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Prediction of tropical cyclone induced wind field by using mesoscale model and JMA best track

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ABSTRACT

Prediction methods for tropical cyclone induced wind field by using mesoscale model and JMA best track of tropical cyclones are proposed. A tropical cyclone database is produced by using JMA best track and NCEP/NCAR Reanalysis Project (NNRP) data. It is found that the identification success ratio of tropical cyclone parameters in present database, which is produced by JMA best track and NNRP data, is higher than previous one, which was produced by surface pressures measurement at weather stations. Predicted wind speeds obtained from present database and previous one show good agreement with measurement. A combined wind field model is proposed to predict tropical cyclone induced wind fields, in which mesoscale model and typhoon model are used. Underestimations of wind speeds caused by mesoscale model at the tropical cyclone center, and those by typhoon model at the outside region are improved by proposed model.

Keywords: Tropical cyclone induced wind field, Mesoscale model, JMA best track

Introduction

The prediction of tropical cyclone (hereafter TC) induced wind fields is important for the design of offshore wind turbines not only for the extreme wind speed estimation but also for the extreme wave simulation where surface wind field is used as boundary condition. Several numerical simulation methods have been proposed to estimate extreme wind field. Larsén et al. (2011) used mesoscale model to predict extreme wind speed caused by extratropical cyclone at Denmark and showed good agreement with observations. However, Yamaguchi et al. (2013) showed that predicted wind speed by mesoscale model tend to underestimate TC induced wind speed.

On the other hand, typhoon models (e.g. Ishihara et al. (1997)) have been proposed to estimate TC induced wind field. This method, TC induced wind fields, which were predicted by a surface pressure model (e.g. Schloemer (1954)), showed good agreement with observation at the center of TC (e.g. Yamaguchi et al. (2013)). However, predicted wind fields by a typhoon model may underestimate the wind speed outside the TC region. Because the accurate prediction of the large domain wind field is necessary for accurate wave simulation, this underestimations cannot negligible.

Another problem of this method is that it often cannot predict the wind field over the ocean. In general, the parameters, the central pressure, the location, the radius of maximum wind speed and the pressure at infinite away place, are required to calculate the wind field by using typhoon model. Although the central pressure and the location can be found in TC track, since other two parameters are unknown, several identification methods of these has been developed. Mitsuta et al. (1979) proposed an identification method of those parameters using observed surface pressure at weather stations, a method commonly used (e.g. Yasui et al.

(2002)). However the identification success ratio become lower over the ocean because there are no available observation stations. To overcome this problem, Ishihara (2004) proposed an identification method which uses both isobars on a weather map and surface pressures measurement data within 500km from the TC center, a method that has improved the identification success ratio over the ocean. However, the identification success ratio was still low because at least 5 number of isobars and observed pressures required.

In this study, a tropical cyclone database is produced by using Japan Meteorological Agency (hereafter JMA) best track and meteorological reanalysis data to improve the identification success ratio over the ocean. Then, a combined wind field model is proposed to improve the accuracy of predicted wind fields by mesoscale model and typhoon model. The accuracy and characteristic of those by mesoscale, typhoon and proposed model are verified by observations.

Identification of tropical cyclone parameters for typhoon model

Typhoon models require 5 parameters at each time step, i.e. the central pressure, the radius of maximum wind speed, the pressure outside the TC, the translation speed and the translation angle. The information of TCs, central pressures and locations, is recorded in JMA best track from 1951 at East and Southeast Asian region. Although translation speeds and the translation angles can be calculated from these locations, the radius of maximum wind speeds and pressures outside the TCs are unknown. In this study, these parameters are identified by using JMA best track and NCEP/NCAR Reanalysis Project (hereafter NNRP) data. In JMA best track, the new information, the radius where wind speed is 15m/s, is recorded from 1977. By using this information, two unknown parameters can be identified without surface pressures measurement at weather stations.

The pressure field within TC was given by Schloemer's equation as follows:

$$\frac{P(r)-P_C}{P_\infty - P_C} = \exp\left(\frac{r}{R_m}\right) \tag{1}$$

where, $P(r)$ is the pressure as a function of distance r from the center, P_C is the central pressure of TC, P_∞ is the pressure at infinite away from TC, and R_m is the radius of maximum wind speed. According to Ueno (1995), TC's radius R_B is determined from empirical relation as follows:

$$V_{15}R_{15} + \frac{fR_{15}^2}{2} = \frac{fR_B^2}{2} \tag{2}$$

where, R_{15} is the radius where wind speed is 15m/s (V_{15}), and f is the Coriolis parameter. Since P_C and R_{15} are found in JMA best track, if surface pressure at R_B is given by NNRP, two unknown TC parameters (i.e. P_∞ and R_m) can be obtained from two conditions as follows:

$$P(r) = P_C + \left(P_\infty - P_C\right)\exp\left(-\frac{R_m}{r}\right)\Bigg|_{r=R_B} = P_B \tag{3}$$

$$V_g(r) = \frac{1}{2}\left[-fr + \sqrt{\left(fr\right)^2 + \frac{4r}{\rho}\frac{\partial P}{\partial r}}\right]\Bigg|_{r=R_{15}} = V_{15} \tag{4}$$

where, P_B is sea level pressure at R_B from NNRP, V_g is gradient wind speed, and ρ is air density. Since NNRP has coarse horizontal resolution, in this study, P_B was given as average on circumference within R_B ± 5km after once interpolated from 2.5° x 2.5° to 0.1° x 0.1°.

Before producing database, the difference of TC parameters identified by different horizontal resolution data was surveyed. The comparison of identified TC parameters by two data, the NNRP with horizontal resolution of 2.5° × 2.5°, and mesoscale model WRF with

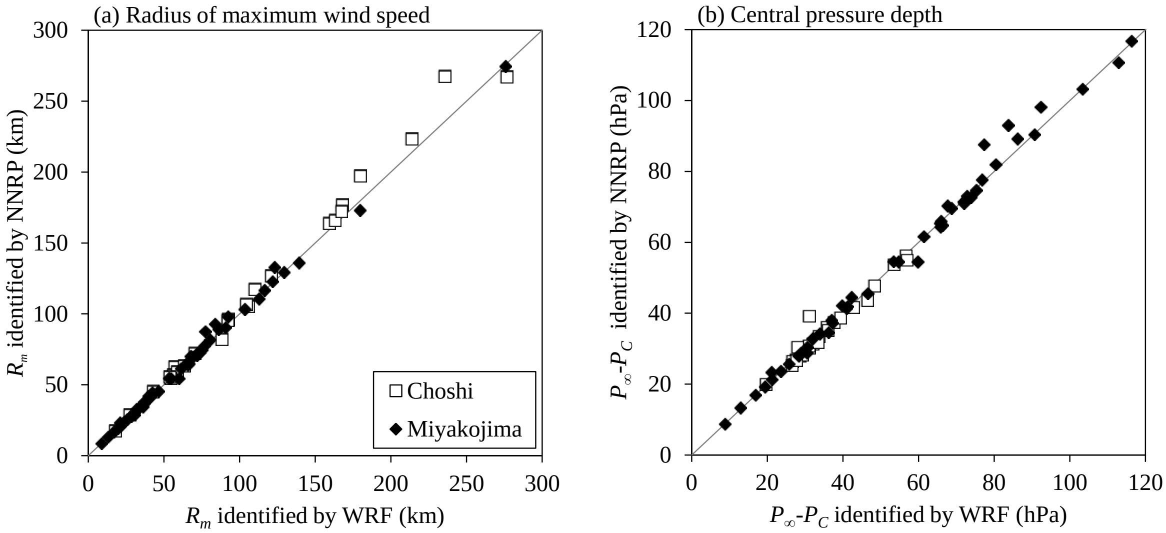

Fig. 1 Comparison of tropical cyclone parameters identified by global reanalysis data (NNRP) and mesoscale model (WRF).

horizontal resolution of 10km × 10km, is shown in Fig.1. Where, TCs passed within 500km radius from Choshi and Miyakojima station (see Fig. 5) from 2000 to 2009, and those parameters identified at closest approach time are compared. The configuration of WRF is stated in the next chapter. The TC parameters that were identified by using two different data show almost the same value, and the effect of resolutions are not prominent. From these results, NNRP was used to produce the database due to its advantages that include its ability to be used without additional computation and its long stored data dating from 1948.

Using the identification method stated above, the tropical cyclone database with central locations (latitude and longitude), central pressures, radii of maximum winds, central pressure differences, translations velocities and approach directions is produced. In this study, all tracks recorded to JMA best track are defined as tropical cyclone, and the database is produced from 1977 to 2007.

In this study, the identification success ratio is defined as the ratio of the number of successfully identified parameters to the total number of TCs with a TC central pressure of 985hPa or lower. Table 1 shows the comparison of the number of TCs successfully identified parameters (the identification success ratio) between previous database produced by Ishihara (2004) method and the present method at closest approach time at Choshi and Miyakojima stations. No difference in the number of identified TC’s was found between previous and present database at Choshi station. However, in previous database, the identification success ratio was low (68.9%) at Miyakojima station, a station located far from the main island of Japan. On the other hand, the present database keeps high (95.7%) success ratio. The spatial differences of the identification success ratio between the previous database and the present

Table 1 Comparison of the number of identified tropical cyclones at Choshi and Miyakojima stations.

	Identified number (ratio)		Total passed number
	Previous study	Present study	
Choshi	68 (76.4%)	68 (76.4%)	89
Miyakojima	111 (68.9%)	154 (95.7%)	161

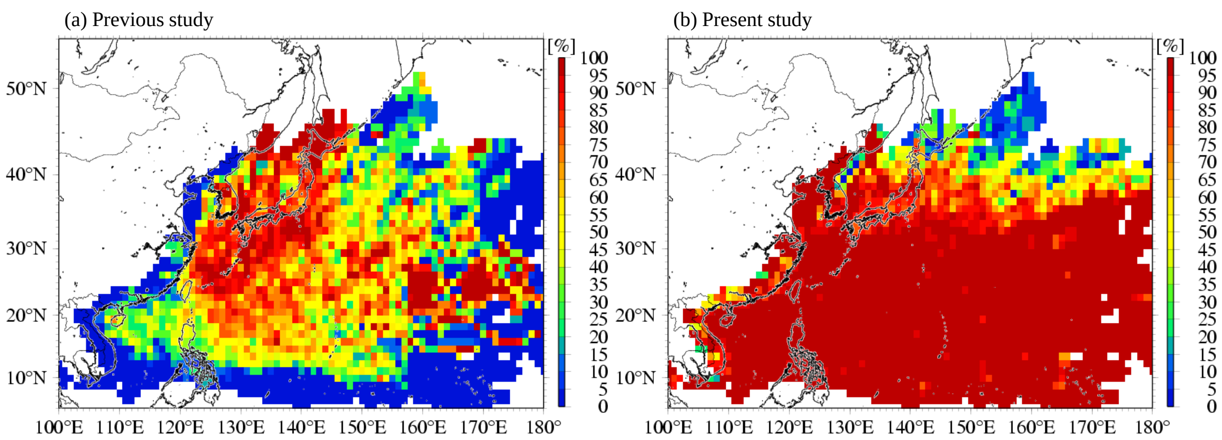

Fig. 2 Identification success ratio of tropical cyclone parameters.

one is shown in Fig. 2. The identification success ratio is improved at the south part of the Japanese islands by using present method. Especially at south of 30°N in the northwestern Pacific Ocean, the identification success ratio by using present method is almost 90% or more.

The identification success ratio for different central pressure of TCs is shown in Fig. 3. The previous database occasionally cannot identify very strong TC with central pressure of 890hPa, the present one can show 100% success ratio up to 930hPa. It is also shown that the identification success ratio of the previous database tend to be lower as central pressure is higher. This is because total number of isobars within 500km radius from TC center becomes fewer as central pressure is higher, and cannot use 5 data to identify, especially over the ocean (see Fig. 2).

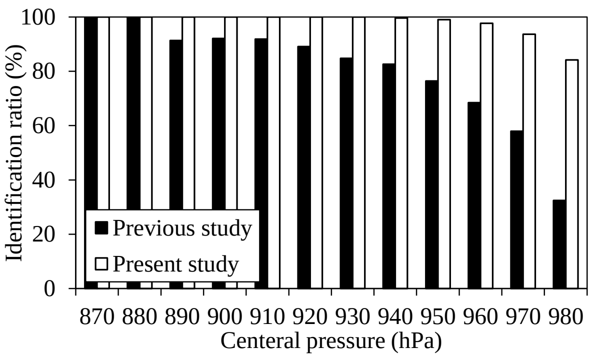

Fig. 3 Comparison of the identification success ratio for the central pressure of tropical cyclone in previous database and present one.

Fig. 4 shows the comparison of measured and predicted wind speeds obtained from previous database and present one. Surface wind speed is calculated by using the model proposed by Ishihara et al. (1997). Measured and predicted wind speeds are moving average of 3 hours data. The detail of comparison method with observed wind speed is stated in next chapter. Predicted wind speeds by previous database and present one show good agreement with measurement.

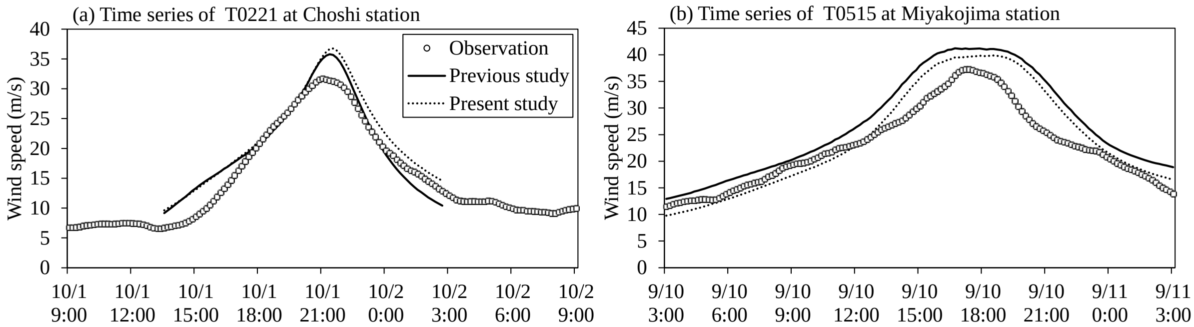

Fig. 4 Comparison of observed and predicted wind speeds by using the previous database and present one.

Proposal of the combined wind field model

Though mesoscale model underestimate TC induced wind speed at the center, it gives fairly good wind speed prediction outside TCs. On the other hand, although typhoon model cannot predict wind speeds outside the TC, it can at the center. From these points of view, in this study, a combined wind field model of predicted wind fields by mesoscale model and typhoon model is proposed. The combined wind speed u_C is obtained from eq. (5)

$$u_C = Wu_T + (1-W)u_M \tag{5}$$

where, u_T and u_M are the wind speeds by mesoscale model and typhoon model respectively, and W is weight function as shown in eq. (6)

$$W = \left(\frac{R_B^2 - r^2}{R_B^2 + r^2}\right)^n \tag{6}$$

where, n = 0.5 is found to be optimum, which will be discussed later.

Weather Research and Forecasting model Ver.3.4 (WRF, Skamarock (2008)) was used for mesoscale model simulation. Computational domains and configuration used in simulations are shown in Fig. 5 and Table 2. Horizontal resolution was set to 10km × 10km, and used 200 × 200 grids. Vertical layers were set to 34 layers. As for initial and boundary conditions, NCEP-FNL was used. Physics options were set the same as NCAR's real-time hurricane that was run in 2012. All TCs which passed the circular area within 500km at

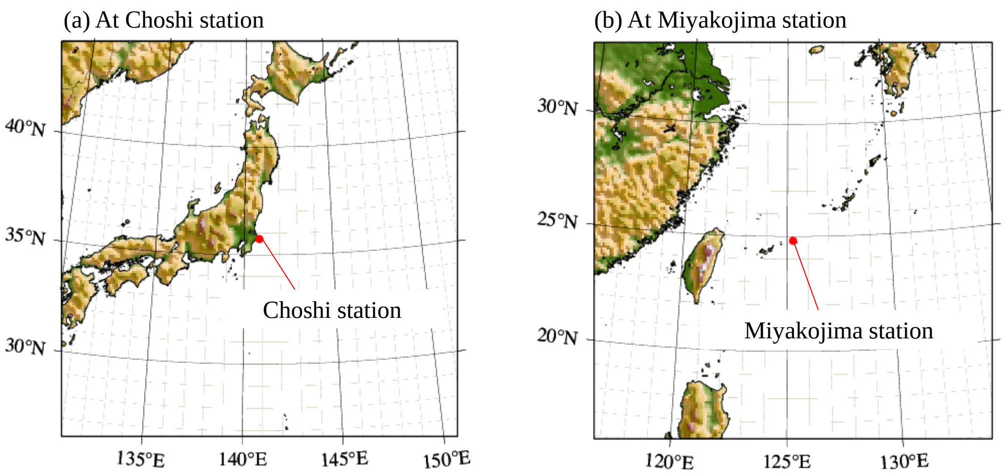

Fig. 5 Computational domains used in the simulations.

Table 2 Configuration of WRF.

Simulation time	3 days (±1.5 days from closest approach time)
Input data	NCEP-FNL (6-hourly, 1° x 1°)
Land use	USGS 30 second
Domain	10km (200 x 200)
Vertical layer	34 levels (surface to 50 hPa)
Physics options	RRTMG short wave radiation, RRTM long wave radiation, WSM 6-calss graupel microphysics, Modifed Tiedtke cumulus parameteriza-tion, Unified Noah land-surface model ,YSU PBL parameterization, Garratt surface enthalpy flux
FDDA option	Grid nudging exclude PBL

Choshi or Miyakojima weather stations from 2000 to 2009 were simulated. Simulation periods were set to ±1.5 days from closest approach time. Grid nudging was used above PBL.

As a typhoon model, Ishihara et al. (1997) model was used. P_∞ and R_m were obtained from identification method stated prior section (sea level pressures predicted by WRF were used to estimate P_B for this time), and a gradient wind speed was calculated. Then, the surface wind speed u_T and the inflow angle γ_T on uniform roughness length and flat terrain are calculated from the gradient wind speed u_g.

$$u_T(z) = u_g \left(\frac{z}{z_g} \right)^{\alpha_u} \tag{7}$$

$$\gamma_T(z) = \gamma_s \left(1.0 - 0.4 \frac{z}{z_g} \right)^{1.1} \tag{8}$$

where, z is the height above ground, α_u is the power law exponent for the wind speed profile, z_g is the gradient wind height, and γ_S is the inflow angle at ground surface. These parameters, which were modeled semi theoretically, can be calculated from gradient wind, surface roughness length and characteristic parameters of PBL.

An example of predicted wind fields from mesoscale, typhoon and combined model is shown in Fig. 6. Predicted wind speeds from mesoscale model are lower than those from typhoon model around the center of TC. In the wind field from typhoon model, on the other hand, wind speeds become lower as the distance from the center of TC is farther. The wind field generated by the proposed combined model use of wind speeds generated by typhoon model for the center of the TC and by the mesoscale model for the region outside.

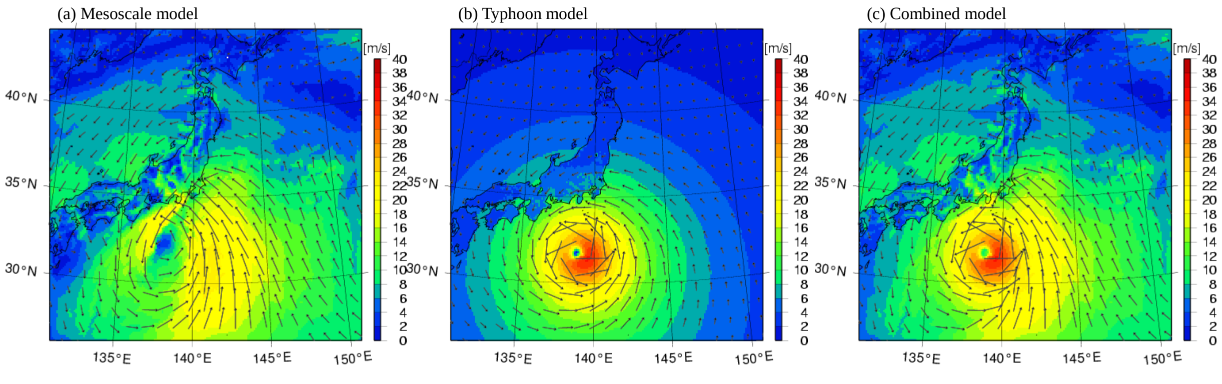

Fig. 6 Predicted wind fields from mesoscale, typhoon and combined models.

Measured and predicted wind speeds from mesoscale model were converted to wind speeds on uniform roughness length and flat terrain by using CFD simulation. In this study, MASCOT (Microclimate Analysis System for Complex Terrain) which has been developed by Ishihara et al. (2003) was used to convert wind speed. Wind speeds and directions affected by topography u_t and θ_t are converted to those on uniform roughness length and flat terrain u_f and θ_f by using following equations:

$$\theta_f = \theta_t - D \qquad (9)$$

$$u_f = u_t / S \qquad (10)$$

where, S and D are topographic multiplier of wind speed and deviation of wind directions respectively and are calculated by the results from two types CFD simulation on topographic and flat terrain. In this study, observed and predicted wind speeds were converted to winds on 0.01m uniform roughness length and 60m height above ground.

Examples of observed and predicted timeseries are shown in Fig. 7. It is known that the averaging time of predicted wind speeds by mesoscale and typhoon model are from 1 to 3 hours, according to Larsén et al. (2012) and Yasui et al. (2002) respectively. Therefore both measured and predicted wind speeds are filtered by using moving average of 3 hours. At Choshi station, the mesoscale model slightly underestimates the wind speed during TC peak, it significantly underestimate the wind speed at Miyakojima station during TC peak. On the other hand, the typhoon model shows good agreement with measurement at both stations during the peak, it underestimates the wind speed before and after the peak. The proposed combined model, can predict both wind speeds during and before/after TC peak.

Next, these characteristics and accuracies of each models are assessed quantitatively. Before assessing these model, the optimum value of weight function n (eq. (6)) is discussed.

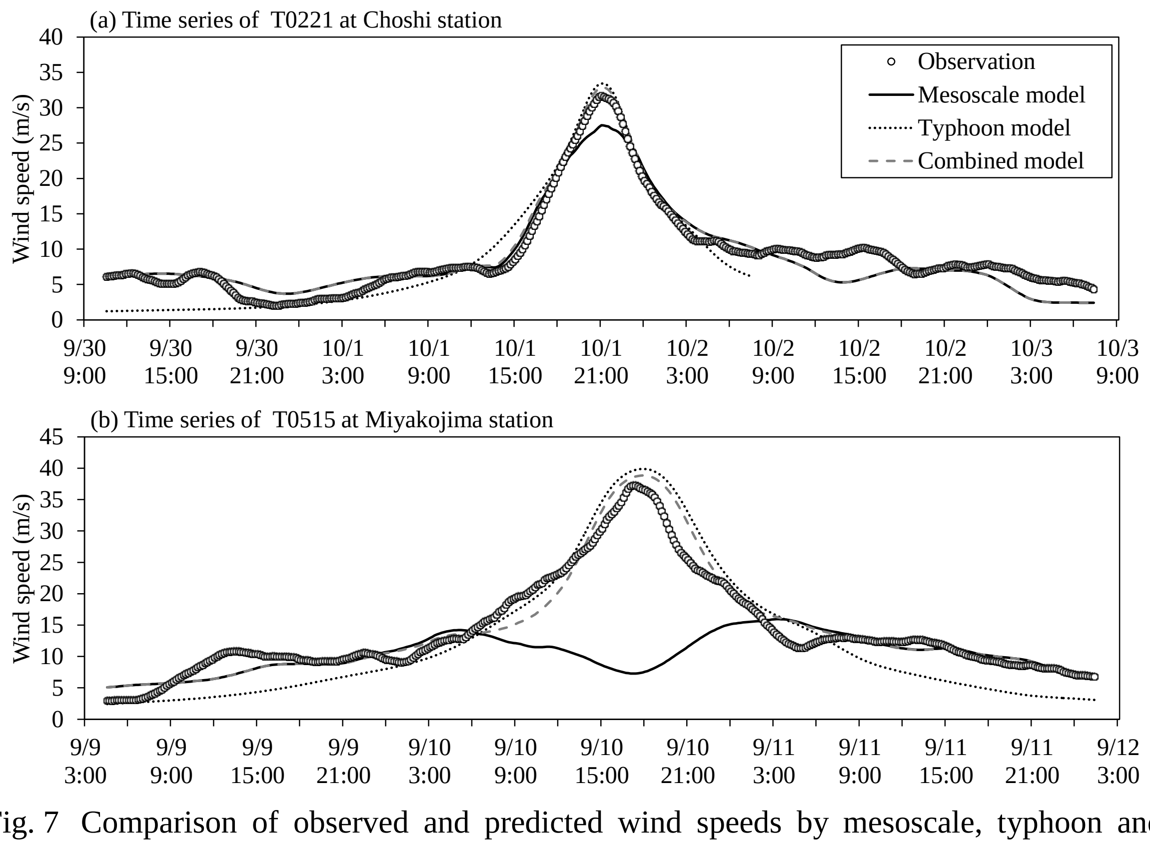

Fig. 7 Comparison of observed and predicted wind speeds by mesoscale, typhoon and combined model.

The variation of biases for combined model by changing weight function n (eq. (6)) is shown in Fig. 8. Smaller n value are used to predict wind field by the typhoon model in larger region, while larger n are used by the mesoscale model mainly the region near the center of TC. Though biases by combined model reach minimum value near the center of TC in the case of n = 0.2, they become large negative value at d ≥ 250km. On the other hand, the case of n = 5, bias becomes significantly negative within 250km from the center of TC at Miyakojima station because wind field by mesoscale model is mainly used. Since significant negative biases are improved at all distances of both stations, shown in Fig. 8, present study chooses the case of n = 0.5 as optimum value.

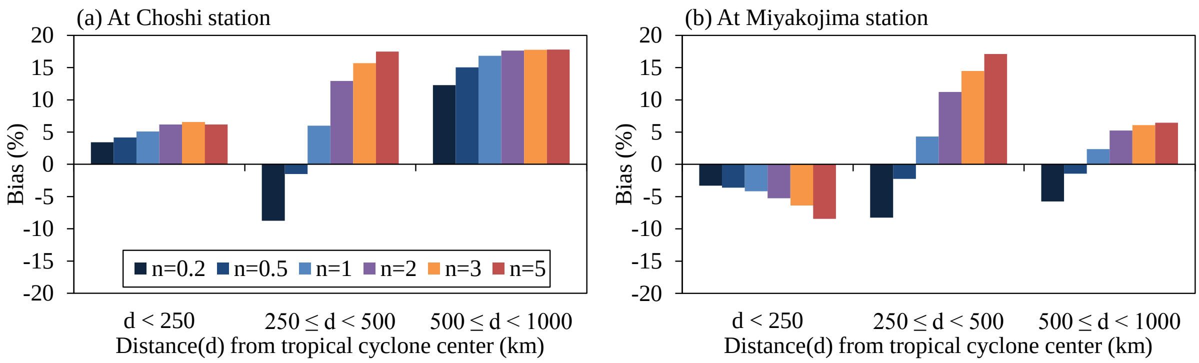

Fig. 8 Comparison of the biases between observed and predicted wind speed by combined model changing weight function.

Variations of biases for different distances from tropical cyclone center at Choshi and Miyakojima station are shown in Fig. 9. TCs which brought annual maximum wind speeds are used for verifications, while the observed and predicted wind speeds are moving average of 3 hours data. Wind speeds are underestimated by the mesoscale model near the TC center (d < 250km). On the other hand, the typhoon model underestimates the wind speeds at locations more than 500km away from the TC center. Wind speeds obtained from the combined model show better biases than those by using mesoscale model or typhoon model independently, and underestimations caused by those models are improved at all distances. Note that underestimations of predicted wind speeds by mesoscale model would be improved somewhat by changing its computational domain or configuration. However, at the center of

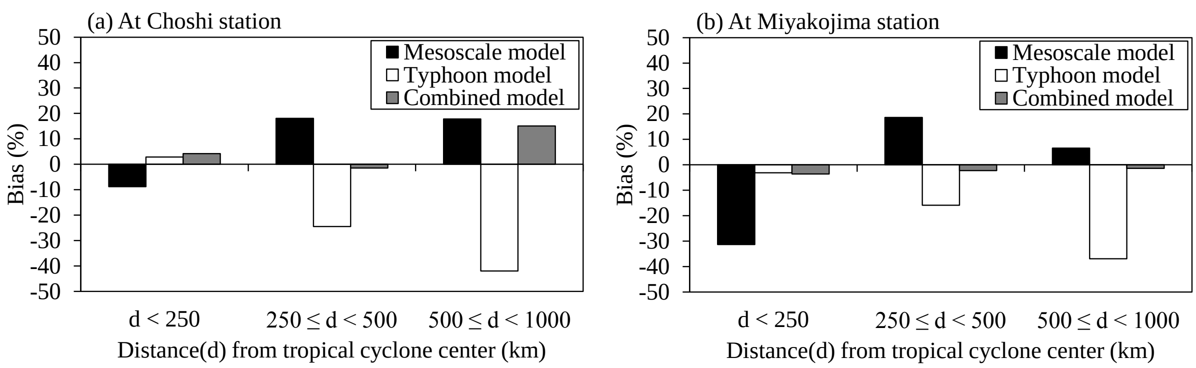

Fig. 9 Variations of the biases between measurement and predicted wind speeds with distances from tropical cyclone center.

TC, the accuracy of those by the combined model is hardly affected by the configuration of mesoscale model due to its advantage of being able to use the central pressure and location of TC from JMA best track.

From the above results, predicted wind field by present model is more accurate than those by individual mesoscale or typhoon model.

Conclusions

In this study, prediction methods for tropical cyclone induced wind speed by using mesoscale model and JMA best track of tropical cyclone are proposed. The following conclusions are obtained:

1) A tropical cyclone database is produced by using JMA best track and NCEP/NCAR Reanalysis Project data. The identification success ratio of tropical cyclone parameters in the present database is higher than the conventional one, which was produced by measured surface pressures at weather stations, especially at south of 30°N in the northwestern Pacific Ocean. Predicted wind speed obtained from the present database and the previous one show good agreement with measurement.
2) A new wind field model was proposed, in which the wind field near the center of tropical cyclone is estimated by using typhoon model and the outside is estimated by using mesoscale mode. This method takes advantage of two models and shows good agreement with measurement regardless of the distance from the center.

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