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Extreme typhoon wind speeds considering the random variation in a full-scale observation

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ABSTRACT : In order to estimate the maximum wind speed under typhoon condition, random variation which exists in a full-scale observation record was evaluated. Taking account of the random variation, a probabilistic approach was proposed which can compute an extreme distribution of wind speed with the Monte-Carlo method. It was found that the conventional method, which could not evaluate random variation, was apt to underestimate the maximum wind speed under typhoon condition. The results of the Monte-Carlo simulation by the proposed approach agreed with the distribution that was obtained from observation records.

1. INTRODUCTION

Typhoon simulation based on the Monte-Carlo method, developed by Russell[1] and modified by many researchers[2][3], is often used to evaluate design wind speed in typhoon-prone regions. In this method, wind speed is indirectly derived from a gradient of atmospheric pressure. Accuracy is dependent on two factors: the reality of the pressure field generated by random number, and the wind field estimation.

The Monte-Carlo simulation requires very huge amount of calculation for wind speed from given pressure field. So, easy to calculate is required as well as accurate for the wind field estimation. In the early stage of the study, Russell[1] used Graham and Nunn's empirical relation[5] between pressure depth and maximum wind speed. It was so simple as not to estimate wind direction. Tryggvason et al.[2] introduced gradient wind model developed by Myers and Malkin[6]. They estimated wind direction as well as wind speed. After this study, surface wind speed had been treated as relation with the gradient wind.

Analytical treatment between gradient wind and surface wind for this kind of simulation employed by Vickery et al.[7] and Meng et al.[8].

In this paper a wind field model developed by Meng et al.[9] [10] has been employed and combined with calibration technique. By using this procedure, there is good agreement with the observed wind speed and the calculated speed in a time series. There is, however, underestimation of the maximum wind speed by using the model, the reason for which is not clear.

In this paper, this underestimation is investigated and a probabilistic approach is proposed that enables estimation of maximum wind speed during a typhoon, taking account of the random variation of a full-scale observation. The Monte-Carlo simulation with extreme distribution is also proposed. By using the proposed method, the underestimation will be eliminated.

2. TYPHOON MODEL

2.1 *Pressure field model*

The typhoon pressure model used here was proposed by Schloemer[4], which was expressed as function of the distance from the typhoon center r.

$$p(r) = p_c + D_P\, \mathrm{e}^{-\frac{R_M}{r}} \tag{1}$$

where p_c is the central pressure of the typhoon; D_P is the pressure depth of the typhoon; and R_M is the radius of maximum winds.

2.2 *Wind field model*

The typhoon wind field model used here was developed by Meng et al.[9][10].

$$u(z) = u_G(z/z_G)^{\alpha_u} \tag{2}$$

$$\gamma(z) = \gamma_G + \gamma_S(1.0 - 0.4\frac{z}{z_G})^{1.1} \tag{3}$$

The exponent index α_u, and gradient height z_G, are expressed as functions of the absolute vorticity f_λ, and the surface Rosby number $Ro_\lambda(=\frac{u_G}{f_\lambda z_0})$.

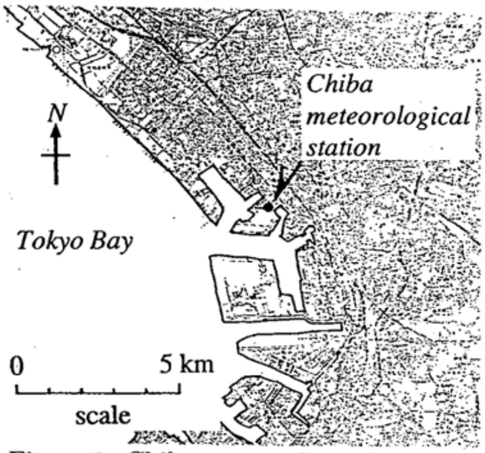


Figure 1: Chiba meteorological station

Table 1: Directional roughness length at Chiba meteorological station

wind direction	NNE	NE	ENE	E
roughness length (m)	3	3	3	1
wind direction	ESE	SE	SSE	S
roughness length (m)	0.3	0.3	0.3	1
wind direction	SSW	SW	WSW	W
roughness length (m)	0.1	0.1	0.1	0.1
wind direction	WNW	NW	NNW	N
roughness length (m)	1	3	5	3

Inflow angle, γ_S, is a function of the homogeneity of vorticity, ξ, and the surface Rosby number.

$$\alpha_u = 0.27 + 0.09 \log z_0 + 0.018 \log^2 z_0 + 0.0016 \log^3 z_0$$
$$z_G = 0.06\frac{u_G}{f_\lambda}(\log Ro_\lambda)^{-1.45}$$
$$\gamma_S = (69 + 100\xi)(\log Ro_\lambda)^{-1.13}$$
$$f_\lambda = \left(\frac{\partial u_{\theta g}}{\partial r} + \frac{u_{\theta g}}{r} + f\right)^{1/2}\left(2\frac{u_{\theta g}}{r} + f\right)^{1/2}$$
$$\xi = \left(2\frac{u_{\theta g}}{r} + f\right)^{1/2} / \left(\frac{\partial u_{\theta g}}{\partial r} + \frac{u_{\theta g}}{r} + f\right)^{1/2}.$$

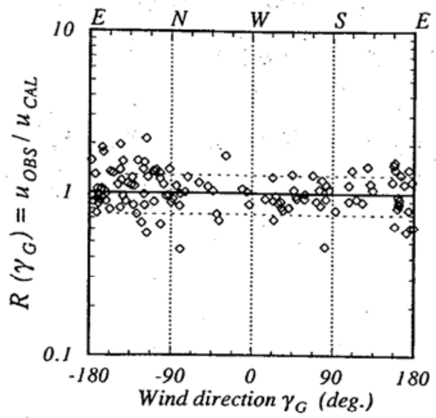
where f is the Coriolis parameter.

The gradient wind speed u_G, and direction γ_G are given by;

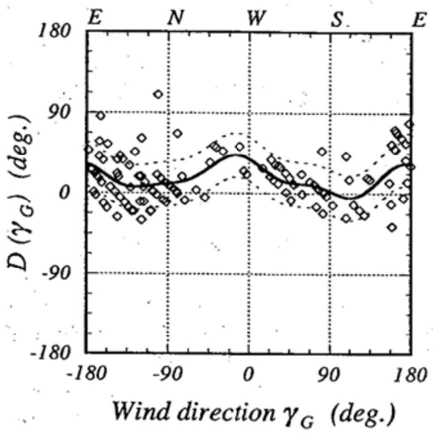
$$u_G = \sqrt{u_{rg}^2 + u_{\theta g}} \quad (4)$$
$$\gamma_G = \theta_0 + \tan^{-1} u_{\theta g}/u_{rg} \quad (5)$$

where θ_0 is the direction to the observation site from typhoon center(positive counter-clock wise); u_{rg} and $u_{\theta g}$ are radial and transverse component of the gradient wind in cylindrical coordinate(r, θ), which is given by;

$$u_{rg} = 0 \quad (6)$$



(a) Wind speed ratio



(b) Wind direction difference

Figure 2: Result of calibration

$$u_{\theta g} = \frac{C \sin\theta_r - fr}{2} + \sqrt{(\frac{C \sin\theta_r - fr}{2})^2 + \frac{r}{\rho}\frac{\partial p}{\partial r}} \quad (7)$$

where θ_r is the angle of typhoon moving direction relative to θ_0 (expressed as $\theta_r = \theta_T - \theta_0$, where θ_T is the moving direction of the typhoon); and C is moving speed of the typhoon center.

2.3 *Calibration with gradient wind*

In the wind profile model, shown above, small scale topography which little affects wind direction can be treated as an equivalent roughness[8]. For large scale topography which affects both wind speed and direction, calibration[11] between observed wind and standard reference wind is effective. In this study, gradient wind balanced with the atmospheric pressure distribution is referred

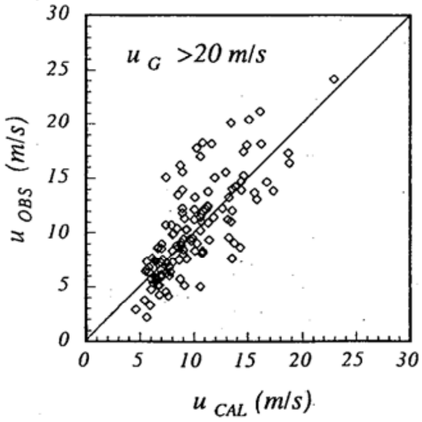


Figure 3: Relation of wind speeds (OBS. vs CAL.)

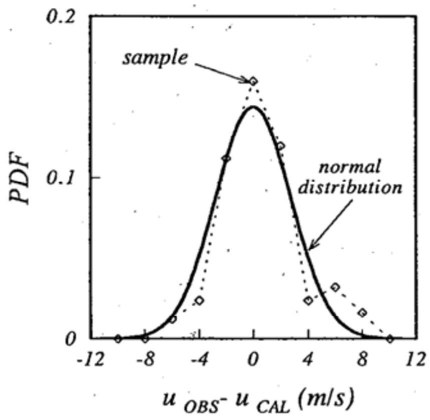


Figure 4: Distribution of residues (OBS.-CAL.)

to as "standard reference wind".

By using the Meng model with directional roughness length $z_0(\gamma)$ and taking the results of calibration into consideration, wind speed during typhoons are evaluated by the following equations.

$$u_{CAL} = R(\gamma_G)u(z) \quad (8)$$
$$\gamma_{CAL} = D(\gamma_G) + \gamma(z) \quad (9)$$

where $R(\gamma_G)$ and $D(\gamma_G)$ are the wind speed ratio and wind direction difference between observed wind and gradient wind, respectively (function of gradient wind direction).

3. EVALUATED SITE DESCRIPTION AND OBSERVED DATA SET

Figure 1 shows a map of the Chiba meteorological station. The station is located between Tokyo bay in the south and a big city in the north. Roughness length for each direction was set as Table 1. These lengths were decided from the appearance of the ground surface.

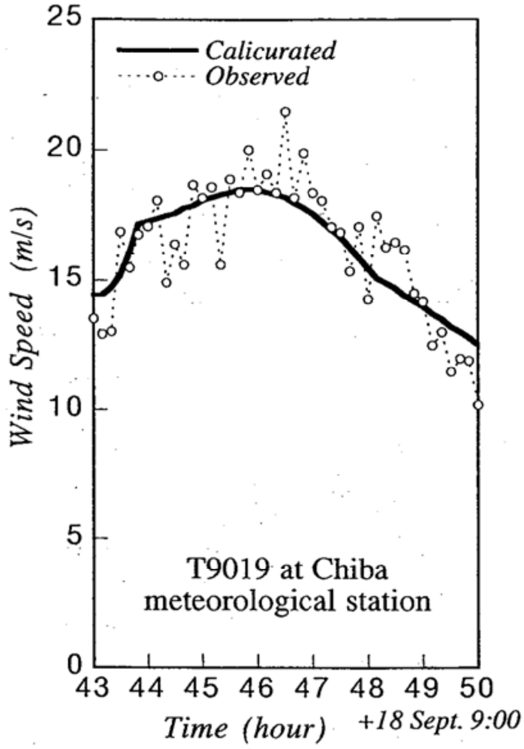


Figure 5: Time series of wind speed (T9119)

Observed wind speed records from 1966 to 1993 were acquired from the meteorological station. The 1966 to 1990 data set consists of 10-minute averaged wind speed for every 3 hour, while the 1991 to 1993 data set consists of one for every hour.

Calibration between observed wind speed and computed wind speed was conducted. Figures 2(a) and (b) show the results of calibration and it provides wind speed ratio and wind direction difference for equations (8) and (9).

Using the results of calibration (bold lines in Figures 2(a) and (b)) as wind speed ratio $R(\gamma_G)$, and wind direction difference $D(\gamma_G)$, wind speed during a typhoon was calculated from equations (1) - (9).

Figure 3 shows the relation between observed wind speed and calculated wind speed, which is in good agreement. Figure 4 shows the distribution of residual value ($u_{CAL} - u_{OBS}$) with a normal probability density function having the same variation. The residual value has a normal distribution.

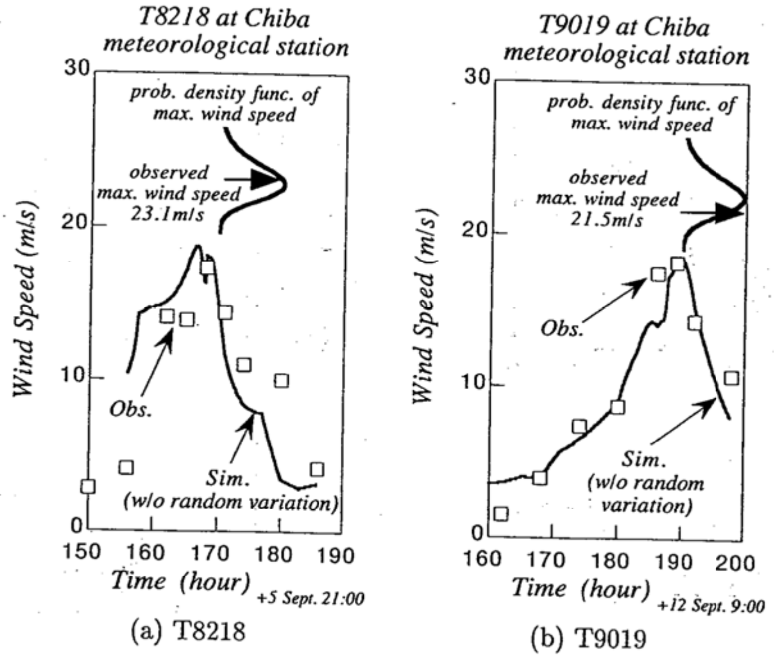


Figure 6: Time series of typhoon wind speed

4. MAXIMUM WIND SPEED ESTIMATION TAKING WIND SPEED FLUCTUATION INTO ACCOUNT

4.1 *Comparison of calculated and observed wind speeds*

Figure 5 shows time series of calculated and observes wind speeds. The calculated values appear to have a good agreement with the observation while there are some fluctuations in the observed records. These fluctuations have not been evaluated in the calculations. One of the reasons for not taking into account the fluctuations was the simplicity of the pressure field. In this method, atmospheric pressure is fitted into an empirical model by Schloemer[4]. As shows in equation 1, the pressure model is expressed as a simple function of relative distance from the center of the typhoon, pressure depth and maximum wind speed radius. The pressure model is simple enough not to express small-scale fluctuation. Wind speed calculated from such simple pressure fields is smoother than the observed wind speed.

4.2 *Extreme distribution of the maximum wind speed*

It is hard to use a more complex function for the pressure field, because there is not enough data for time and space. In the real observed record, the wind speed have a random fluctuation caused by the fluctuation in pressure even for 10-minute averaged wind speed. In order to evaluate such fluctuation, random variation of wind speed is considered and a probabilistic approach is proposed which could compute an extreme wind speed distribution.

The extreme distribution of the maximum wind speed is expressed as equation (10) under the following assumptions:

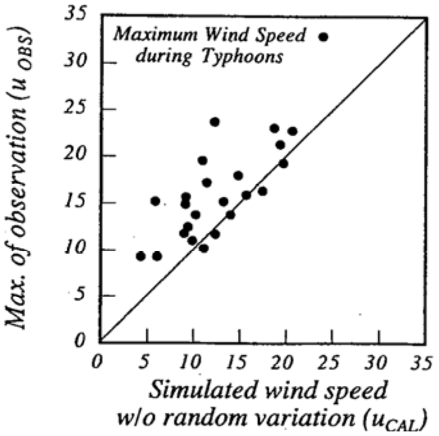
- Calculated wind speeds evaluated by equations (1) - (9) have good agreement except for the fluctuation
- Wind speed fluctuation for 10-minute averaged wind speed occurs at random, independent of time.

$$F_T(u) = P(u_1 \le u, u_2 \le u, \cdots, u_n \le u) = \prod_j F_j(u) \qquad (10)$$

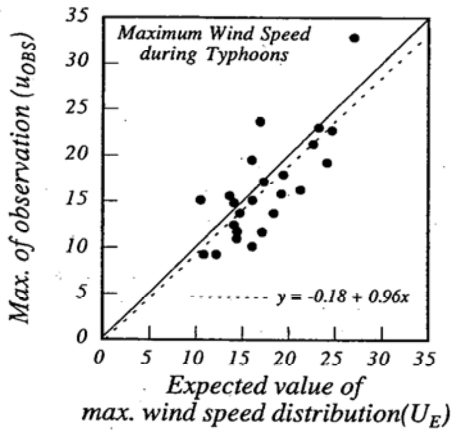
$F_j(u)$ is the probability distribution function of the 10-minute averaged wind speed. Referring to Figure 4, normal distribution is used here.

$$F_j(u) = N(u_j, \sigma_{uj}^2) \qquad (11)$$

where $N(x, \sigma^2)$ is normal distribution whose average and standard deviation are x and σ, respectively. Probability density function $f_T(u)$ of $F_T(u)$



(a) OBS. vs CAL.:w/o the random variation



(b) OBS. vs CAL.:with the random variation

Figure 7: Relation of maximum wind speeds

is defined as

$$f_T(u) = \frac{\mathrm{d}}{\mathrm{d}u} F_T(u) \tag{12}$$

Figures 6(a) and (b) show examples of calculated and observed wind speed. In these figures probability density functions evaluated by equation (12) and observed maximum wind speeds are also shown.

To estimate the effect of equations (10) - (12), the results of the two cases described below are compared.

- CASE (a): without taking the effect of wind speed fluctuation into consideration in the maximum wind speed calculated by equations (1)-(9)

Table 2: Probability distribution of pressure parameters

Variable [distribution]	Group1 -180°~ -135° 67.5°~ 180°	Group2 -135°~ 67.5°
D_P (hPa) [LN]	$46.6e^{0.280N(0,1)}$	$50.8e^{0.334N(0,1)}$
R_M (km) [LN]	$134.0e^{0.750N(0,1)}$	$109.0e^{0.771N(0,1)}$
C (m/s) [LN]	$15.0e^{0.436N(0,1)}$	$11.1e^{0.596N(0,1)}$
θ_T	perpendicular to θ_{min}	
m [PO] $(= m_1 + m_2)$	$\overline{m_1} = 0.907$	$\overline{m_2} = 1.535$
θ_{min}(deg.)	$N(142.3°, 23.6°^2)$	$N(-44.2°, 28.6°^2)$
r_{min}(km) [PL]	$260.1\mathrm{uni}(0,1)$ $+197.9\mathrm{uni}(0,1)^2$	$500.0\mathrm{uni}(0,1)$

N(0,1): standard normal distribution, uni(0,1): uniform distribution, [LN]: log normal, [PO]: Poisson, [PL]: polynomial

- CASE (b): taking into consideration the effect of wind speed fluctuation on the expected value U_E, of the distribution obtained from equation (10)

$$U_E = \int u f_T(u) \mathrm{d}u$$

Figures 7(a) and (b) show the maximum wind speed during typhoons. Figure 7(a) shows a comparison between observed wind speed and calculated speed, where random variation is not taken into account, while in Figure 7(b) the random fluctuation is considered.

It is clear that maximum wind speed in a typhoon is well estimated with little bias by the model in which the random fluctuation is taken into account.

5. DISTRIBUTION OF ANNUAL MAXIMUM WIND SPEED

Distribution of the annual maximum wind speed is computed by the Monte-Carlo simulation taking account of an extreme distribution of wind speed during a typhoon.

The distribution of annual maximum wind speed is given by the following equation.

$$F_A(u) = \int_{\Omega} F(u > V|\Omega) f(\Omega) \mathrm{d}\Omega \tag{13}$$

where $\Omega = \{D_P, R_M, C, \theta_T, m, r_{min}, \theta_{min}\}$ are probability valuables describing typhoon pressure field, annual number of occurrence and position of occurrence. They are pressure depth of typhoon

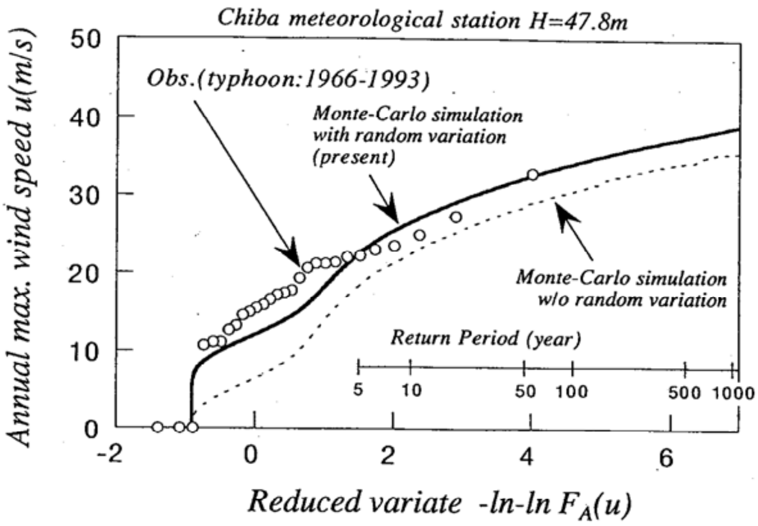


Figure 9: Distribution of annual max. wind speed

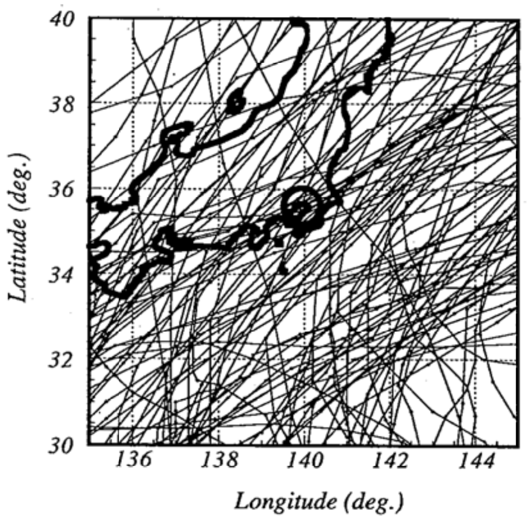


Figure 8: Tracks of typhoons around the site

center D_P, radius of maximum winds R_M, moving speed C, moving direction θ_T, annual number of occurrence m, and nearest position of typhoon center (r_{min}, θ_{min}). $F(u > V|\boldsymbol{\Omega})$ is the probability of occurrence of $u > V$ conditional upon the occurrence of event $\boldsymbol{\Omega}$ and $f(\boldsymbol{\Omega})$ is the density function of $\boldsymbol{\Omega}$.

In order to obtain the integration of equation (13), the Monte-Carlo simulation was conducted. To reflect the effect of the wind speed fluctuation obtained above in the simulation, the following steps are proposed.

1. Generating the amount of probability valuables $\boldsymbol{\Omega}$ for N_T years, based on random number reflecting their stochastic characteristics

2. Calculating the extreme distributions of the k-th typhoon wind in the i-th year ${}_iF_{Tk}(u)$, according to equation (10)

3. Obtaining the annual maximum distribution from equation (14).

$$F_A(u) \simeq \frac{1}{N_T}\sum_{i=1}^{N_T}\left\{\prod_{k=1}^{m_i} {}_iF_{Tk}(u)\right\} \qquad (14)$$

The distribution of annual maximum wind speed caused by typhoons at the Chiba meteorological station is calculated along the proposed steps.

Figure 8 shows tracks of typhoons which passed inside the 500km radius of the site center circle. Typhoons are divided into two groups according their nearest direction from the site. One is the group which moves on the Pacific Ocean side, whose nearest direction ranges from -135°to 67.5°. Stochastic characteristics of each group are shown in table 2.

Following the table, the Monte-Carlo simulation was conducted. The simulation year N_T was set at 10000.

Figure 9 shows the results of the simulation. A Hazen plot of observed annual wind speed caused by typhoons and result of conventional method (without fluctuation) are juxtaposed on the figure.

The proposed method that reflects wind speed fluctuation showed larger wind speed than did the conventional method in all ranges of return period and showed good agreement with the plots of observation. In return periods of 5 year or less, the difference is especially pronounced.

6. CONCLUSION

1. In order to evaluate the maximum wind speeds during typhoons, a probabilistic approach has been proposed that takes account of the random variation of a full-scale observation.

2. It was found that the conventional method, which does not evaluate random variation, was apt to underestimate the maximum wind speed during a typhoon.

3. The results of the Monte-Carlo simulation by the proposed approach had good agreement with the distribution that was obtained from the observation records.

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