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A numerical simulation on the genesis and structure of a tornado spawned by a supercell storm

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A supercell tornado has been successfully simulated by using a quasi-compressible non-hydrostatic mesoscale model (ARPS Ver. 4.5.1; Xue et al., 1995) with a horizontally uniform resolution of 70m and a vertically variable resolution. The calculation domain is 66.4kmx66.4km in the horizontal direction and 15.1km in the vertical. Only the warm rain process has been considered. The calculation is started from a horizontally uniform state taken from an upper air sounding representing the environment of a tornado-spawning supercell storm in Okalahoma state in the United States. An ellipsoidal thermal bubble the radii of which are 10km and 1.5km in the horizontal and vertical directions respectively is placed at the horizontal center of the calculation domain at the height of 1.5km to initiate the storm. The horizontal boundaries are open, and the vertical boundaries are free-slip and adiabatic.

Within 35 min from the start of the calculation, a supercell storm that has a mesocyclone and an associated hook-shaped precipitation distribution has been formed. After 60 min, perturbation pressure at 2km AGL (Above Ground Level) starts to decrease and rapidly accelerates the updraft between 1 and 4km AGL. A detailed analysis of the pressure field shows that this pressure decrease is associated with an interaction between the vertically sheared horizontal flow and the updraft of the storm. The intensified updraft starts to tilt the horizontal vorticity which is associated with the vertically sheared horizontal flow and generated baroclinically and then stretches the resulting vertical vorticity. After 65 min, this causes an intensified mesocyclone at 0.8km AGL and a much larger pressure drop. This pressure drop, in turn, produces an updraft of more than 40m/s at 1km AGL.

Near the surface, a gust front is formed between the warm moist environmental air and a cold outflow from the precipitation area. The strong horizontal shear flow near the gust front is subject to barotropic instability and results in a number of vortices. Most of the vortices finish their lifetime without appreciable intensification. A vortex below the extremely intensified updraft, however, starts to be stretched by the updraft and has developed into a tornado. This mechanism seems to explain why only 20 percent of mesocyclones spawn tornadoes. The simulated tornado is associated with a funnel cloud that develops downward from the cloud base as the tornado intensifies and shrinks upward as it dissipates. The horizontal distributions of the horizontal wind and precipitation particles around the tornado and the mesocyclone are surprisingly similar to those observed by Doppler radars, confirming that our simulation has succeeded in reproducing a major tornado associated with a typical supercell storm.

The simulated tornado is used to study the detailed structure and dynamics of a tornado. For example, the simulated tornado is located near the boundary between the updraft and downdraft as previous observations point out. Our vorticity budget analysis shows that the nearly axisymmetric structure of the vertical vorticity is maintained in the manner that intensified (weakened) vorticity by stretching (compressing) due to the updraft (downdraft) is advected to the region of the downdraft (updraft) where compressing (stretching) reduces (intensifies) the vorticity.