Numerical simulation of a strong tornado in eastern China with different microphysical schemes

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A tornado that occurred in eastern China on June 23, 2016 was simulated with the Weather Research and Forecasting (WRF) model (version 3.9) using three different microphysical schemes (WRF single-moment 6-class [WSM6] scheme, Morrison double-moment scheme, and Milbrandt–Yau [MY] scheme). The results showed that the Morrison scheme’s simulation result was the best among the three schemes. The Morrison scheme simulated a better structure of three layers, including a cold pool near the ground, thick heating layer in the middle levels, and cooling again above 14 km. From the microphysical processes, the possible formation mechanism was that the convective activity was first evoked by the near-ground cold pool, and then the horizontal vortex tube was raised and vertically stretched before turning in the vertical direction by the release of latent heat caused by the water vapor condensation. Thereafter, the vortex tube was cut off by the downward movement caused by the cloud water evaporation and the snow melting in the front of the convection system, causing the violent vertical lift of the rear vortex tube, forming the tornado.

KEYWORDS
microphysical schemes, tornado, tornado-like vortices, vortex tube

1 | INTRODUCTION

A tornado is a rotating air column that extends downward through cumulonimbus clouds, usually accompanied by funnel clouds. Typically, a tornado is around a few hundred meters in diameter, and the maximum surface wind speed can reach 140 m/s. In eastern China, there are around 200–300 tornadoes every year, among which 10–15 tornadoes can lead to disastrous consequences. With the frequent occurrence of tornado-related disasters, scientific research in this field has grown considerably in recent years.

Donaldson (1970) was the first to describe a “tornado cyclone” when studying a supercell. The theory of mesocyclones within storms was proposed by Ray et al. (1975), which further accelerated research into tornado theory.
Brown (1978) found a velocity-field vortex characteristic in Doppler radar data that might be accompanied by a tornado whose scale is smaller than that of a mesocyclone, referred to as the “tornado vortex signature” (TVS).

In recent years, high-resolution numerical modeling has been developed to spatial resolutions of the micro-α and micro-β scale, and thus the numerical simulation of tornadoes has improved accordingly. Snook and Ming (2008) used idealized numerical experiments to show that a certain intensity of the near-ground cold pool is conducive to a continuous maintenance of the strong updraft near the center of the low-level circulation center, which in turn is conducive to the formation of a tornado. Schenkman et al. (2014) simulated a tornado that occurred in Oklahoma and found that the tilt of baroclinic velocity may affect the tornado’s location.

Although the above studies have produced a series of achievements, there are still some key scientific problems requiring urgent attention:

1. It remains a challenge to simulate and reproduce the formation and evolution of tornadoes completely and effectively.
2. The differences among the various microphysical schemes available in terms of tornado simulation remain unclear.
3. The mechanisms that influence the different microphysical schemes with respect to their simulation of tornadoes are yet to be fully elucidated.

### 2 | CASE DESCRIPTION

A severe tornado that occurred in eastern China on June 23, 2016 was studied in this work. At 0600 UTC, the tornado emerged in the east of China then moved northeast before developing into its mature stage at 0630 UTC. The wind speed of the tornado exceeded 73 m/s which reached EF4 (enhanced F scale) (Fujita, 1981).

Based on the Global Forecast System (GFS) reanalysis data from the National Centers for Environmental Prediction (NCEP), the meteorological environments of the tornado were analyzed. The synoptic circulation background of this tornado was a typical rainstorm circulation (Chu, 1934) with high temperatures and high humidity. When the western Pacific subtropical high moved northward, at 500 hPa (figures omitted) there were cold vortices with a low trough moving eastward and low vortices moving eastward at 700 and 850 hPa. The northeast cold vortices moved southward, and the rear of the cold vortices carried strong and cold air moving southward, gradually affecting the north where the tornado generated.

The value of CAPE (convective available potential energy) reached 1867 J/kg. The vertical wind shear of the bottom layer was large. The high convective instability energy and strong vertical wind shear provided conditions for the occurrence of the tornado.

### 3 | COMPARISON OF SIMULATION RESULTS

#### 3.1 | Design of experiments

The Weather Research and Forecasting (WRF) model v3.9 was used to simulate the tornado. The model was configured with three domains and one-way nesting using “ndown.” In order to study the influence of microphysical processes on the tornado’s simulation, three different microphysical schemes—the Morrison double-moment scheme (hereinafter referred to as the Morrison scheme), the Milbrandt–Yau (MY) Double-Moment 7-class scheme, and the WRF Single-Moment 6-class (WSM6) scheme—were used to simulate the tornado. We used the same YSU planetary boundary scheme, Noah land surface model, and CAM radiation scheme. The 3-hr GFS data were chosen as the initial and boundary conditions, with a resolution of 0.5°.

We chose 4 km as the outmost horizontal resolution, because it could well simulate the large-scale circulation background. Based on that the 1,333 and 444 m were adopted as the inner resolution. We did a series of experiments with different resolutions. The higher the resolution was, the better the experimental result was. Due to the existing computing resources and limited time, so far we could well simulate the tornado with the resolution of 444 m. The higher resolution will be for further study.

#### 3.2 | Radar reflectivity and surface rainfall

Figure 1 shows the observed and simulated radar reflectivity and precipitation. Compared with observed radar reflectivity, the three schemes simulated a wide range of radar reflectivity, whose shape and position were similar to the observation; however, the simulated reflectivity had a northerly deviation, where the tornado generated, compared to the observation. Also, the strength of reflectivity was weaker than observed.

Figure 1e–h shows the accumulated precipitation per hour, from which we can see that the three schemes produced good results, as compared with observations. Generally speaking, the three schemes simulated the strong convective weather process well and, comparatively, the simulated result using the Morrison scheme was superior to that of the other schemes. Generally speaking, the observed tornado was a strong tornado; however, our simulated tornado was weaker than the observed. The maximum surface wind speed we simulated could reach 56 m/s which was an EF2 grade.
FIGURE 1  The radar reflectivity (units: dBZ) from (a) observation, (b) the Morrison scheme, (c) the MY scheme, and (d) the WSM6 scheme at 0600 UTC; and the 1-hr total rainfall (units: mm) from (e) observation, (f) the Morrison scheme, (g) the MY scheme, and (h) the WSM6 scheme during 0600–0700 UTC June 23, 2016.
4 | DYNAMIC, THERMODYNAMIC, AND MICROPHYSICAL ANALYSIS

4.1 | Diagnosis and analysis of dynamic and thermodynamic structure

This section presents the dynamic and thermodynamic structure of convective systems simulated by different microphysical processes (see Figure 2). Figure 2a1,a2,a3 illustrates a synthetic field of horizontal wind and vertical velocities. It can be seen that the Morrison scheme and WSM6 scheme simulated the central sinking of the convective system and the external rising structure of the tornado supercell, whereas the simulated result of the MY scheme was weak.

Figure 2b1,b2,b3 shows a simulated non-adiabatic heating process. Among the three schemes, the Morrison scheme (Figure 2b1) simulated a typical and more obvious three-layer structure, including a cold pool near the ground, a middle layer of the heating layer, and a cooling layer above 15 km. In contrast, the high-level cooling effect in the WSM6 simulation (Figure 2b2) was not obvious, while the cold pool of the MY scheme (Figure 2b3) was insignificant.

From the profile of radar reflectivity (Figure 2c1,c2,c3), the intensity of reflectivity according to the Morrison scheme (Figure 2c1) was obviously stronger than that of the WSM6 scheme (Figure 2c2) and the MY (Figure 2c3) scheme, in which the low layer had a strong reflectivity center in the two strong updraft regions and exceeded 60 dBZ, reaching the reflectivity characteristics of a supercell defined by Browning (1963). The MY scheme and WSM6 scheme produced reflectivity of 55 dBZ at the bottom of the maximum reflectivity center.

In accordance with the definition by Schenkman (2012) of a tornado-like vortex system, the system we studied had closed circulation at the low level, lasting at least 2 min. The central maximum vertical vorticity was more than 0.2 s⁻¹, and the wind speed reached at least 29 m/s (EF-0 level). Among the three schemes, the intensity of the vorticity center of the MY scheme and the WSM6 scheme reached 0.2 s⁻¹ (Figures 2d2 and 3), and the maximum vorticity center of the Morrison scheme reached 0.35 s⁻¹ (Figure 2d1).

The well simulated tornado had a typical three-layer thermodynamic structure, including a cold pool near the ground, thick heating layer in the middle levels, and cooling again above 14 km. The thick heating layer in the middle levels corresponded to the ascending motion. Thus, from the dynamic aspect, initial disturbance accompanied by the cold pool triggered the convective activities, the thick heating layer provided power for the ascending motion, and then the tornado occurred.

4.2 | Diagnosis and analysis of non-adiabatic heating in microphysical processes

The latent heating associated with cloud microphysical processes in the formation and development of convective activities have an important influence on the formation, propagation, and development of convective systems. The latent heat released by cloud microphysics especially the deposition and condensation drove airflow in the convective systems to continue to rise and reach a greater height (Mao et al., 2018).

In order to investigate the influence of the different microphysical schemes on the formation of the tornado, we analyzed and compared the vertical structure of non-adiabatic heating in the different schemes for the strong convective system that triggered the tornado.

Figure 3 presents the heat budget of the different microphysical schemes in a strong convective system. It can be seen that the main heating source was cloud water condensation (Figure 3a2,b2,c2), while the main cold sources were very different. The main cold sources of the Morrison scheme were the evaporation of cloud water (Figure 3a4), the melting of snow (Figure 3a5), and the evaporation of rainwater (Figure 3a3); the main cold source of the MY and WSM6 schemes was the evaporation of rainwater (Figure 3b3,c5), albeit obviously weaker than in the Morrison scheme.

From the vertical structure, the differences among the adiabatic heating of the three schemes were quite pronounced. From the heat source, the cloud water condensation process of the Morrison scheme mainly occurred in the low-middle layers. The spatial distribution range was large and the densest zone was in the region of the two strong updrafts. The cloud water condensation process (Figure 3b2) of the WSM6 scheme occurred from near-ground to 4 km. The spatial distribution was mainly concentrated in the area of strong rising motion. For the MY scheme, the freezing of rainwater as a source of heat, which mainly occurred in the low-middle layers (Figure 3b4), was significant for heating; the condensation of water vapor was obviously smaller; and the freezing effect of hail melting was remarkable. As the cold source, the front subsidence area of the Morrison scheme corresponded to the strong evaporation of cloud water, snow melting, and the evaporation of rainwater, and thus an obvious cold pool near the ground formed. The rainwater evaporation of the WSM6 scheme was not obvious (Figure 3c2); it was concentrated and weak, and the low level had a strong hail effect.

5 | POSSIBLE MECHANISM BY WHICH MICROPHYSICAL PROCESSES AFFECTED THE TORNADO

In order to analyze the influence of the microphysical processes on the tornado, we discuss the possible mechanism of interaction between dynamic and microphysical processes and how this influenced the formation of the tornado.
FIGURE 2  The (a1, a2, a3) horizontal wind speed (shading; units: m/s) and storm-relative wind field (vectors), in which the thick black line denotes the location of cross sections. The remaining panels show vertical cross sections of (b1, b2, b3) potential temperature perturbation (units: K) and the storm-relative wind field (vectors), (c1, c2, c3) radar reflectivity (shading; units: dBZ), and (d1, d2, d3) vertical velocity (units: m/s). (a1, b1, c1, d1) are for the Morrison scheme; (a2, b2, c2, d2) are for the WSM6 scheme; and (a3, b3, c3, d3) are for the MY scheme. The black solid line is the water content of 0.2 g/kg, which denotes the outline of the storm.
FIGURE 3  Legend on next page.
5.1 Diagnosis and analysis of the vorticity equation

In this paper, we introduce the vorticity equation to analyze the differences in the dynamic and thermodynamic fields of the convective system simulated by the different microphysical schemes.

The vorticity equation is expressed as follows:

\[
\frac{\partial \zeta}{\partial t} = - \left( \frac{\partial \zeta}{\partial x} u + \frac{\partial \zeta}{\partial y} v \right) - \left( \frac{\partial f}{\partial x} + \frac{\partial \Omega}{\partial y} \right) - \frac{\partial \omega}{\partial p}
+ \left( \frac{\partial \omega}{\partial x} \frac{\partial u}{\partial x} - \frac{\partial \omega}{\partial x} \frac{\partial v}{\partial p} \right) - \left( f + \zeta \right) \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right).
\]

We use the difference method to calculate the partial differential. Each layer was calculated from the land to the top. Here, \( \zeta \) is vorticity, \( f \) is the geostrophic parameter, and \( u \) and \( v \) are the wind speeds in the horizontal \( X \) and \( Y \) directions, respectively. The left-hand term of the equation is the variation of vorticity with time; while on the right, the first term is relative vorticity advection; the second is geostrophic vorticity advection; the third is the vertical transmission of vorticity; the fourth is the vorticity tilting term; and the last is the divergence term.

Figure 4 is a decomposition diagram of the vorticity tendencies equation. Vorticity can be used to diagnose the vertical movement. In order to verify the accuracy of the calculation, we compared the distribution of vertical movement and the vorticity varies with time. The shape of the area of descending motion (Figure 2a) was very similar to the shape of the area where the vorticity decreased with time (Figure 4a), while the outer ascending motion area was consistent with the area where the vorticity increased with time. The vertical movement was consistent with the vorticity which proved that the computational results were basically accurate and could be used for further analyze.

It can be seen that the main terms affecting the variation in vorticity are the vorticity tilting term (Figure 4a4,b4,c4) and the divergence term (Figure 4a5,b5,c5), which indicates that the variation in vorticity of the tornado was mainly caused by these two terms. The vorticity tilting term indicates the variation in vorticity caused by the uneven horizontal distribution of vertical movement, and its physical meaning is vertical movement making the vortex tube tilt. For the Morrison scheme, the large-value center of the tilting term was located in the updraft of the front of the tornado supercell (Figure 4a4), indicating the tilting effect of the vortex tube was mainly due to the strong downward movement of the front of the tornado supercell and the updraft. The center of the divergence term was located in the updraft of the tornado supercell center, indicating that the strong convergence near the ground was an important factor for the enhancement of vorticity in the tornado center.

5.2 Possible mechanisms by which microphysical processes affected the formation of the tornado

Figure 5 is a conceptual diagram of the influence of microphysical processes on the formation of the tornado. The analysis of the vorticity equation showed that the tilting term and divergence term were the main reasons for the rapid enhancement of vorticity, indicating that the convergence and divergence of the center and the tilting of the vortex tube in the peripheral airflow were the key physical processes in forming the tornado. The microphysical non-adiabatic forcing analysis showed that the cold pool near the ground triggered convection, and the central vorticity increased rapidly and rose under the radiation of the near-ground. The rising air rapidly condensed large quantities of latent heat and strengthened the vertical upward movement of the convention center. The environmental cooling, including cloud water evaporation and snow melting, strengthened the secondary ring. The vertical movement of the sinking branch cut off the vortex tube, resulting in the vertical lifting of the rear vortex tube, forming the tornado.

Thus, it can be seen that the key physical processes were the cloud water condensation in the center of the convection system, the evaporation of cloud water in the surrounding environment, and the evaporation of rain at ground level. A reasonable description of the above process is key to simulating tornadoes in numerical models. This is also an important reason why the Morrison scheme outperformed the other two schemes.

6 SUMMARY AND DISCUSSION

This study used the WRF model to simulate a tornado that generated in eastern China using three different microphysical schemes. The main conclusions are as follows:

1. The simulated results showed that among the three schemes, the Morrison scheme simulated the typical tornado supercell structure relatively well, while the WSM6 and MY schemes simulated the TVS due to their weaker intensity.
2. For the strong convective system, the heat budget of the microphysical schemes showed that cloud water condensation was the main source of water condensate. In the Morrison scheme, the large-scale cloud water...
FIGURE 4  Vorticity budget analysis at 0600 UTC June 23 at 850 hPa: (a1, b1, c1) variation of vorticity with time; (a2, b2, c2) relative vorticity advection; (a3, b3, c3) vertical transmission of vorticity; (a4, b4, c4) vorticity tilting term; (a5, b5, c5) divergence term. (a1, a2, a3, a4, a5) are for the Morrison scheme; (b1, b2, b3, b4, b5) are for the MY scheme; and (c1, c2, c3, c4, c5) are for the WSM6 scheme. The arrows are horizontal wind speed at 850 hPa.
condensation process provided the main energy for the rising motion of the tornado, and the strong rainwater evaporation to form the cold pool near the ground.

3. The vorticity budget analysis of the strong convective system where the tornado occurred showed that the vorticity tilting term and divergence term played a major role with all three schemes.

4. The possible formation mechanism, based on this case, is that the convective activity is first evoked by a near-ground cold pool, and then the horizontal vortex tube is raised and vertically stretched before then turning into the vertical direction by the release of latent heat caused by the water vapor condensation. Subsequently, the vortex tube is cut off by the downward movement caused by the cloud water evaporation and the snow melting in the front of the convection system, causing a violent vertical lift of the rear vortex tube.

In this study, we discussed the possible mechanism through which the tornado formed. However, more tornado cases are needed to confirm our conclusion. In fact, the simulation and analysis of tornadoes requires a more detailed scale (horizontal resolution: 20–30 m) and more observational data for in-depth and detailed research. Research on the formation mechanism of tornadoes is still in its infancy, and therefore requires further study before consensus can be reached.

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REFERENCES
Brown, R.A., Lemon, L.R. and Burgess, D.W. (1978) Tornado detection by pulsed Doppler radar. Monthly Weather Review, 106(106), 29.
Browning, K.A. and Donaldson, R.J. (1963) Airflow and structure of a tornadic storm. *Journal of the Atmospheric Sciences, 20*(20), 533–545.

Chu, B.C. (1934) The enigma of southeast monsoon in China. *Acta Geographica Sinica*, 1, 1–27.

Donaldson, R.J., Jr. (1970) Vortex signature recognition by a Doppler radar. *Journal of Applied Meteorology*, 9, 661–670.

Fujita, T.T. (1981) Tornadoes and downbursts in the context of generalized planetary scales. *Journal of Atmospheric Sciences*, 38(8), 1511–1534.

Mao, J.H., Ping, F., Yin, L. and Li, X.F. (2018) A study of cloud microphysical processes associated with torrential rainfall event over Beijing. *Journal of Geophysical Research: Atmospheres*, 123(16), 8768–8791.

Ray, P.S., Doviak, R.J., Walker, G.B., Sirmans, D., Carter, J. and Bumgarner, B. (1975) Dual-Doppler observation of a tornadic storm. *Journal of Applied Meteorology*, 14(8), 1521–1530.

Schenkman, A.D., Xue, M. and Shapiro, A. (2012) Tornadogenesis in a simulated mesovortex within a mesoscale convective system. *Journal of the Atmospheric Sciences*, 69(11), 3372–3390.

Schenkman, A.D., Xue, M. and Hu, M. (2014) Tornadogenesis in a high-resolution simulation of the 8 may 2003 Oklahoma city supercell. *Journal of the Atmospheric Sciences*, 71(1), 130–154.

Snook, N. and Ming, X. (2008) Effects of microphysical drop size distribution on tornadogenesis in supercell thunderstorms. *Geophysical Research Letters*, 35(24), 851–854.

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