Prevalence of tornado-scale vortices in the tropical cyclone eyewall

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Analyses of datasets from manned research flights that penetrated hurricane eyes and tropical cyclone (TC) damage surveys strongly suggest the existence of tornado-scale vortices in the turbulent boundary layer of the TC eyewall. However, their small horizontal scale, their fast movement, and the associated severe turbulence make the tornado-scale vortex very difficult to observe directly. To understand tornado-scale vortices in the TC eyewall and their influence on the TC vortex, mesoscale rainbands, and convective clouds, a numerical experiment including seven nested domains with the smallest horizontal grid interval of 37 m is conducted to perform a large eddy simulation (LES) with the Advanced Weather Research and Forecast (WRF) model. We show that most of the observed features associated with tornado-scale vortices can be realistically simulated in the WRF-LES framework. The numerical simulation confirms the existence of simulated tornado-scale vortices in the turbulent boundary layer of the TC eyewall. Our numerical experiment suggests that tornado-scale vortices are prevalent at the inner edge of the intense eyewall convection.

O bservational studies based on the datasets from manned research flights that penetrated hurricane eyes and tropical cyclone (TC) damage surveys speculate upon the existence of the tornado-scale vortex in the TC boundary layer (TCBL) (1–5). Analysis of a dataset from GPS dropsondes released into TCs indicates that extreme low-level (0 km to 3 km) updrafts that are sometimes associated with extreme horizontal wind speeds can occur in the TCBL, also suggesting the existence of the small-scale (~1 km) vortex in the TCBL (6, 7). However, its small horizontal scale, its fast movement with the TC-scale flow, and the associated severe turbulence make it very difficult to observe directly. To date, the tornado-scale vortex in TC eyewalls has not been numerically simulated, and whether it is common in the TCBL remains unknown.

Although the extreme updrafts have been documented in many TCs (2–4, 6–10), the small-scale feature encountered by a National Oceanic and Atmospheric Administration (NOAA) research aircraft during the eyewall penetration of Hurricane Hugo (1989) was the first relevant analysis on the tornado-scale vortex in the TCBL (1–5). On September 15, 1989, a research aircraft from NOAA conducted a mission to penetrate the eyewall of Hurricane Hugo at the lowest safe altitude. On its first pass at the altitude of ~450 m, the aircraft encountered intense turbulence in the inward side of the eyewall. Following an engine fire and shutdown of one of the four engines, sudden loss of altitude, and 2 h loitering in the eye attempting to gain altitude, a rescue was performed by an Air Force WC-130J, which led the NOAA WP-3D safely through a “soft spot” in the eyewall, allowing it to return to the base. Later analysis suggests that the dangerous turbulence was associated with an EVM, which is comparable to a weak tornado in terms of its horizontal scale and the estimated peak cyclonic vorticity (3). As a result, aircraft eyewall penetration in the hurricane boundary layer has been prohibited by NOAA since the dangerous turbulence was encountered in Hurricane Hugo (1989). In addition, an updraft of 25 m s⁻¹ observed just below 800 hPa in Hurricane Isabel (2003) and an updraft of 31 m s⁻¹ at the flight altitude (~3 km) in Hurricane Felix (2007) are believed to be an indication of the EVM (2, 4). These studies suggest that the tornado-scale vortex associated with extremes in updraft and wind speed occurs along the eye—eyewall interface with a strong radial gradient in radar reflectivity.

Advances in mesoscale models and computational capability have made it possible to numerically simulate the small-scale feature in the TCBL and its influence on the evolution of the TC. TC simulations have been conducted in the Advanced Weather Research and Forecast (WRF) model with the large-eddy simulation (LES) technique (11), by which the energy-producing scales of 3D atmospheric turbulence in the TCBL are explicitly resolved, while the smaller-scale portion of the turbulence is parameterized (12–15). These studies demonstrate the capability of the WRF model in simulating the TCBL features on the subkilometer scale. It is suggested that sub-100-m grids are needed to simulate the development of 3D turbulent eddies in the TCBL (13).

In this study, we present the results of a numerical experiment in which a TC evolves in a typical large-scale background over the western North Pacific. To simulate energetic 3D turbulent eddies in the TC eyewall and their influence on the TC vortex, mesoscale rainbands, and convective clouds, the model contains six two-way interactive domains with the innermost domain horizontal grid size of 37 m. In particular, we will address whether the simulated small-scale feature is common in the simulated TC eyewall.

Numerical Experiment

The numerical experiment conducted in this study is similar to that in ref. 16, in which an initial vortex is embedded in the large-scale background of Typhoon Matsa (2005). We use the WRF model with six two-way interactive domains inside a 27-km-resolution outermost domain centered at 30.0°N, 132.5°E to

Significance

Tornado-scale vortices in the intense tropical cyclone eyewall have been speculated upon for more than two decades, but their small horizontal scale, their fast movement, and the associated severe turbulence make them very difficult to observe directly, except for the case of Hurricane Hugo (1989) in the Atlantic basin. Using the Advanced Weather Research and Forecast large eddy simulation framework with the unprecedented horizontal grid size of 37 m, the numerical experiment in this study confirms the existence of simulated tornado-scale vortices similar to the Hugo case in the turbulent eyewall boundary layer and further suggests that tornado-scale vortices are prevalent at the inner edge of the intense eyewall convection.

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account for complicated interactions among various scales. The horizontal spacing decreases by a factor of 3 with each domain level. The innermost domain \((90 \times 90 \text{ km}^2)\) covers the eye and eyewall with a resolution of \(1/27 \text{ km}\) \((\sim 37 \text{ m})\). The LES is used to replace the PBL parameterization scheme in the domains with horizontal grid size less than 1 km. There are 75 vertical levels (19 levels below 2 km), with a top of 50 hPa. The model is run over an open ocean with the constant sea surface temperature of 29 °C.

The adjustment of the simulated turbulence from the coarser grids to the finer grids is a challenge for nested LES simulations. In the WRF model, it has been reported that the numerical noise that is generated along the nest boundary can be effectively reduced by using a relatively large innermost domain and a relaxation zone at the boundary of the nested domain (17). In our simulation, the innermost domain covers an area of \(90 \times 90 \text{ km}^2\), which is much larger than 5 times the boundary layer height. The relaxation zone is used for the nested domains in the WRF model (18).

The model is run for 36 h, and the 1/9-km-resolution and 1/27-km-resolution domains are activated at 24 h. Our analysis focuses on the output of the innermost domain during the last 10 h. The simulated TC takes a northern northwest track, and the instantaneous maximum wind speed at 10 m fluctuates between 61.8 m·s\(^{-1}\) and 76.6 m·s\(^{-1}\) during the 10-h period, while the azimuthal maximum wind speed is relatively small, ranging from 43.5 m·s\(^{-1}\) to 48.8 m·s\(^{-1}\). The model output is regularly stored at 1-h intervals, but a few variables during a 22-min period from the 30th hour are also stored at 3-s intervals.

**Simulated Tornado-Scale Vortex**

Fig. 1A shows the simulated 500-m radar reflectivity at 30 h, indicating an open eyewall of the simulated TC with the intense eyewall convection mainly on the northern side. The reflectivity pattern remains similar over the 10-h period since the vertical wind shear of the environmental flow between 200 and 850 hPa is northwesterly during the period. Fig. 1B shows the instantaneous 10-m wind speed and 500-m perturbation wind fields of the TC eyewall in an area of \(10 \times 12 \text{ km}^2\) at 30 h. Note that the perturbation wind field is the difference between the wind field and the 3-km moving average of the wind field. In agreement with the previous observation (19, 20), the streaks of alternating high and low wind speeds are clear and roughly aligned with the TC-scale flow. In the 500-m perturbation wind field there are a few distinct cyclonic circulations in the inner edge of the intense eyewall convection. The strong 10-m wind speeds occur on the radially outward side of the cyclonic circulation.

We plot the vertical cross-section of the cyclonic circulation along the line perpendicular to the quasi-linear streak shown in Fig. 1B (Fig. 2). The 500-m cyclonic circulation coincides with the intense updraft that extends upward to \(\sim 2 \text{ km}\). The strong updraft with a maximum of 35.8 m·s\(^{-1}\) occurs at 400 m, which is associated with a horizontal roll on the radially outward side. The wind speed jumps suddenly across the intense updraft within a horizontal distance of \(\sim 1 \text{ km}\). There is a rapid speed jump of \(\sim 45 \text{ m·s}^{-1}\) at 500 m. Moreover, the 10-m wind speed increases suddenly from \(\sim 30 \text{ m·s}^{-1}\) in the updraft to \(\sim 60 \text{ m·s}^{-1}\) in the downdraft, suggesting the influence of the small-scale feature on the near-surface wind gusts. While the strong wind gusts result in...
from vertical momentum transport (21–25), the superposition of the perturbation flow of the cyclonic circulation can further enhance the wind gusts on the radially outward side.

The streamlines of the horizontal perturbation winds clearly show the 3D structure of the simulated small-scale feature (Fig. 3). Its horizontal flows rotate cyclonically around the intense updraft, and the cyclonic circulation is mainly confined to the TCBL below ∼1.5 km. The component of vertical relative vorticity anomaly shows a maximum of 0.48 s⁻¹ at 300 m, which is comparable to the estimate in Hurricane Hugo (3). We can see that the updraft/downdraft couplet, the sudden jump of the wind speed, the radial location, and the horizontal scale suggest that the simulated small-scale feature is very similar to the observed tornado-scale vortex in real hurricanes (3, 4). It is indicated that the observed tornado-scale vortex can be simulated numerically in the WRF-LES framework with the finest horizontal resolution of 37 m.

Prevalence of the Tornado-Scale Vortex

Is the tornado-scale vortex a common feature of the simulated TC eyewall? To address this question, we detect the tornado-scale vortices using the 1-h and 3-s model outputs, respectively. Based on previous studies (2–4), the tornado-scale vortex is defined as a small-scale cyclonic circulation with the maximum updraft not less than 15 m s⁻¹ or 20 m s⁻¹ and maximum relative vorticity not less than 0.2 s⁻¹ below the altitude of 3 km. The grid points that satisfy the thresholds of vertical motion and relative vorticity belong to the same vortex if they are within a distance of 1 km in the horizontal and vertical direction.

There are 24 and 89 tornado-scale vortices during the 10-h period when the maximum vertical motions of 20 m s⁻¹ and 15 m s⁻¹ are applied to the 1-h output (Fig. 4A). We examine the duration of the tornado-scale vortex in the 3-s output. The duration is estimated as the consecutive period during which the maximum vertical motion and relative vorticity are not less than the thresholds. The mean duration is 40 s, with the longest of 138 s for the threshold of the vertical motions of 20 m s⁻¹. Such a short duration may be one of the reasons for sparse sampling in observations. Therefore, we conclude that the identified tornado-scale vortices in the 1-h output are not repeatedly counted.

The tornado-scale vortices detected in the 3-s output are shown in Fig. 4B. Note that a tornado-scale vortex can be counted many times in the 3-s output during the 22-min period. There are 499 and 3,597 tornado-scale vortices identified with the maximum vertical motions of 15 m s⁻¹ and 20 m s⁻¹ during the 22-min period, respectively. We can see that the tornado-scale vortices move with the background TC flows. Fig. 4 indicates that most of the detected vortices occur in the inward side of the radius of maximum wind (RMW) or close to the RMW. The vertical motion maxima associated with the vortices are found between the 200- and 1,500-m altitudes. Most of them are found at around the 500-m altitude. Fig. 4 suggests that the tornado-scale vortices are common at the inner edge of the intense eyewall convection. It is important to note that ref. 3 shows, in Hugo, that real tornado-scale vortices appear to be embedded in mesoscale vortices that move along the edge of the eyewall with a time scale on the order of 15 min to 20 min, or approximately one rotation around the eyewall. A signature of the
mesoscale vortex feature in our model can be seen in the cyclone-curved, inward-penetrating reflectivity filaments just south of the box shown in Fig. 1A.

Summary

TCs at landfall often spawn tornadoes in outer rainbands (26, 27), but a few studies based on limited data from manned research flights and TCspectrum, TC vortex, mesoscale organization, down to fine-scale turbulent eddies, are allowed by using the LES technique in the WRF model. It is indicated that the observed tornado-scale vortex can be simulated numerically in the WRF-LES framework with the finest horizontal resolution of 37 m. The features of the simulated tornado-scale vortex are very similar to those derived from the observation in terms of the updraft/downdraft couplet, the sudden jump of the wind speed, the radial location, and the horizontal scale (3, 4).

Although wind perturbations associated with the tornado-scale vortex are less than those in supercell tornadoes, the enhanced surface wind gusts can lead to significant damage, since the vortex moves with the strong background eyewall flow (5). The associated intense turbulence can pose a severe threat to the eyewall penetration of manned research aircraft. Moreover, the tornado-scale vortex at the inner edge of the eyewall convection can play an important role in mixing the eye air into the eyewall (2, 4) although the influence of the mixing on increasing TC intensity is still argued (28, 29). Therefore, understanding of the tornado-scale vortex in the TC eyewall is very important for damage mitigation, structural engineering, and intensity prediction, especially when intense TCs make landfall.

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