Analysis and Synthesis of Typhoon Wind Pattern over Japan

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Abstract

The present status of the studies on analysis and synthesis of surface wind pattern of severe typhoons over the main islands of Japan made by the group of the present authors by the aid of Grant-in-Aid of Research on Natural Disasters is reviewed in the present paper. Forty nine severe typhoons in the period from 1951 to 1984 were analyzed and a statistical character of sever typhoons hitting the Japanese archipelago was obtained. Numerical simulation of a typhoon with the pressure pattern statistically consistent with the result was attempted to estimate severe wind conditions of a point. At the same time simpler method to construct the probable severe wind patterns caused by a typhoon model was also proposed. Some problems in translation of the gradient wind speed into the surface wind speed were also discussed.

1. Introduction

In most parts of Japan the strongest wind to be considered in disaster prevention works may be that caused by a typhoon. Estimation of the highest expected typhoon wind speed at a given location is one of the most important tasks in applied meteorology.

For this purpose, there may be a few approaches. One is the direct processing of the past wind records at the point following the extreme theory. However, the number of existing wind observation sites with along history of recorded data is too small to estimate wind distribution over the complex topography of Japan. The longest observation period is over 100 years or so, which is not long enough to obtain reliable results considering the rare severe typhoon occurrence at any point, e.g. once in ten years. The second method is estimation of wind severity by the multicorrelation of various parameters such as geographic position, inclination of the ground, height, distance from the sea or mountain, and so on. But the applicable observed data to determine these relations are limited to the JMA stations and are too small in number to be able to cope with the complexibility of the problem, thus precluding a direct approach on this method. The third approach is wind estimation from pressure patterns. The relation between pressure pattern and wind is well established since the beginning of modern meteorology with weather maps long consisting of isobars in the middle latitudes, because an isobar is more stable and easier to trace than an isotach. The parameters ascribing the pressure pattern of a typhoon are stable and suited to delineate the character of the typhoon. The wind pattern balancing to the pressure field, or friction free wind (FFW) pattern, can easily be obtained. Based on certain emprical relation, the determination of the relation between FFW and surface wind distribution will be attempted.

The third approach is considered to be the most practical by the present authors. Therefore, the analysis of typhoon winds can be reduced into analysis of the typhoon pressure pattern and the relation between the pressure pattern and the surface wind distribution. The results of the studies on this approach are presented in the present paper.

2. The typhoon area in Japan

A typhoon, which originates over the north-western Pacific Ocean, moves to the west and generally slightly poleward, then may recurve and move into the mid-latitude westerlies. Therefore, most of the typhoons hitting the Japanese islands move towards the north or north-east, the typhoon area being the middle and southern part of Japan. The frequency of the most severe winds emanating from typhoons based the ten highest recorded daily maximum (10 min average) wind speeds without respect to their origins for each weather station in Japan is shown in **Fig. 1.** As is clear from this figure, the typhoon area to which most of the strongest winds come from typhoon covers about two-thirds of the area of Japan. This area excludes

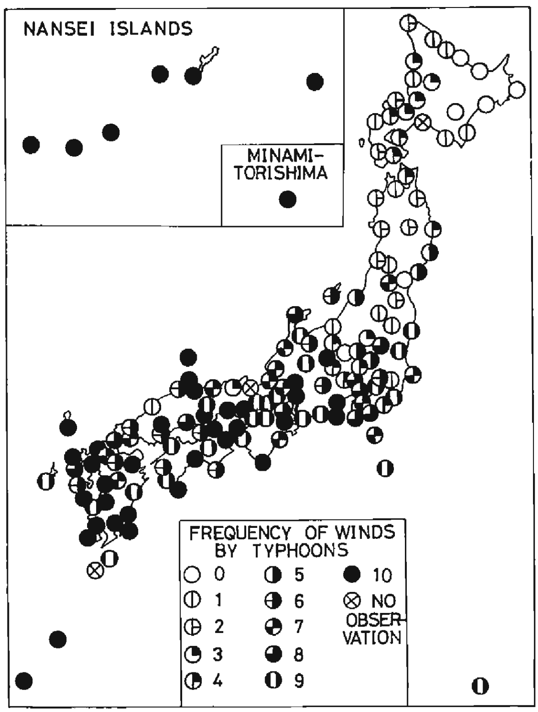


Fig. 1. The frequency of typhoon winds based the 10 highest (10 min mean) wind speeds for each weather station since its establishment.

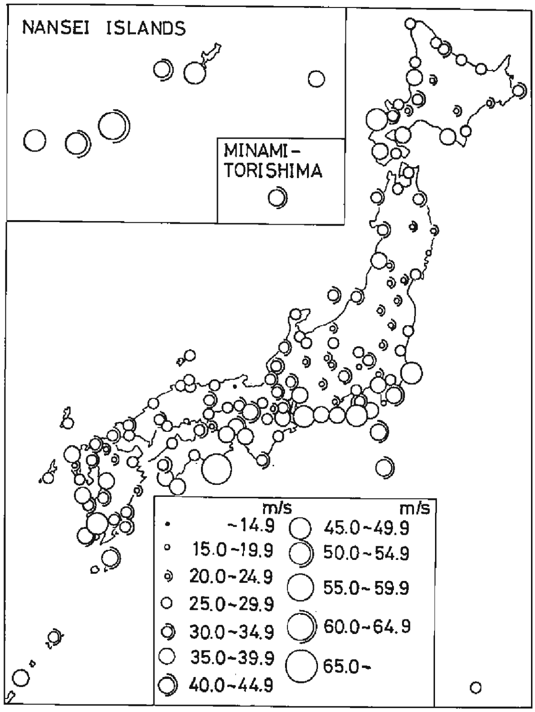


Fig. 2. The highest (10 min mean) wind speed for each weather station in Japan.

Hokkaido, Tohoku and some parts on the Japan Sea coast in which storms of extra-tropical cyclones in cold seasons are more severe than typhoons. The following considerations are applicable only to this typhoon area of Japan.

The distribution of the maximum (10 min average) wind speed at weather stations is shown in **Fig. 2.** The Pacific and the East China Sea coasts in middle and western Japan are the highest wind zone which may correspond to the zone of typhoon landing. The other high wind zone is in Hokkaido, the northern island of Japan where the highest wind speeds are as high as 30 to 40 m/s, comparable to typhoon winds in south-western Japan. The estimation of high winds caused by extra-tropical cyclones in the northern part of Japan will be discussed in a separate paper.

3. Analysis of a typhoon pressure pattern

For the purpose of analysis of pressure patterns of severe typhoons that have landed on the Japanese main islands, the hourly data of the typhoon observations at weather stations of Japan Meteorological Agency (JMA) within a range of 200 km from the typhoon tracks were collected and stored as a data-base. The data of the total number of 49 severe typhoons, of which central pressures are lower than

980mb at the time of landing, are collected in the period from 1951 to 1984.

The hourly sea-level pressure data at stations were analyzed by the objective method developed by the present authors[1]. In the course of analysis, the surface pressure pattern of a typhoon is assumed to be represented by concentric circular isobars with an exponential profile proposed by Schloemer[2], after preliminary studies

Table 1. Statistical characteristics of the severe typhoons (central pressure less than 980 mb) which landed on the Japanese main islands in the period from 1951 to 1984. Area A means Kyushu Area, Area B Shikoku and Kinki Areas and Area C Tokai and Kanto Areas

Number of landing per year				
Frequency distribution—Poisson				
Mean value	1.04 for Area A			
	0.50 for Area B			
	0.67 for Area C			
	uniform distribution in each area			
At the time of landing:				
Probability distribution—Log-Normal.				
Mean value and standard deviation. Numbers in parentheses indicate a common logarithmic value.				
Central pressure depth:				
Δp (mb)	Area A	$F(m-\sigma)$=26(1.42),	$F(m)$= 39(1.59),	$F(m+\sigma)$= 57(1.76)
	B	25(1.41),	38(1.58),	58(1.76)
	C	24(1.38),	33(1.51),	44(1.65)
Radius of Maximum Cyclostrophic Wind:				
r_m (km)	$\Delta p<30$mb	$F(m-\sigma)$=74(1.87),	$F(m)$=100(2.00),	$F(m+\sigma)$=136(2.13)
	30mb$\leqq\Delta p<$45mb	45(1.65),	81(1.91),	146(2.16)
	45mb$\leqq\Delta p$	46(1.67),	71(1.85),	107(2.03)
Speed of translation:				
C(km/hr)	Area A	$F(m-\sigma)$=19(1.28),	$F(m)$= 30(1.47),	$F(m+\sigma)$= 46(1.66)
	B	32(1.50),	47(1.67),	70(1.85)
	C	31(1.50),	47(1.67),	69(1.84)
Direction of translation:				
γ (deg)	Area A	$F(m-\sigma)$=43(1.63),	$F(m)$= 67(1.83),	$F(m+\sigma)$=105(2.02)
	B	52(1.71),	72(1.86),	100(2.00)
	C	47(1.67),	60(1.78),	76(1.88)
	$F(m)$: the mean value on the regression line.			
	$F(m-\sigma)$: a value smaller by a standard deviation than $F(m)$.			
	$F(m+\sigma)$: a value larger by a standard deviation than $F(m)$.			
Time change after landing:				
Δp	No time change before landing and exponential decay with the time after a landing.			
	Decay rate	Area A	$-a=0.042$	
		B	$-a=0.084$	
		C	$-a=0.167$	
r_m	No time change.			
C	No time change.			
γ	No time change.			

on pressure profiles, as follows

$$p = p_c + \Delta p e^{-(1/x)} \tag{1}$$

where p_c is the central pressure, Δp the central pressure depth $(=p_\infty - p_c)$, p_∞ the peripheral pressure, and $x=r/r_m$, r the distance from the center and r_m the radius of the maximum cyclostrophic wind speed. Assuming this pressure profile, the best fit typhoon center and pressure pattern were chosen from the hourly data by the least square error method independent of the previous time.

All of the results have published in a separate report[3], as well as summaries of the data and the statistical analysis of the results published in two earlier papers[1)4]. The statistical analysis was made, dividing the Japanese main islnds into three parts[4]. Occurrence probability of typhoon landings on each part over a year may be described by Poisson distribution. The central pressure depth, speed and direction of forward motion are described by log-normal distribution. The direciton of motion is well fitted to this distribution when the angle is measured counter-clockwise from the east. The radius of the maximum cyclostrophic wind speed, the other important typhoon parameter, is the function of the central pressure depth without respect to the areal division. The results of typhoon characteristic analysis are summarized in **Table 1.**

4. Numerical simulation of typhoon over Japan

Once statistical characteristics have been obtained, we can estimate probable storm wind speed and direction based on the numerical simulation of typhoon pressure pattern statistically consistent with the experienced typhoon characteristics. The first attempt of typhoon simulation over Japan was made by the present authors[5].

The occurrence and translation path of typhoons that hit the main islands of Japan in 10,000 years are simulated together with central pressure and radius of maximum cyclostrophic wind speed by the use of Monte Carlo technique, following the statistical characteristic of the typhoon. Either a long period or a large number of typhoons is necessary to obtain reliable estimates of severe winds for a return period of 100 years or so. Examples of the generated return periods of the central pressure depth at the time of ladning for A: Kyushu area B: Shikoku & Kinki area and C: Tokai and Kanto area are shown in **Fig. 3.**

In employing the Monte-Carlo method, the occurrence of the phenomenon was limited within 1 to 99% of the occurrence probability, which means the existence of upper and lower limits of the parameter. This was practical trial to prevent unrealistic results. For example, we can expect the existence of the upper limit of the central pressure depth of typhoon from the meteorological point of view. However, the value of the corresponding occurrence probability, 99% should be checked again in more detail in future. The recent numerical experiment on the minimum attainable surface central pressure over the Pacific Ocean by Emanuel[6], whose result

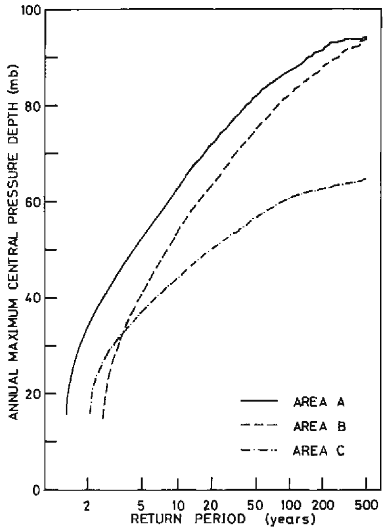


Fig. 3. Return period of annual maximum central pressure depth at the time of landing of simulated typhoons in 10,000 years for each area. (A: Kyushu, B: Shikoku and Kinki, C: Tokai and Kanto) (after Mitsuta and Fujii[4]).

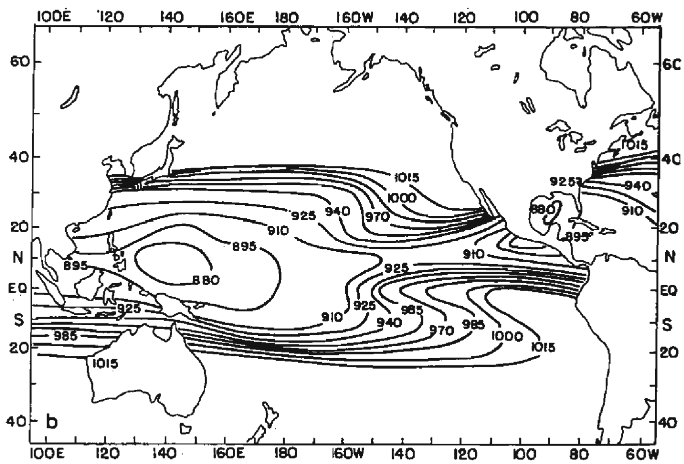


Fig. 4. Minimum attainable surface central pressure (mb) in September for Pacific Ocean. (after Emanuel[6]).

for the mean sea surface temperature of September shown in **Fig. 4**, may be used for this purpose.

The gradient wind or friction free wind (FFW) distribution balancing to a stationary pressure pattern shown in eq. (1) can be computed by the gradient wind equation shown as

$$v_{gr}^2/r_t + f v_{gr} = \frac{1}{\rho}\frac{\partial p}{\partial r} \tag{2}$$

where v_{gr} is the gradient wind speed, r_t the radius of curveture of trajectory that is the same as the radius of an isobar in stationary condition, ρ the density of air approximated by 1.1 kg/m^3 (960 mb at 300K), and f Coriolis parameter approximated by $7\times10^{-5}\,s^{-1}$ (at 35 N). The pressure gradient can be computed from the eq. (1).

If the isobar is moving, the radius of the trajectory of the air parcel differs from the radius of the streamline or the isobar and can be shown by the following Blaton's formula as

$$\frac{1}{r_t} = \frac{1}{r}\left(1+\frac{C}{v_{gr}}\sin\theta\right) \tag{3}$$

where r is the radius of isobar, C the speed of translation and θ is the direction angle of the radius vector measured anticlockwise from the direction of translation. This idea is not satisfactory from the theoretical point of view[7] but is convenient and easily applicable for practical purposes.

In translating FFW to the surface wind, there are still some problems to be

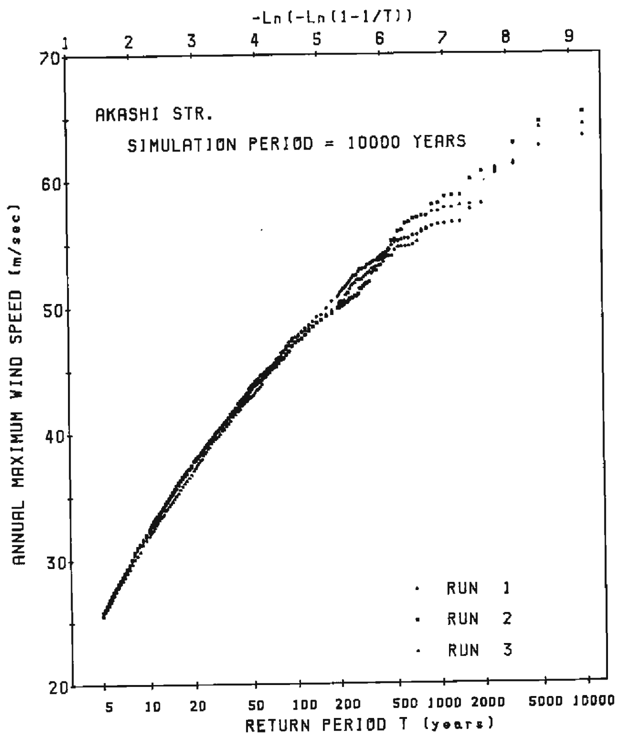


Fig. 5. Return period of the annual maximum wind speed at Akashi Straits simulated for 10,000 years. Runs 1, 2 and 3 correspond to different random number series. (after Mitsuta and Fujii[5]).

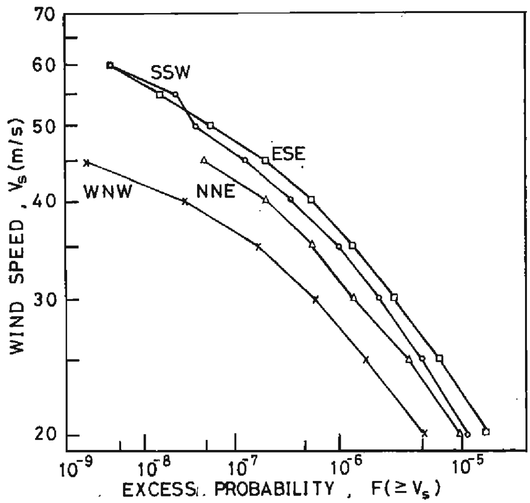


Fig. 6. Excess probabilities of simulated wind speeds at Akashi Straits for four main wind directions. (after Mitsuta and Fujii[5]).

solved. One is the boundary layer wind profile in the gradient wind balance conditions. And the second is supergradient wind speed seen in the eye wall region of the typhoons. Both problems interact with each other making the situation very complex. The last point is the effect of small scale topography on surface winds. These details will be discussed in later sections.

In the first attempt of typhoon wind simulation, the authors adopted a very simple approximation for these problems[5]. The speed ratio of the surface and gradient wind speed is assumed to be 1/2 over land and 2/3 over water, and deviation of wind direction is 40° over land and 30° over water. Wind speed is increased following an experimental formula derived from the past two typhoons inside of the eye wall.

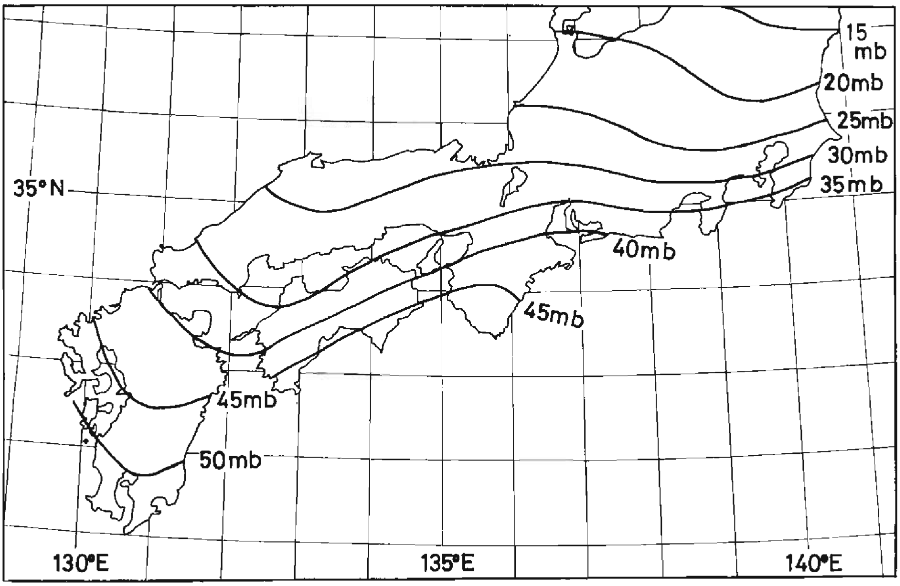
The wind estimates over water at Akashi Straits were computed as an example. As a result, the return period of the annual maximum wind speed is as shown in **Fig. 5.** There are three estimates in this figure which correspond to the different series of random number in the Monte Carlo methcd. If the simulation period is as short as 1,000 years, the results are more scattered.

The storm wind speed and direction distribution over 10,000 years was computed for Akashi Straits. The excess probabilities of simulated winds for four typical wind directions are shown in **Fig. 6.** The probability is shown in the ratio to the total time. The excess probability of ESE wind of 40 m/s or more is about 6×10^{-7} and is about 50 hr in 10,000 years.

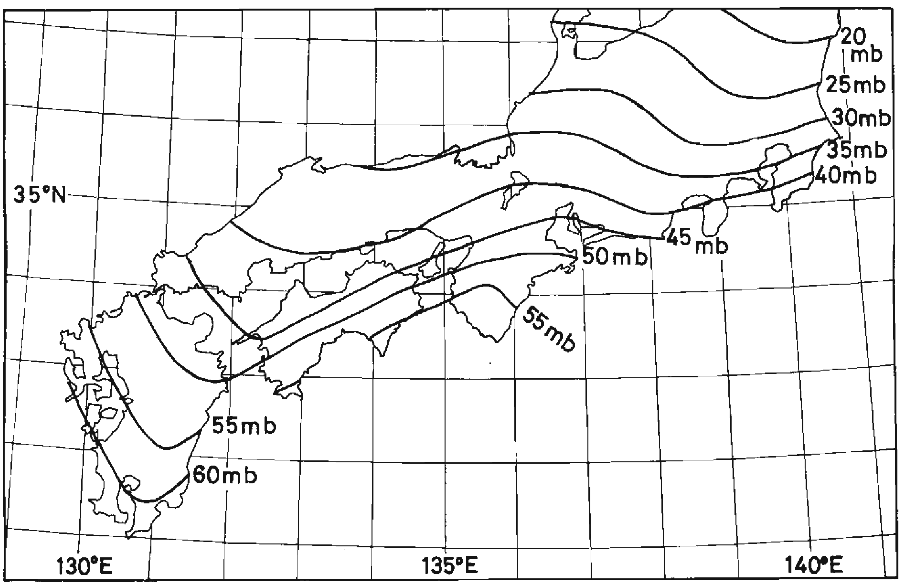
5. Standard project typhoon

Computations of typhoon wind simulation at a given point is a somewhat troublesome process requiring much computer time. A simplified approach is the Standard Project Typhoon. Standard Project Typhoon is analogous to the Standard Project Hurricane defined by the U.S. Corps of Engineers and Weather Bureau[8] as the most severe storm that is considered reasonably characteristic of the region.

Constructing the model of typhoons, which has specifications consistent geogra-



(a)



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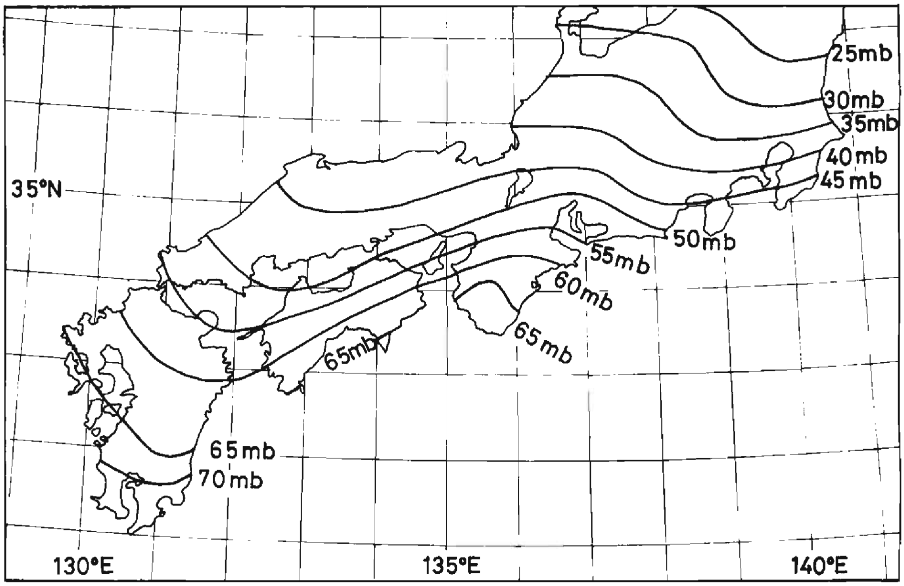

(c)

Fig. 7. Distribution of the central pressure depth of simulated typhoon for return period of 50 years (a), 100 years (b) and 200 years (c) within 20 km from the point.

phically and meteorologically with the experienced statistical characteristics shown before, and moving it along the most dangerous path for the point of interest, we can easily estimate the most severe storm condition and its time changes easily by a simple method. Such a model is called the Standard Project Typhoon (SPT).

Synthesis of Standard Project Typhoon can be completed in the following way. From the results of the first step of typhoon simulation shown before, we can figure out the probability distribution of the central pressure depth of the typhoon which has occurrence probability of once per 50, 100 or 200 years within 20 km from a point as shown in **Fig. 7.** This may be used as the central pressure index of the Standard Project Typhoon.

The pressure profile is as shown in eq. (1). The radius of the maximum cyclostrophic wind speed is the function of central pressure depth and the regression curve is derived from the results of analysis as shown in **Fig. 8.**

SPT can move towards NE, NNE and N in Kyushu to the Kinki area, and NE and NNE in Tokai and Kanto area, as shown in **Table 1.** The mean translation speeds are 30 km/hr for the typhoon landing on Kyushu and 47 km/hr for those on the other areas. Speed range may be ± 20 km/hr including about 68% of all. And the track of SPT is a straight line over the Japanese islands.

The FFW distribution can be computed by the same method as typhoon simulation shown in the previous section using the above parameters. An example of the FFW distribution for the model with $\Delta p = 60$ mb, $r_m = 60$ km and $C = 10$ m/s is shown

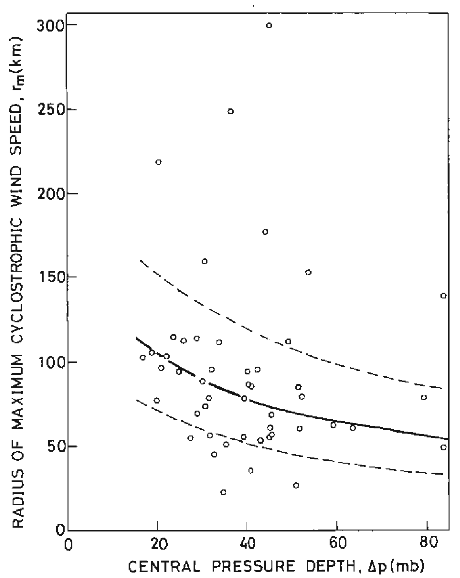

Fig. 8. Variation of radius of the maximum cyclostrophic wind speed with the central pressure depth. The dotted lines show the standard deviation from the mean value (solid line) on log scale.

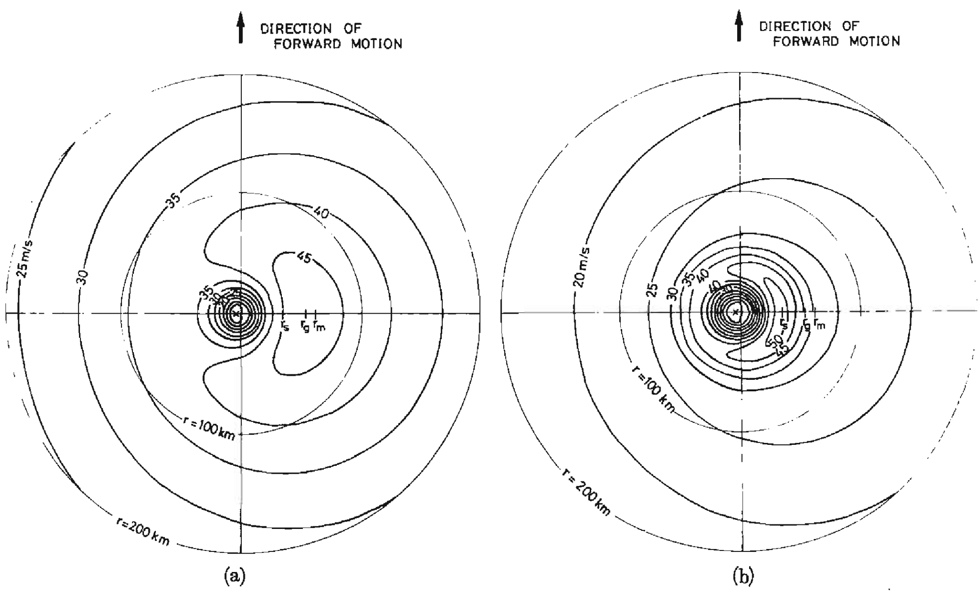

Fig. 9. An example of (a) the friction-free wind (FFW) speed distribution for a model typhoon of $\Delta p=$ 60 mb, $r_m=60$ km and $C=10$ m/s, and (b) the surface wind distribution of the same model over sea following the method shown in Section 6. The origin is at the pressure center, the cross indicates the circulation center, r_m the radius of maximum cyclostrophic wind, r_g the radius of gradient wind (FFW) and r_s being the radius of the maximum surface wind. (after Mitsuta and Fujii[35]).

in **Fig. 9** in which the corresponding surface wind pattern over sea is also shown. The center of rotation of wind is at a little left of the pressure center. Wind speed is larger in the right semi-circle. The maximum wind speed is seen at the right hand side of the center and a little inside the radius of maximum cyclostrophic wind. The left and right wind speed difference is the largest at the radius of the maximum wind speed and the difference is as high as the magnitude of translation speed, C. Conversion of FFW to the surface wind pattern has the same problem as in the case of typhoon simulation, which will be discussed in the next section.

6. Some problems in translating FFW into surface wind

The largest problem in translating FFW into surface wind (defined as 10 min mean wind speed and direction at 10 m high from the surface) is the effects of topography or the surface roughness conditions, because wind is largely dependent on them.

The preliminary studies on the relation between surface wind and FFW in cases analyzed in the previous study[1] in the way shown in Section 4 are compared with the observed surface wind at the station. The results are summarized in **Table 2.** The over all average of wind speed ratio is 0.50 ± 0.19 and that of wind deflection angle being $41° \pm 17°$. These values can be used as a rule of thumb over land.

However, these values are different locally. The maximum wind ratio (exclud-

Table 2. The average values and the standard deviations (S.D.) of the deflection angle of the surface wind from the friction-free wind, and those of the ratio of the speed of surface wind and the friction-free wind (after Mitsuta *et al.*[9])

Station	Wind direction of FFW	Number of cases	Deflection of wind direction		Ratio of wind speed	
			Mean (deg)	S.D. (deg)	Mean	S.D.
Fukuoka	N	17	20	23	.75	.23
	E	45	60	18	.58	.18
	S	—	—	—	—	—
	W	6	1	47	.45	.15
	Total	68	45	33	.61	.21
Kumamoto	N	30	35	18	.43	.13
	E	40	65	16	.31	.10
	S	4	80	28	.54	.36
	W	19	32	30	.39	.17
	Total	93	49	26	.38	.16
Miyazaki	N	—	—	—	—	—
	E	—	—	—	—	—
	S	42	39	11	.56	.17
	W	52	34	16	.54	.16
	Total	94	36	14	.55	.17

Table 2 (continued)

Kagoshima	N	5	20	7	.58	.09
	E	2	30	3	.97	.12
	S	7	30	32	.40	.09
	W	62	17	15	.48	.13
	Total	76	19	18	.49	.15
Hiroshima	N	9	12	20	.56	.31
	E	23	75	22	.54	.15
	S	18	67	23	.42	.15
	W	4	36	33	.48	.14
	Total	54	61	32	.50	.19
Kochi	N	11	57	21	.27	.11
	E	4	44	3	.54	.15
	S	29	49	19	.50	.17
	W	18	31	15	.39	.12
	Total	62	45	20	.43	.17
Osaka	N	4	44	11	.44	.07
	E	8	68	12	.66	.14
	S	30	81	21	.34	.16
	W	10	43	11	.51	.09
	Total	52	69	24	.43	.18
Shionomisaki	N	—	—	—	—	—
	E	—	—	—	—	—
	S	19	16	13	.76	.18
	W	24	12	16	.70	.10
	Total	43	13	15	.73	.15
Nagoya	N	4	19	23	.56	.12
	E	2	96	29	.39	.14
	S	21	33	14	.51	.13
	W	7	34	50	.52	.10
	Total	34	35	32	.51	.13
Shizuoka	N	6	41	37	.31	.16
	E	—	—	—	—	—
	S	14	29	17	.40	.09
	W	6	47	18	.40	.10
	Total	26	36	25	.38	.11
Tokyo	N	—	—	—	—	—
	E	2	19	26	.52	.05
	S	15	40	23	.46	.10
	W	2	17	35	.31	.19
	Total	19	36	23	.45	.12
Total		621	41	17	.50	.19

ing cases smaller than 5) is 0.76 at Shionomisaki for southerly winds and the minimum being 0.27 at Kochi for northerly winds. The maximum deflection angle is 81° at Osaka for southerly winds and the minimum being 1° at Fukuoka for westerly winds. The larger deflection angle corresponds to the smaller wind speed ratio, suggesting the effects of surface drag on the planetary boundary layer profile. The over all regression of the deflection angle and the speed ratio shown in **Table 2** is shown as

$$D = 75-67R \tag{4}$$

where D is the deflection angle (degree) and R is the wind speed ratio of surface wind to FFW. If R is 0.27 as the case of Kochi northerly winds, the deflection angle becomes 57° which is the same as in the observations.

The magnitude of the ratio of surface wind speed to gradient wind speed or FFW can be correlated with the surface roughness along the line of wind direction in upwind side. One of the authors has studied this relation[10] adoptnig the standard deviation of weighted land surface elevations within 30 km from the point on the upwind side as a parameter of the surface roughness. The relation between the speed ratio and surface roughness is as shown in **Fig. 10.** The functional relation was obtained as follows

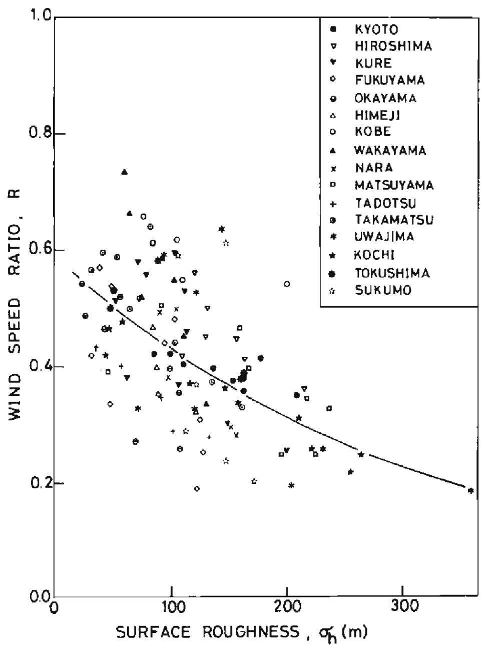

Fig. 10. The ratio of observed surface wind and synthesized FFW in relation to surface roughness, σ_h (=standard deviation of land surface elevation in the wind direction within 30 km from the station. (after Fujii[10]).

$$R = 0.59 \exp(-0.003\,\sigma_h) \tag{5}$$

where σ_h is the standard deviation of the weighted land surface elevation within 30 km upwind from the point. The speed ratio and deflection angle over open sea may be 2/3 and 30° as stated before.

The other difficulty in the conversion of FFW into surface wind comes from the nature of typhoon. As is well known, a typhoon has an eyewall, a cloud area surrounding the eye, in which wind and rain are most severe. The radius of the maximum cyclostrophic wind almost coincides with this area of the most severe convective action, where the maximum upward motion is expected. However, the surface wind speed increases with decreasing distance from the center even at and inside the radius of maximum cyclostrophic wind in a severe typhoon, and shows its maximum at the inside of the eye wall (Mitsuta *et al.*[12]). Sometimes the surface wind speed exceeds the gradient wind speed displaying supergradient wind. This may be caused by over shooting of converging surface wind in the surface layer. Therefore, this supergradient wind should be taken into account in conversion to the surface wind. The supergradient wind is not thoroughly explained by theoretical considerations[11]. Therefore, an empirical approach is the only way. This phenomenon is not clearly seen in the case of moderate or weakened typhoons. An example of wind speed ratio with the relative distance from the center (r/r_m) for T7705 over Southwest Islands of Japan[12] is shown in **Fig. 11.** A functional relation was given in the previous paper[5]. A modified form containing the effects of typhoon intensity is proposed here tentatively as:

$$M = 1 + 3.3A_0\, x e^{-2x^2}$$

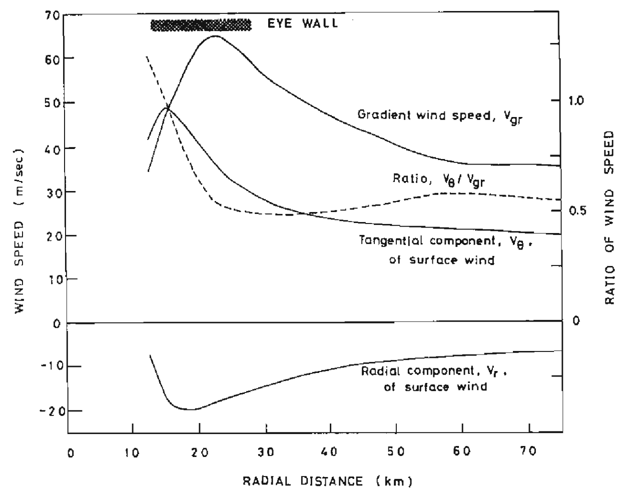

Fig. 11. Distribution of gradient wind speed, tangential and radial components of observed surface wind and the ratio of tangential wind to gradient wind, as function of radial distance from the typhoon center near the eye wall of typhoon 7705, Vera. (after Mitsuta *et al.*[12])

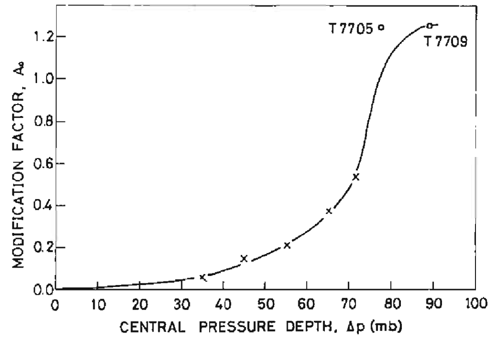

Fig. 12. The magnification factor as a function of the central pressure depth. See the text for details.

where M is magnification factor of surface wind speed, x the relative distance from the center (r/r_m) and A_0 being the function of central pressure depth (Δp) as shown in **Fig. 12.** This is based on speculation from a few cases in the course of analysis. This modification factor, M, is to be applied to the surface wind speed obtained from FFW, e.g. by the procedure shown above for topography by eq. (5).

The surface wind direction is also a function of distance from the center in the region where surface wind speed tends to increase in the eye. The vertical profile of wind speed in such a region is also different from that outside of the eye. More detailed studies on this point will be made in near future.

7. Conclusive Remarks

The present status of the studies on analysis and synthesis of surface wind pattern of a severe typhoon are summarized in the present paper.

The procedure of typhoon simulation is still under development. However the complete program together with an analysis program will be open for public testing in near future. The standard project typhoon (SPT) can be constructed at any site based on the following procedure: Choose the central pressure index for any return period at the site from **Fig. 7.** The radius of maximum cyclostrophic wind is determined from **Fig. 8.** The most dangerous direction of typhoon motion is chosen within the range NE, NNE and N in Kyushu, Shikoku and Kinki areas, and NE and NNE in Tokai and Kanto areas. The translation speed can be chosen as 30 ± 15 km/hr for the Kyushu area, and 47 ± 20 km/hr for other areas. Deviation from the mean value may be chosen depending on the nature of disaster under consideration. Then FFW can be computed by the method shown in Section 4. Translation from FFW into surface wind can be roughly made following the procedure shown in the previous section. The wind speed ratio can be derived from the relation shown in eq. (5), or 1/2 over land and 2/3 over sea. The deflection angle can be computed by eq. (4), or given as 40° over land and 30° over sea. Thus the surface wind pattern can be obtained. Furthermore, if the typhoon is severe, the surface wind speed obtained by eq. (5) should be modified by the factor given by eq. (6) for the relative distance from the center. More detailed studies on the remaining problems will be made in near future. However, the minimum knowledge to pursue the synthesis of surface winds in the severe typhoon are shown in this paper.

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