Super high-resolution simulation of the fine-scale tornado structure

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1. Introduction

Detailed structure of tornadoes has not been clarified enough because of difficulties in collecting observational data with fine spatial and temporal resolutions. Most of previous studies have been conducted by photogrammetric analyses, laboratory experiments and idealized simulations such as a large eddy simulation, which contains calculational errors or some obvious unrealistic aspects. In this study, we performed downscale experiments with realistic conditions for Tsukuba supercell tornado (2012) using nested grids with as small as 10-m horizontal grid spacing to resolve the fine-scale tornado structure. The Tsukuba tornado rated F3 on the Fujita scale, which is one of the most destructive tornadoes ever in Japan, hit Tsukuba City in eastern Japan on 6 May 2012 and caused severe damage. The main objective in this study is to understand the detailed structure of a severe tornado and the dynamics which govern the smaller-scale disturbances within a tornado.

2. Model description and experimental design

The numerical model used in this study is the Japan Meteorological Agency Nonhydrostatic Model (JMA-NHM; Saito et al. 2006), which is operationally used in JMA. It is based on fully compressible equations with a map factor. Unlike previous numerical studies on tornadoes, this simulation includes a full physics model that parameterizes surface processes and starts from a realistic initial condition obtained from an operational regional analysis of JMA that adopts a four-dimensional variational data assimilation system.

Quadruply nested one-way grids are used to conduct super high-resolution simulation with a horizontal gird spacing of 10 m (NHM10m). The NHM10m contains 4001 x 3001 grid points in the horizontal and 250 vertical levels with grid intervals of 10 m near the surface. The initial time is 12:02 JST (= UTC + 9 hours) on 6 May 2012, and the integration time is 18 min. The initial and boundary conditions are provided from the simulation results with 50-m horizontal gird spacing (NHM50m), which successfully simulated a supercell tornado (Fig. 1).

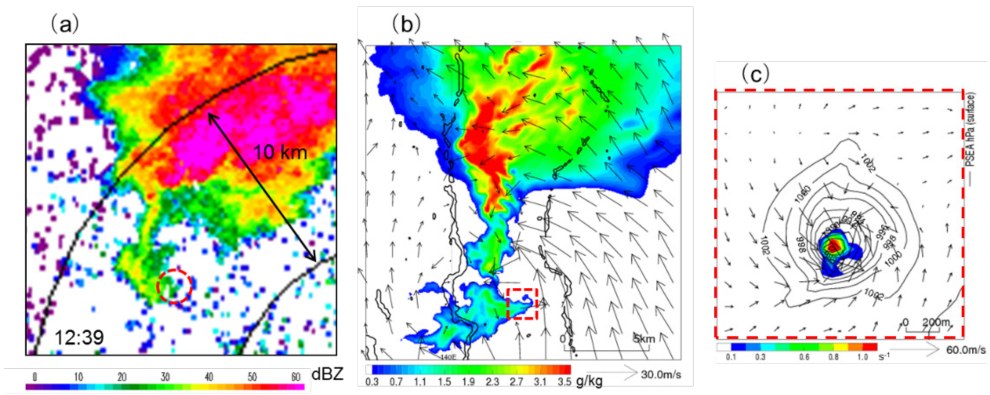

Fig. 1. (a) Radar reflectivity observed by C-band radar about 15 km away from storm center. Red circle indicates tornado location. (b) Horizontal distribution of the mixing ratio of hydrometeors (sum of rainwater, snow, and graupel) at a height of 1 km simulated by NHM50m. Arrows denote storm-relative winds. (c) Vertical vorticity at a height of 10 m simulated by NHM50m. The displayed area corresponds to the red rectangle in (b). Contour lines denote sea level pressure at intervals of 2 hPa.

3. Simulation results

Figure 2 shows the time series of minimum sea level pressure and maximum wind velocity within a simulated tornado from the rapid intensifying stage to decaying stage. Minimum pressure reaches 937 hPa (pressure deficit; 65 hPa), and maximum ground-relative surface wind speeds exceed 70 m s^{-1} around 12:15 JST.

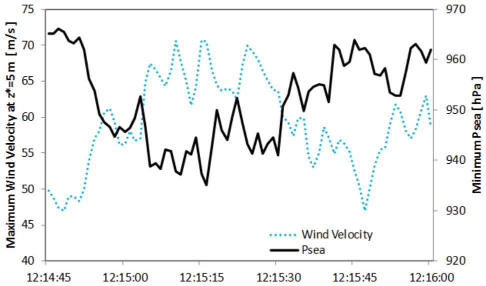

Fig. 2. Time series of minimum sea level pressure and maximum wind velocity at a height of 5 m.

During the rapid intensifying stage, the vortex core region accompanying large vertical vorticity contracted and was gradually occupied by downdraft (Fig. 3). After that, the central downdraft intensified, and multiple vortices formed with an increase of horizontal dimension of a tornado. Thus, it is evident that the simulated tornado evolved from one-celled to two-celled tornado and subsequently exhibited multiple vortices, which are consistent with a tornado-like vortex evolution in laboratory experiments. Figure 4 illustrates an asymmetric structure of a tornado at 12:16 JST when most significant multiple vortices formed. There exist two prominent cyclonic subvortices associated with pressure deficit. Although subvortices locally intensify winds owing to the superposition of the velocity field associated with the small-scale subvortex and the larger-scale tornado, the strongest wind is found in the shrinking stage prior to multiple vortices.

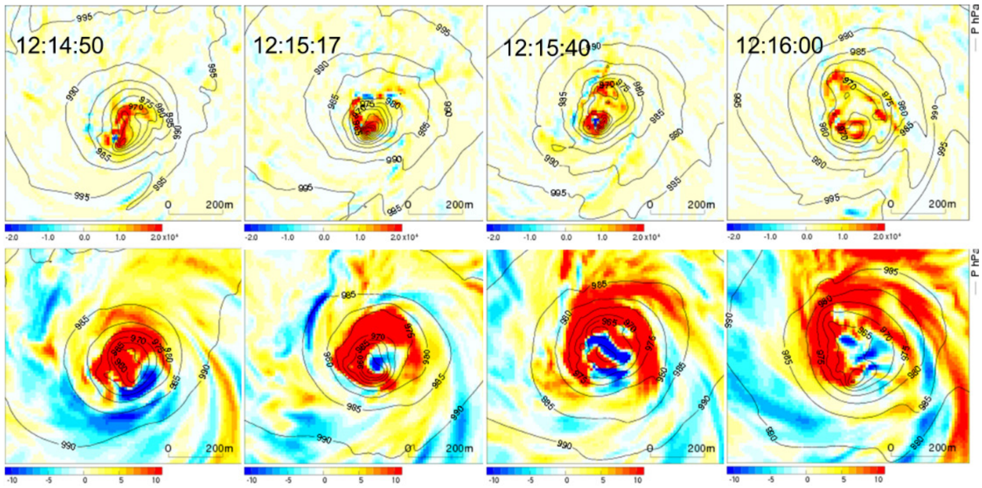

Fig. 3. Evolution of vertical vorticity at a height of 26 m (upper panels) and vertical velocity at a height of 79 m (lower panels). Contour lines indicate pressure at intervals of 5 hPa.

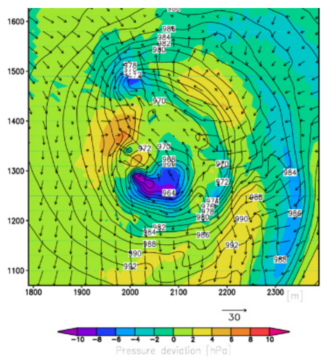

Fig. 4. Asymmetric structure at a height of 26 m at 12:16 JST. Shaded colors show pressure perturbation, and arrows denote asymmetric winds. Contour lines indicate pressure at intervals of 2 hPa.

Acknowledgements

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References

Saito, K., and co-authors, 2006: The operational JMA nonhydrostatic mesoscale model. *Mon. Wea. Rev.*, **134**, 1266-1298.