NOTES AND CORRESPONDENCE

Sensitivity to Horizontal Resolution of the Simulated Intensifying Rate and Inner-Core Structure of Typhoon Ida, an Extremely Intense Typhoon

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Abstract

The model-resolution sensitivity of simulated intensifying and deepening rates of an extremely intense tropical cyclone (TC), Typhoon Ida (1958), was investigated using the Japan Meteorological Agency/Meteorological Research Institute nonhydrostatic atmospheric model with horizontal resolutions of 20, 10, 5, and 2 km. The results revealed great differences in the intensifying and deepening rates and their associated structural changes among simulations. The typhoon simulated by a finer horizontal resolution resulted in a greater maximum intensity associated with more rapid intensification. The differences were also revealed in the hourly precipitation pattern, the radius of maximum wind speed at 2-km altitude (RMW) and its shrinking behavior, near-surface inflow, and the axisymmetrization of the inner core. Only the cloud-resolving 2-km model, with explicit microphysics, could reproduce the observed maximum intensity and extreme intensification rate of the typhoon realistically because the model could produce the deep, intense, and upright updrafts inside RMW around the vorticity-rich area over the strong near-surface inflow. The results suggest that the appropriate horizontal resolution of the model should be used in dynamical downscaling experiments to examine extremely intense TCs with extremely high intensifying rates.

Keywords typhoon; typhoon intensity; numerical simulation; nonhydrostatic model

1. Introduction

A considerable number of category 4 and 5 tropical cyclones (TCs), on the Saffir–Simpson Hurricane Scale (<http://www.nhc.noaa.gov/aboutsshws.php>), occur in both the North Atlantic and the North-

western Pacific oceans (e.g., Hurricane Katrina and Hurricane Wilma in 2005; Typhoon Haiyan in 2013; Typhoon Vongfong in 2014). According to Kaplan and DeMaria (2003), most such high-intensity TCs are characterized by rapid intensification (RI). Thus, more accurately predicting intensity changes of TCs, particularly RI, is a key factor for accurate TC intensity forecasts and projections.

Although some recent studies have indicated that environmental parameters are skillful predictors of Atlantic TCs (e.g., Kaplan et al. 2010), other studies

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have suggested that the intensifying rate of a TC is only weakly dependent on environmental conditions (e.g., Hendricks et al. 2010). Furthermore, many observational and numerical studies have shown that RI processes are closely related to the inner-core structure and convective activity of TC (e.g., Kieper and Jiang 2012; Rogers et al. 2013; Wang and Wang 2014). The phenomena that have been proposed to link convection with RI include vortical hot towers (Montgomery et al. 2006), convective asymmetry (Braun et al. 2006), axisymmetrization of the inner-core triggered by deep convection (Guimond et al. 2010), and an upper-level warm core (Chen and Zhang 2013).

Simulations of convection associated with TCs are strongly influenced by the horizontal resolution of the model used. Previous studies have suggested that an atmospheric model with a horizontal resolution of a few kilometers is necessary to reproduce the inner-core structure and associated convection of TC (e.g., Braun and Tao 2000; Gentry and Lackmann 2010). In addition, the downscaling experiments using a 2-km-mesh atmospheric nonhydrostatic model (NHM2) for the six most intense TCs in the climate run by a 20-km-mesh atmospheric general circulation model (AGCM20) showed significant differences in the intensifying rate and the locations of the minimum central pressure (MCP) for simulated TCs in AGCM20 and NHM2 (Kanada et al. 2013). These results raise the following question: How does the horizontal resolution of a simulation affect the intensity and intensifying rate of a simulated extremely intense TC?

In this study, we investigated the impact of model resolution on not only TC intensity but also the TC intensifying rate by carrying out simulations of Typhoon Ida (1958), one of the most intense typhoons with the greatest rapid deepening recorded since 1951. We paid special attention to differences in the convective activity and inner-core structure among TCs simulated at horizontal resolutions of 20, 10, 5, and 2 km to improve the knowledge for the downscaling experiments of an intense TC in both TC forecasts and projections.

2. Model and methods

2.1 Model and experimental design

We used a non-hydrostatic atmospheric model based on the Japan Meteorological Association (JMA) operational non-hydrostatic mesoscale model (JMANHM; Saito et al. 2007) and conducted four sensitivity experiments using a different hori-

zontal resolution with each of the following: 20 km (NHM20), 10 km (NHM10), 5 km (NHM5), and 2 km. The NHM20, NHM10, and NHM5 simulations used spectral nudging (SN; Nakano et al. 2012), the Kain–Fritsch cumulus parameterization scheme (KF; Kain and Fritsch 1993), and the Level 3 Mellor–Yamada–Nakanishi–Niino closure turbulence scheme (Nakanishi and Niino 2004). In this study, moreover, a 5-km-mesh atmospheric nonhydrostatic model with explicit microphysics and without the KF scheme (NoKF5) was used to study the impact of the cumulus parameterization scheme. The SN method developed for the downscaling experiments (Nakano et al., 2012) was applied above a height of 7 km for large-scale wave components (wavelength > 1000 km) to reduce the track error of typhoons. Using NHM5, Nakano et al. (2012) conducted the sensitivity experiments for 17 typhoons and showed that the central pressure (CP) of typhoons using the SN method was almost comparable to that of those without using the SN method. The Louis scheme was used as the surface boundary layer scheme (Louis et al. 1982), with a surface–roughness–length formulation based on Kondo (1975). The computational domain was 5400 km × 4600 km (Fig. 1). The number of vertical levels was set to 55 (the top height was approximately 27 km). NHM20, NHM10, and NHM5 used a time step of 40, 30, and 15 s, respectively. Other fundamental configurations were the same as those used by Kanada et al. (2012, 2013). Initial and lateral atmospheric boundary conditions (horizontal resolution, 1.25°) and initial sea surface temperature (SST) conditions (horizontal resolution, 0.56°) were provided every 6 h from the JMA 55-year Reanalysis dataset (hereafter, JRA-55). Wind-profile retrieval data surrounding TCs were assimilated in JRA-55 with the same prescribed observational errors as those used for TC bogus data in JMA's operational system. (See Ebita et al. 2011 for a detailed description).

In NHM2 simulations, initial and lateral boundary conditions were provided every 6 h by the NHM5 simulation. NHM2 applied the Deardorff–Blackadar scheme (Deardorff 1980; Blackadar 1962) and bulk-type cloud microphysics with an ice phase that included ice, snow, and graupel (Murakami 1990) but did not apply the SN method or the cumulus parameterization scheme. The computational domain of NHM2 was 3980 km × 2380 km (Fig. 1), and the time step was 8 s. Otherwise, the configuration of NHM2 was the same as that of NHM20, NHM10, and NHM5. Numerical simulations with NHM20, NHM10, and NHM5 nested in JRA55 were

Fig. 1. L(a) Map of the simulation domain used for the NHM20, NHM10, and NHM5 simulations, with the NHM2 simulation domain shown by the red rectangle. The circles show the tracks at 6-h intervals, and the stars show the location where the minimum central pressure (MCP) was reached, in the NHM20 (purple), NHM10 (green), NHM5 (blue), and NHM2 (red) simulations. The black symbols show the best-track data and MCP location of Typhoon Ida, and the numbers indicate the day of the month in September 1958. Temporal variations of (b) central pressure (CP; hPa), (c) the CP drop rate (dCP; hPa 6 h⁻¹), (d) maximum wind speed (MWS; m s⁻¹), and (e) MWS radius (RMW; km) at an altitude of 2 km in the NHM20 (purple), NHM10 (green), NHM5 (blue), and NHM2 (red) simulations. Best-track (black circles) and JRA-55 (open circles) data are also shown in panels (b) and (c). RI, rapid intensification; ERI, extremely rapid intensification.

performed starting at 0000 UTC on September 21, 1958. Then, using the NHM5 results, NHM2 numerical simulation was conducted from 0000 UTC on September 22, 1958.

2.2 Analytical methods

The storm center was determined as the approximate geometric center (centroid) of the sea-level pressure (SLP) field in each of the NHM20, NHM10, NHM5, and NHM2 simulations, based on the methodology of Braun (2002). Radial and tangential wind speeds (hereafter, V_r and V_t , respectively) relative to the storm center were calculated for each Cartesian grid cell. In this study, positive values of V_r indicate inflow. The azimuthal mean non-axisymmetric component of near-surface V_r is defined by $\frac{1}{N} \sum |\bar{V}_r - V_r|$. Following Rogers et al. (2013), the radius (r) was normalized by the radius of the

maximum azimuthally mean V_t at an altitude of 2 km (hereafter, RMW): $r^* = r/\text{RMW}$, where the normalized radius $r^* = 1$ indicates the location of RMW.

3. Results

3.1 General characteristics

First, we give a brief overview of Ida. On September 20, 1958, a tropical depression formed from an easterly wave around the Marshall Islands, and it received the name Ida at 1800 UTC (Fig. 1). The storm moved westward while maintaining CP of 985 hPa (Fig. 1b). Then, at 0000 UTC on September 22, the typhoon began to move northwestward and rapidly intensified. From 0000 UTC to 1200 UTC on September 23, the typhoon underwent extremely rapid drops in CP at rates exceeding 20 hPa per 6 h, and at 0600 UTC on September 24, MCP of 877 hPa was reached according to the observations by aircraft reconnaissance. The maximum drop rate of CP per 6 h

Table 1. Minimum central pressure (MCP; hPa), maximum drop in central pressure (Max. dCP; hPa 6 h^{-1}), maximum near-surface wind speed (MWS; m s^{-1}) and its maximum change (Max. dMWS; m s^{-1}), and the 99th updraft percentile at an altitude of 8 km in the eyewall region (W99th; m s^{-1}).

Obs/Model	MCP	Max. dCP	MWS	Max. dMWS	W99th
Best track	877	39	—	—	—
JRA55	926	12	54.4	4.9	—
NHM20	940	6	42.2	5.6	2.2
NHM10	916	8	54.5	6.1	4.5
NHM5	889	18	70.1	9.1	9.2
NoKF5	894	16	67.8	8.1	10.2
NHM2	878	35	74.3	18.9	13.0

(hereafter, dCP) was 39 hPa (Table 1).

The NHM20, NHM10, NHM5, and NHM2 simulation results were verified by comparisons with best-track data obtained from the Regional Specialized Meteorological Center Tokyo. The storm tracks of the NHM20, NHM10, and NHM5 simulations were comparable to the best-track data. Although the storm track of the NHM2 simulation without using the SN method differed by a few degrees from the best-track data, the location of the simulated MCP, at around 20°N , 135°E , was close to that of the best-track MCP. The location tended to shift northward in the simulations with relatively coarser horizontal resolutions, i.e., in the NHM20 and NHM10 simulations.

The maximum near-surface wind speed (hereafter, MWS), MCP, and their change rates greatly differed between the NHM20, NHM10, and NHM5 simulations and the NHM2 simulation (Table 1 and Fig. 1). In general, models with finer resolutions simulated lower MCPs, stronger MWSs, and greater change rates. There was no large difference between the results in NHM5 and NoKF5 simulations. In particular, when simulated by NHM2, the typhoon underwent an extremely rapid dCP of 35 hPa, which was comparable to that in the best-track data and twice the dCP value in the NHM5 simulation. The maximum change rate of MWS per 6 h in the NHM2 simulation, 18.9 m s^{-1} , was more than twice the maximum rate in the NHM5 simulation.

The large differences in MCP, MWS, and their change rates, however, did not appear until after 0000 UTC on September 23, 1958. Therefore, we defined the onset of extremely RI (ERI) as 0000 UTC on September 23, which corresponds to the time when dCP exceeded 10 hPa in the NHM2 simulation and best-track data. Thus, we refer to the period from 1200 UTC on September 22 to 0000 UTC on

September 23 as the preERI period and the period from 0100 UTC on September 23 to 1200 UTC on September 23 as the ERI period.

During and after the preERI periods, dCP was around 10 hPa or less in the best-track data and in all simulations. In the NHM2, NHM5, and NHM10 simulations, CP, MWS, and RMW were almost the same during this period (Figs. 1b–e), whereas the typhoon simulated by NHM5 was the most intense among the four simulations. After the onset of ERI, the typhoon simulated by NHM2 started to develop rapidly, and its RMW shrank. During the ERI period, dCP exceeded 30 hPa. The typhoon simulated by NHM2 turned out to be the most intense of the four simulated typhoons. In contrast, the typhoons simulated by NHM20, NHM10, and NHM5 developed slowly: dCP was approximately 0 and 10 hPa in the NHM10 and NHM5 simulations, respectively. RMW also differed distinctly among the simulations: the minimum RMW in the NHM10, NHM5, and NHM2 simulations was 60, 45, and 34 km, respectively. The finer the horizontal resolution was, the smaller the minimum RMW became.

3.2 Intensifying rate and axisymmetrization

Figure 2 displays the horizontal distributions of hourly precipitation at 0000 UTC on September 23. Each rainfall pattern showed wavenumber-1 asymmetry with clusters of convective precipitation ($> 30\text{ mm h}^{-1}$). Wide regions of intense precipitation greater than 50 mm h^{-1} were located in the southern sector, outside RMW, in the NHM10 and NHM5 simulations. However, precipitation regions and amounts in the NHM2 simulation were relatively small. The most intense precipitation ($> 50\text{ mm h}^{-1}$) in the NHM2 simulation was actually just inside RMW.

The asymmetric patterns of near-surface winds

Fig. 2. Storm-centered composite horizontal distributions of hourly precipitation (colors) and horizontal wind at an altitude of 10 m (arrows) in (a) JRA-55, (b) NHM20, (c) NHM10, (d) NHM5, and (e) NHM2. The black contours represent mean sea-level pressure (contour interval, 10 hPa), and RMW is depicted by the bold black circle.

rapidly changed to axisymmetric patterns at 0600 UTC and 0000 UTC on September 23 in the NHM5 and NHM2 simulations, respectively (Fig. 3). However, no axisymmetric structures appeared in the NHM20 and NHM10 simulations. During the preERI period, the area of the asymmetric component of V_r varied widely, from a radius of approximately 20 km to that of 150 km, in all simulations. After 0600 UTC and 0000 UTC on September 23 in the NHM5 and NHM2 simulations, respectively, the area of the asymmetric component of $V_r > 4 \text{ m s}^{-1}$ rapidly decreased, and it appeared only inside RMW. After the onset of ERI, RMW steadily decreased to 34 km in the NHM2 simulation, whereas in the NHM5 simulation, RMW remained approximately constant at 45 to 50 km.

Thus, the structures of two of the simulated typhoons were transformed from an asymmetric pattern to an axisymmetric pattern, with RMW smaller than 50 km. After the axisymmetric transition, one simulated typhoon underwent further rapid inten-

sifying, and RMW decreased to 34 km, indicating the occurrence of ERI. These results raise the question as to what determines the large difference in intensifying and deepening rates of simulated typhoons in NHM10, NHM5, and NHM2.

3.3 Intensifying rate and inner-core convection

We compared conditions during the preERI period within the inner-core area of the simulated typhoons in normalized radius–altitude cross sections among the NHM10 (Figs. 4a–d), NHM5 (Figs. 4e–h), and NHM2 (Figs. 4i–l) simulations. During this period, CP, MWS, and RMW were similar to one another in all three simulations, although the typhoon developed slightly more rapidly in the NHM5 simulation (Figs. 1b, d, 1e).

Convection was most active around RMW ($0.6 < r^* < 2.0$) in the NHM2 simulation (Fig. 4i). In addition, in the NHM2 simulation, the maximum updraft around RMW was the most intense and tallest: the top of regions of intense updraft greater than 3 m s^{-1}

Fig. 3. Radius–time cross sections of the non-axisymmetric component of V_r ($z = 10$ m) in the NHM20, NHM10, NHM5, and NHM2 simulations. The bold black line shows RMW (km).

reached an altitude of 15 km. The intense, tall updraft allowed the relative humidity above 10 km altitude to exceed 80 % around RMW in the NHM2 simulation (Fig. 4i). However, mean updrafts around RMW were relatively weak in the NHM10 and NHM5 simulations and tilted outward as the altitude increased (Figs. 4a, e). The region of high relative humidity (> 80 %) stayed below an altitude of 8 km. In the NHM5 simulation, a warm core had already developed in the preERI period (Fig. 4f). Regions of high vertical vorticity ($> 25 \times 10^{-4} \text{ s}^{-1}$) were distributed inside RMW ($0.0 < r^* < 0.75$) around the vorticity-rich area over the leading edge of intense near-surface inflow in the NHM5 and NHM2 simulations (Figs. 4g, 4k). In particular, a vorticity-rich area ($> 20 \times 10^{-4} \text{ s}^{-1}$) was concentrated just inside RMW around the leading edge of the near-surface inflow in the NHM2 simulation (Fig. 4k). The intense, tall, and upright updraft in the NHM2 simulation formed at the leading edge of the shallow, intense near-surface inflow (Fig. 4l).

We further analyzed convective activity around the eyewall by examining eyewall updrafts around RMW (Fig. 4). Following Rogers et al. (2013), we defined convection around the eyewall as convec-

tion within $0.75 < r^* < 1.25$. Four percentile values (1 %, 50 %, 99 %, and 99.9 %) were used to show the vertical profile of the cumulative distribution function representing eyewall vertical velocity (Fig. 5). The 99th and 99.9th percentiles, indicating the most vigorous updrafts (convective bursts; CBs), considerably differed among the NHM20, NHM10, NHM5, and NHM2 simulations at altitudes above 8 km, in particular, during the preERI period. Meanwhile, there was no large difference between the 99th percentile profiles in NHM5 and NoKF5 experiments. The vertical velocity of the 99th percentile at 13 km altitude was 13 m s^{-1} in the NHM2 simulation, whereas in the other three simulations, it was smaller than 10 m s^{-1} . When CBs were defined as the top 1 % of the vertical velocity distribution at 8-km altitude (Rogers et al. 2013), the CB threshold (hereafter, W99th) was determined to be 2.2 (NHM20), 4.5 (NHM10), 9.2 (NHM5), and 13.0 (NHM2) m s^{-1} (Fig. 5a and Table 1). Thus, W99th increased approximately twofold from the NHM20 to the NHM10 simulation and from the NHM10 to the NHM5 simulation, whereas it increased approximately 1.5-fold from the NHM5 to the NHM2 simulations.

Using the W99th threshold, we investigated the

Fig. 4. Normalized radius–altitude cross sections during the preERI period in the (a)–(d) NHM10, (e)–(h) NHM5, and (i)–(l) NHM2 simulations: Azimuthal mean (a, e, i) relative humidity (colors; %), updrafts (black contours; 1, 2, and 3 m s^{-1}), and V_t (white contours; contour interval, 10 m s^{-1}); (b, f, j) temperature anomaly (colors; $^{\circ}\text{C}$), equivalent potential temperature (black contours; contour interval, 5 K), and vertical velocity (white contours; 1, 2, and 3 m s^{-1}); (c, g, k) vertical vorticity (colors; 10^{-4} s^{-1}), V_t (black contours; 2, 5, and 10 m s^{-1} , dotted; -10, -5, -2 m s^{-1}), and vertical velocity (white contours; 1, 2, and 3 m s^{-1}); and (d, h, l) V_t (colors; m s^{-1}) and vertical velocity (black contours, 1 m s^{-1}). r^* indicates the radius normalized by RMW. Arrows indicate the wind field in the section. Positive values of V_t indicate inflow in this study.

Fig. 5. Vertical profiles of the 1st and 99th (thin lines) and 50th and 99.9th (thick lines) percentiles of the cumulative distribution of eyewall vertical velocity in the NHM10 (green), NHM5 (blue), and NHM2 (red) simulations between 1200 UTC on September 22 and 0000 UTC on September 24 (a) and during the preERI (b) and ERI (c) periods. Black-dashed lines indicate 99th in the NoKF5 simulation. Temporal evolution of the total frequency of convective bursts (CBs) within $r < 2 \times \text{RMW}$ (gray bars) and of the frequency of CBs just inside RMW (i.e., $r^* = 0.75$) (orange bars) in the (d) NHM10, (e) NHM5, and (f) NHM2 simulations between 0600 UTC on September 22 and 0000 UTC on September 24. The temporal evolution of vertical vorticity within RMW below an altitude of 500 m is shown in each panel by the black line. The total frequency of CBs within $r < 2 \times \text{RMW}$ (black-bordered bars), the frequency of CBs just inside the RMW (cyan bars), and vertical vorticity within RMW below an altitude of 500 m (black-dashed line with open-circles) in the NoKF5 simulation are shown in Fig. 5e.

temporal evolution of the total frequency of CBs within $r^* < 2$, corresponding to the inner core, and the frequency of CBs just inside RMW (i.e., $r^* = 0.5\text{--}0.75$) between 0600 UTC on September 22 and 0000 UTC on September 24 in the NHM10, NHM5, NoKF5, and NHM2 simulations (Figs. 5d–f). There was a large number of CBs during the preERI period in the NHM2 simulation. As the integration time progressed, frequencies of CBs inside RMW rapidly

increased and reached 74 % of the total at 0600 UTC on September 23. They corresponded to the upright eyewall updrafts formed at the leading edge of the intense near-surface inflow. At that time, the mean vertical vorticity inside RMW also started to increase rapidly, with the result that the typhoon simulated by NHM2 was the most intense among the four simulated typhoons.

According to Vigh and Shubert (2009), RI is

avored in TCs in which at least some eyewall convection occurs inside RMW. As the warm core matures and static stability increases in the inner core, the inner-core conditions become less favorable for producing deep upright convection, and the storm thus tends to approach a steady state. Using composites of airborne Doppler observations, Rogers et al. (2013) also found that an intensifying TC, different from steady-state TCs, has a ring-like monopole vorticity structure inside RMW. According to Fig. 4, the typhoon simulated by NHM5 had a more intense warm core and areas with high vertical vorticity within $r^* < 0.5$. The development of the warm core in the NHM5 simulation caused an increase in stability inside RMW, which prevented further formation of deep upright convection and CBs.

4. Concluding remarks

We investigated the sensitivity of typhoon intensifying and deepening rates to model resolution in the case of an extremely intense typhoon, Typhoon Ida (1958), using a nonhydrostatic atmosphere model with a horizontal resolution of 20 km (NHM20), 10 km (NHM10), 5 km (NHM5), and 2 km (NHM2). The results revealed great differences in intensifying and deepening rates and associated structural changes among the simulations. This study demonstrated that a horizontal resolution of 5 km or finer was required to simulate the shrinking of RMW and the transition of the inner-core structure of Ida from asymmetric to axisymmetric. Furthermore, only the 2-km-mesh model with the deep, intense, and upright updrafts just inside RMW could reproduce the observed maximum intensity and extremely intensify rate of the typhoon. The updrafts were formed around the vorticity-rich area over the leading edge of the shallow and strong near-surface inflow. The relationship between the updrafts and the near-surface inflow should be investigated in the future.

We should note that the JMANHM used in this study is only an atmospheric model. SST was prescribed as a boundary condition only at the initial time, and during the simulations, SST was constant. However, a typhoon can induce a cold wake during and after its passage, and the cold SSTs directly affect the sensible and latent heat fluxes from the ocean (Wada et al. 2012). The impact of TC–ocean interaction on the intensity and intensifying rate of an intense TC remained to be another issue to be solved. Nevertheless, we demonstrated, at least in this case study, that model resolution has a crucial impact on the simulated intensity and intensifying rate of an

extremely intense typhoon. In reality, the inner-core structure and associated atmospheric conditions are likely to differ for different typhoons. Therefore, more case studies should be strongly encouraged to deepen our understanding of the changes in the intensity of an extremely intense typhoon simulated by fine-mesh nonhydrostatic models.

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