On the Ocean Waves due to Tropical Cyclones (3rd paper). Mean Distribution of Wave Heights and Periods

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Abstract

Arranging various kinds of wave materials obtained by visual observations from weather ships or military planes for ninety five typhoons, several maps showing the mean distribution of wave heights and periods were constructed, and the relation of wave heights and periods to the speed and the central pressure of the storm was discussed. Moreover, the rate of decrease of waves with the distance from the storm center and the difference of wave distribution among quadrants in the storm were investigated. From the results thus obtained, empirical formulas and diagrams were derived, which will serve as a first approximation for the calculation of wave heights and periods, although discrepancies between calculated and observed values are not always small because of the variety of wave distribution and the complicated spectral structure of storm waves.

1. Preface

The distribution map of wave heights and periods in a typhoon has scarcely been obtained in spite of its importance because a simultaneous observation over a wide-spread rough sea is extremely difficult. So far as the present author knows three maps have been published. Two of them were obtained by Ootani and Takasina⁽¹⁾ who arranged a lot of reports from merchant vessels, and another one was introduced by the Hydrographic Department of former Imperial Japanese Navy⁽²⁾ on the basis of reports from the Red 4th Fleet attacked by a typhoon on Sept. 26, 1935 in maneuvering east off Japan proper. These maps show the distribution of wind waves and swell, and they are very valuable. But they do not inform us of the distribution of wave periods, and also they do not necessarily represent the whole of wave distribution which differs for individual storm.

On the other hand, even in the current wave theories which have been developed remarkably, the constancy of wind is assumed, and their application for waves due to a typhoon in which wind speed and direction change very rapidly with time and place requires much empirical knowledge.

Under such circumstances, the attempt to make clear the mean distribution of waves

by arranging various kinds of data will not be useless. However, it must be kept in mind that the distribution of waves depends greatly on the individualities of a typhoon, such as the extent, the track and the stage of development, and also on the existence of fronts and lands, as emphasized in the author's first⁽³⁾ and second⁽⁴⁾ papers.

2. Materials and the method of analysis

Materials used in this paper are as follows:

1. Results of marine meteorological observations made at the Ocean Weather Station TANGO (29°N, 135°E), which contain the data for forty seven typhoons during 1949~1956. The data give the scale and direction of wind waves and swell, and the height and period of prevailing waves, as well as usual meteorological elements. These heights and periods may be considered to correspond to those of significant waves according to the opinion of Sverdrup and Munk⁽⁵⁾. The accuracy of the data is not so sufficient because they are obtained by visual observations, but they are very useful if we only proceed with adequate caution. Examples of the data are found in Figs. 4~8 of the first paper⁽³⁾.

2. Results of marine meteorological observations made at the Ocean Weather Station EXTRA (39°N, 153°E), which contain the data

for twelve typhoons during 1949~1953. Observed elements are the same as those at TANGO. In both cases, however, materials are scanty in the vicinity of the storm center.

3. A report on typhoon reconnaissances from May through November of 1946 conducted by Meteorological Squadron ONE at Guam, Airforce, United States Pacific Fleet⁽⁶⁾. It contains thirty four composite charts obtained by the same number of flights made in and around eight typhoons. The charts show the scale of the state of the sea and the direction of swell as well as various meteorological elements but do not inform us of wave periods. The present author roughly estimated the wave height on the assumption that the wave has the central value of height corresponding to the scale number of the state

of the sea. Examples of composite charts are found in Figs. 3a~k of the second paper⁽⁴⁾.

4. Distribution maps⁽²⁾ showing the scale and direction of wind waves in the typhoon of September 26, 1935 with the central pressure of about 957 mb, already mentioned in the former section, and a report⁽⁷⁾ on the typhoon of October 1944 with the lowest central pressure of about 898 mb that the weather ship "No. 4 Kaiyo-maru" encountered.

Using these materials, weather maps and the data in the Geophysical Review (published by the Japan Meteorological Agency), the central pressure and speed of the typhoon, and the position (r, θ) of the ship or aircraft relative to the storm center were determined at each observation time, where r is the dist-

Table 1. Wave height due to a typhoon (in meter).

Central pressure of the typhoon (mb)	Distance from the typhoon center (sea mile)	Angle measured clockwise from the direction of movement of the typhoon center								Mean wave height (m)
		0° ~ 45°	45° ~ 90°	90° ~ 135°	135° ~ 180°	180° ~ 225°	225° ~ 270°	270° ~ 315°	315° ~ 360°	
<940	0~100	10.9	10.4	8.7	8.2	8.7	8.7	9.6	10.4	9.5
	100~200	—	7.0	7.8	7.7	5.5	4.8	5.8	—	6.4
	200~300	4.7	6.3	7.0	—	4.8	—	—	—	5.7
	300~400	4.0	4.1	7.1	—	6.0	—	—	2.4	4.7
	400~500	2.7	3.9	5.1	—	2.7	—	—	2.1	3.3
	500~600	2.5	3.0	2.4	—	2.7	—	—	—	2.7
940~960	0~100	9.3	10.3	13.0	13.1	9.8	10.5	9.4	7.4	10.4
	100~200	7.1	6.1	6.9	8.5	8.4	6.8	6.2	6.4	7.1
	200~300	4.2	4.8	7.2	6.8	6.9	4.0	4.0	4.9	5.4
	300~400	3.8	4.6	5.3	5.3	5.2	—	—	4.9	4.8
	400~500	2.4	2.8	4.4	4.4	4.8	—	—	1.8	3.4
	500~600	1.4	2.4	3.3	4.3	5.0	4.0	—	1.5	3.1
960~980	0~100	6.7	6.1	8.8	8.9	8.3	7.5	7.8	7.5	7.7
	100~200	5.0	5.6	6.9	8.2	7.3	6.4	6.5	4.9	6.4
	200~300	5.4	5.3	6.2	5.5	5.0	4.4	3.7	3.2	4.8
	300~400	3.2	3.8	4.6	4.4	4.3	2.6	3.2	1.9	3.5
	400~500	2.4	2.8	3.5	4.1	3.0	2.4	2.8	1.8	2.9
	500~600	2.1	1.8	3.0	3.9	2.9	2.3	—	1.9	2.6
>980	0~100	4.7	5.8	6.1	4.6	5.8	4.5	3.3	4.8	5.0
	100~200	3.8	2.8	4.0	4.2	3.6	3.8	3.2	3.3	3.6
	200~300	3.3	2.5	2.7	2.3	3.2	2.8	2.3	3.3	2.8
	300~400	3.6	2.1	2.9	3.2	3.3	1.0	1.9	2.1	2.5
	400~500	2.1	—	2.3	2.3	2.8	—	1.5	1.9	2.2
	500~600	2.2	1.9	2.3	2.7	2.3	—	1.5	1.6	2.1

ance from the storm center and θ the angle measured clockwise from a line showing the direction of movement of the storm center.

Next, the typhoon were classified according to their central pressure into four (lower than 940, 940~960, 960~980 and higher than 980 mb) and the speed of the storm into three classes (less than 20, 20~40 and more than 40 km/hr). Moreover, r was divided into six parts at intervals of 100 nautical miles and θ into eight parts at intervals of 45 degrees. And then, the average of wave heights and periods was taken according to the class of the central pressure and speed of the storm, and to the position of ships or aircrafts.

Hereafter, we shall assume that the mean wave height and period determined in the above-mentioned way represent a wave height and period at the center of the area over which the mean is taken, and that they are caused by a typhoon whose speed and central pressure agree respectively with the central value of each class for which the mean is taken.

3. Distribution of wave heights

The result of calculation for wave heights is given in Table 1, from which we could construct distribution maps of wave heights as shown in Fig. 1. As an empirical formula

Fig. 1. Mean distribution map of wave heights due to a typhoon (in meter). For convenience' sake, a region where the wave height is more than 6 m is bordered with short oblique lines.

that expresses them as felicitously and also simply as possible, we constructed the following one applicable in the range of $r > \varepsilon$:

$$H = a\{1 + n \cos(\theta - \alpha)\}$$

$$\times \frac{1 + \frac{\varepsilon}{r_0}}{1 + \frac{r}{r_0}} \times \begin{cases} \frac{1}{7}(1030 - p_0); 1000 > p_0 > 950, \\ 11.43 & ; p_0 < 950, \end{cases} \quad (1)$$

where H is the wave height in meter, p_0 the central pressure of the typhoon in millibar, r the distance from the storm center in nautical mile and θ the angle mentioned in the former section. ε means the distance from the storm center to the region where the highest wave is raised, and a , n , α and r_0 are constants, which differ according to the storm.

In the range of $r < \varepsilon$, however, sufficient knowledge to construct an empirical formula has not yet been obtained. Therefore, only a qualitative expression is given here for the sea condition expected in the eye of a tropical cyclone as follows:

$$\begin{cases} \text{less confused} & \text{when } C < V, \\ \text{very confused} & \text{when } C \sim V, \\ \text{rather confused} & \text{when } C > V. \end{cases}$$

Here C is the speed of the storm and V the group velocity of the wave (usually 30 km/hr or so under present conditions⁽³⁾). This relationship has been proved in the author's second paper⁽⁴⁾ from the result of observations and a theoretical consideration.

Moreover, for convenience' sake in the following discussion, we rewrite Eq. 1 as $H = k \times \bar{H}$, where

$$k = a\{1 + n \cos(\theta - \alpha)\}. \quad (2)$$

In a mean state, we may put $a=1$ approximately as shown later (see Table 2). Then, $\bar{H}$ means a wave height which is assumed to be a function of r only, i.e.

$$\bar{H} = \frac{1}{2\pi} \int_0^{2\pi} H d\theta = \bar{H}_{\text{Max}} \frac{1 + \frac{\varepsilon}{r_0}}{1 + \frac{r}{r_0}}, \quad (3)$$

where

$$\begin{aligned} \bar{H}_{\text{Max}} &= (\bar{H})_{r=\varepsilon} \\ &= \begin{cases} \frac{1}{7}(1030 - p_0); 1000 > p_0 > 950, \\ 11.43 & ; p_0 < 950. \end{cases} \quad (4) \end{aligned}$$

We shall examine these distribution maps and empirical formulas in the following sections.

4. Inequality in wave heights among quadrants in a typhoon

The most remarkable feature in Figs. 1a~d is the asymmetry of the distribution of wave heights to the storm center. For example, calculating the ratios of wave heights for $\theta = 45^\circ, 135^\circ, 225^\circ$ and 315° at $r = 50, 150, 250$ and 350 nautical miles, respectively, in four cases of Fig. 1 and averaging them, we have

$$H_{45^\circ} : H_{135^\circ} : H_{225^\circ} : H_{315^\circ} = 1.01 : 1.25 : 0.93 : 0.81.$$

It is clear that the wave height is greatest in the right rear quadrant of the storm and smallest in the left front quadrant, while the great difference is not found between the wave height in the right front quadrant and that in the left rear quadrant.

The fact that the wave is the greatest in the right rear quadrant within a tropical cyclone has already been pointed out by Cline⁽⁸⁾ and others. At this place, the present author wishes to correct a misunderstanding which he made in his first paper⁽³⁾. There, he stated that the existence of greatest waves in the right rear quadrant is in direct opposition to Cline's opinion, but that is not the case. Cline's opinion, however, is liable to cause a misunderstanding on the distribution of waves out of the storm, because he did not take the movement of the storm into consideration. Therefore, the present author wishes to call special attention to the fact that, out of the typhoon too, we can find swells with greater size and length in the rear than in the front, as well as within the storm, as is clearly recognized in Figs. 1, 4 and 8.

First, comparing the right semi-circle of the storm with the left semi-circle, we may consider the following items as the causes of such distribution of waves:

1. As is known universally, winds blow with greater velocity in the right or dangerous semi-circle than in the left or navigable semi-circle.

2. In the right semi-circle waves move in a direction near to that of movement of the storm; therefore, the fetch and duration of winds become longer than in the left semi-circle.

Second, comparing the front semi-circle with the rear semi-circle of the storm, the following items shall be considered:

3. Generally speaking, the wind velocity at a point on the sea surface increases more and more as the storm approaches, while it decreases less and less after the storm center passed there. Accordingly, the mean wind velocity taken for a certain length of duration is greater when the point is located in the rear semi-circle than when it is located in the front semi-circle, even if the distance from the point to the storm center is equal in both cases.

4. In the rear semi-circle we can usually find remarkable swells which were originated in the front semi-circle and were left behind. Consequently, wind waves generated in the rear semi-circle are superposed on and raised by these swells. Particularly, in the rear region not so distant from the storm center, mountainous and pyramidal waves are apt to be raised when the storm passes by with a speed beyond a certain level.

As an empirical formula which expresses

the difference of wave heights among quadrants, we adopted Eq. 2. According to Fig. 2a which shows values of k to θ in a mean state, the formula will be approximately recognizable if we put $a=1.02$, $n=0.2$ and $\alpha=135^\circ$.

5. Relation between the wave height and the central pressure of a typhoon

It is reasonable that a storm with a lower central pressure causes higher waves as clearly recognized by comparing Figs. 1b, c and d, but we could not find the distinct difference of wave heights between two cases when the central pressure is lower than 940 mb (Fig. 1a) and 940~960 mb (Fig. 1b). This seems to be attributed to the data used here. In the case when the central pressure is lower than 940 mb, almost all data in the vicinity of the storm center were obtained from the report⁽⁶⁾ on typhoon reconnaissance-flights conducted in low latitudes, and the sphere of the storm was not so wide in proportion to its low central pressure. On the other hand, in the case when the central pressure is higher than 940 mb the data were not only taken in low latitudes but also in higher latitudes, and in the latter region the typhoon was rather large and strong in spite of its relatively high central pressure. Thus, the difference of wave heights between both cases seems to become obscure.

Consequently, as an empirical formula in which the above facts are taken into consideration, we assumed Eq. 4, which shows that the wave height increases linearly as the central pressure becomes low, but that it keeps constant below 950 mb. According to Fig. 3a, this relation may be verified on the whole.

However, it is expected that this formula might require some amendment with further accumulation

Fig. 2. Relation between $\frac{H}{\bar{H}} (=k)$ and θ , where $\bar{H}$ is given by Eq. 3.

Small circles indicate the mean value within 400 sea miles from the storm center, calculated on the basis of distribution maps.

Fig. 3.

- Relation between the central pressure (p_0) of a storm and the mean wave height ($\bar{H}$) at three locations. Hooked lines are based on Eq. 3.
- Decrease of mean wave height ($\bar{H}$) with distance from the storm center. The curved line is drawn based on Eq. 3.
- Decrease of mean wave period ($\bar{T}$) with distance from the storm center. The straight line is drawn due to Eq. 5.

of exact data, particularly in the case of extremely strong typhoons.

6. Relation between the wave height and the distance from the storm center

Based on the data in the last column of Table 1, the rate of decrease of the mean wave height with the distance from the storm center is represented graphically in Fig. 3b, which contains also the theoretical results calculated by Eq. 3 for the case of $\epsilon=20$ nautical miles and $r_0=200$ nautical miles. The discrepancies between them are not so large.

ϵ or the distance from the storm center to the region where $\bar{H}_{\text{Max}}$ is raised shall be different for each individual storm, although we have hardly any exact knowledge about it. It is expected that ϵ is large when the storm moves fast and when the diameter of the eye of storm is large. It is also conceivable that the greatest wave will be raised near the region where the strongest wind blows. According to Takahashi's investigation⁽⁹⁾, the distance from the region of strongest wind to the storm center was 15 nautical miles at the smallest and 40 nautical miles at the largest in thirteen typhoons. But, so far as we take little notice of minute distribution of waves, the small fluctuation of ϵ is not so important because $\bar{H}$ depends on the ratio of ϵ to r_0 . Thus, we simply assume $\epsilon=20$ nautical miles in this paper.

r_0 shall also be different for individual storm, but we roughly assumed it to be constant (200 nautical miles) independently on the intensity of the storm (see Fig. 3b).

Moreover, strictly speaking, the rate of decrease of wave height differs among quadrants in a typhoon. It is great in the front and small in the rear. Therefore, it will be better, for example, to consider that H is proportional to $\left\{1 + \left(\frac{\epsilon}{r_0}\right)^m\right\} / \left\{1 + \left(\frac{r}{r_0}\right)^m\right\}$ and m depends on θ , but the empirical formula then becomes too complicated for practical use.

On the basis of Eq. 1, we drew a mean distribution map of wave heights for a typhoon with an intensity of 950 mb, as shown in Fig. 6a. Comparing this with actual maps shown in Figs. 1a and b, the general features of wave

distribution seem to agree with each other except in a forward region more than 400 nautical miles distant from the storm center, where the calculated heights are fairly over-estimated. Therefore, we had better to confine the range of application of the formula within 400 nautical miles from the storm center because of the above-mentioned fact and another fact that a sea area far distant from the storm is frequently disturbed by other disturbances.

7. Effects of the speed of a typhoon on wave heights

Twelve distribution maps of wave heights were constructed according to the combination

of the speed (divided into three classes) and the central pressure of a typhoon (divided into four classes). Three typical examples of them are represented in Fig. 4.

As an empirical formula in which the effects of the speed of a storm are taken into consideration, we will again use Eq. 1 on the assumption that the constants a , n and α are functions of C respectively.

In four classes of p_0 , $H/\bar{H}$ ($=k$) was calculated at $r=50, 150, 250$ and 350 nautical miles in relation to θ , where H was given in distribution maps and $\bar{H}$ by Eq. 3. Averaging all of them, we have small circles shown in Figs. 2b, c and d corresponding to $C=0\sim20$, $20\sim40$ and more than 40 km/hr, respectively.

Fig. 4. Mean distribution maps of wave heights (in meter) due to typhoons whose central pressures are 960~980 mb in either case but whose speeds differ.

In order to fit a curve of $k=a\{1+n \cos (\theta-\alpha)\}$ to these observed values as closely as possible (see Fig. 2), each constant must have values given in Table 2.

Table 2. Values of a , n and α .

C (km/hr)	a	n	α	Source
0~20	0.90	0.25	105	Fig. 2b
20~40	1.11	0.10	150	Fig. 2c
>40	1.06	0.30	155	Fig. 2d
Mean state	1.02	0.20	135	Fig. 2a

Further, empirical curves of a , n and α to C are boldly obtained as shown in Fig. 5 based on this table. Examples of theoretical distribution maps are shown in Figs. 6b, c and d according to the speed of a typhoon in the case of $p_0=950$ mb.

Fig. 5. Empirical curves of a , n and α to C .

From these results (Fig. 4, Fig. 6 and Table 2) the followings are understood.

1. A constant " a " is greatest in the case of $C=20\sim40$ km/hr, and it suggests that waves most remarkably develop when the speed of a storm is near to the group velocity of waves. This is naturally attributed to the increase of duration and fetch of winds.

2. Moreover, waves are rather high when the storm moves fast than when it moves very slowly, and this seems to be closely connected with the fact pointed out by Ando⁽¹⁰⁾ that a typhoon with a larger speed is usually of a greater size.

3. When the storm moves slowly considerably wide area of rough sea is located in the right front quadrant as well as in the right rear quadrant, while such area gradually shifts towards the rear as the speed of storm increases. That is to say, in the former case the area of rough sea is wider in the right semi-circle than in the left semi-circle, while in the latter case it is wider in the rear semi-circle than in the front semi-circle. Accordingly, a constant " α ", meaning a value of θ along which the maximum wave height is found, increases from about 90° to about 160° as the speed of the storm becomes large.

4. A constant " n ", showing the degree of asymmetry of wave-height distribution, differs according to the speed of a typhoon. The asymmetry is less remarkable when the speed of typhoon is moderate, rather remarkable when it is small and very remarkable when it is large.

Using Eq. 1, $\varepsilon=20$ sea miles, $r_0=200$ sea miles and values of a , n and α given in Fig. 5, we constructed a diagram for the calculation of wave heights as shown in Fig. 9. The result of comparison between observed and calculated heights is represented in Fig. 7. The standard deviation (σ) of discrepancies between them is 1.6 m on the average. Strictly speaking, it depends naturally on the absolute wave-height. From this viewpoint we obtain $\sigma=H/4$ approximately, which is fairly large. However, it will be understood that such large discrepancy is inevitable under present conditions, if we consider the accuracy of the data, the complicated spectral structure of storm waves, the variety of wave distribution due

Fig. 6. Theoretical distribution maps of wave heights (in meter) calculated by Eq. 1 when the central pressure of typhoons is 950 mb in either case but the speed of them differ.

to the individualities of typhoon and the fact that a typhoon which progresses straightly with a constant speed and a constant central pressure never exists actually.

On the other hand, as an empirical formula which gives the height of swell due to a typhoon at Todorō in Miyazaki Pref., Uda⁽¹¹⁾ established

$$H = 0.65 \sqrt{\frac{1013 - p_0}{r}},$$

using the result of observations in Kathleen Typhoon of Sept. 1952, where r is measured in 111 km unit. However, this formula is not always suitable to be applied for other circumstances as is recognized from the purpose of

the formula.

8. Distribution of wave periods

In the case of wave periods, particularly in the vicinity of the storm center, the number of materials was considerably smaller than that of wave heights for lack of period observation in the reconnaissance flights, and it cannot be helped that the following discussion will remain insufficient in comparison with the case of wave heights. Moreover, it should be kept in mind that actual seas constitute a complicated spectrum including waves of various periods.

Distribution maps of periods of prevail-

Fig. 7. Comparison between observed (with suffix "obs") and calculated values (with suffix "cal") of wave heights and periods, respectively. The former is based on visual observations at TANGO in thirty eight typhoons and the latter is calculated using Fig. 9. (σ : standard deviation)

ing waves are represented in Fig. 8, and the mean wave period ($\bar{T}$) which is a function of r only is given in Table 3. Further, Table 4 shows the effect of the speed of a typhoon on period distribution and the difference of wave periods among four quadrants in a typhoon, and Table 5 indicates the frequency distribution of wave periods within three hundred nautical miles from the storm center which corresponds to the radius of a considerably strong typhoon. From these maps and tables, the followings will be made clear.

1. Waves with great length are more frequently raised in the rear semi-circle than in the front semi-circle.

2. It is distinctly ascertained that the wave period increases as the central pressure of typhoon becomes low. Namely, according to Table 5, the mean wave-period is about 10

sec in strong typhoons and 8 sec in weak typhoons with a standard deviation of 1.3~1.6 sec.

3. On the average, the wave period of prevailing waves decreases as the distance from the storm center becomes large.

4. The wave period in the front semi-circle is likely to decrease as the speed of storm becomes great. According to Table 4, for example, the period in the right front quadrant ($0 < \theta < 90^\circ$) is 9.2 sec when the typhoon with an intensity of 940~960 mb moves at a speed less than 40 km/hr, while it diminishes to 8.6 sec when the typhoon moves at a speed more than 40 km/hr.

5. The wave period which is frequently raised in a typhoon is of seven to eleven seconds, that is somewhat smaller than the observed values at Hachijo Island as shown in Table 1 of the author's first paper⁽³⁾. This is probably attributed to the fact that the latter was obtained in a shallow water and accordingly, short waves are likely to vanish and to be merged into longer waves.

6. In conclusion, we may say that the distribution of wave periods is generally similar to that of wave heights although the former is more complicated and more confused.

Then, it is difficult to establish a simple empirical formula in which the difference of wave periods among quadrants and the effect of the speed of typhoon are taken into consideration. Accordingly, we are compelled to be satisfied with such empirical formula as

$$\bar{T} = T_0 - \frac{r}{250} = 48.5 - \frac{p_0}{25} - \frac{r}{250} \quad (5)$$

The relation of $(T_0 - \bar{T})$ to r is indicated in Fig. 3c, showing that Eq. 5 holds approximately. A diagram for the calculation of mean wave period is given in Fig. 9. The result of comparison between calculated and observed values in thirty eight typhoons is indicated in Fig. 7b. The standard deviation of discrepancies was 1.4 sec.

9. Concluding remarks

We have constructed the mean distribution maps of wave heights and periods, and discussed the characteristics of them, on the basis of various materials. The materials, however, were scanty in the vicinity of the

Fig. 8. Mean distribution map of wave periods in a typhoon (in second). For convenience' sake, a region where the wave period is more than 9 sec is bordered with short oblique lines.

Table 3. Mean wave period ($\bar{T}$, in second)

r (sea mile)	0~100	100~200	200~300	300~400	400~500	500~600
p_0 (mb) $\left\{ \begin{array}{l} < 940 \\ 940 \sim 960 \\ 960 \sim 980 \\ > 980 \end{array} \right.$	—	—	10.1*	10.1*	9.7*	8.9*
	10.3	9.4	9.4	9.2	8.5	8.7
	9.6	8.8	8.2	8.5	8.1	8.2
	8.5	8.2	8.1	7.6	7.5	6.3

* The mean was taken only in the right semi-circle.

storm center, and the accuracy of them was not necessarily sufficient, although these must be considered as an inevitable consequence of the circumstances.

Moreover, our simple empirical formulas

and calculation diagrams for wave heights and periods are not satisfactory, although they can be expected to be useful as a first approximation. The main fault is due to that the past state of the storm and also individual

Table 4. Effect of the speed of a typhoon on wave periods (in second).
(The mean was taken within 600 nautical miles from the storm center.)

p_0 (mb)		940~960				960~980			
θ		0° ~90°	90° ~180°	180° ~270°	270° ~360°	0° ~90°	90° ~180°	180° ~270°	270° ~360°
C (km/hr)	0~20	9.2	9.5	—	—	8.3	9.1	9.2	7.8
	20~40	9.2	8.5	—	9.0	8.6	9.3	8.7	8.1
	>40	8.6	9.7	9.6	8.7	7.9	9.2	8.8	8.0
Mean		9.0	9.2	(9.6)	(8.9)	8.3	9.2	8.9	8.0

Fig. 9. Calculation diagrams for heights and periods of prevailing waves based on Eqs. 1 and 5, where we put $\epsilon=20$ S.M. and $r=200$ S.M.

[The direction for use]

1. Using values of the central pressure of a typhoon and the distance from its center to a place in question, read $\bar{H}$ and $\bar{T}$ (wave period) in the left-hand diagram.
2. Using values of the speed of the typhoon and an angle of the place in question, seek the value of k in the right-hand diagram.
3. Then, the wave height required is given by the product of k and $\bar{H}$.

Table 5. Frequency distribution of wave periods within 300 nautical miles from the typhoon center (%).

Period (sec)	5	6	7	8	9	10	11	12	13	Mean (sec)	Standard deviation (sec)
p_0 (mb) $\left\{ \begin{array}{l} <940 \\ 940 \sim 960 \\ 960 \sim 980 \\ >980 \end{array} \right.$	—	—	8	3	39	17	11	14	8	9.9	1.6
	—	—	5	12	35	25	13	—	10	9.7	1.5
	—	8	9	24	34	19	6	—	—	8.7	1.3
	1	8	20	35	25	7	2	1	1	8.2	1.4
Mean	0	4	10	19	33	17	8	4	5	9.1	1.5

variations of wind distribution among typhoons are not taken into consideration. Then, errors are liable to become large when the intensity, speed and direction of movement of the storm change violently.

Therefore, it is hoped that the results obtained in this paper will be amended with further accumulation of exact data. Particularly, it is important that the spectral structure of storm waves which consist of wind waves and swell will be made clear.

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