MM5 Simulations of the 24 September 1999 Tornadic Outbreaks in the Outer Rainband Associated with Typhoon Bart

Jun Yoshino, Hirohiko Ishikawa and Hiromasa Ueda

Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto, Japan

E-mail: yoshino@storm.dpri.kyoto-u.ac.jp
Web address: http://ssrs.dpri.kyoto-u.ac.jp/~yoshino/index_E.html
Fax number: +81-774-38-4158, Office phone: +81-774-38-4162

1. Introduction

It has long been recognized that tornadoes associated with tropical cyclone (TC) rainbands frequently cause damages in the United States and Japan. Geographically, hurricane-tornadoes in the United States prefer to occur in the coastal areas along the Gulf of Mexico. In Japan, typhoon-tornadoes also prefer to take place in the coastal regions of the Pacific side of the Japan islands.

Over the past few decades, a considerable number of the climatological and statistical studies have been made on American hurricane-tornadoes (Hill et al. 1966 ; Novlan and Gray 1974 ; Gentry 1983 ; McCaul 1991) and Japanese typhoon-tornadoes (Omoto 1982 ; Hayashi et al. 1994 ; Niino et al. 1996). According to these studies, TC-tornadoes, in general, are formed in the regions of strong vertical shear of horizontal wind at low levels in the right front quadrant relative to TC motion. They also suggested that most of them were spawned in the outer rainbands rather than in the inner ones. Although there has been some interest in such the climatology of TC-tornadoes, little is known about the possibility of the TC-spawned tornado prediction, the initiating and developing mechanism, and the meso-γ-scale internal structure, because of the lack of the datasets with good enough temporal and spatial resolution. Recently, high-resolution techniques, using Doppler radar observations (Snell and McCaul, 1993 ; Suzuki et al. 2000) and idealized numerical simulations (McCaul and Weisman, 1996), have been applied to the TC-tornado cyclones, and have indicated that there were the marked difference in the character of the TC-tornadoes to that of the Great Plains tornadoes. Further profound knowledges, however, are required in order to fully understand the mechanism of TC-tornadoes.

In this study, we conducted realistic numerical simulations of a Japanese TC-tornadic event using the MM5 model with a realistic orographic field and realistic initial atmospheric fields. Our MM5 simulations possessed different methods from those in McCaul and Weisman (1996) in which the storms were initialized with a ellipsoidal thermal bubble in the idealize hurricane-tornado environment. Finally, the present investigation leads to the conclusions that the shear–CAPE combinational parameters evaluated by MM5 outputs indicate a high possibility of forecasting TC-tornadoes, and the influence of a preexisting horizontal convergence line at low levels, which was induced by the high mountains, the so-called Japan Alps, played an important role in developing the strong vertical vorticity in miniature supercell storms.

2. Overview of the tornadic events

At 1200JST 24 September 1999, typhoon Bart was located at 35.7°N, 132.6°E in the Sea of Japan with the central pressure of 965-hPa. It then moved northwestward and was drastically decreasing its strength (+30 hPa day^{-1}), as shown in Figure 1. At that instant, a total of four tornadoes was spawned around Toyohashi City, which located in about 250-km west from Tokyo along the Pacific coast. It was approximately 500-km away from the center of Bart. The strongest one, which passed through Toyohashi City toward the north-northeast, has reached F3 intensity (wind speed ranging from 70.4 to 92.5 m s^{-1}). Figure 1 also shows that the occurrent location was surrounded by a part of the TC outer rainband posited in the right front quadrant relative to the TC motion. The TC outer rainband has been in that quadrant before Bart struck the Kyushu island. An upper-air observation in close proximity to the outer rainband (at Shionomisaki observational station) showed the atmospheric conditions of low static stability (CAPE = 2246 J kg^{-1}) and strong vertical shear (0–3-km SREH = 346 m^2 s^{-2}). Additionally, the bulk Richardson number of 24.5 and the energy-helicity index of 4.9, which were evaluated by the same sounding, indicated the high probability of developing supercell storms, so the environment might apt for producing significant tornadoes around there.

3. Model configuration

The numerical model used in this study is the Pennsylvania State University and National Center for At-

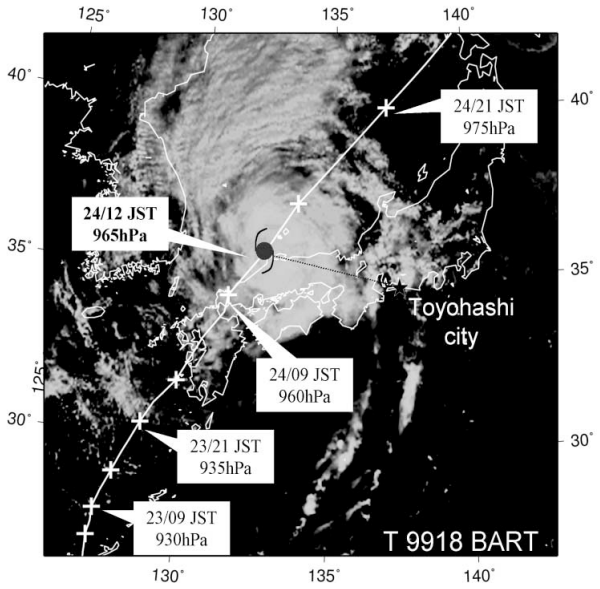

Figure 1 : Track of Typhoon Bart (1999) and GMS5 visible image at 1140JST 24 Sep. 1999, when the Toyohashi tornadoes broke out. A solid line and plus marks indicate typhoon track and every 6-h positions, respectively.

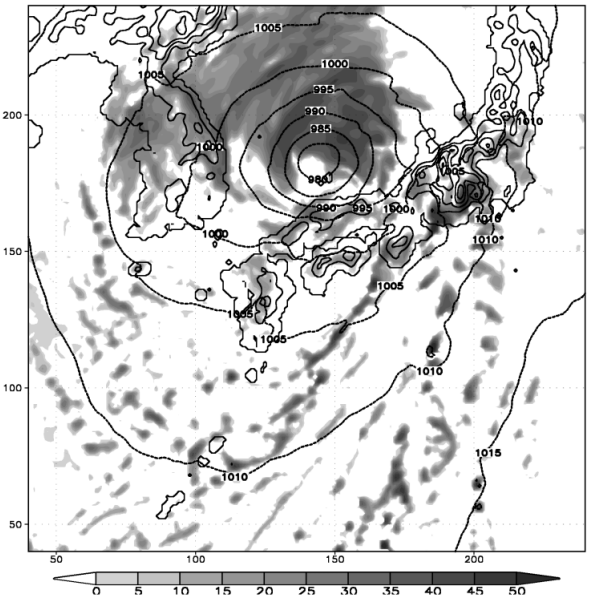

Figure 2 : D1-simulated radar reflectivity [dBz] (shaded) on 0.91 half sigma level and sea-level pressure field (contoured by dashed lines) at 1200JST 24.

mospheric Research Mesoscale Model MM5 version 2.

In this study, triply one-way nested computational domains (hereafter D1, D2 and D3) are employed. D1, D2 and D3 have grid increments of 9-km, 3-km and 1-km, respectively. D1, centered at 32°N, 131°E, covers the track of Bart and the surrounding synoptic systems. The one-way nested intermediate domain D2 is employed in order to reproduce the outer rainband and surrounding environment. The finest one-way nested domain D3 is posited around Toyohashi City so as to simulate the internal finer structure of mesoscale cyclones associated with the TC outer rainband. Calculations for each domain are performed for mesh sizes of 250×250, 250×220 and 300×220 points, and time steps of 30-sec, 9-sec and 3-sec, respectively. Tirty-six vertical full-sigma levels are used from surface pressure level to 100 hPa in all domains. The initial and lateral boundary conditions for D1 are provided by the Japan Meteorological Agency regional 20×20 km resolution analyses (JMA–RANAL), which includes typhoon bogussing. The datasets are also used as the initial conditions of the operational regional spectral model (JMA–RSM) over East Asia. The sea surface temperature field is provided by the weekly 1×1 degree resolution optimum interpolation SST analysis (Reynolds and Smith 1994), and is held constant throughout the whole periods in all simulations. D1 is initialized at 1500JST 23 September 1999 by JMA–RANAL. The nested D2 and D3 are initialized after 18-h and 19-h from the initialization of D1. The boundary conditions of the two nested domains are updated at 30-min and 5-min intervals, respectively, using each mother domain information. The options with regard to the analysis and observational nudging are not used in all experiments.

The high-resolution Blackadar PBL scheme composed of four stability regimes is adopted for D1. For the other nested D2 and D3, the Burk and Thompson PBL scheme, which is the TKE equation model based on the Mellor and Yamada turbulence closure, is employed. A surface temperature over land is calculated using the force-restore slab model. The Reisner graupel microphysics scheme, which accounts for cloud-resolving processes, are used in all domains. Additionally, the Grell cumulus parameterization scheme is applied, except for the finer D2 and D3, in which convective process is resolved by the explicit scheme only. The model uses the longwave and shortwave radiation scheme for all domains that renewed each grid value at every 1-min.

4. Environments of the TC tornado cyclones

The MM5-D1 experiment (9-km resolution) could reproduce a realistic cloud pattern of typhoon Bart as illustrated in Figure 2. The reproduced outer rainband was consistent with the GMS5 imagery (see Figure 1). The TC outer rainband was formed in the confluence zone between the cyclonic and anti-cyclonic horizontal circulations. In the region just behind this rainband,

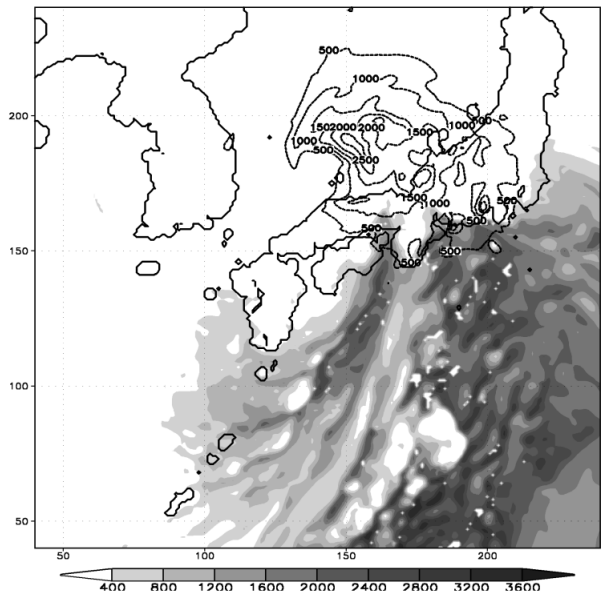

Figure 3 : D1-simulated CAPE [J kg^{-1}] (shaded) lifted from 0.965 half sigma level and 0–3-km SREH [m^2 s^{-2}] (contoured by dashed lines) at 1200JST 24.

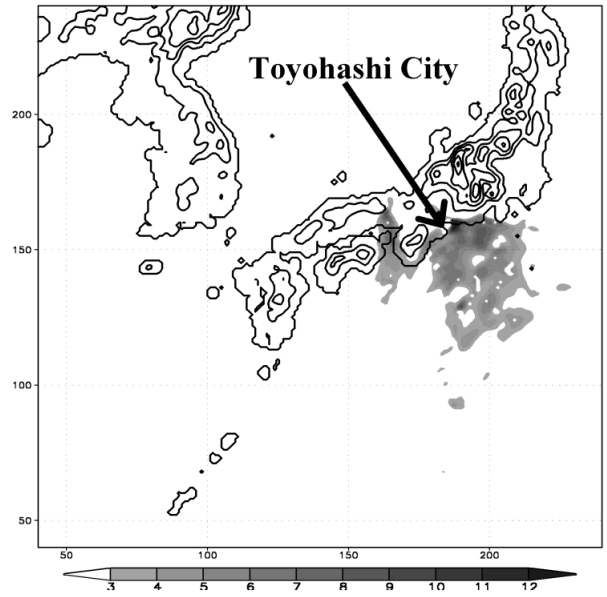

Figure 4 : Energy-helicity index distribution (shaded) calculated on each grid of the D1-simulation at 1200JST 24.

the relatively dry and cold air, which originated in continental air-mass and prevailed in the western part of Bart (not shown), intruded into the TC circulation and brought the upper cold front (so called moisture front).

To investigate the most deterministic parameter for forecasting tornado outbreaks when the TC outer rainband just has passed around Toyohashi City, the various dynamical and thermodynamical parameters that describe the vertical structure of atmosphere have been analyzed on each grid of D1 in the same manner as analyzing on rawinsonde observations. Figure 3 depicts the horizontal distribution of the convective available potential energy (CAPE) and 0–3-km storm relative environment helicity (SREH) in D1. At that time, there was a fairly strong SREH region (over 1000 m^2 s^{-2}) in the northeast quadrant of TC. Although the value of the SREH around Toyohashi City (approx. 500 m^2 s^{-2}) was not so large as near the center of Bart, it was large enough to develop supercell storms. Additionally, the high CAPE region (over 2000 J kg^{-1}) widely covered the western North Pacific Ocean to the south of the Japan islands as well as around Toyohashi City. These values evaluated by MM5 outputs were in good agreement with the those evaluated by available upper-air soundings. Although these parameters might indicated the high probability area for this tornadic event, the areas were distributed too widely to predict the specific tornadic event with pinpoint accuracy. In recent years, many investigators have proposed that the shear-CAPE combinational parameters such as the "bulk Richardson number", "vorticity generation parameter" and "energy-helicity index", would be good tools for predicting tornado cyclones and supercell storms. We therefore computed the energy-helicity index, which is proportional to the product of CAPE and SREH, and the result is shown in Figure 4. This parameter exhibited a maximum value around Toyohashi City. This case study supports the usefulness of energy-helicity index for the prediction of TC-associated tornadoes. Whatever was chosen as the best, it was certain that all physical parameters related to atmospheric vertical structure gave suggestion of a high probability of the Toyohashi tornado outbreaks.

5. Simulation of the TC tornado cyclones

The finest MM5-D3 experiment (1-km resolution) also successfully reproduced the features of the Toyohashi tornado cyclones such as the rainwater distribution at lower atmosphere shown in Figure 5. It should be noted that the developing mesoscale cyclones were passing around Toyohashi City, which were consistent with the radar imagery (see in Figure 6). These storms had strong vertical vorticity ($\zeta \sim 0.01$ s^{-1}) at the lower troposphere (under 4000-m AGL). Before the landing of mesoscale cyclones, an intensive low-level convergence zone has been preexisting around Toyohashi City. It was created between the oncoming flow in the outer rainband and stagnant flow in the upwind side of the high mountains, the so-called Japan Alps. The formation of the stagnant region could be explained by the upstream blocking effect at low levels due to the

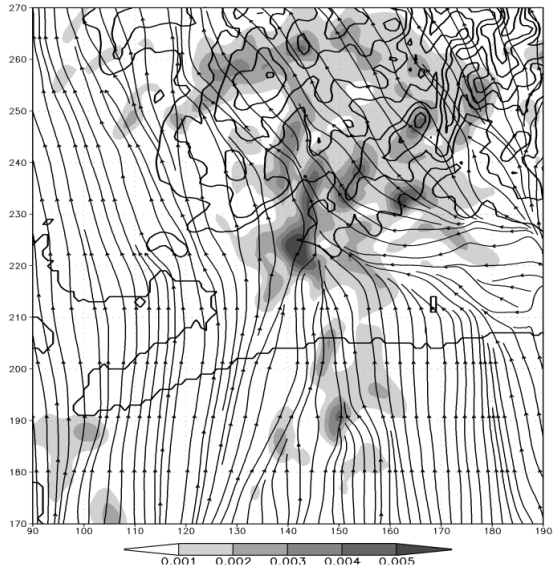

Figure 5 : D3-simulated mesoscale cyclones and stream lines on 0.999 half sigma level. Mixing ratio of rain water [kg kg^{-1}] is shaded. Solid lines indicate terrain heights every 200-m.

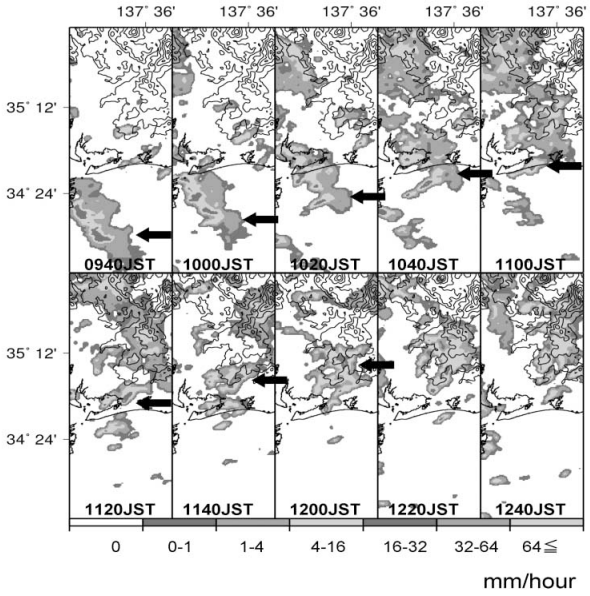

Figure 6 : Precipitation intensity imagery estimated by the reflectivity of Nagoya Radar (provided by the Japan Meteorological Agency) on 24 Sep. 1999.

orographic obstacle and by the effect of the difference of roughness length between land and sea. It might induce horizontal shearing instability and produce intensive vertical vorticity with the vorticity stretching due to accelerated cloud formations. Thus, the simulated mesoscale cyclones embedded in the TC outer rainband might have fully developed around Toyohashi City, when they have just passed over the preexisting convergence line. In addition to the sufficient environments (high-CAPE and high-SREH) for tornadogenesis, the existence of the low-level convergence line would contribute to the development of miniature supercell storms, in which the mechanism is well-known as "non-supercell tornadogenesis".

6. Conclusions

The PSU/NCAR MM5 has been used to determine the predictable parameter of the Toyohashi tornado outbreaks and to reproduce the realistic meso-γ-scale cyclones in consistency with various observations. It is concluded that both the low- and high-resolution MM5 simulations have some potential abilities to forecast TC-tornadoes.

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