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Development of Typhoon Simulation Model for Insurance Risk Estimation

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ABSTRACT

A typhoon simulation model for risk estimation was developed for an insurance company. The insurance company required highly accurate prediction of the total insurance loss caused by typhoon. Therefore, the coast-crossing model was selected, since it can simulate the tracking of a typhoon from the formation to its disappearance. In order to improve the accuracy for predicting the surface wind speed, Ishihara's semi empirical equation was introduced to the coast-crossing model. This equation is able to evaluate the effect of roughness, and the accuracy was confirmed by the simulating significant past typhoons.

INTRODUCTION

Typhoons that have occurred in Japan rank 6th, 14th, and 17th in the list of the highest insurance losses from 1970 to 2004 (Tab. 1). Typhoon Mireille caused the domestic insurance companies to disburse \$7,831 million. After this incident, there have been significant efforts to evaluate the insurance risk by typhoon simulation.

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Tab. 1. The 20 most expensive insurance losses from 1970 to 2004, indexed to 2004

No.	Event	Insured loss (in USD m)
1	Hurricane Andrew	21,542
2	Terror attack on WTC	20,035
3	Northridge earthquake (M6.6)	17,843
4	Hurricane Ivan	11,000
5	Hurricane Charley	8,000
6	Typhoon Mireille/No 19	7,831
7	Winterstorm Daria (Europe)	6,639
8	Winterstorm Lothar (Europe)	6,578
9	Hurricane Hugo	6,393
10	Hurricane Frances	5,000
11	Seaquake (M9.0)、tsunamis	5,000
12	Storm and floods in Europe	4,988
13	Winterstorm Vivian	4,613
14	Typhoon Bart/No 18	4,582
15	Hurricane Georges	4,091
16	Hurricane Jeanne	4,000
17	Typhoon Songda/No 18	3,585
18	Tropical storm Allison	3,361
19	Tornadoes, hail (USA)	3,292
20	Explosion on platform Piper Alpha	3,195

A typhoon is a convective activity governed by fluid dynamics. Its characteristics can be simulated accurately provided the initial conditions are known. However, it is necessary to evaluate not only the characteristics but also the probability of typhoon formation. Therefore, in this study, we develop a probabilistic typhoon model using a “Monte Carlo” simulation. This typhoon simulation model can be roughly categorized into three types, namely, the circular-subregion model (Fig. 1), the full-track model (Fig. 2), and the coast-crossing model (Fig. 3).

The circular-subregion model was proposed by L.R. Russell. This model can simulate a hurricane within a radius of 500 km from the target point, and evaluate the wind speed generated at this point (L.R. Russell 1971). Matsui enhanced the circular-subregion model for simulating typhoons in Japan (Matsui 1994). This model can accurately evaluate the wind speed at the target point for a long period of time. It can also evaluate wind loading, which is required for designing a bridge or a tall building. However, two or more points of the wind speed cannot be evaluated simultaneously by this model; hence, it is not possible to evaluate the total payment expected by an insurance company after typhoon. Therefore, the circular-subregion model does not match the requirements of the insurance company.

The full-track model is a technique for simulating all processes—from a formation of a typhoon to its disappearance. A study in Japan was reported that the technique to form a typhoon in the south of Japan and simulate for it to go north (Fujii 1975). However, since the full-track model requires a long-time simulation, it does not have the same accuracy as that of the circular-subregion model.

The coast-crossing model is a technique for simulating a typhoon from its formation using gates set along the coastlines. A model for arranging gates along the coastlines of Japan was reported (Fujii and Mitsuta 1986).

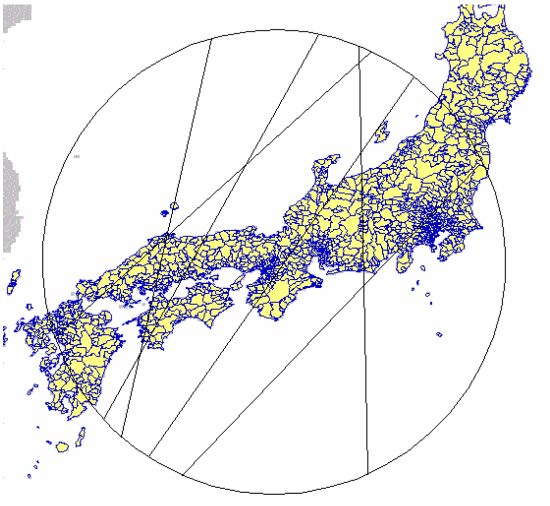


Fig. 1. Circular-subregion model

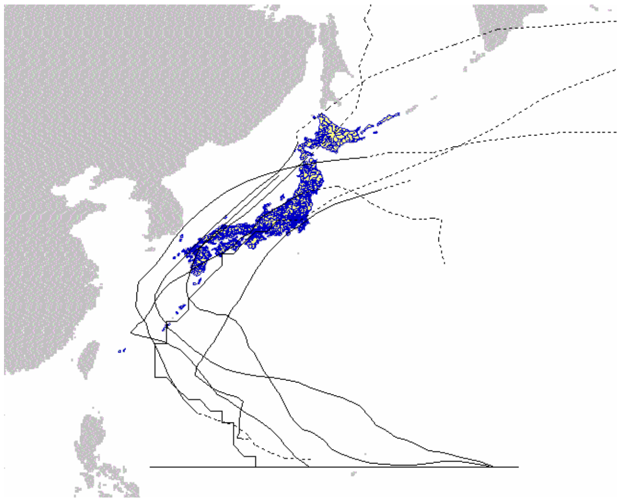


Fig. 2. Full-track model

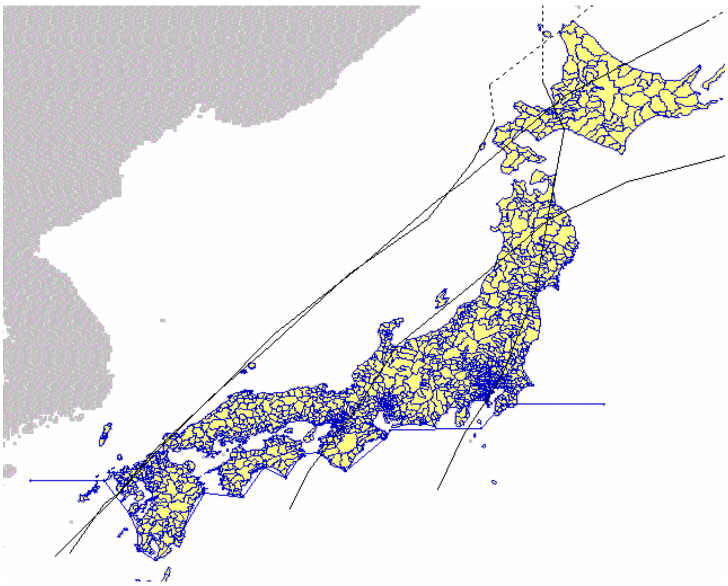


Fig. 3. Coast-crossing model

Since the purpose of the development of typhoon simulation model is to evaluate the risk estimation for insurance company, it is necessary to select the full-track model or the coast-crossing model. In this study, the coast-crossing model was selected because it is more accurate than the full-track model.

It is important to maintain a high accuracy while predicting the surface wind speed because the insurance loss estimation is predicted according to the surface wind speed at the target point. A technique for evaluating the surface wind speed from the gradient wind speed was proposed (B.V.Tryggvason 1976), and many typhoon simulation models have adopted this technique.

The relational formula was applied to the empirical formula based on several observations (P.N.Georgiou 1983, Fujii 1986). Since the formula cannot evaluate the effect of roughness at each location, the surface wind speed is overestimated in a region that comprises a large number of houses. In reality, however, the surface wind speed reduces due to the large number of buildings and houses.

The circular-subregion model capable of evaluating the effect of roughness was developed (Matsui 1998, Vickery 1995). Matsui applied Ishihara's semi-empirical equation to the relational formula, while Vickery applied Shapiro's semi-empirical equation. Shapiro's equation is based on the equation of horizontal motion, which is vertically averaged through the depth of the planetary boundary layer. Both results are in good agreement with the recorded observations. In this study, Ishihara's equation was selected for the relational formula because no report is available for verifying Shapiro's equation for the characteristic of typhoon in Japan.

The developed simulation model is validated by comparing its wind speed results for significant past typhoons with the observed wind speeds. In addition, the accuracy of Ishihara's equation is compared with that of the empirical equation, which has been employed in previous techniques. In order to verify the model for Typhoon No. 21, which occurred in 2002, we collected data of the affected houses. After the location of the affected houses estimated output by the GIS software, a correlation was observed between these locations and the strong surface wind areas predicted by the typhoon model.

TYPHOON SIMULATION MODEL

The surface wind speed is evaluated from the gradient wind speed, which is evaluated from the pressure distribution. The evaluation techniques for the pressure distribution, gradient wind speed, and surface wind speed are explained blow.

Pressure distribution model

It is well known that pressure isobars in the domain of a typhoon are distributed approximately in concentric circles with respect to the center of the typhoon. This relationship is given as follows (Holland 1980):

$$P(r) = P_C + D_P \exp\left\{-\left(\frac{R_M}{r}\right)^B\right\} \tag{1}$$

where $P(r)$ is the pressure as a function of the distance r from the center of the typhoon; P_C, central pressure; D_P, central pressure difference; R_M, maximum radius of the winds; and B, profile coefficient. B assumes an appropriate value between 1.0 and 2.5. A study reported that pressure isobars in Japan are distributed approximately in a concentric circle when the central pressure is 985 hPa or less. Moreover, the profile coefficient of the model is set as B=1 (Fujii 1995).

Georgiou's gradient-level wind field

A gradient wind speed is expressed by the following formula derived from the motion equation, which balances the pressure gradient force and the sum of the centrifugal and Coriolis forces:

$$v_{rg} = 0 \tag{2}$$

$$v_{\theta g} = \frac{c \cdot \sin\theta - fr}{2} + \sqrt{\left(\frac{c \cdot \sin\theta - fr}{2}\right)^2 + \frac{r}{\rho}\frac{\partial P(r)}{\partial r}} \tag{3}$$

where v_{rg} is the gradient wind speed in the direction of r in cylindrical coordinates; $v_{\theta g}$, gradient wind speed in the direction of θ; c, translation velocity of a typhoon; Θ, angle (anticlockwise indicates positive); f, Coriolis parameter; and ρ, air density.

Ishihara's wind-field model

The average wind speed $v(z)$ can be calculated as the sum of the gradient wind speed in free atmosphere and the component $v'(z)$. The component $v'(z)$ at a height of z is caused by friction on the ground surface:

$$v(z) = v_{\theta g} + v'(z) \tag{4}$$

where the expression for $v_{\theta g}$ is given by (3) in cylindrical coordinates. The component $v'(z) = \{v'_r, v'_\theta\}$ can be linearized as

$$-\xi \cdot f_\lambda v' = \frac{\partial}{\partial z}\left(K_m \frac{\partial v'_r}{\partial z}\right) \tag{5}$$

$$\frac{1}{\xi} \cdot f_\lambda v'_r = \frac{\partial}{\partial z}\left(K_m \frac{\partial v'_\theta}{\partial z}\right) \tag{6}$$

where f_λ is the absolute vorticity; ξ, parameter of the axial nonuniformity of vorticity; and

K_m, vortex viscous coefficient. Ishihara applied the closure model to K_m and estimated the velocity component in the atmospheric boundary layer as follows (Ishihara 1996, Mellor and Yamada 1974):

$$U(z) = v_{\theta\lambda}\left(\frac{z}{Z_G}\right)^{\alpha_M} \tag{7}$$

$$\gamma(z) = \gamma_s\left(1 - 0.4\frac{z}{Z_G}\right)^{1.1} \tag{8}$$

$$\alpha_M = 0.27 + 0.09\log_{10} z_0 + 0.018(\log_{10} z_0)^2 + 0.0016(\log_{10} z_0)^3 \tag{9}$$

where $U(z)$ is the wind velocity at the height z; $\gamma(z)$, angle deviation; α_M, index parameter, z_0, roughness length; and γ_s, surface shearing stress angle. Using Eqs. (7)-(9), we can evaluate the wind velocity and wind direction at any arbitrary height.

For employing the coast-crossing model to evaluate all regions in Japan, it is necessary to set the roughness length for these regions. The land-use mesh data obtained from the Geographical Survey Institute was classified into 15 divisions according to the land use form. The roughness length was set for all regions in Japan with a 1-km mesh according to the land use form. The wind speed is evaluated using the 1-km mesh as well as the roughness length.

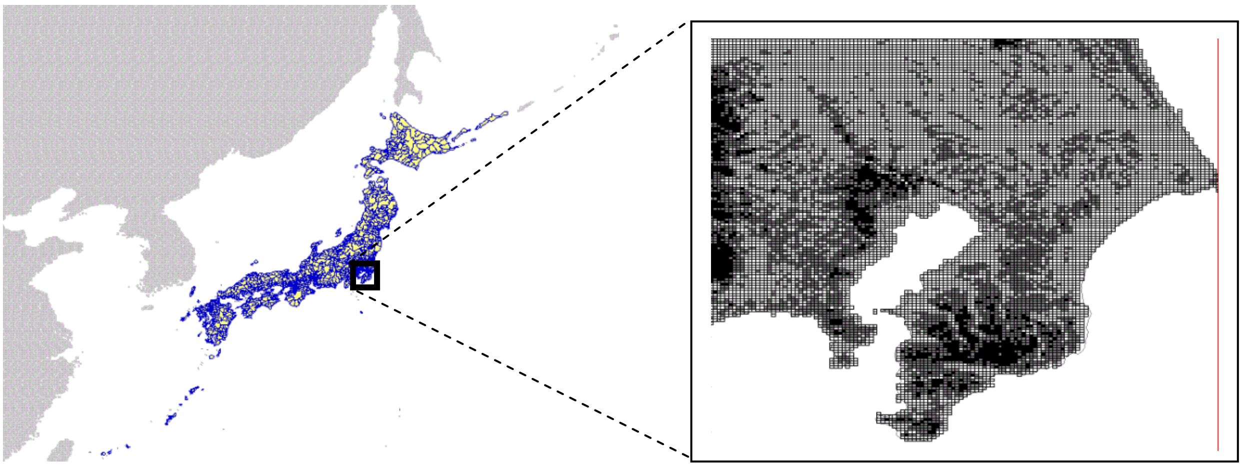


Fig. 4. Roughness distribution in the Kanto region; the roughness length is greater than 0.7 m, and 0.3 m in the black and grey regions, respectively, and less than 0.3 m in the white region

VALIDATION OF THE MODEL

The surface wind speed estimated by the simulation was compared with the observed wind speeds of significant past typhoons. Typhoons Mireille and Songda were selected from Tab.1. Typhoon Vicki and Higos were also selected because they passed regions other than those passed by Mireille and Songda. For Typhoon Mireille, the observation locations were Sasebo and Makurazaki (Fig. 6). The observation was conducted between 1500 and 2200 hours on September 27, 1991. For Typhoon Songda, the observation locations were the same as those for Typhoon Mireille (Fig. 7), and the observation was conducted between 0400 and 1700 hours on September 7, 2004. Typhoon Vicki, was observed from Kyoto and Himeji (Fig. 8) between 1200 and 2400 hours on September 22, 1998. Finally, Typhoon Higos, was observed from Katsuura and Chooshi (Fig. 9) between 1900 and 2400 hours on October 1, 2004.

The surface wind speed implied a 10-min mean wind speed for which the regional influence is smoothed. Figs. 10-13 show the results of the comparison between the observed data and the simulation data for 1-h time intervals.

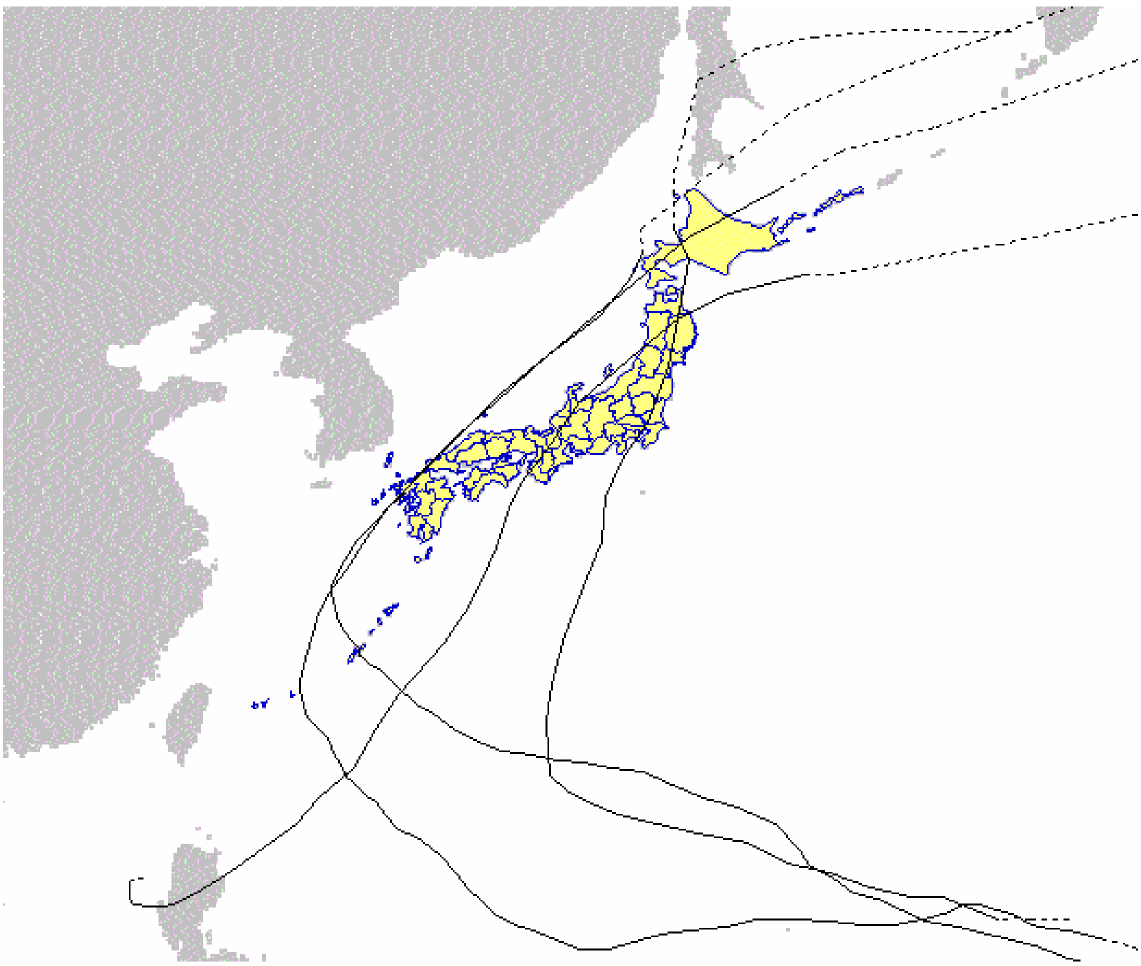


Fig. 5. Paths of four simulated typhoons

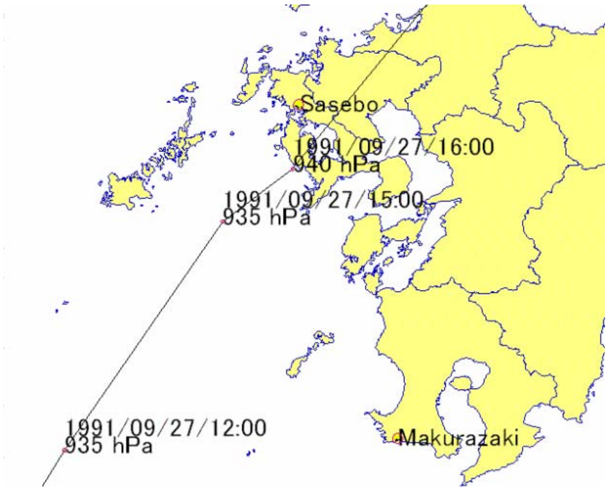


Fig. 6. Paths of Typhoons Mirelle (1991) and and the observations

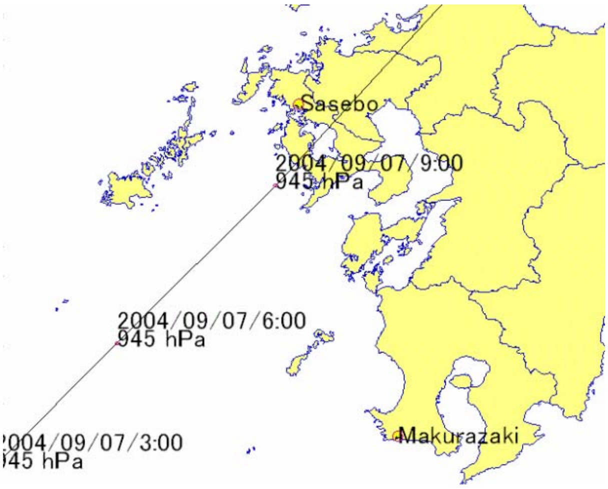


Fig. 7. Paths of Typhoon Songda (2004) and the observations

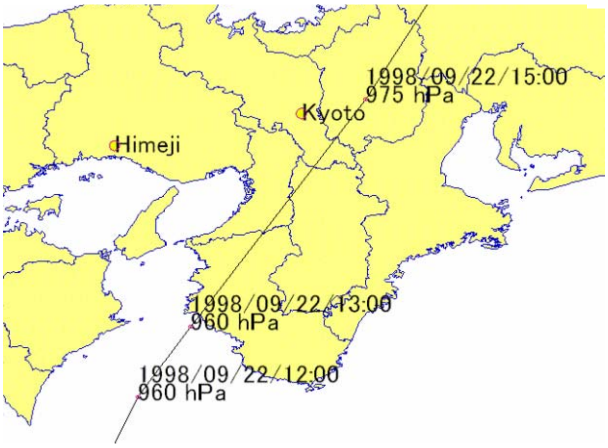


Fig. 8. Path of Typhoon Vicki (1998) and the observations

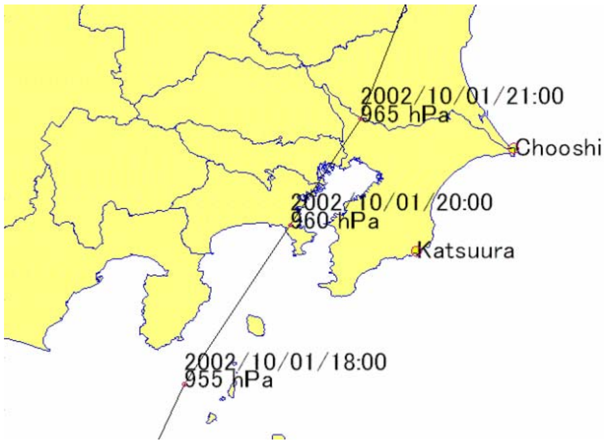


Fig. 9. Path of Typhoon Higos (2002) and the observations

The accuracy of Ishihara's equation is compared with that of the empirical equation, which has been employed in previous techniques. The empirical equation relates the gradient wind speed to the surface wind speed was proposed (Fujii 1986). The expression is as following and this expression called the "gradient model" in this study:

$$V_{so} = V_{gr} \times G(\infty) \times \left[1 + \left(\left(10^{0.0231 \times \Delta p - 1.96} \right) \right) \times \left(\frac{x}{x_p} \right)^{k-1} \exp\left[\left(1 - \frac{1}{k} \right) \left\{ 1 - \left(\frac{x}{x_p} \right)^k \right\} \right] \right] \qquad (10)$$

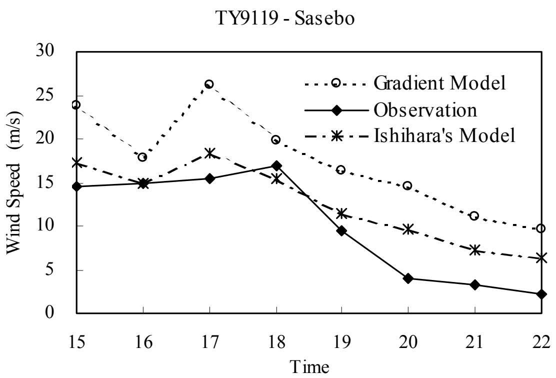
where V_{gr} is the gradient wind speed; V_{so}, surface wind speed; and $G(\infty)$, parameter corresponding to the land condition. In the case of plains, $G(\infty)=1/2$, and in the case of seas, $G(\infty)=2/3$. This expression does not evaluate the roughness and terrain effects for each region. A comparison of the accuracy for predicting the surface wind speed is presented in Tab. 2. The error in the comparison is expressed as follows:

$$error = \frac{1}{n}\sum_{t=1}^{n}\left(Y_t - \hat{Y}_t\right)^2 \tag{11}$$

where Y_t is the simulated wind speed by1-h time intervals; $\hat{Y}$, observed wind speed.

As a result, it was confirmed that Ishihara's model is more accurate than the gradient model for almost all the observations. However, the surface wind speeds estimated by Ishihara's model do not entirely correspond to the observed values. This is because of the environmental conditions and the uncertainty of the typhoon simulation model. The observations are influenced by local effects. The typhoon simulation model has an uncertainty for each calculation step. In particular, this model is unable to evaluate the roughness and terrain effects corresponding to the wind direction. Moreover, the increment in the central pressure difference is 5 hPa (e.g. 960 hPa, 965 hPa, and 970 hPa) in the observations of the Japan Meteorological Agency.

In the case of Typhoon Higos, information on insured buildings was collected. The reason for selecting Typhoon Higos is that the number of damaged buildings is not large and all the information on insured buildings is available. Chiba prefecture was the only region considered for the investigation, and a database was developed for 205 residential houses. Fig. 14 shows the distribution of the peak gust wind speed (maximum instantaneous wind speed) calculated using Ishihara's model and the gradient model. The plotted points correspond to the locations of the insured houses that were damaged by Typhoon Higos. It is confirmed that these locations agree with the strong wind speed areas.



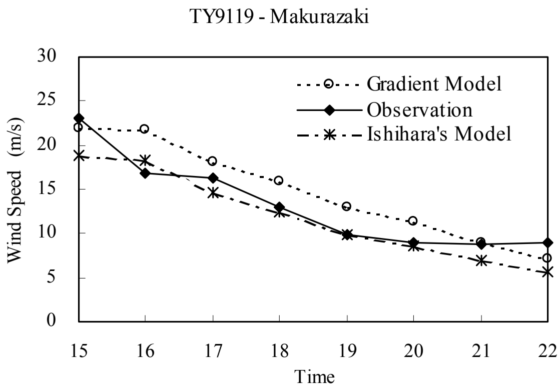


Fig. 10. Comparison of the 10-min mean wind speed of Typhoon Mireille in Sasebo and Makurazaki

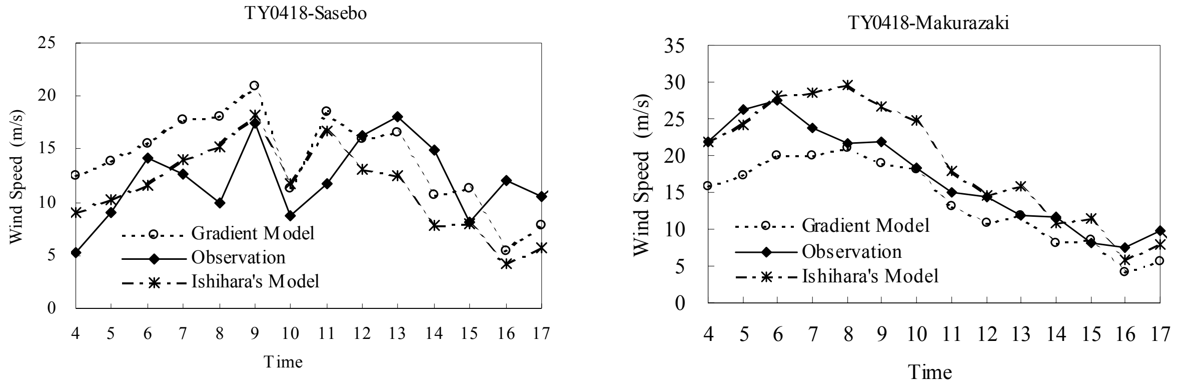


Fig. 11. Comparison of the 10-min mean wind speed by Typhoon Songda in Sasebo and Makurazaki

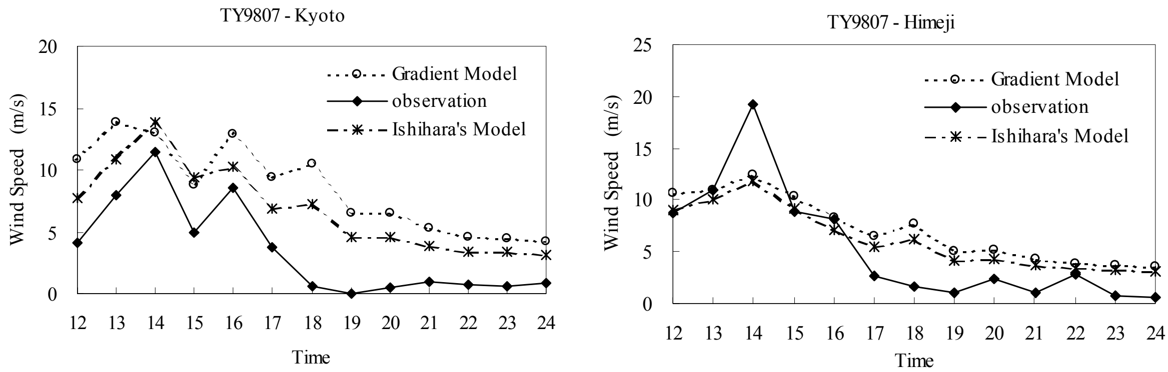


Fig. 12. Comparison of the 10-min mean wind speed by Typhoon Vicki in Kyoto and Himeji

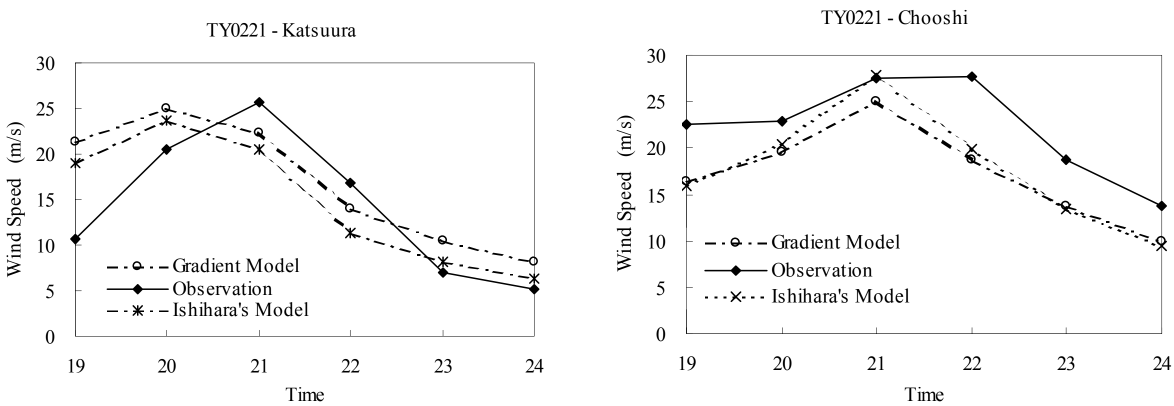


Fig. 13. Comparison of the 10-min mean wind speed by Typhoon Higos in Katsuura and Chooshi

Tab. 2. Comparison of the surface wind speed

Typhoon & Location	Ishihara's model error	Gradient model error
Mireille (1991)		
Sasebo	11.2	61.9
Makurazaki	4.8	7.1
Songda (2004)		
Sasebo	18.8	22.6
Makurazaki	31.4	18.1
Vicki (1998)		
Kyoto	13.2	29.6
Himeji	9.1	12.0
Higos (2002)		
Katuura	23.1	29.7
Chooshi	25.6	28.4

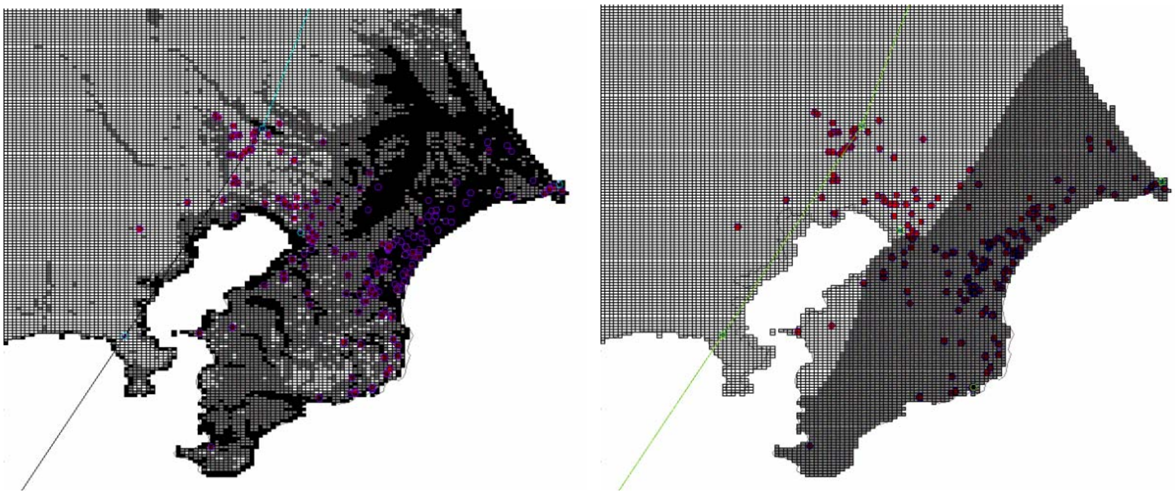


Fig. 14. Distribution of the peak gust wind speed calculated using Ishihara's model (left) and the gradient model (right) with a 1-km mesh. The wind speeds in the black and grey regions are greater than 50m/s and 40m/s, respectively, while the wind speed in the white region is less than 40 m/s. The plotted points indicate the locations of the insured houses that were damaged by Typhoon Higos.

CONCLUSIONS

The coast-crossing typhoon simulation model was developed by employing Ishihara's model. Using the developed model, the surface wind speed can be evaluated for any site corresponding to the roughness length.

Four significant past typhoons were simulated, and it was confirmed that Ishihara's model is more accurate then the gradient model for almost all the observations.

In the case of Typhoon Higos, information on the insured buildings was collected, and it was confirmed that the locations of the insured buildings damaged by Typhoon Higos agree with the strong wind speed areas.

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