Representation of Extreme Weather during a Typhoon Landfall in Regional Meteorological Simulations: A Model Intercomparison Study for Typhoon Songda (2004)

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Abstract:

The representations of extreme weather during the landfall of Typhoon Songda (2004) in regional simulations at 1-km resolution are described and compared for two cloud-resolving models: Non-hydrostatic Model (NHM) and the Weather Research and Forecasting model (WRF). Both models, using the same 5-km-mesh outputs from NHM as their initial and boundary conditions, successfully reproduced the observed typhoon track and intensity. The comparison of surface winds indicated that WRF evaluates more enhanced extremes than NHM; on the other hand, the representations of rainfalls indicated that the extremes of hourly and accumulated rainfalls simulated by the two models are evaluated differently. Slight differences in the model topography between the two models, though produced by the same terrain dataset, were shown to significantly affect the representations of the extremes in each model. It should be recognized that not only the differences in model numerics and physics but also slight changes in the reproduction of topography induce differences in the representations of extreme weather.

KEYWORDS extreme weather; typhoon; cloud-resolving simulation; model intercomparison; topography

INTRODUCTION

A dynamical downscaling technique with the use of a non-hydrostatic regional meteorological model initialized and forced by global climate simulations is an important tool for evaluating disastrous weather such as heavy rainfall and strong wind under future climate conditions. This approach critically depends on the performance of regional models in representing extreme values and therefore should be warranted for existing real cases that correspond to disastrous weather. Moreover, it is desirable that the representations of extreme values be independent of the choice of models, if the differences in model numerics and physics employed in regional models are minimized. Furthermore, numerical simulations need to be performed by cloud-revolving models (Tao et al., 2009), since disastrous weather is mainly due to convective processes and thus explicit representation of cumulus convection is essential.

Kanada et al. (2008) examined the performance of regional climate simulations with a non-hydrostatic model at 5-km resolution in reproducing maximum daily precipitation over Japan as 5-year warm-season climatology and showed that the simulated precipitation properties agree well with the observations. Hayashi et al. (2008) compared the regional weather forecasts over Japan and Southeast Asia in periods of January and July 2007 by using two different non-hydrostatic models and indicated that the forecasts in the Tropics are worse than those for the midlatitude region and are sensitive to the season and model. Although both studies are more or less interested in the representation of extreme values, the simulations were conducted with the use of cumulus parameterization. There are model intercomparison studies in the cloud-resolving range where cumulus clouds are explicitly represented under the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study framework (e.g., Tao et al., 2009); however, the simulations were performed under idealized conditions. Therefore, model performance in simulating extreme weather under real conditions in a cloud-resolving range should be investigated in order to better evaluate the disasters due to extreme weather.

This study examines the representations of extreme values in different non-hydrostatic regional models by focusing on a landfalling strong typhoon as an extreme case. We chose Typhoon Songda (2004) as our case study, which had a minimum central pressure of 925 hPa and made landfall on Kyushu Island, Japan, with a central pressure of 945 hPa. For this study we use two different models: Non-hydrostatic Model (NHM) (Saito et al., 2006) developed by the Japan Meteorological Agency (JMA) and the Meteorological Research Institute (MRI), and the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) developed by the National Center for Atmospheric Research (NCAR). After comparing the simulated results with the observations, the characteristics of the extremes of surface wind speeds and rainfalls over Kyushu Island are investigated. Furthermore, a possible influence of topography on the representation of extremes is examined.

MODEL CONFIGURATION AND SIMULATION DESIGN

The two models, NHM and WRF, are configured to simulate the landfall of Typhoon Songda (2004) over the computational area of 600 km by 600 km which covers the Kyushu Island and its surroundings at 1-km resolution with 50 vertical levels. Although the definitions of terrain-following vertical coordinate systems differ between NHM and WRF, the distributions of the vertical levels are set as equal to each other as possible. The physics parameterizations for NHM are identical to the settings used by Kanada et al. (2008) for their 5-km
NHM runs except that a cumulus parameterization and a spectral boundary coupling technique are not used in the present 1-km run. The parameterizations for WRF are chosen to be comparable to those for NHM: the six-class warm-rain and ice-phase scheme of Hong and Lim (2006) is chosen for cloud microphysics, and a Mellor-Yamada Level 2.5 scheme of Janjic (2002) for planetary boundary layer mixing. Although the physics schemes chosen for the NHM and WRF simulations are not exactly the same as each other, their physics backgrounds in parameterizing the processes are similar. In all the 5-km and 1-km resolution runs, the terrain dataset for creating model topography is the United States Geological Survey’s GTOP030 (with 30-sec resolution). The land-use/land-category dataset used is the 100-m mesh Geographical Information System database from Japan’s Ministry of Land, Infrastructure, Transport and Tourism, indicating that the parameters for surface roughness and characteristics are exactly the same in both models.

The initial and boundary conditions for the 1-km simulations are produced with the use of hourly outputs from a 5-km grid NHM simulation. The model settings for this 5-km run are the same as those in Kanada et al. (2008) except for a slight difference in the domain size (i.e., horizontal grids of 721 by 577 instead of 669 by 527). This 5-km run was conducted during 1200 UTC 6 September and 0600 UTC 7 September 2004, initialized and forced by 20-km-mesh operational regional analysis data of JMA. Using these 5-km outputs, NHM and WRF at 1-km resolution are run from 1500 UTC 6 September to 0600 UTC 7 September. The simulated outputs are stored at 4-min intervals.

**RESULTS**

**Comparison with the observations**

Reproducing the track and intensity of a typhoon is essential in order to represent resulting extreme weather in a regional simulation. Figure 1 compares the tracks of the simulated Typhoon Songda (2004) by NHM and WRF with the best track of JMA. It is shown that both simulations are quite successful in reproducing the typhoon track; the distances from the best track at the times denoted in Figure 1 are 15.3–37.2 km for NHM and 17.3–48.4 km for WRF. It is also indicated that the difference between the models (4.5–21.5 km) is smaller than that between the observation and the simulation. In addition, the central pressures simulated in NHM and WRF were also well reproduced within differences of 0.6–3.0 hPa and 1.6–4.2 hPa, respectively, from the best-track data.

It is noted that the locations of the typhoon center and the change of the central pressure in the simulations were slightly delayed behind the best track. These differences lead to the differences in the temporal changes of surface wind and rainfall. For example, the temporal changes of surface winds at a location where the typhoon center passed nearby indicate that the simulated changes are overall behind the observations (Figure 2). We have compared the temporal changes of simulated surface winds with AMeDAS observations and have found that in general the simulations capture the patterns and the peaks of the observed changes well, except for a consistent delay in the simulations. The model results were further compared with the upper-air observations at Fukuoka and Kagoshima and were found to agree well with wind speed, direction and temperature observations, with less agreement in reproducing the humidity profile. Again, the differences between the models were minor.

These comparisons strongly indicate that the models perform well in simulating the typhoon and that the model results can be used to investigate the characteristics of the extreme values due to the typhoon.

**Extreme value representation**

The characteristics of the extreme values caused by the typhoon landfall are examined through their frequency distributions over space (the grid points on Kyushu Island) as well as over time (the simulated period). Severe wind and heavy rainfall induced by typhoons are in general located in right-side areas relative to the direction of typhoon movement.

Figure 3 shows the frequency distributions of wind speed and its maximum evaluated at a 10-m height above the ground for all the grid points over the whole Kyushu Island (gray bars). The maxima were determined from the time series during the simulation period at every grid point. The distributions shown by black bars are for grid points where the maximum slope angle exceeds 7.5 degrees (which corresponds to 100-m height against 1000-m distance) and slope direction is to the southeast between 45 and 225 degrees. The reason for specifically focusing on the steep slopes is because it is expected that the wind and precipitation are enhanced over steep terrains facing southeast when considering the typhoon track and the topography. The shapes of the wind speed distributions for the WRF and NHM runs at every land grid appear to be similar to each other. The modes are almost the same, with the value for NHM being a little larger. These features are also true for the case of the steep grids.

While there are some similarities, a remarkable difference is seen in the higher tails of the distribution. The WRF simulation produces higher wind speeds more frequently than NHM. This difference in representing extremes is reflected on the distribution of wind speed maximum, where the total frequency of greater than 20 m s⁻¹ is significantly larger in the WRF case than in
Comparing the frequencies at all the grids and at the steep grids, the role played by the steep terrains in representing the higher tails in the distribution seems to be more evident. Note that the highest extremes generally appear around the mountain peaks whose slopes are not so steep.

The statistical difference in model topography is shown in Figure 4. Although both models produce their model topography from GTOPO30, there exists an obvious difference between them. The model topography of WRF is steeper. Actually NHM applies smoothing on slopes whose angle is larger than 8.5 degrees in order to strictly assure numerical stability. The difference in model topography may be a cause of the difference in the wind speed distribution.

The rainfall extremes are then examined. The frequency distributions of hourly rainfall and its maximum both at all the land grids and the steep grids are shown in Figure 5. Although the shapes of the distributions of hourly rainfall for WRF and NHM look similar

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to each other, the representation of higher extremes in the distribution is more enhanced in the NHM simulation than in WRF (Figure 5a). For rainfall maxima, higher extremes are also more enhanced in NHM than in WRF (Figure 5b). In this way the representation of hourly rainfall extremes over land indicates an opposite sense to that of wind speed extremes. Comparing the frequencies between over the whole land and at the steep terrains in Figure 5, the effects of the steep terrains on hourly rainfall appear to be more pronounced with a higher value of rainfall. Furthermore, this characteristic seems to be more evident in the NHM run than in the WRF run.

This seemingly inconsistent representation of wind and rainfall extremes in the two models needs some explanation. The difference in the representations of wind speed extremes in WRF and NHM is reasonable, since WRF reproduces steeper and higher topography than NHM and winds become higher in steeper terrain. On the other hand, rainfall is produced by cumulonimbus clouds which are controlled not only by terrain features but more by atmospheric forcings such as static stability and mesoscale and synoptic-scale backgrounds. Taking into account this point as well as the fact that a single cumulonimbus cloud has typically a lifetime of an hour, short-term rainfall seems to be influenced not only by topography but by various factors such as atmospheric forcings. Figure 5 suggests that the difference in the terrain representation between the models plays a minor role in reproducing short-term rainfall extremes.

In contrast, if rainfall duration increases, the effects of topography may be identified more clearly. This is due to the following consideration: heavy rainfall with a long duration period is in general due to repeatedly developing clouds embedded in convective systems at a stationary location; and topography plays a critical role as a stationary forcing in developing convective clouds repeatedly at the same location if there are no other forcings such as air-mass boundaries and convergence lines. Therefore, for typhoons which move at a fast speed and thus support no stationary atmospheric forcing, the effects of topography should be considerable.

These considerations lead us to examine the representation of accumulated rainfall during the simulated time period (i.e., 15 hours). Figure 6 clearly exhibits the difference in the frequency distribution of the accumulated rainfall over the grids on Kyushu Island as well as over the steep grids. The frequencies of rainfall over 100 mm are higher overall in the WRF case than in NHM. The representation in the higher ends of the distribution extends to larger values of rainfall in WRF than in NHM. This feature is opposite to that found in the hourly rainfall distribution, but is consistent with the wind speed distribution. Again, the higher extremes are more frequently found at steep grids; this strongly suggests that steep terrain affects the location and accumulation of intense rainfall.

CONCLUSIONS

The representations of extreme weather spawned by a landfalling typhoon in two different regional models, NHM and WRF, with similar physics parameterizations were investigated. Due to the difference in processing terrain data between the models, the modeled topography was shown to be slightly different. The higher extremes of wind and rainfall were evaluated differently by the two models: the WRF model (which has...
steeper slopes and higher elevations) represents higher and more frequent extremes. It was indicated that the reproduction of steep terrain in models plays a significant role in representing the extreme value, in addition to other conceivable factors, such as numerical and physical schemes, that will influence the difference of the model performance. If we deal with some thresholds in the extremes obtained by downscaling simulations from future climate predictions, we at least need to be aware of the consequences that may result from the terrain representation. It should be recognized that not only the differences in model numerics and physics but also slight changes in the representation of topography induce significant differences in the representations of extreme weather.

In the present study, we focus on a landfalling typhoon, owing to the fact that severe meteorological disasters are mostly due to typhoons and/or tropical cyclones. Although typhoons affect a wide area during their passage, the duration of extreme weather at a single location is not so long. Thus, the present kind of simulations should be extended to other cases, specifically for Baiu season rainfall. A long-term regional climate simulation will be required for fully evaluating the representation of topography in numerical models.

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