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Wind Field Model and Mixed Probability Distribution Function for Typhoon Simulation

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ABSTRACT

Typhoon simulation method generates pressure fields of typhoons using a stochastic approach, and the free friction wind at any location could be predicted from the field. This research proposed a hybrid method combining a semi theoretical model and CFD to evaluate the surface wind speed. Effect of typhoons pressure field is predicted with the semi theoretical model and the effect of topography is calculated by the CFD. A mixed probability distribution function (MPDF) was proposed for typhoon simulation, which is applicable to any locations by changing a weighted parameter. A modified orthogonal decomposition (MOD) was also proposed to simultaneously reproduce probability distributions of typhoon parameters and their correlations. The proposed methods showed more favorable agreements with the observation data compared with the conventional method.

INTRODUCTION

Conventional evaluation method of design wind speeds uses observation data of annual maximum wind speeds. However, the observation data is only available back to a few decades in specific locations especially in town areas, which is not enough for a reliable estimation for the long return period wind speed evaluation. Typhoon simulation is an alternative approach to evaluate extreme winds over long periods of time by computer simulation using so-called "Monte Carlo" method. This method was first suggested by Russell (1971) and developed by Tryggvason et al. (1976); Batts et al. (1980); Georgiou (1983); and Vickery and Twisdale (1995).

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Several methods were proposed to estimates the surface wind speeds based on the observation data of typhoons. Shapiro (1983) proposed a slab boundary layer model of constant depth to analyze the steady flow under a specified translating symmetric vortex in gradient balance. In this method, vertically averaged boundary-layer assumption has lead to excessive estimates of radial velocities (and thus inflow angles) compared to those obtained in a more sophisticated multilevel model.

Georgiou (1983) proposed a model to compute surface wind speed using an identified relationship between surface and gradient wind speeds. In this model, the gradient wind speed was obtained from the cyclostrophic balance, and the ratio of surface to gradient wind speeds, *G(r)* was determined from the observation data. Afterwards, Mistuta and Fujii (1986) expressed the ratio *G(r)* as a constant, which is larger on the sea and smaller on the land. However, the vertical features of the typhoon boundary layer and the surface terrain conditions were not considered.

Ishihara et al. (1995) proposed a semi theoretical model of the vertical wind speed and direction in the boundary layer to simulate the characteristic of typhoons, and calculate the surface wind speed with consideration of surface roughness. However, this method can only evaluate the surface wind speed on surface with uniform roughness. To predict the local wind on a complex terrain, a numerical simulation method was proposed by Ishihara et al. (2002) and Yamaguchi et al. (2003). The method incorporates database of land use and elevations of Japan, enables the prediction of wind at any pinpoint locations for complex terrain.

The success of typhoon simulation program mainly depends on the accuracy of the statistical representation of the typhoon parameters. In United Sates, the central pressure difference, which is the most significant parameter of typhoon simulation, is normally modeled with Weibull distribution (Georgiou 1983, Vickery 1995) whereas the log-normal distribution is used in Japan (Mitsuta and Fujii 1986a, Matsui 2001). The use of different probability distribution function (PDF) in these two countries was due to the different latitude of the simulated locations. It is a normal practice to engage same PDF to model a parameter even for different locations in a country. However, as proved in this paper, a PDF for a particular parameter that fit a specific location may generate serious error in another location.

Conventional method of typhoon simulation could not generate all the correlations between typhoon parameters simultaneously. Hence, as shown in this paper, the annual maximum wind speed that simulated by the conventional method is overestimated in the long return period. Vickery et al. (1995) proposed a method to consider the correlations between parameters but this method is limited to a pair of parameters at a time. On the other hand, Matui et al. (2003) used orthogonal decomposition method to evaluate the correlations but could not produce better accuracy of the correlations and PDF of the parameters at the same time.

Hence, this research proposed an evaluation method for design wind speed to improve the accuracy of the simulation with consideration of the problems stated above. First, the hybrid method of the typhoon simulation and CFD for the evaluation of surface wind speed is presented. Then, the typhoon simulation method with the application of Mixed Probability Distribution Function and Modified Orthogonal Decomposition is described.

ESTIMATION OF SURFACE WIND SPEED

The estimation of wind speed near the ground surface is important, as it is the value that used for design. Wind speed near ground surface is influenced by surface roughness, and topography. Solving the Navier-Stokes equation directly by numerical simulation method could enable us to calculate the wind speeds from the pressure fields with consideration of the topography effects. However, in the typhoon simulation methodology, large samples (over ten thousands) of typhoons are needed to obtain the design wind speed for long return periods. Solving the equations directly for each typhoon would take years. A typhoon model, which could be easily predicted, is needed in the typhoon simulation.

Wind field model for gradient wind

The gradient wind speed is predicted with the model proposed by Ishihara et al. (1995). In the model, the solution of the Navier-Stokes equation is separated into upper inviscid layer of cyclostrophic balance and a lower friction layer controlled by a surface drag coefficient and eddy viscosity. That is to say, the average wind velocity *v(z)* is represented as the sum of the friction free gradient wind speed v_g, and the wind speed caused by the friction *v'(z)*. Then, assuming that the wind field moves with the translation velocity of the typhoon and perturbation analysis is performed to obtain the tangential and radial boundary layer velocity in the friction region.

$$v_{rg} = 0 \tag{1}$$

$$v_{\theta g} = \frac{C\sin\theta_r - fr}{2} + \sqrt{\left(\frac{C\sin\theta_r - fr}{2}\right)^2 + \frac{r}{p}\frac{\partial p}{\partial r}} \tag{2}$$

Here, v_{rg}, $v_{\theta g}$ is the gradient wind speed (radial and tangential direction), C is the translation velocity of the pressure field, θ_r is the angle between the vector from the center of pressure field to the site of interest, f is the Coriolis parameter and ρ is the air density.

Wind field model for surface wind

This research uses the semi-theoretical model proposed by Ishihara et al. (1997) for the prediction of the typhoon induced wind field in a boundary layer. Being a non-empirical formula and the ability to evaluate terrain roughness are the advantages of the model. In the model, vertical profile of wind speed is given in an exponential form as Eq.(3) and Eq.(4), which is similar to the model that is normally used in wind engineering.

$$U(z) = U_g\left(\frac{z}{z_g}\right)^{\alpha_u} \tag{3}$$

$$\gamma(z) = \gamma_S \left(1.0 - 0.4\frac{z}{z_g}\right)^{1.1} \quad (4)$$

Here,

$$\alpha_u = 0.27 + 0.09\log(z_0) + 0.018\log^2(z_0) + 0.0016\log^3(z_0) \quad (5)$$

$$z_g = 0.052\frac{U_g}{f_\lambda}(\log Ro_\lambda)^{-1.45} \quad (6)$$

$$\gamma_S = (69 + 100\xi)(\log Ro_\lambda)^{-1.13} \quad (7)$$

$$f_\lambda = \left(\frac{\partial v_{\theta g}}{\partial r} + \frac{v_{\theta g}}{r} + f\right)^{1/2}\left(2\frac{v_{\theta g}}{r} + f\right)^{1/2} \quad (8)$$

$$\xi = \left(2\frac{v_{\theta g}}{r} + f\right)^{1/2} / \left(\frac{\partial v_{\theta g}}{\partial r} + \frac{v_{\theta g}}{r} + f\right)^{1/2} \quad (9)$$

<u>Modeling of typhoon boundary layer with consideration of the topography effects</u>

We consider the scale different of typhoons to the topography. The horizontal scale of a typhoon is a few hundred kilometers and the vertical one is about 20 kilometers. Meanwhile, the scale of topography that is considered in this paper is few kilometers horizontally and a few hundred meters vertically. In other words, the scale of the topography is so small comparing to the scale of the typhoon that we can separate the effect of the topography from the effect of the typhoon's pressure field. This concept is represented in the following equation for wind speed, $U(x,y,z,t)$ and wind direction, $\theta(x,y,z,t)$.

$$U(x,y,z,t) = U_{TC}(x,y,z,t) \times C_i(x,y,z) \quad (10)$$

$$C_i(x,y,z) = \frac{U_{Ti}(x,y,z)}{U_{Fi}(x,y,z)} \quad (11)$$

$$\theta(x,y,z,t) = \theta_{TC}(x,y,z,t) + \Delta\theta_i(x,y,z) \quad (12)$$

$$\Delta\theta_i(x,y,z) = \theta_{Ti}(x,y,z) - \theta_{Fi}(x,y,z) \quad (13)$$

Surface wind speed, $U_{TC}(x,y,z,t)$ caused by the typhoon's pressure field on a flat terrain is predicted using the wind field model as explained in previous section and the topographic multiplier $C_i(x,y,z)$ is evaluated by CFD. In this part, topographic multiplier is calculated as the ratio of wind speed over an actual terrain with roughness changes, $U_{Ti}(x,y,z)$, to the wind speed on a flat terrain with uniform roughness, $U_{Fi}(x,y,z)$. The multiplier $C_i(x,y,z)$ is a function of 16 wind directional sectors. Similarly, the deviation of wind direction, $\Delta\theta_i(x,y,z)$ is obtained by subtracting the wind direction on a flat terrain, $\theta_{Fi}(x,y,z)$, from the wind direction over an actual terrain with roughness changes,

$\theta_{Ti}(x,y,z)$. Proposed method is shown graphically as Figure 1 and Figure 2.

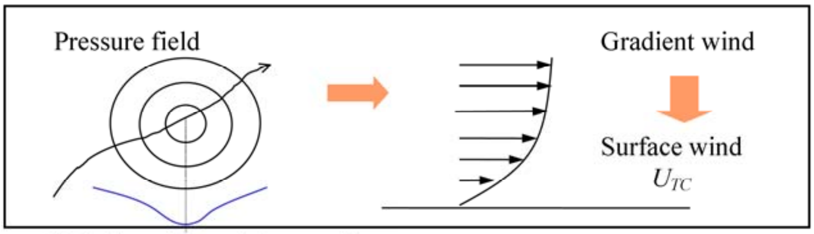


Figure 1 Estimation of the surface wind speed from the pressure field

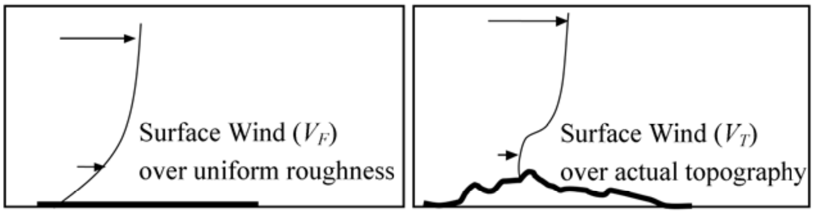


Figure 2 Determination of the wind speed ratio, *C(x,y,z)*

Numerical simulation for the wind field on a topography

The topographic multiplier and deviation of wind direction are calculated using CFD. In this research, a CFD program, MASCOT (Microclimate Analysis System for COmplex Terrain) developed by Ishihara and Hibi (2002) is used. Continuous equation and the Navier-Stokes equations are solved to obtain the wind speed.

$$\frac{\partial \bar{\rho}_j}{\partial x_j} = 0 \tag{14}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \rho \bar{u}_j \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right) \tag{15}$$

Here, $\bar{u}_i$ and u_i' are the average and fluctuation of velocity in the x_i component. $\bar{p}$ is the pressure, ρ is the density of the air, μ is the viscosity and $\overline{u_i' u_j'}$ is the Reynolds stress. The Reynolds averaged Navier-Stokes equations and k-ε turbulence model are used in the present study. To suit the computation of complex flow, the arbitrary non-orthogonal collocated grid system is used. The governing equations are rewritten in the curvilinear coordinate system and are solved using a common discrete method. In this study, finite volume method and the SIMPLE algorithm are adopted. The QUICK scheme is employed for the convection terms in the Navier-Stokes equations, the first order upwind difference for the convection terms in the equations of k and ε and the second order central difference for the other terms. The Rhie and Chow's PWIM (pressure weighted interpolation method) is used to avoid pressure-velocity decoupling. Detail information refers to Ishihara and Hibi (2002).

Typhoon-by-typhoon comparison

To verify the accuracy of the proposed method, comparison with the full-scale records is performed. Surface wind speed estimated from the pressure fields' data are compared with the recorded wind speed. The observation wind speed record is obtained from the "AMeDAS 10-minutes interval data" which is available from year 1995, and the observed pressure fields are obtained from the "Surface Observation Data". These data are published by the Japan Meteorological Business Support Center. Typhoons from 1995~2002, at Nagasaki are predicted.

Nagasaki Nagasaki Meteorological Station is located in a hilly terrain where the influence of topography is significant (Figure 3). The wind speed observed at Nagasaki is actually very low, being shielded by the surrounding hills and forests. The average annual wind speed is less than 2.5m/s, and the highest maximum wind speed is only 26.1m/s (Table 1).

Table 1 Maximum wind speed observed at Nagasaki Meteorological Station

rank	wind speed	wind direction	date	rank	wind speed	wind direction	date
1	26.1	SW	1956.08.17	**6**	21.4	SSW	1956.09.10
2	25.6	W	1991.09.27	**7**	20.8	N	1955.09.30
3	24.2	SW	1960.09.07	**8**	20.2	SWW	1954.09.14
4	23.3	SW	2004.09.07	**9**	19.4	W	1985.08.31
5	23.2	SW	1957.12.12	**10**	19.1	SW	1959.09.17

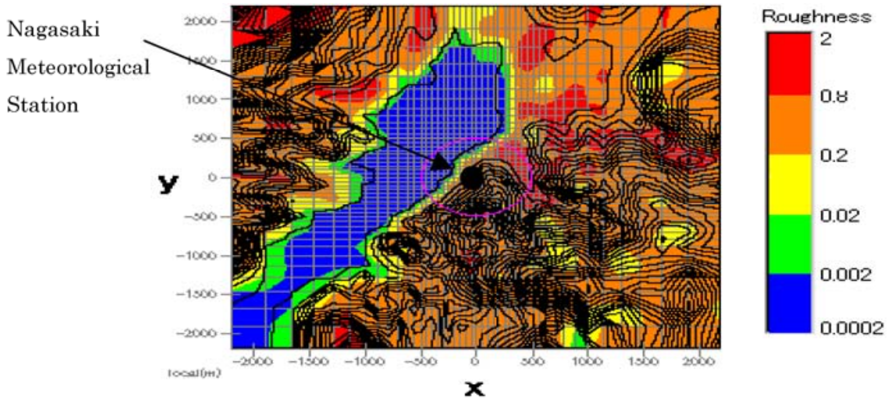


Figure 3 Roughness and elevation at Nagasaki

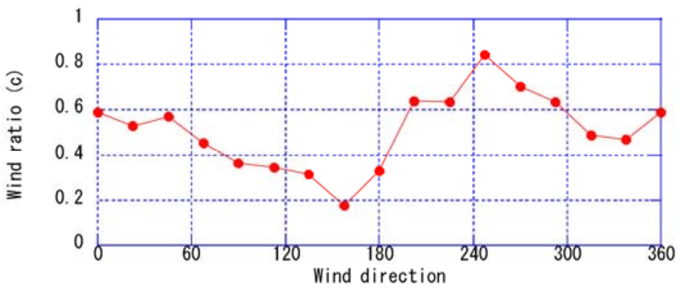


Figure 4 The topography multiplier for Nagasaki Meteorological Station

Figure 4 shows the predicted topographic multiplier, the ratio of wind speed over the actual terrain with elevation and roughness changes, to the wind speed over a flat terrain with uniform roughness. Wind speed is reduced in all directions except for the wind from 247.5 degree. This is because when the wind is from south-westerly direction, the wind blows along a valley over sea surface (Figure 3). This result is consistent with the observation data (Table 1) that the strongest winds generally occur at the south-westerly direction.

Figure 5 show the wind speeds and wind directions predicted with the proposed method and results by multiplying gradient wind speed with 0.5 (Mitsuta and Fujii 1986b), in comparison with the observation data.

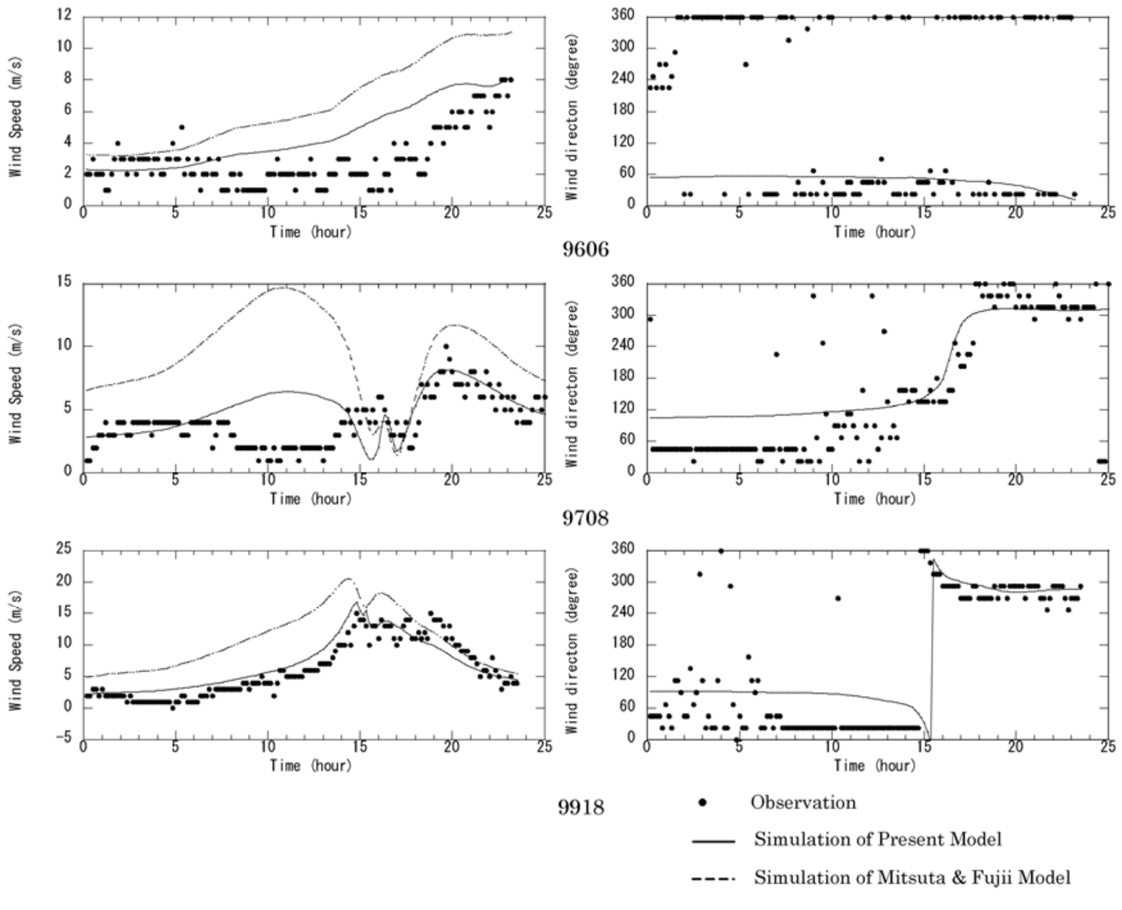
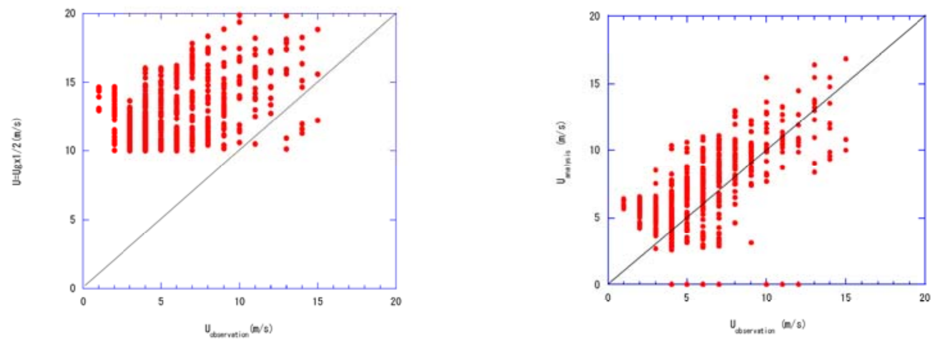


Figure 5 Time series of predicted and observed wind speeds and wind directions at Nagasaki Meteorological Station

The results show that wind speed by the proposed method is very close to the observation data, because the effect of topography is taken into account with this method. On the other hand, wind speed obtained by Mitsuta and Fujii Model (hereafter, M&F Model) overestimates the wind speed for all typhoons.



a) M&F Model b) Present Model

Figure 6 Comparison of predicted surface wind speeds

The predicted results against the observed one, clearly shows that the wind speeds estimated with M&F Model are far deviated from the observed data. (Figure 6) Root mean square (RMS) error for the present model is 2.62m/s, and 7.64m/s for the M&F Model. The bias is 1.20m/s for the present model and 7.11m/s for M&F Model.

TYPHOON SIMULATION

Design wind speed could be decided by using the distribution of observed annual maximum wind speed. However, only about 40 years of data is available, a stable distribution could not be obtained. Moreover, prediction of wind speed with a return period that is longer than the observation term would not be accurate. A large sample, which is the annual maximum wind speed of at least several thousand years, is required to estimate the design wind speed with a return period of 50 years or a longer. Typhoon simulation method was proposed because of these reasons.

Simulation methodology

Typhoon simulation is first done with determining the best fitting statistical distribution functions for 6 main parameters, which is the occurrence frequency, λ; minimum distance from the site, d_{min}; translation velocity, C; pressure difference, ΔP; radius to maximum wind speed, R_m; and approach angle, θ. From the statistical distribution, a large number (about 10000 years) of parameters representing the typhoons' fields are simulated artificially by Monte Carlo simulation. The generated parameters represent the typhoons' pressure at the minimum distance from the site of interest, as the original distributions of observed parameters are obtained at the closest distance. Using the minimum distance, translation velocity and approach angle, paths of the typhoons are calculated. The paths of the typhoons are assumed to be straight lines, and the parameters to be constant in time.

After that, the gradient winds at the site of interest are predicted from the simulated pressure field using a wind field model. Surface wind speeds are then predicted using the method as explained in previous section. Annual maximum wind speed is extracted from the predicted data. Gumbel distribution for the annual maximum wind speed is then used to obtain the design wind speed of a certain return period.

In this research, observation data are obtained from the database given by Ho

(2004). The typhoon simulation is performed with a simulation program called MOST (MOnte-Carlo Simulation for Typhoon) developed by Ishihara et al. (2004).

Statistical distribution of typhoon parameters

As the gradient wind speeds of typhoons depend on the paths, translation speeds, and the pressure field, both statistical distributions for each parameter and the correlations between them have to be reproduced accurately. In this research, a mixed probability distribution function, which is applicable to any locations by changing a weighted parameter, is used. A modified orthogonal decomposition that could simultaneously reproduce probability distributions or typhoon parameters and their correlations is incorporated into the simulation method.

To verify the accuracy of the simulation method used in this research, the simulation results are compared with the wind speeds predicted from the observed parameters. In this research, theoretical model for the estimation of gradient winds by Ishihara et al. (1995) are used. Case studies were conducted at five typical sites in Japan. The annual maximum wind speeds at the five sites showed favorable agreements with the observations.

Mixed probability distribution function Due to the inconsistency of results by using same PDF at different locations, a mixed probability distribution function was proposed in this research. The function is written as below:

$$MPDF = a \times \frac{1}{\sqrt{2\pi}\sigma_{\ln x}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \mu_{\ln x}}{\sigma_{\ln x}}\right)^2\right] + (1-a) \times \frac{k}{C}\left(\frac{x}{C}\right)^{k-1} \exp\left(-\left(\frac{x}{C}\right)^k\right) \in [0,\ 1] \tag{16}$$

Here, a is the mixed parameter, the value is 0 for weibull distribution and 1 for normal distribution. To obtain the mixing parameter a for the *MPDF*, least square method is used. Using this distribution function for Naha and Chiba, it is observed that $a = 1$ (log-normal distribution) for Chiba Meteorological Station, and for Naha Meteorological Station, $a = 0.2$ (close to Weibull distribution). Figure 7 shows the fitting of observation data by using log-normal and Weibull distribution while Figure 8 using the mixed probability distribution function. It is noticed that the mixed probability distribution function exhibits satisfactory fitting.

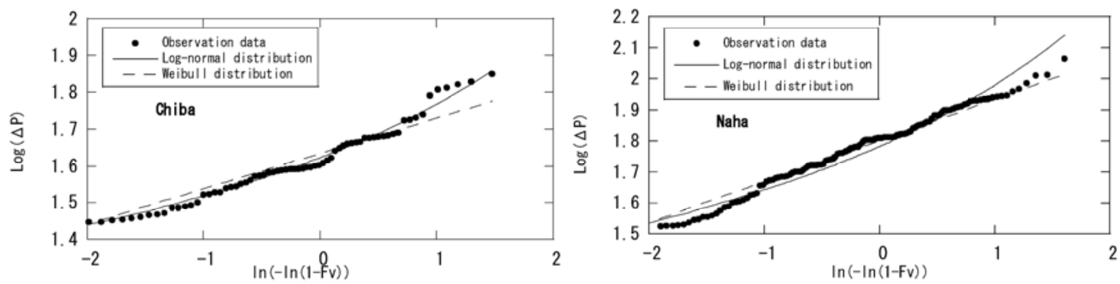


Figure 7 Approximation of central pressure difference by log-normal and Weibull distribution

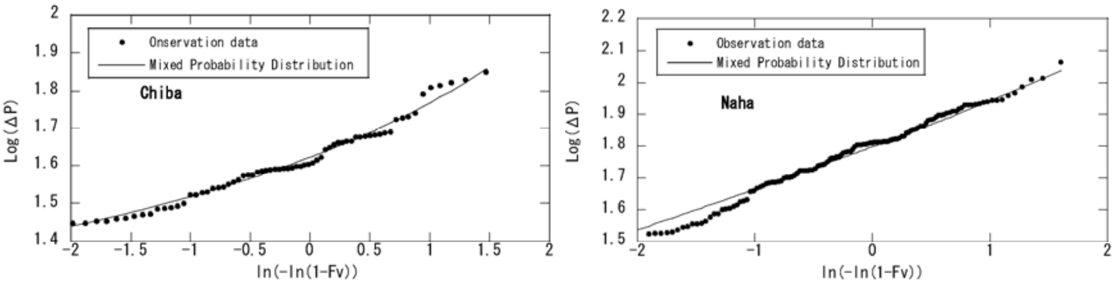


Figure 8 Approximation of central pressure difference with mixed probabilistic distribution

The mixed probability function is applied to a total of 5 meteorological stations in Japan (from Naha in the south to Sendai in the north). These sites located both at the side of Japan Sea and the side of Pacific Ocean. The value of mixed parameter *a* for these sites is shown in Figure 9. It increases from 0.2 with the latitude, and after 34°N, it approaches 1.0. This is due to the fact that locations in the north are less prone to strong typhoon attacks. Since Naha and Florida located at almost same latitude (around 26degree), the use of Weibull distribution is famous in United States.

Actually, not only the central pressure difference but also the radius to maximum wind speed and translation speed could be fitted using the mixed probability distribution function with good accuracy. The mixed parameter of translation speed behaves oppositely to that of central pressure difference. It becomes smaller with the increase of latitude. This is because typhoons move faster as they get to the north.

To show the effect of the mixed probability model, annual maximum gradient wind speed predicted with the method and the conventional one is compared (Figure 10). Overestimation of wind speed by the conventional method is improved with the use of mixed probability distribution function. The summary of probability distribution function for typhoon parameters that used in this research is shown in table 3.

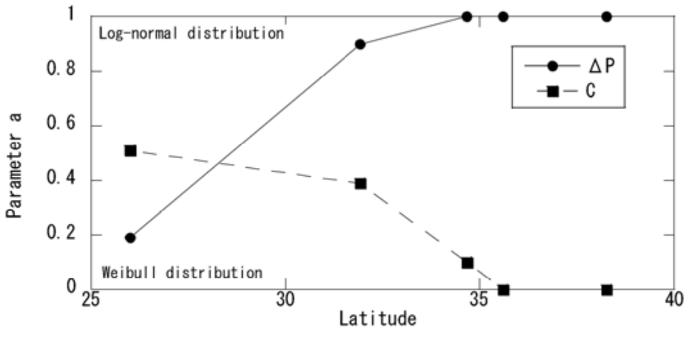


Figure 9 Changes of parameter *a* with latitude

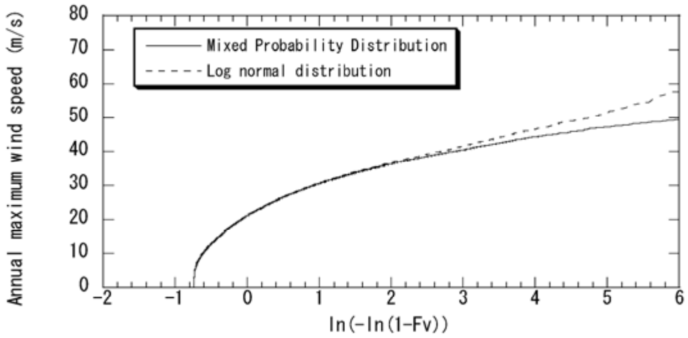


Figure 10 Annual maximum gradient wind speeds in Chiba

Table 3 Summary of probability distribution function for typhoon parameters

Parameters	**Distribution**
Frequency of occurrence, λ	Poisson
Minimum distance, d_{min}	Quadratic Function
Approach Angle, θ	Normal distribution
Pressure depth, ΔP	*MPDF*
Radius to Maximum Wind, R_m	*MPDF*
Translation Speed, c	*MPDF*

Orthogonal decomposition method Table 4(a) shows the correlation of parameters passing the circular sub region centered with a radius of 500km at Chiba. Some of the parameters, for example ΔP and d_{min} show a strong correlation. This correlation is due to the typhoon passing the east side of Chiba is stronger than those passing the west, as the typhoons decay faster when making land fall on the west side. Ignoring this correlation, strength of typhoons making land fall on the west side, and then the annual maximum wind speed would be overestimated.

Table 4 Correlations between typhoon parameters at Chiba

	a) Observation					b) Orthogonal Decomposition					c) Modified Orthogonal Decomposition				
	ΔP	R_m	C	θ	d_{min}	ΔP	R_m	C	θ	d_{min}	ΔP	R_m	C	θ	d_{min}
ΔP	1.00					1.00					1.00				
R_m	-0.28	1.00				-0.28	1.00				-0.28	1.00			
C	0.01	0.37	1.00			0.02	0.35	1.00			0.02	0.35	1.00		
θ	-0.03	-0.03	-0.27	1.00		-0.04	-0.02	-0.25	1.00		-0.04	-0.02	-0.25	1.00	
d_{min}	0.33	-0.25	-0.37	-0.28	1.00	0.33	-0.24	-0.37	-0.29	1.00	0.33	-0.24	-0.37	-0.28	1.00

The method proposed by Vickery (1995) could not reproduce the probability distribution and correlations between parameters at the same time. Besides, this method could only consider the correlation between a pair of parameters at one time. Thus, this research proposed a modified orthogonal method (MOD) in order to reproduce the probability distribution and correlation at the same time. The steps of the proposed method are as follow:

1) Orthogonal decomposition to independent parameters

Here, parameters describing a typhoon are normalized and written in vector form.

$$\{x_i\}^T = \{\ln(\Delta P), \ln(R_m), \ln(C), \theta, d_{\min}\} \tag{17}$$

The correlation matrix is written as S, relation between eigen value and eigen vector becomes

$$[S - \lambda_k E]\{\phi\}_k = 0 \tag{18}$$

Parameters of typhoons x_i could be transformed into independent parameters z_i by the following equation.

$$\{z_i\} = [\phi]\{x_i\} \tag{19}$$

Obtained independent parameters are fitted by a mixed probability function of normal and uniform distribution.

2) Transforming to parameters with correlations

Then, using the fitted probability function, independent parameters are simulated for a certain number of years, and then multiply by the inverse correlation matrix. The correlated parameters of typhoon are obtained.

$$\{x_i^{'}\} = [\phi]^{-1}\{z_i^{'}\} \tag{20}$$

The correlations between parameters obtained with this method are much closed to the observation data (Table 4(b)).

3) Modification of parameters

However, the probability distributions of the simulated parameters are found not identical to the observation data. To correct this problem, slight modification is made to the transformed parameters. Transformed parameters of typhoons are rearranged in an ascending order, and modified so that its probability distribution is same as the observation data. This modification does not change the combination of the parameters, and thus does not affect the correlations very much (Table 4(c)). Modified $ln(R_m)$ is shown in Figure 11.

The advantage of this method is verified using the observed parameters. Figure 12 shows the relation between gradient wind speeds and return period. Comparing to the conventional method, the proposed method shows better agreement with the observation data.

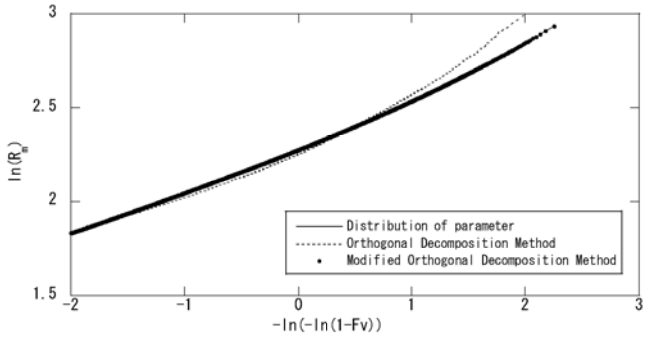


Figure 11 Result of modified orthogonal decomposition method

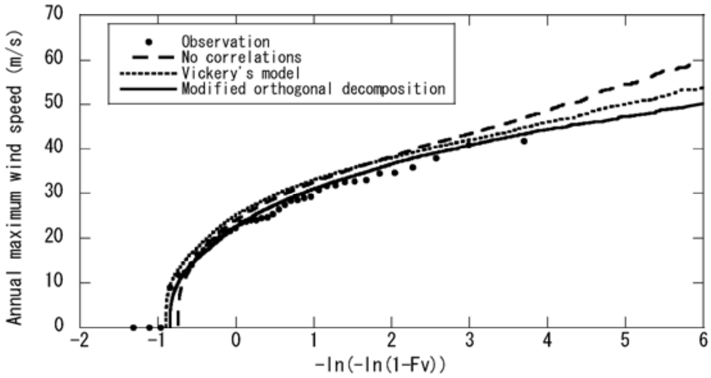


Figure 12 Gradient wind speeds at Chiba

Using the proposed method, annual gradient wind speeds for Naha, Miyazaki, Osaka, Chiba, and Sendai with 50 years of return period were estimated. As shown in Figure 13, the expected annual maximum wind speed reduced with the increase of latitude. This result agrees with the fact that typhoons get weaker when moving to the north. Contrarily conventional method that does not reproduce the probability distribution and correlation at the same time gives unnatural results. The maximum wind speed becomes larger for the latitude greater than 34° N. Figure 14 shows the simulation results of annual maximum wind speed at 10 different selected sites.

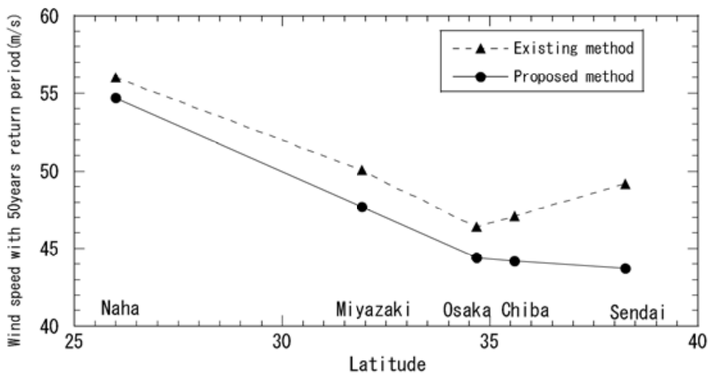


Figure 13 Annual maximum wind speeds with 50 years return period

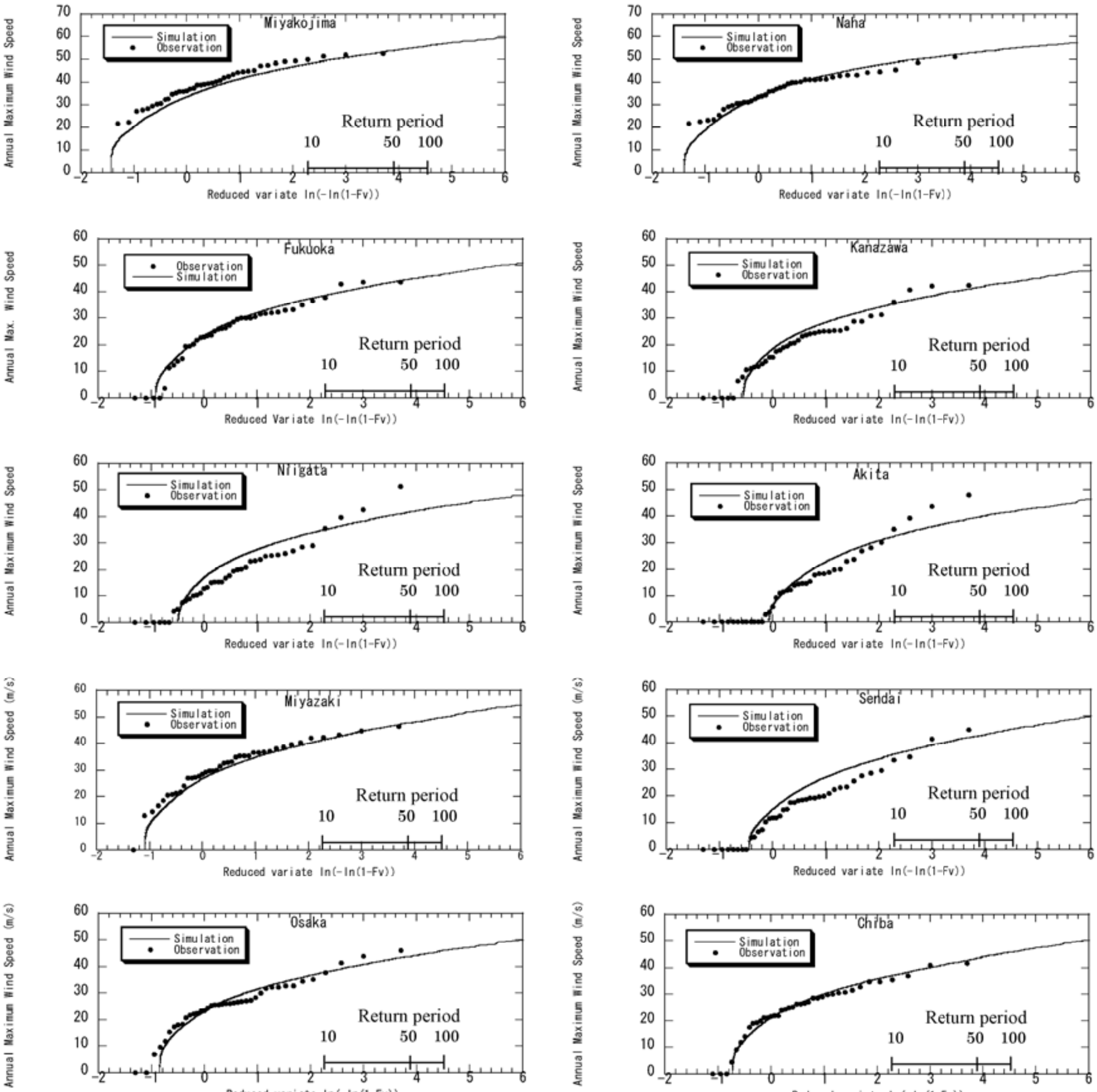


Figure 14 Annual Maximum Wind Speed in Several Sites

CONCLUSIONS

Estimation of surface wind speed was separated into two parts. One is the prediction of wind speed due to pressure fields and another is the evaluation of topography and roughness change effect by CFD. Comparison shows that wind speed predicted with this method is more accurate over the conventional method. The RMS error and bias for M&F Model is 7.64m/s and 7.11m/s. These have been improved to 2.62m/s and 1.2m/s in the proposed method.

The general mixed probability distribution function which combines the Weibull and log-normal distributions improved the fitting of observation data. The modified orthogonal decomposition method is able to satisfy both probability distribution function and correlations at the same time. Results of modified orthogonal decomposition method exhibit favorable fitting to the distribution of parameters. Gradient winds predicted with this method agree well with the observation data, and the overestimation of annual maximum wind speed was improved.

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