Super High-Resolution Simulation of the 6 May 2012 Tsukuba Supercell Tornado: Near-Surface Structure and Its Evolution

Wataru Mashiko¹ and Hiroshi Niino²

¹Meteorological Research Institute, Tsukuba, Japan
²Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, Japan

Abstract

A super high-resolution simulation of the 6 May 2012 Tsukuba supercell tornado with a horizontal grid spacing of 10 m is conducted to investigate its fine-scale structure under realistic environmental conditions including surface friction. The simulated tornado repeatedly exhibits evolutions from one-cell to two-cell vortex, and subsequently to a multiple-vortex structure, where the vortex structure is sensitive to a swirl ratio. Subvortices in the multiple-vortex structure are located on the immediate inside of the radius of the maximum tangential wind speed, and cyclonically rotate around the tornado center with a slower speed less than half of the maximum tangential wind speed. The subvortices have a feature of a suction vortex accompanied by strong horizontal convergence and strong updraft near the surface. Although a superposition of the swirling winds associated with the subvortices and the parent tornado vortex causes locally intensified winds, the maximum horizontal and upward winds over the tornado’s lifetime occur at the stage of shrinking of the vortex radius right before a transition to a multiple-vortex structure.

(Citation: Mashiko, W., and H. Niino, 2017: Super high-resolution simulation of the 6 May 2012 Tsukuba supercell tornado: Near-surface structure and its evolution. SOLA, 13, 135–139, doi:10.2151/sola.2017-025.)

1. Introduction

The detailed structure of a tornado, especially its evolution, near-surface wind fields, and dynamics, remains largely unknown because of its smallness, short lifetime and extremely violent winds. Photogrammetric analysis of the near-surface tornadic wind structure (e.g., Hoecker 1960) often assumes axisymmetry, which gives rise to concerns about the accuracy of the estimation. Using Doppler on Wheels mobile radar, Wurman (2002) observed wind perturbations of 40–50 m s⁻¹ associated with multiple vortices at about 100 m height, which resulted in the strongest wind within a tornado vortex. Wurman et al. (2013) have attempted in situ measurements of the interior structure of an EF-2 tornado in Wyoming using an armored vehicle and obtained a temporal record of horizontal winds at 3.5 m height near the tornado center. However, an observation of near-surface wind fields within a tornado vortex is quite rare and has offered only fragmentary information. Previous laboratory experiments (Ward 1972; Church et al. 1979) and highly idealized numerical studies using large eddy simulation (LES) (e.g., Rotunno 1979; Lewellen et al. 1997) have shown that a tornado-like vortex exhibits various types of structure, such as a one-cell vortex containing a single updraft, a two-cell vortex exhibiting a downdraft at the vortex center, and multiple vortices. However, the extent to which the reproduced vortex in these studies can be applied to an actual tornado is open to further discussion.

Recent progress of computational technology has made it possible to explicitly simulate a supercell tornado using a three-dimensional numerical model. However, most of the numerical studies often employed a grid spacing insufficient for resolving the inner structure of a tornado vortex (Mashiko et al. 2009; Mashiko 2016b) or used free-slip lower boundary conditions (Orf et al. 2017). The surface friction is likely to have a great effect on the tornado vortex structure, as demonstrated by a laboratory experiment (Leslie 1977). Xue et al. (2014) successfully simulated a fine-scale tornadic vortex including multiple vortices using a full physics model with a 50-m horizontal grid, although the simulated subvortices were represented by only a couple of model grid points.

In this study, we performed a super high-resolution simulation of the 6 May 2012 Tsukuba City F3 supercell tornado with a horizontal grid spacing of 10 m under realistic environmental conditions. This tornado had a multiple-vortex structure near the surface for a short period, which was captured by a number of photographs and videos. The purpose of this study is to understand the detailed structure of a strong tornado and its evolution under realistic environmental conditions.

2. Numerical model and experimental design

Super high-resolution simulation with a horizontal grid spacing of 10 m was performed for the Tsukuba tornado using the Japan Meteorological Agency Nonhydrostatic Model (JMAnHM; Saito et al. 2006). The physical processes used in the simulation are the same as those of Mashiko (2016a). Surface fluxes are calculated using a bulk method based on Beljaars and Holtslag (1991). Subgrid turbulent mixing is computed using the 1.5-order TKE-based closure model by Deardorff (1980). The model includes cloud microphysical processes with six water species (water vapor, cloud water, rain, cloud ice, snow, and hail/graupel) (Ikawa et al. 1991). A two-moment microphysics scheme for ice particles was employed. A terrain following vertical coordinate system z* was used: z* = H(z − z_s)/(H − z_s), where z_s is the surface height and H is the constant height of the model top. The model includes realistic topography and vegetation provided by the Geospatial Information Authority of Japan.

The model domain is a 40 km by 30 km area (4001 × 3001 horizontal grid points) that covers the supercell storm during the simulation period. In this simulation area, z is nearly constant at about 20 m. Thus, z* is approximately coincided with the height above ground level. The model contains 250 vertical levels with a variable interval of Δz* = 10 m at the surface to 50 m at the model top (H = 10760 m). The initial and boundary conditions are provided by the 50-m grid spacing simulation results of Mashiko (2016a), which successfully reproduced the supercell tornadogenesis. The initial time of 12:02:00 JST (JST = UTC + 9 h) is 6 min prior to the tornadogenesis. Here, h, m, and s in the time h:m:s denote hour, minute, and second, respectively. The integration time is 18 min, and the model time step is 0.05 sec. The following analyses are conducted using 1 sec-interval output data.

3. Evolution of the tornado-vortex structure

The 10-m grid spacing simulation reproduced a tornado on the rear-flank gust front at the tip of the hook-shaped horizontal distribution of hydrometeors, as in the 50-m grid spacing sim-
Mashiko and Niino, Super High-Resolution Simulation of the Tsukuba Supercell Tornado

Simulation (Mashiko, 2016a). The timing of the tornadogenesis is about 25 min earlier than the observations, and the simulated tornado track is displaced northward by about 3 km, compared to the damage track reported by Japan Meteorological Agency (2012). The tornado moved east-northeastward at about 60 km h$^{-1}$. Figure 1 plots the time series of pressure and wind velocity near the surface within the tornado vortex during the intensifying and mature stages. The minimum sea-level pressure drops to 935 hPa at 12:15:16 JST, which gives a pressure deficit of about 70 hPa compared to the surrounding area. The maximum horizontal wind velocity at $z^* = 5$ m exceeds 70 m s$^{-1}$, and the updraft at $z^* = 10$ m reaches 52.3 m s$^{-1}$ at around the same time. This extremely strong updraft near the surface is found near the tornado center. In addition to the short-period oscillation of about 15 sec, maximum winds undergo a distinct periodic change with their peak at around 12:14:00 and 12:15:15 JST.

Figure 2 presents evolutions of vertical vorticity and vertical velocity near the surface at 12:14:50, 12:15:17, and 12:16:00 JST during the last periodic change shown in Fig. 1. During the intensifying stage, the vortex core with large vertical vorticity became concentrated and was gradually occupied by a downdraft. After this time, the central downdraft intensified, and multiple vortices formed while increasing the horizontal dimension of the tornado vortex. Thus, the simulated tornado evolved from a one-cell to a two-cell structure, and subsequently exhibited a multiple-vortex structure. Such a transition of the vortex structure was also observed in previous laboratory experiments (Ward 1972; Church et al. 1979), idealized simulations using LES (e.g., Rotunno 1979; Lewellen et al. 1997), and observational studies (e.g., Wurman 2002, Lee and Wurman 2005, Wurman et al. 2014). The multiple-vortex structure was most distinct at about 26 m height and became obscure above 200 m height. It is worthwhile to note that the maximum horizontal and vertical winds and minimum pressure are found not at the timing of a multiple-vortex structure, but a concentrated single-vortex structure, which is qualitatively consistent with the result of the recent idealized LES simulations.

Fig. 1. Time series of (a) minimum sea level pressure (red line) and swirl ratio (black line), and (b) maxima of horizontal wind at $z^* = 5$ m (green line) and vertical wind at $z^* = 10$ m (blue line) within the simulated tornado vortex during the intensifying and mature stages. Blue shading indicates the period during which the tornado exhibits a multiple-vortex structure. Wind data in (b) are smoothed using the method of Grell et al. (1994) to remove two-grid-length noise. The vertical orange lines correspond to the times shown in Fig. 2.

Fig. 2. Evolution of the tornado vortex near the surface. Vertical vorticity (color shading) at $z^* = 26$ m at (a) 12:14:50, (b) 12:15:17, and (c) 12:16:00 IST. (d)–(f) As in (a)–(c), but for vertical velocity at $z^* = 79$ m. Contour lines indicate pressure every 5 hPa.
study (Nolan et al. 2017). Actually, the Tsukuba tornado caused the most destructive damage of F3 when it had a single-vortex structure, which was captured by a number of videos (e.g., Sassa and Miyagi 2013). The area of horizontal wind exceeding 25 m s\(^{-1}\) at \(z^* = 5\) m associated with the simulated tornadic vortex is 250–500 m in width in this period, which is comparable to that of the observed damage track. It indicates that the model with a 10-m horizontal grid reproduced the tornado on a realistic horizontal scale, in contrast to the 50-m grid model (Supplement 1).

Figure 3 shows the temporal variation of horizontal distance between the tornadic vortex centers at the surface and at each level, where the tornado center is determined as an approximate geometric center of pressure field at each level using a variational approach of Braun (2002). The center is a location where the sum of azimuthal variance of pressure at all radii of 10 m intervals within 250 m radius is minimized. This way of determining the tornado center is adopted because the locations of surface vorticity maximum or minimum pressure do not represent the circulation center on a tornado-vortex scale, as shown in Fig. 2. Although the tornadic vortex is tilted northeastward, which is close to the moving direction of the tornado (east-northeastward), the inclination at lower levels (approximately below 200 m), where the pronounced structural transition among single-cell, two-cell, and multiple-vortex regimes occurred, is small. It is noted that, when the vortex becomes upright, the horizontal and vertical winds tend to intensify (cf. Figs. 1b and 3) and the high vorticity region becomes more concentrated (cf. Figs. 2 and 3).

Radius-height cross sections of the azimuthally averaged vertical and radial winds through the vortex center for the times in Fig. 2 are shown in Fig. 4. At 12:14:50 JST most of the central region of the tornado was occupied by strong updrafts (Fig. 4a). As the tornado intensified, however, the central downdraft started to dominate (Fig. 4b) and finally occupied most of the central region except near the ground (Fig. 4c). While the tornado exhibited a multiple-vortex structure, strong updrafts persisted at the vortex center near the surface (the central downdraft does not reach the ground), which differs from the result of the previous laboratory experiments and idealized simulations using LES (e.g., Davies-Jones 1986; Lewellen et al. 1997).

Another noteworthy feature is that the inflow is located below roughly 50 m height and is strongest near the surface. The inflow exceeds 25 m s\(^{-1}\) at around the radii of 100 m, 70 m, and 150 m at 12:14:50, 12:15:17, and 12:16:00 JST, respectively. The maximum tangential velocity, on the other hand, is located at about 30 m height, which is above the height of the strongest inflow (not shown).

### 4. Multiple-vortex structure

Figure 5 illustrates the multiple-vortex structure and its evolution when several cyclonically-rotating subvortices with large vertical vorticity and pressure deficit became prominent within the tornadic circulation. The horizontal scale of large vertical vorticity associated with the subvortices is 50 m or less. The multiple-vortex pattern is very complex, and some subvortices interact with each other. The subvortices are located on the immediate inside of the radius of the maximum tangential speed. The subvortices had a feature of a suction vortex (Fujita 1971) accompanied by strong horizontal convergence and strong updraft near the surface. Horizontal winds are locally intensified due to the superposition of the cyclonically swirling winds associated with the subvortex and the larger-scale tornadic vortex. The maximum winds are found within these subvortices, as in Xue et al. (2014). The strong subvortex A in the lower-left side (rear-right quadrant) of the tornado shown in Fig. 5 remained almost stationary with respect to the tornado, which was moving east-northeastward, and split in two subvortices (A and D). Subvortices B, C, and D cyclonically rotated around the tornado center at a speed less than half the maximum tangential velocity of the tornadic vortex, which is consistent with the laboratory experiment (Ward 1972) and idealized numerical studies (Lewellen et al. 1997). The movement of these subvortices is somewhat reminiscent of a trochoidal motion of subvortices observed by Doppler radar (Wurman et al. 2014) and the damage path associated with a suction vortex (Fujita 1971).

The subvortex B eventually merged with the subvortex A on the southwestern side of the tornado. The period during which the tornado had a multiple-vortex structure is indicated by blue shading in Fig. 1, where the multiple-

---

**Fig. 3. Temporal variation of horizontal distance between the tornadic vortex centers at the surface and at each level.**

**Fig. 4. Radius-height cross sections of azimuthally averaged vertical velocity (color shading: red and blue colors show updrafts and downdrafts, respectively) and radial winds (contour lines) at (a) 12:14:50, (b) 12:15:17, and (c) 12:16:00 JST. Solid (dashed) contour lines indicate outflow (inflow). Arrows represent wind vectors projected on the radial-height plane.**
vortex structure is defined as follows: More than two extrema of vertical vorticity averaged over a 50 m by 50 m area at \( z^* = 26 \text{ m} \) persist for more than 2 seconds within a 250 m radius from the tornado center. Furthermore, in order for each extremum of vertical vorticity to be regarded as a subvortex, the following conditions schematically depicted in Fig. 6 must be satisfied: 1) The extremum is larger than 75% of the maximum vertical vorticity in a tornado vortex. 2) The extrema are more than 50 m apart. 3) A minimum of vertical vorticity that is less than 75% of linearly-interpolated vertical vorticity between two extrema must exist. The tornadic vortex satisfying these conditions is identified as exhibiting the pronounced multiple-vortex structure, which contains several distinct subvortices at separate locations.

The tornado repeatedly exhibited a multiple-vortex structure in conjunction with diminished tangential wind and updraft (Fig. 1b). Note that the strongest horizontal and vertical winds near the surface occurred at the stage of shrinking of the vortex radius as shown in Figs. 2b and 2e.

Previous laboratory studies (Ward 1972; Church et al. 1979) have demonstrated that the structure of a tornado strongly depends on the swirl ratio \( S \) defined by

\[
S = \frac{R_0 \Gamma}{2Q} = \frac{V_\theta}{W_0},
\]

where \( R_0, \Gamma, Q, V_\theta, \) and \( W_0 \) are the updraft radius, circulation at radius \( r = R_0 \), the outward volume flux from the top of the tornado chamber, tangential velocity at \( r = R_0 \), and mean updraft for \( r < R_0 \), respectively. Although the variables in Eq. (1) are controllable and \( S \) is easily computed in the laboratory studies, it is difficult to calculate \( S \) for a tornado having an asymmetric structure in a realistic environment (Lee and Wurman 2005). In this study, we tried to calculate \( S \), assuming an axisymmetric structure of the tornado vortex. \( R_0 \) is determined as the location where the azimuthally averaged updraft is 5 m s\(^{-1}\) at the height of 250 m, which is higher than the top of a multiple-vortex structure. \( V_\theta \) and \( W_0 \) are computed at the height of 250 m using the above value of \( R_0 \).

Time series of \( S \) defined above are plotted in Fig. 1a. Evolution of the tornado structure appears to be sensitive to \( S \). When \( S \) is relatively large, the central downdraft intensifies, and the tornado evolves into a multiple-vortex structure. Although the value of \( S \) is quite large, this result is qualitatively consistent with those of the previous laboratory experiments (e.g., Church et al. 1979; Davies-Jones 1986) and idealized numerical simulations (e.g., Rotunno 1979; Lewellen et al. 1997; Nolan et al. 2017). It was confirmed that the results are robust even if \( V_\theta \) and \( W_0 \) are calculated by using \( R_0 = 200 \text{ m} \) at a height of 250 m.
5. Summary

We have performed 10-m grid spacing simulation of the 6 May 2012 Tsukuba supercell tornado to clarify the fine structure of a strong tornado using realistic environmental conditions including surface friction. The simulated tornado exhibits cyclic evolution from one-cell through two-cell to multiple vortices, and this structure change depends strongly on the swirl ratio. Such a structural transition occurred approximately below 200 m height, where the forward tilting of the tornado vortex is small. Subvortices in the multiple-vortex structure are located on the immediate inside of the radius of the maximum tangential velocity, and rotate cyclonically around the tornado center at less than half that velocity. The multiple-vortex tornado is characterized by several subvortices, which are associated with strong horizontal convergence and strong updraft near the surface. These features are consistent with the results of previous laboratory experiments (Ward 1972; Church et al. 1979), idealized numerical simulation (e.g., Rotunno 1979; Lewellen et al. 1997), and observational studies (Wurman 2002; Lee and Wurman 2005). Although horizontal winds are locally intensified by the subvortices, the strongest wind of the tornado occurs at the stage of shrinking of the vortex radius just prior to a transition to a multiple-vortex structure. Strong updrafts of around 50 m s\(^{-1}\) are also found near the surface (z* = 10 m) at the tornado center prior to the transition to a multiple-vortex structure.

Acknowledgments

The authors are grateful to anonymous reviewers for their constructive comments. This work is supported by the FLAGSHIP2020, MEXT within the priority study (No.4: Advancement of meteorological and global environmental predictions utilizing observational “Big Data”). This research used computational resources of the K computer provided by the RIKEN Advanced Institute for Computational Science through the HPCI System Research project (Proposal number hp12082, hp130012, hp140220, hp150214, hp150289, hp160229). This work is partly supported by JSPS KAKENHI Grant Number 15K05295 and 24244074.

Edited by: T. Kawano

Supplement

Supplement 1 shows the simulation results by the 50-m horizontal grid spacing model. The experiment was conducted using the same conditions, such as the domain size, vertical layers, and initial and boundary data, as in the 10-m grid run. The tornado vortex simulated by the 50-m grid does not exhibit a ring-shaped distribution of large vorticity surrounding the central downdraft nor multiple-vortex structure throughout the simulation period. As shown in Section 4, the subvortices have a horizontal scale of ~50 m, thus the 50-m horizontal grid model is insufficient to resolve the fine-scale tornadic structure such as multiple vortices.

References


Manuscript received 14 April 2017, accepted 28 June 2017
SOLA: https://www.jstage.jst.go.jp/browse/sola