Statistical analysis of simulated direct and indirect precipitation associated with typhoons around Japan using a cloud-system resolving model

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Abstract:

To validate the reproducibility of simulated typhoons and related precipitation, perfect boundary condition experiments, forced by 20-km-mesh Japan Meteorological Agency (JMA) operational regional objective analysis (RANAL) data from June to October in 2002–2006, are performed using a 5-km-mesh cloud-system resolving nonhydrostatic regional climate model (NHM-5km). NHM-5km reproduced all 57 typhoons observed in the model domain during the experiment period. Relative to JMA best track data for the typhoons, the average position error of typhoon centers is 130 km at 72 hours after typhoon genesis or when the typhoon first enters the model domain. The simulated minimum central pressures of typhoons are similar to those in RANAL data. The precipitation within (outside of) a 300-km radius from the center of each typhoon is defined as direct (indirect) precipitation. The distributions of the simulated direct and indirect precipitation of typhoons show good agreement with precipitation analyses by JMA. For hourly precipitation amounts exceeding 5 mm, direct precipitation is observed more frequently than is indirect precipitation, especially for amounts exceeding 20 mm. These features are well reproduced by NHM-5km. The appearance frequency of simulated direct precipitation for hourly precipitation amounts also shows a good quantitative agreement with that measured by raingauges.

KEYWORDS Regional climate model; typhoons; precipitation

INTRODUCTION

Typhoons approaching and/or making landfall on the Japanese Islands cause not only strong winds but also heavy precipitation, endangering lives and resulting in widespread damage to property. Two types of precipitation are associated with typhoons: precipitation produced in the eye wall and spiral rain bands of the typhoon itself (herein referred to as “direct precipitation” or DP for short) and precipitation induced by indirect or remote effects of the typhoon (“indirect precipitation” or IP for short; Wang et al., 2009).

When a typhoon travels south of the Japanese Islands, a large amount of water vapor is commonly transported to the Japanese Islands by environmental circulation associated with the typhoon. Orographic-induced updrafts lift the transported water vapor and induce convective activity, resulting in IP on the Pacific side of the Japanese Islands.

From the point of adaptation to climate change, it is important to investigate future changes in the characteristics of DP and IP associated with typhoons. To project future changes in weather extremes in the Japan region, the research group KAKUSHIN Team 3 (Kitoh et al., 2009) plans to perform numerical simulations of climate forced by the results of a 20-km-mesh atmospheric general circulation model (AGCM-20km; Mizuta et al., 2006) for the present (1979–2005), near-future (2015–2039), and future (2075–2099) climates using a cloud-system resolving nonhydrostatic regional climate model with a horizontal resolution of 5 km (NHM-5km). It is best to at least assess the reproducibility of weather phenomena in the present climate before projecting climate changes due to global warming. To validate the reproducibility of weather phenomena predicted by regional climate models, perfect boundary condition experiments (e.g., Christensen et al., 1997) are generally conducted using initial and boundary conditions produced from objective analysis/re-analysis data. In perfect boundary experiments, we can avoid errors in an outer model and concentrate on detecting errors produced by regional climate model itself.

The goal of this study is to statistically examine the prediction accuracy of direct and indirect typhoon-related precipitation simulated using NHM-5km, which is intended for use in climate change experiments, based on the characteristic features of observed precipitation. In this study, NHM-5km is nested within 20-km-mesh operational regional objective analysis (RANAL) data produced by the Japan Meteorological Agency (JMA).

NUMERICAL MODEL AND EXPERIMENTAL DESIGN

The regional climate model used in this study (NHM-5km) is modified from the JMA nonhydrostatic model (JMANHM; Saito et al., 2007). The high performance of JMANHM in reproducing extreme weather associated with typhoons is shown in previous studies (Murata 2009; Oku et al. 2010). The NHM-5km model domain occupies an area of 3345 x 2635 km², covering the Japanese Islands, Korean Peninsula, Taiwan, and eastern China (Figure 1). The vertical grid contains 50 levels with intervals that vary from 40 m (near the surface) to 886 m (top of the domain); the model top is located at a height of 21.8 km. The Mellor–Yamada–Nakanishi–Niino Level 3 scheme (Nakanishi and Niino, 2004) is used for the planetary boundary layer. A bulk-type microphysics scheme with ice phase (Lin et al., 2004) is used for the cloud physics. The model has a horizontal resolution of 5 km (NHM-5km).

Gusts of strong winds and heavy precipitation associated with typhoons are observed in the vicinity of the typhoon center. In this study, the model domain of the JMANHM is expanded over 300 km from the center of each typhoon. NHM-5km reproduced all 57 typhoons observed in the model domain during the experiment period. Relative to JMA best track data for the typhoons, the average position error of typhoon centers is 130 km at 72 hours after typhoon genesis or when the typhoon first enters the model domain. The simulated minimum central pressures of typhoons are similar to those in RANAL data. The precipitation within (outside of) a 300-km radius from the center of each typhoon is defined as direct (indirect) precipitation. The distributions of the simulated direct and indirect precipitation of typhoons show good agreement with precipitation analyses by JMA. For hourly precipitation amounts exceeding 5 mm, direct precipitation is observed more frequently than is indirect precipitation, especially for amounts exceeding 20 mm. These features are well reproduced by NHM-5km. The appearance frequency of simulated direct precipitation for hourly precipitation amounts also shows a good quantitative agreement with that measured by raingauges.

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1983; Murakami, 1990) and the Kain–Fritsch convective parameterization scheme (Kain and Fritsch, 1990) are used in combination for precipitation processes. A clear sky radiation scheme (Yabu et al., 2005) and a cloud radiation scheme (Kitagawa, 2000) are used. To reduce the inconsistency in atmospheric states between NHM-5km and RANAL data (which arises from long-term integration), the spectral boundary coupling (SBC) scheme (Kida et al., 1991) is used above 7 km height for large-scale wave components (wavelength > 1000 km) of horizontal momentum and potential temperature. It should be noted that Yasunaga et al. (2005) examined the accuracy of regional climate states (sea-level pressure, temperature, and precipitation) in Japan simulated by the previous version of NHM-5km with/without SBC scheme and showed that NHM-5km with SBC scheme reproduced them better.

NHM-5km is continuously integrated from 00 UTC 17 May to 00 UTC 01 November for the years 2002–2006. Output during the first 15 days is discarded as the spin-up period, and data from 00 UTC 01 June is analyzed for each year.

**TYPHOON TRACKS AND CENTRAL PRESSURE**

Figure 1 shows the simulated typhoon tracks and position errors of typhoon centers in comparing NHM-5km results with JMA best track data once each typhoon has formed or has entered the model domain. A simple nearest-neighbor method is employed for tracking typhoons. The JMA best track data recorded 57 typhoons in the model domain during the analysis period of June–October in the years 2002–2006; all of these are reproduced by NHM-5km (Figure 1a). Four of the detected typhoons were generated in the model domain (green lines in Figure 1a).

Position errors for typhoon centers are generally less than 200 km at the times when typhoons entered the model domain (blue lines at t = 0 in Figure 1b), and are 100–320 km at the times when typhoons were generated in the model domain (green lines at t = 0 in Figure 1b). The average position error of typhoon centers increases with time, being 130 km at 72 hours after each typhoon is generated or enters the model domain (red line in Figure 1b), which is smaller than that for operational typhoon track forecasts of the JMA (250 km at 72 hours; Onoda and Komori, 2009). This could result from two factors; the effect of boundary conditions produced from objective analysis data and the usage of the SBC method in order not to depart from analyzed large scale atmospheric states.

Figure 2 compares the simulated minimum central pressures of typhoons with those from JMA best track data and RANAL data. Most of the simulated minimum central pressures are higher than those from the JMA best track data; some are more than 50 hPa higher. In contrast, the simulated minimum central pressures show good agreement with those from RANAL data. The value of Pearson’s correlation coefficient (R), root mean squared error (RMSE) and mean error (ME) also show that simulated minimum central pressures fit
better to those from RANAL data. One explanation of these results is that most of the minimum central pressures detected from RANAL data are higher than those in the best track data, which is the same as for the 5km-NHM results (data not shown). Other contributing factors may be the horizontal resolution of the model and physical processes near the surface (e.g., latent heat flux). It should be noted that the simulated minimum central pressures fit to those from JMA best track data better in the region north of latitude 30°N (R = 0.73, RMSE = 16.7 and ME = 12.2) compared with the whole model domain. This result indicates that thermodynamic structures of typhoons are well simulated by NHM-5km in the vicinity of the Japanese Islands.

CHARACTERISTIC FEATURES OF DIRECT AND INDIRECT PRECIPITATION

In this study, precipitation within (outside of) a 300-km radius from the typhoon center is defined as direct (indirect) precipitation. Typhoons that pass over the region enclosed by red lines in Figure 1a are defined as "approaching-Japan typhoons". The DP and IP caused by all 42 of the approaching-Japan typhoons are analyzed for the 143 days when they exist in the NHM-5km domain.

Figure 3 shows the distributions of daily DP simulated by NHM-5km and depicted from Radar-Raingauge analyzed precipitation (R-R) data produced by JMA. The daily DP amounts are calculated by dividing total DP for each grid point by 143 days when 42 approaching-Japan typhoons existed in the NHM-5km domain. The simulated distribution of DP shows a good agreement with that of the R-R data. It should be noted that it is difficult to use the R-R data for a quantitative comparison because it contains inaccurate regions due to orographic-induced shadow areas in the radar observations. Therefore, the simulated daily DP amounts at the nearest land-based grid points for each AMeDAS station, and show similar features to the frequencies obtained using all grid points on the Japanese Islands.

The appearance frequency of observed DP with $R_1$ smaller (larger) than 5 mm is lower (higher) than that of indirect and non-typhoon precipitation. DP is observed more frequently for $R_1 > 5$ mm than the others, being several times higher than those for $R_1 > 20$ mm. These results indicate that the characteristics of DP differ from that of indirect and non-typhoon precipitation. These features are well reproduced by NHM-5km. The appearance frequency of simulated DP shows a good quantitative agreement with observation data. In contrast, the appearance frequencies of indirect and non-typhoon precipitation are underestimated for $R_1 > 15$ mm. The observed IP for $R_1 > 10$ mm appears more frequently than non-typhoon precipitation (blue and black dashed lines in Figure 5, respectively), although this difference is not reproduced clearly in the simulations (blue and black solid lines in Figure5, respectively).
STATISTICAL ANALYSIS OF SIMULATED DIRECT AND INDIRECT PRECIPITATION ASSOCIATED

SUMMARY AND DISCUSSION

To validate the reproducibility of simulated typhoons and accompanying precipitation, perfect boundary condition experiments were performed using NHM-5km for the period June–October in the years 2002–2006, using initial and boundary conditions derived from RANAL data. Fifty-seven typhoons observed in the model domain are successfully reproduced by NHM-5km. The average position error at 72 hours after each typhoon was generated or entered the model domain was very small (~130 km). The simulated minimum central pressures are similar to those detected from RANAL data. The distribution of simulated direct (indirect) precipitation, defined as precipitation inside (outside) a 300-km radius from the typhoon center, shows good agreement with that obtained from R-R data, although areas with simulated heavy precipitation (daily precipitation amounts exceeding 20 mm) are erroneously shifted from inland to coastal regions on the Pacific side of the Japanese Island. The appearance frequency of simulated DP over land areas throughout the Japanese Islands is comparable with that observed by AMeDAS, whereas the appearance frequencies of simulated indirect and non-typhoon precipitation are underestimated for R1 > 15 mm. The appearance frequency of observed IP for R1 > 10 mm is higher than that of non-typhoon precipitation, although this difference is not reproduced clearly in the simulations.

A fixed threshold radius of 300 km is used to separate DP and IP in this study; however, it is well known that precipitation areas associated with typhoons vary according to their structural changes, especially in mid-latitudes. In order to examine the sensitivity for the threshold radius, we performed another analysis using a threshold radius of 500 km. The daily direct (indirect) precipitation amounts averaged over the land of Japan again show a good agreement between observation and simulation, 5.0 (5.9) mm day\(^{-1}\) and 5.9 (6.1) mm day\(^{-1}\), respectively. The appearance frequencies of DP and IP show almost the same features; the appearance frequency of observed DP with R1 smaller (larger) than 5 mm is lower (higher) than that of IP. This result indicates that some variation of the threshold radius hardly yields differences for statistical features of direct and indirect precipitation of typhoons.

The present study shows that NHM-5km can reproduce intense precipitation (especially for direct precipitation) associated with typhoons in the vicinity of Japan, as well as large-scale fields which affect typhoon tracks. This indicates that by using good results of AGCM-20km which reproduce present climatic features (e.g., large-scale circulation and number of typhoon genesis), NHM-5km can show more accurate small scale information on possible changes of precipitation characteristics associated with typhoons in the vicinity of Japan in the future climate.

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REFERENCES

Christensen JH, Machenhauer B, Jones RG, Schär C, Ruti PM, Castro M, Visconti G. 1997. Validation of present-day regional climate simulations over Europe: LAM simulations with observed boundary conditions. Climate Dynamics 13: 489–506. doi:10.1007/s003820050178.

Kain JS, Fritsch JM. 1990. A one-dimensional entraining/detraining plume model and its application in convective parameterization. Journal of the Atmospheric Sciences 47: 2784–2802. doi:10.1175/1520-0469(1990)047<2784:AODEPM>2.0.CO;2.

Kida H, Koide T, Sasaki H, Chiba M. 1991. A new approach for coupling a limited area model to a GCM for regional climate simulations. Journal of the Meteorological Society of Japan 69: 723–728.

Kitagawa H. 2000. Radiation processes. Separate volume of annual report of NPD 46: 16–31 (in Japanese).

Kitoh A, Ose T, Kurihara K, Sasaki H, Chiba M. 1991. A new approach for coupling a limited area model to a GCM for regional climate simulations. Journal of the Meteorological Society of Japan 69: 723–728.

Lin YL, Farley RD, Orville HD. 1983. Bulk parameterization of the snow field in a cloud model. Journal of Applied Meteorology 22: 1065–1092. doi:10.1175/1520-0450(1983)022<1065:BPOTSF>2.0.CO;2.

Mizuta R, Oouchi K, Yoshimura H, Noda A, Katayama K, Yukimoto S, Hosaka M, Kusunoki S, Kawai H, Nakagawa M. 2006. 20-km-mesh global climate simulations using JMA-GSM model – Mean climate states –. Journal of the Meteorological Society of Japan 84: 165–185. doi:10.2151/jmsj.84.165.

Murakami M. 1990. Numerical modeling of dynamical and microphysical evolution of an isolated convective cloud – The 19 July 1981 COPE cloud. Journal of the Meteorological Society of Japan 68: 107–128.

Murata A. 2009. A Mechanism for Heavy Precipitation over the Kii Peninsula Accompanying Typhoon Meari (2004). Journal of the Meteorological Society of Japan 87: 101–117. doi:10.2151/jmsj.87.101.

Nakanishi M, Niino H. 2004. An improved Mellor-Yamada Level-3 model with condensation physics: Its design and verification. Boundary-Layer Meteorology 112: 1–31. doi:10.1023/B:BOUN.0000020164.04146.98.

Narita M. 2008. Improvement and adjustment of Kain–Fritsch scheme. Separate volume of annual report of NPD 54: 103–111 (in Japanese).

Oku Y, Takemi T, Ishikawa H, Kanada S, Nakano M. 2010. Statistical analysis of simulated direct and indirect precipitation associated with typhoons around Japan using a cloud-system resolving model. Hydrological Research Letters 4: 1–6. doi:10.3178/HRL.4.1.

Onoda H, Komori T. 2009. Validation of tropical cyclone track forecast in WGNE. Separate volume of annual report of NPD 55: 167–169 (in Japanese).

Oouchi K, Yoshimura J, Yoshimura H, Mizuta R, Kusunoki S, Noda A. 2006. Tropical cyclone climatology in a global-warming climate as simulated in a 20km-mesh global atmospheric model: Frequency and wind intensity analysis. Journal of the Meteorological Society of Japan 84: 259–276. doi:10.2151/jmsj.84.259.

Saito K, Ishida J, Aramachi K, Haru T, Segawa T, Naret M, Honda Y. 2007. Nonhydrostatic atmospheric models and operational development at JMA. Journal of the Meteorological Society of Japan 85B: 271–304. doi:10.2151/jmsj.85B.271.

Wang Y, Wang Y, Fudeyasu H. 2009. Effect of typhoon Songda (2004) on remote heavy rainfall in Japan. Monthly Weather Review 137: 3699–3716. doi:10.1175/2009MWR2933.1.

Yabu S, Murai S, Kitagawa H. 2005. Clear sky radiation scheme. Separate volume of annual report of NPD 51: 53–64 (in Japanese).

Yasunaga K, Sasaki H, Wakazuki Y, Kato T, Muroi C, Hashimoto A, Kanada S, Kurihara K, Yoshizaki M, Sato Y. 2005. Performance of Long-Term Integrations of the Japan Meteorological Agency Nonhydrostatic Model Using the Spectral Boundary Coupling Method. Weather and Forecasting 20: 1061–1072. doi:10.1175/WAF894.1.