of state ($\rho_d = p/R_dT_v$). Therefore, the reflectivity factor ($Z$) is a function of model variables $q_r$, $q_s$, $q_g$, $T_v$, and $p$. Equations (A2)–(A5) are used for simulating the radar reflectivity factor from model forecasts.

REFERENCES


