Abstract

A major tornado spawned by a supercell is reproduced by a fine-resolution three-dimensional numerical simulation, and its genesis mechanism and structure are clarified. The tornado, which is associated with a maximum vertical vorticity of 0.85 s⁻¹ and a pressure drop of 27 hPa, originates from one of the small-scale vortices on the gust front that forms between a warm moist environmental air and a rain-cooled air produced by the storm. Only the small-scale vortex that develops into a major tornado is located right under the low-level updraft associated with the low-level mesocyclone; the others that fail to develop are not. Several interesting previously-unexamined characteristics of the three-dimensional structure of the simulated tornado vortex are also reported.

1. Introduction

Extensive efforts have been made for several decades to reveal the generation mechanism and structure of a tornado in a supercell storm. In order to observe airflows around tornadoes, mobile Doppler radars have been invented and utilized successfully (e.g., Wurman and Gill 2000; Bluestein and Pazmany 2000). Because of the short lifetime and the small horizontal scales of the vortices, however, comprehensive data that reveal their structure and generation process have not been obtained so far. However, the recent development of computer technology and mesoscale numerical models has allowed a numerical simulation to be a promising tool to reveal the dynamics of tornadoes. Several studies have succeeded to reproduce a tornado in a supercell storm numerically (e.g., Wicker and Wilhelmson 1995; Grasso and Cotton 1995; Finley et al. 2001). However, the generation mechanism and structure of a supercell tornado have not been clarified in a satisfactory manner.

This paper reports the results of a high-resolution numerical simulation in which a classical supercell and an associated tornado are reproduced realistically. Based on the simulation results, the generation mechanism and structure of the supercell tornado are clarified.

2. Numerical model

The three-dimensional model of the compressible atmosphere used in the present study is ARPS Version 4.5.1 (Xue et al. 1995). The calculation domain is 66.4 km × 66.4 km in the horizontal directions and 15.1 km in the vertical direction. The horizontal grid size is uniform and is 70 m. The vertical grid size varies from 10 m near the ground to 760 m near the top of the calculation domain. As in the previous studies, free-slip and adiabatic conditions are assumed at the top and bottom boundaries for simplicity. Radiation conditions are applied to the lateral open boundaries. Rayleigh damping with an e-folding time of 300 s is introduced above 12 km AGL (Above Ground Level) to prevent reflections of gravity waves at the top boundary. As for cloud physics, only the Kessler-type warm rain process is considered for the sake of reducing a computer resource. The turbulent mixing is given by the 1.5-order closure scheme based on the prediction of turbulent kinetic energy. The Coriolis force is not included.
stretches the vertical vorticity near the ground to produce the intense low-level updraft, which, in turn, occurs in response to this low-level mesocyclone. The second pressure drop at about 1 km AGL causes the tilting of the low-level streamwise horizontal vorticity and subsequent stretching, resulting in the development of a low-level mesocyclone. The enhanced updraft below the pressure drop is caused by a sequential evolution of the perturbation pressure field. After time $t = 3300$ s, the pressure perturbation starts to drop at around 1.8 km AGL. This pressure drop accelerates the updraft between 1 and 1.8 km AGL, while the buoyancy force due to latent heat release nearly maintains the updraft against the downward pressure gradient force above 1.8 km AGL. After time $t = 3800$ s, another pressure drop starts at around 1 km AGL. This eventually causes an extremely strong updraft between 1 and 2 km AGL.

A detailed analysis of the pressure field as performed in Rotunno and Klemp (1982; hereafter RK82) exhibits that the first pressure drop at around 1.8 km AGL is caused by an interaction between the strong updraft and the vertical wind shear, which is similar to the finding by RK82 except that the vertical wind shear is contributed largely by the storm-induced horizontal wind instead of the environmental one. The enhanced updraft below the pressure drop causes tilting of the low-level streamwise horizontal vorticity and subsequent stretching, resulting in the development of a low-level mesocyclone. The second pressure drop at about 1 km AGL occurs in response to this low-level mesocyclone, and produces the intense low-level updraft, which, in turn, stretches the vertical vorticity near the ground to generate the tornado. The tornado lasts for 377 s from $t = 4334$ s to 4711 s. Although Fig. 1 shows only the first 5000 s of the simulation, the storm continues to maintain its strength until 10000 s when the simulation was terminated. A cyclic generation of a mesocyclone (e.g., Adlerman et al. 1999) and an associated tornado are observed after time $t = 5000$ s. In the present study, however, only the first tornado is examined in detail.

Figures 2a and 2b show horizontal distributions of the rain water mixing ratio and ‘Doppler velocity’, which would be observed from the southwest direction, respectively, in the southern part of the simulated supercell at 1 km AGL at $t = 4504$ s. The Doppler velocity field (Fig. 2b) shows a pair of positive and negative velocity peaks approximately 4 km apart, indicating an existence of a cyclonically swirling airflow caused by the mesocyclone. This swirling airflow advects the rain water cyclonically from the main precipitating area in the upper half of Fig. 2a, causing a hook-shaped rain water distribution. The northeastern end of the hook further shows a small-scale spiral pattern (x = 29 km, y = 23.5 km) in Fig. 2a, indicating the presence of a circulation due to the tornado. These features of the tornadic supercell storm have been often reported since 1950s (Stout and Huff 1953). Recently, Wurman (http://www.cswr.org/dataimages/2004-06/web-images-2004-06/tornado/index.php?path=%2Fhanston) used a mobile Doppler radar to successfully observe a fine structure of a tornado and its parent supercell storm in Jetmore, Kansas on May 17, 1995. His reflectivity and Doppler velocity maps are surprisingly similar to those in Fig. 2.

Figure 3 shows a three-dimensional view of isosurfaces of cloud water and vertical vorticity around the simulated tornado as seen from the east at $t = 4504$ s. The size of the view is 8.4 km in the north-south direction and 2.3 km in the vertical direction. The horizontal line near the bottom indicates the ground level. Gray and red colors show isosurfaces of cloud water (0.1 g kg$^{-1}$) and vertical vorticity (0.5 s$^{-1}$), respectively. Note that only the clouds in the foreground is shown.

3. Results

The storm evolves into a typical supercell storm as in the previous studies (e.g., K81). Figure 1 shows a time-height cross section of the maximum updraft, the maximum vertical vorticity and the minimum perturbation pressure, where the maximum updraft, for example, is the largest vertical velocity over the whole horizontal calculation domain at each height level. The updraft (Fig. 1a) gradually intensifies with time after the initiation of the storm, and keeps its strength of more than 30 m s$^{-1}$ above 4 km AGL due to condensational heating of water vapor.

After $t = 4000$ s, however, the updraft intensifies rapidly below 4 km AGL, and exceeds 40 m s$^{-1}$ between 1 and 2 km AGL after $t = 4200$ s. In response to the rapid increase of the updraft, the vertical vorticity (Fig. 1b) starts to increase near the ground after $t = 4300$ s, indicating tornado development. By $t = 4504$ s, the vertical vorticity reaches its maximum of 0.85 s$^{-1}$. Figures 1a and 1c show that the rapid intensification of the updraft is caused by a sequential evolution of the perturbation pressure field. After $t = 3300$ s, the perturbation pressure starts to drop at around 1.8 km AGL. This pressure drop accelerates the updraft between 1 and 1.8 km AGL, while the buoyancy force due to latent heat release nearly maintains the updraft against the downward pressure gradient force above 1.8 km AGL. After $t = 3800$ s, another pressure drop starts at around 1 km AGL. This eventually causes an extremely strong updraft between 1 and 2 km AGL.

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middle of the figure. A small-scale skirt-shaped cloud with lower cloud base exists at the northern part of the storm-scale cloud base. This is a wall cloud which is often observed during a tornadic phase of the storm. A funnel cloud extends further downward from the wall cloud to the ground. The vertical vorticity of the tornado shows a columnar-shape inside the funnel, and reaches more than 1 km AGL inside the cloud. In accord with the observed tornado lifecycle, the simulated funnel cloud extends downward as the vorticity increases and shrinks into the cloud base as the vorticity weakens.

Figure 4 shows the time-evolution of the vertical vorticity right near the ground (5 m AGL) and the updraft at 200 m AGL between \( t = 3900 \) s and 4504 s. By \( t = 3900 \) s, the rain-cooled air inside the storm to the west is colliding with the warm moist environmental air to the east and forms a convergence line called a gust front. It is associated with a significant vertical vorticity due to the horizontal wind shear between the westerly and northeasterly winds. Several vortices (hereafter denoted by Vortices A, B, C and D) are generated along the gust front presumably by a barotropic instability of the horizontal shear flow.

Vortices A, B, C and D move southward due to the advection of the environmental northerly wind, and go out of the domain of Fig. 4 without noticeable amplification. At \( t = 3968 \) s, a new vortex (Vortex E) appears near the southern end of the updraft region. Though Vortex E exhibits a considerable amplification until its vertical vorticity exceeds 0.3 s\(^{-1}\), it eventually dissipates without developing into a major tornado (Such a vortex may correspond to a gustnado, e.g., Doswell and Burgess 1993). The dissipation of Vortex E occurs because the strong low-level rotation generates a downward pressure gradient, which results in compression of the vertical vortex tube due to a vortex-scale downdraft. By \( t = 4069 \) s, another new Vortex F emerges below the updraft center of the low-level mesocyclone. The updraft stretches the vertical vorticity of Vortex F, developing it into the tornado. Thus, the genesis of the supercell tornado is found to be somewhat similar to that of the non-supercell tornado (Wakimoto and Wilson 1989; Lee and Wilhelmson 1997). The largest difference, however, is that the major tornado in a supercell develops in association with the updraft of the low-level mesocyclone that continuously stretches the vertical vorticity of the vortex associated with the gust front. As Vortex F is strengthened, the entire shear layer associated with the gust front starts to wrap up, developing it into the major tornado.

Finally, the structure of the simulated tornado is examined. Figures 5a and 5b show horizontal cross sections of the vertical velocity (contour interval (c.i.): 0.2 m s\(^{-1}\)) and (b) perturbation temperature (c.i.: 0.5 K) at 5 m AGL. Vertical cross sections of (c) horizontal wind (c.i.: 5 m s\(^{-1}\)) and (d) perturbation pressure (c.i.: 5 hPa) along \( y = 23.35 \) km. The vertical vorticity is shown by the gray scale. The zero contour lines are omitted in (a).
which is caused by an adiabatic cooling by the pressure drop of 27 hPa, is seen near the vortex center.

Figures 5c and 5d show vertical cross sections of the horizontal wind speed and the perturbation pressure near the tornado, respectively. The vertical vorticity is strongest near the ground, and gradually decreases with increasing height. The axis of the maximum vorticity tilts westward with height, since the low pressure center of the mesocyclone is located to the west of the surface vortex center (Fig. 4). The radius of the tornado defined by the wind speed exceeding 32 m s$^{-1}$ is about 400 m near the ground, and increases with height, becoming more than 700 m at 1 km AGL (Fig. 5c). The axis of the minimum pressure coincides with that of the maximum vertical vorticity (Fig. 5d).

4. Summary and discussions

We have successfully reproduced a major tornado associated with a supercell storm by means of a high-resolution numerical simulation and studied the genesis and structure of the simulated tornado. The tornado genesis in the present simulation proceeds as follows: An airflow structure typical of a supercell accompanied by a mesocyclone is formed by 20 min after the initiation of the storm. As the direction of the storm-induced vertical wind shear vector starts to align at approximately 1.8 km AGL, a pressure drop is caused at this level by the interaction between vertical wind shear and the storm-scale updraft after 50 min. This pressure drop accelerates the updraft below 2 km. The updraft generates a low-level mesocyclone at around 1 km AGL by tilting of the horizontal vorticity and subsequent stretching after 60 min. The pressure drop caused by the cycloidal rotation of the low-level mesocyclone further accelerates the updraft below.

Near the ground, on the other hand, several vortices are developing along the gust front. Among these vortices, only one vortex right below the strong updraft associated with the low-level mesocyclone develops into a tornado due to the stretching of vertical vorticity by the updraft after 70 min. Thus, the direct source of the vertical vorticity of a supercell tornado is in the vertical vorticity of the gust front near the ground, but not in that of the mesocyclone. It is also noted that the present numerical simulation has no vertical vorticity initially. Thus, the vertical vorticity of the gust front must have been produced through the tilting of horizontal vorticity. Although, there have been several successful simulations of a tornadogenesis in a supercell (Wicker and Wilhelmson 1995; Grasso and Cotton 1995; Finley et al. 2001), none has clarified the correspondence between the small-scale vortices in the gust front and the tornado.

The existence of a number of vortices, most of which do not develop into a tornado, along the gust front is not only consistent with a recent mobile Doppler radar observation by Bluestein et al. (2003), but also very interesting in the light of previous observational studies. Burgess (1997) reported that only 20 percent of radar-observed mesoclines spawn a tornado, suggesting that an existence of a mesocyclone alone is not sufficient for generating a tornado. It is also pointed out that apparently very similar morphologies of mesoclines do not assure a tornadogenesis (Wakimoto and Cai 2000). Integrating these observational facts and the results of the present study, it appears that the timing and relative location between the development of the vortices along the gust front and that of the low-level updraft associated with the low-level mesocyclone is important for the genesis of a supercell tornado.

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References


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