Simulation of Strong Wind Field by Non-hydrostatic Mesoscale Model and Its Applicability for Wind Hazard Assessment of Buildings and Houses

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Abstract:
The strong wind field caused by Typhoon Songda, which passed through Kyushu in Japan in 2004, was simulated numerically. A non-hydrostatic mesoscale model was used for the numerical simulation. The simulated wind field was compared with the observed wind field in terms of wind speeds and directions, which were measured by the wind observation network, NeWMeK. It was found that the temporal variation of the calculated wind speeds at 1 km horizontal mesh grids correspond to the average of the observed wind speeds over a ten to fifteen minute time period. The temporal variation of the calculated wind directions showed good agreement with the observations. The maximum values of the calculated wind speeds were highly correlated to the maximum values of the observed wind speeds. The applicability of the mesoscale model for the wind hazard assessment of buildings was examined, and it was found that the maximum values of the calculated wind speeds at higher altitudes showed higher correlations with the rates of damaged houses caused by Typhoon Songda.

KEYWORDS Non-hydrostatic mesoscale model; strong wind field; wind hazard to buildings and houses

INTRODUCTION

Recent progress in computational technology and meteorological models has enabled numerical simulations for weather prediction and the calculation of meteorological events such as typhoon, heavy rainfall and so on. Presently, a number of meteorological models are available and used not only for research purposes (WRF of the WRF group in USA, MRI/NPD-NHM of JMA and CReSS of RIST in Japan, etc.), but also for operational purposes (UM of UKMO in UK, LM of DWD in Germany, WRF-NMM of NCEP in USA, etc.).

Strong winds are mainly caused by typhoons in Japan. In this study the strong wind field caused by Typhoon Songda, which passed through Kyushu in Japan in 2004, was focused on. The wind field simulated by the Japan Meteorological Agency NonHydrostatic Model (Saito et al., 2007; hereafter abbreviated as JMA-NHM) was examined and the calculated wind field was compared with wind observations from the Network for Wind Measurement in Kyushu (Tomokiyo et al., 2004; hereafter abbreviated as NeWMeK).

Finally, the use of the wind fields simulated by mesoscale models for the purpose of the wind hazard assessment of buildings was investigated. The correlations to the damage rates of buildings and houses were investigated with the observed wind speeds and the calculated wind speeds.

STRONG WIND FIELDS CAUSED BY TYPHOON SONGDA

Overview of simulation and observation

A non-hydrostatic model, JMA-NHM, was used for the simulation. The governing equations for fluid and various quantities were discretized by the finite difference method. The wind field caused by Typhoon Songda was simulated for the region of Kyushu in Japan (Figure 1) for the period between September 6 and 7 in 2004. Thereby, the initial condition required for the simulation for the large region with 5 km mesh was interpolated from the JMA-RANAL (Japan Meteorological Agency Regional objective ANALysis) data, and the JMA-RSM (Japan Meteorological Agency Regional Spectral Model) data were used for the boundary condition. The small region with 1 km mesh grids was nested to the large region at every one-hour time step. The simulation was performed with the control parameters and calculation settings tuned in such a way that the track of the simulated typhoon was as equivalent to that of the historical typhoon as possible. The track and the temporal variation of the

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Figure 1. Calculation regions of JMA-NHM. Two regions, i.e. a large region with 5 km horizontal mesh grids and a small region with 2 km mesh grids, were used for the calculation.
central pressure of the simulated typhoon showed good agreement with the best track of the typhoon (Figures 2 and 3). The calculated values of the three dimensional wind velocity and pressures (Figure 4) at all the mesh grids were stored at every calculation time step.

NeWMeK is a wind observation network, which covers the area of Kyushu in Japan with more than one hundred observation points (Figure 5) at a height ranging from 12 m to 195 m from the ground surface. The wind speeds and directions measured by aerovanes on the transmission towers are recorded at every one second.

Comparison of wind records

The temporal variations of horizontal wind speeds and directions calculated from the simulation were compared with the wind speeds and directions measured at the observation points in NeWMeK. Thereby, the values of the calculated wind speeds at the observation points were obtained by linear interpolations using the wind speeds calculated at the mesh grids close to the observation points. Figure 6 shows the horizontal wind speeds and the wind directions at an observation point near the city of Fukuoka located on the north coast of the island of Kyushu, where the center of Typhoon Songda passed through. The time history of the calculated wind speeds and directions showed moderate fluctuation. It is found that the temporal variation of the calculated wind speeds corresponds to that of the observed wind speeds averaged over the time period of ten minutes. A possible reason for this is the filtering effect of numerical viscosity by the discretization of the governing equations. And it can also depend on the parameterization
of sub-grid scale turbulence and other calculated quantities such as temperature, water vapor and so on. This equivalent time average duration of ten to fifteen minutes is estimated by comparing all the observed wind speeds with the calculated wind speeds. The temporal variations of the calculation and observation wind directions showed good agreement. The correlations between the maximum values of the calculated wind speeds and the maximum values of the observed ten-minute averaged wind speeds as well as the observed maximum gusts were investigated. The simulated and observed wind speeds were highly correlated as shown in Figure 7. The correlation coefficients are 0.71 in the case of the maximum values of the ten-minute averaged wind speeds, and 0.64 in the case of the maximum values of the gust wind speed. The calculated maximum wind speeds were faster than the maximum values of the observed ten-minute averaged wind speeds and were slower than the maximum values of the observed gust wind speeds. This was also mentioned in other papers (Maruyama et al., 2007, etc.). A coarse mesh discretization corresponds to a modeling of smoother ground surface and the friction becomes weaker, which in turn results in faster wind speeds near the ground surface. The relations between the maximum values of the calculated wind speeds $V_{\text{NHM-max}}$ and the maximum values of the observed ten-minute averaged wind speeds, $V_{\text{NeWMeK-10min-max}}$, and the maximum values of the observed wind gust $V_{\text{NeWMeK-max-gust}}$, were approximated by the least squares method as follows:

$$V_{\text{NeWMeK-10min-max}} = 0.83V_{\text{NHM-max}} \quad (1)$$
$$V_{\text{NeWMeK-max-gust}} = 1.30V_{\text{NHM-max}} \quad (2)$$

### WIND HAZARD TO BUILDINGS AND HOUSES

The number of damaged buildings and houses was reported for several cities in Kyushu (Tomokiyo et al., 2005). The damaged house rate $R_d$ was defined as the ratio of the number of damaged buildings and houses over the number of households. Here, the number of damaged buildings and houses is the sum of completely collapsed, half collapsed and partially damaged buildings/houses. Figure 8 shows the geographical distribution of the damaged house rate in Kyushu. The areas where the high damage rates were experienced were located at the east side of the track of the typhoon with the range of about 150 km and in southern coastal areas. The areas where strong winds were observed during the travel of the typhoon correspond to the highly damaged areas (Figure 9).

The correlations between the damaged house rates and the maximum values of the calculated and observed wind
speeds were investigated. The observed ten-minute averaged wind speeds were obtained from NeWMeK as well as AMeDAS (Automated Meteorological Data Acquisition System) operated by the JMA. The maximum observed wind gusts were obtained from NeWMeK. Whereas the damaged house rates show low correlation with the maximum values of the observed wind speed (Figure 10), the maximum values of the calculated wind speeds $V_m$ showed higher correlation with the damaged house rate $R_d$ (Figure 11). Furthermore, it is seen that the correlation becomes higher with the wind speeds calculated at higher altitudes in the simulation. The relation between $R_d$ and $V_m$ was approximated by the least squares method as follows:

$$R_d = C V_m(z)^\alpha$$ (3)

where $V_m(z)$ is the maximum value of the wind speeds at the height $z$ from the ground surface at the location of the municipal office in each city. The variation of the coefficient $C$, the power exponent $\alpha$ in Equation (3), and the correlation coefficients between $R_d$ and $V_m$ as the function of the height $z$ were summarized in Table I.

The wind speeds were observed at different heights and at different locations. For the purpose of standardizing the observed wind speeds, the observed wind speeds were extrapolated to the wind speeds at 10 m height from the ground surface by the power law formula for the vertical wind profile with the exponent 1/7, whereby the wind speeds at the locations of the municipal offices in different cities were approximated by the wind speeds observed at the observation points closest to the locations of the offices. However, the wind speeds observed at the observation points were affected by the surrounding wind environment, e.g. local topography, surface roughness and so on. On the other hand, the maximum values of the simulated wind speeds $V_m$ were interpolated using the wind speeds calculated at the calculation points in the 1 km horizontal mesh grids, which may fail to represent the ground surface conditions in detail. This implies that the simulated wind speed corresponds to a representative value filtered over a certain area. Thus, it should be more highly correlated with the damaged house rate, because the damaged house rate is defined as an accumulated number of damaged buildings and houses over a certain area, i.e. city. The energy that causes damage to buildings and houses originates in stronger

![Figure 10. Variation of correlation between damaged house rate $R_d$ and the maximum values of the observed wind speeds during Typhoon Songda passing through Kyushu in 2004.](image)

![Figure 11. Variation of correlation between damaged house rate $R_d$ and the maximum values of the calculated wind speed $V_m$ as a function of the height during the pass of Typhoon Songda through Kyushu in 2004.](image)

| $z$ (m) | 10 | 60 | 228 |
|--------|----|----|-----|
| $C$    | 0.029 | 0.021 | 0.018 |
| $\alpha$ | 39 | 42 | 44 |
| correlation coefficients | 0.31 | 0.37 | 0.39 |
winds which come from a higher altitude. This is also consistent with the estimated higher correlations between the simulated wind speeds at higher altitudes and the damaged house rates. Hence, for the wind hazard assessment of the buildings and houses, the calculated maximum wind speeds are more applicable than the wind speeds from NeWMeK or AMeDAS.

CONCLUSION

The strong wind field caused by Typhoon Songda was simulated by JMA-NHM, and the performance of the simulated wind field was examined through comparison with the wind speeds observed by NeWMeK. In order to facilitate the assessment of the wind hazard, the correlations between the maximum values of the calculated wind speeds and the damage rates of buildings and houses were examined. The obtained results are summarized as follows:

1. The temporal variation of the calculated wind speeds with the 1 km horizontal mesh grids is considered to correspond to the observed wind speeds averaged over the time period of approximately ten to fifteen minutes.
2. The temporal variation of the calculated wind directions showed good agreement with the observed wind directions.
3. The maximum values of the calculated wind speeds were highly correlated to the maximum values of the observed wind speeds; however, the maximum values of the calculated wind speeds tended to be larger than the maximum values of the observed ten-minute averaged wind speeds and to be smaller than the maximum values of the observed gust wind speeds.
4. The damaged house rates showed higher correlation with the maximum values of the calculated wind speeds in comparison to the maximum values of the observed wind speeds.
5. The calculated wind speeds at the higher altitudes up to 228 m show higher correlation with the damaged house rates.

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