Typhoon Development and the Sea Temperature

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Suguru ISHIJIMA *

This is preliminary research to appreciate quantitatively the role of the sea as an energy supplier for developing typhoons. Dependency of the typhoon development upon the sea surface water temperature was examined in the first place, and followingly the vertical change of the sea temperature over a point Tango (29 N, 135 E) in a typhoon passage over or by the point was investigated to make a rough estimate of the amount of the energy supplied from the sea to a typhoon system. It was ascertained that a typhoon experiences a development generally in a region with the sea surface water temperature above 28.5°C and the inverse in a region below 27°C. No quantitative results were obtained on the degree of a typhoon development by a given amount of the temperature change at the sea surface. The heat supplied from the sea to a typhoon for a day, on the average, amounts to 7 to 15×10^{25} erg.

1. Introduction

The importance of the sea as an energy source for formation, development and maintenance of the typhoon has been continuously stressed among many meteorologists, but relatively few works have been accomplished in this field probably because of inavailability of the observational data over the ocean especially during the occurrences of typhoons. Moreover, even those[1) who somehow attempted to make researches in this line treated only a single typhoon case. Therefore, there is no guarantee whether the results they derived are essential and applicable for all other typhoon cases. It is understandable that an analysis of a sufficient number of typhoons can hardly be done because of the limited working hours. However, when we think that a typhoon is not intensified or decreased only by the influence of the sea but by several other meteorological factors whose effects might be varied from one typhoon to another, the treatment of a single typhoon case would not always bring us a correct idea on the contribution of the sea. Therefore, to acquire more reliable knowledge on the sea effect on a typhoon, it is requested that some number of typhoons should be treated together and analysed from the statistical aspect. Here, in this paper, a group of 32 typhoon cases was selected for the analysis

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* Short Course Division, University of the Ryukyus

of the relation between the central pressure and the sea surface water temperature; another group of 24 cases was selected for the analysis of the vertical sea-temperature change in a typhoon passage.

The fact that the sea surface water temperature above 26—27 °C is a critical limit for the formation of a typhoon[2)] suggests that a typhoon breeds with the supply of the heat energy from the oceanic region with high temperature. Heat energy from the sea surface to the lower atmosphere is mainly transferred through the turbulent conduction of sensible heat, the turbulent transport of water vapor produced in evaporation, and the back radiation from the sea surface of the earth as a black body. It is explainable that the amount of heat transferable from the sea to the lower atmosphere through the above three processes tends to increase when the sea surface water temperature rises. Therefore, we can expect that there is a correlation in which a typhoon will intensify herself when she goes into a warm region and decay into a cold region of the ocean. On the other hand, the sea surface is not an energy donor, but merely a plane where the sea and the air are in contact with each other and through which energy is transported in or out. It is unquestionable that a whole upper surface layer of the ocean with a certain depth acts as an energy source, and the research on this layer will surely bring us more concrete ideas concerning the role of the sea to typhoon development than what a study restricted to the sea suface will accomplish.

2. Data and Method of Analysis

The selected 32 typhoons occurred in the south-western region of the Pacific Ocean D (10—35 N, 120—160 E) during the years 1960 through 1966 and were analysed to study the dependency of the development of a typhoon on the surface water temperature. A list of these selected typhoons was prepared in Table 1. Upon the basis of the fact that a central pressure is a good indicator of the intensity of a typhoon and the heat is supplied to her through the whole area of a typhoon covering, a relation between the central pressure and the sea surface water temperature averaged over the circle zone of 5 lat. radius (550 Km) around the moving typhoon center positions was studied.

The central pressure data at the hours 03, 09, 15, and 21 of each day during the movement of typhoons over the region D were taken out from the monthly "meteorological Reports (kishoyoran) " issued from the Japan Meteorological Agency, and these four data each day were averaged to obtain one-day average central pressure. The data are readily available for the central pressure by flight observation or synoptic weather map analysis, but scarcely available for the sea water temperature due to the difficulty of the observation ınder the occurrence of the typhoon. Therefore, it is impossible to have one-to-ɔne correspondence between the surface water temperature and the central pressure at an arbitrary time in the typhoon period, without using estimates of the surface water temperature. A scholar[1] estimated the surface water temperature for his analysis of Hurricane Esther (1960) by using three week mean sea surface water temperature that he constructed for the period of the Hurricane. Here, in the present paper, two kinds of one-day average surface water temperatures were estimated with use of the 10 day Mean Sea Surface Water Temperature Distribution Maps given in the "Meteorological Reports" previously introduced; one by taking the average of the temperature estimates over the course of a moving typhoon at the hours 03, 09, 15, and 21 of each day read from the 10 Day Mean Distribution Map whose mean period covers the most part of a typhoon life for which the analysis was made, and the other by taking the average of those estimates read from the other 10 Day Mean Distribution Map whose mean period covers 10 days before the former's period. Hereafter, the surface water temperature estimated from the former Map is called a during-typhoon surface water temperature (T_1); that estimated from the latter Map a before-typhoon surface water temperature (T_2) . For instance, when a typhoon passed over the region D from 8 through 14 August, we obtained two one-day average surface water temperatures; one (T_1) derived from the 11−20 day Mean Map of August, and the other (T_2) from the 1−10 day Mean Map of August, and made an analysis for 11 through 14 of the typhoon central pressure dependency on the two sorts of surface water temperatures, T_1 and T_2. The analysis period and the period of the 10 Day Mean Maps from which T_1 and T_2 were obtained are presented in Table 1.

Table 1. Typhoons, minimum central pressure, analysis period, a period of averaging the sea surface water temperature

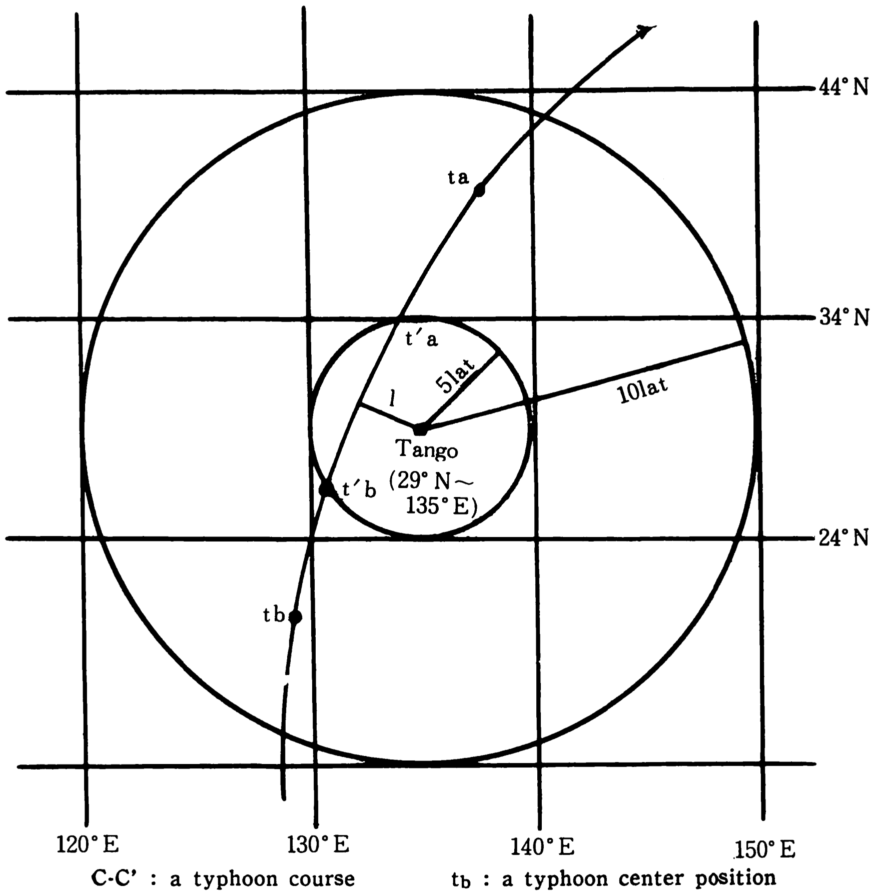
Typhoon number	Minimum Central Pressure (mb)	Analysis Period (month/date)	Averaging Period of SST_1 * *	Averaging period of SST_2 * * *
6006 *	950	7/21−7/27	7/21−7/31	7/11−20
6009	930	8/6−8/7	8/1−8/10	7/21−7/31
6018	945	8/27−8/30	8/21−8/31	8/11−8/20
6123	925	10/1−10/3	10/1−10/10	9/21−9/30
6124	895	10/6−10/9	10/1−10/10	9/21−9/30
6128	930	11/11−11/14	11/11−11/20	11/1−11/10
6207	960	7/23−7/25	7/21−7/31	7/11−7/20
6212	915	8/17−8/20	8/11−8/20	8/1−8/10
6214	950	8/23−8/25	8/21−8/31	8/11−8/20
6217	940	9/1−9/4	9/1−9/10	8/21−8/31
6222	890	10/4−10/10	10/1−10/10	9/21−9/30
6224	955	10/24−10/30	10/21−10/31	10/11−10/20
6228	900	11/14−11/16	11/11−11/20	11/1−11/10
6304	935	6/16−6/18	6/11−6/20	6/1−6/10
6307	930	7/14−7/15	7/11−7/20	7/1−7/10
6309	930	8/3−8/7	8/1−8/10	7/21−7/31

6314	920	9/8–9/10	9/1–9/10	8/21–8/31
6317	920	10/2–10/4	10/1–10/10	9/21–9/30
6318	930	10/7–10/11	10/1–10/10	9/21–9/30
6319	940	10/15–10/19	10/11–10/20	10/1–10/10
6411	940	7/30–7/31	7/21–7/31	7/11–7/20
6414	948	8/14–8/20	8/11–8/20	8/1–8/10
6420	895	9/21–9/23	9/21–9/30	9/11–9/20
6515	950	8/2–8/4	8/1–8/10	7/21–7/31
6517	940	8/20–8/21	8/11–8/20	8/1–8/10
6520	940	8/30–9/1	8/21–8/31	8/11–8/20
6523	940	9/7–9/9	9/1–9/10	8/21–8/31
6524	935	9/12–9/16	9/11–9/20	9/1–9/10
6528	900	9/30–10/3	10/1–10/10	9/21–9/30
6529	914	10/8–10/9	10/1–10/10	9/21–9/30
6615	970	8/20–8/22	8/21–8/31	8/11–8/20
6616	938	8/27–9/1	8/21–8/31	8/11–8/20

* — reads Typhoon No. 6 occurred in 1960

* * — abbreviates the during-typhoon sea surface water temperature

* * * — abbreviates the before-typhoon sea surface water temperature



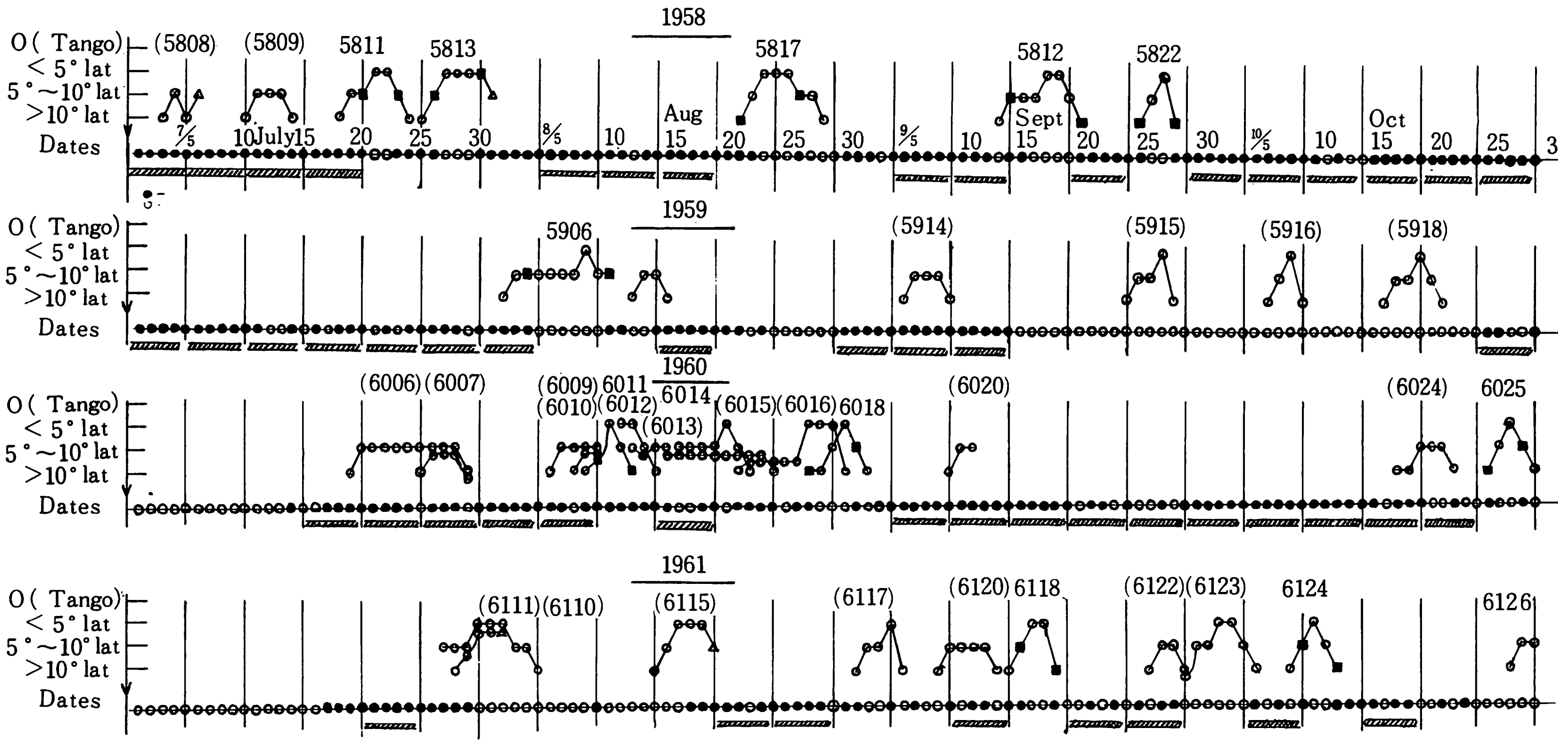
C-C' : a typhoon course t_b : a typhoon center position of the day before a typhoon passage t_a : a typhoon center position of the day after a typhoon passage l : the closest distance of the typhoon course to Tango

Fig. 1. The map for illustrating the geography of Tango and the circle zones used for terminology of t_b, t_a, etc.

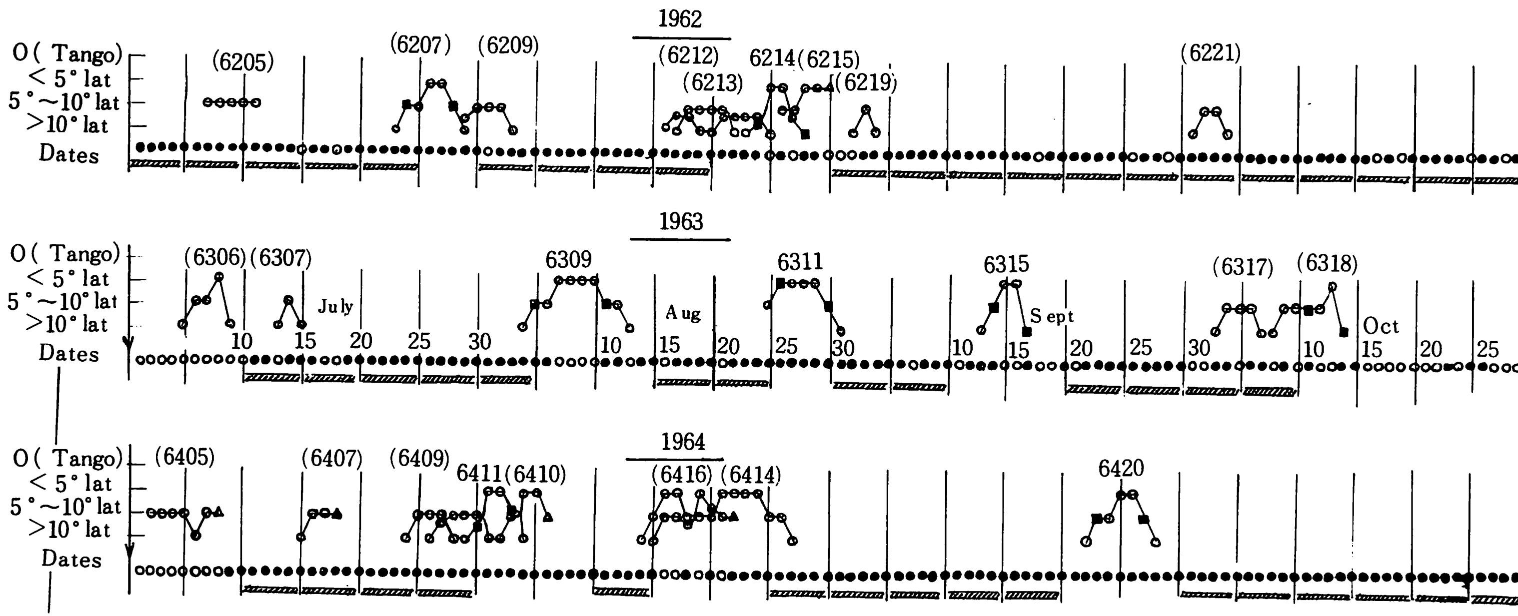
For analysis of the vertical structure of the sea temperature were used the sea temperature observations within the area (28.00–30.00 N; 134.00–136.00 E) around Tango (29 N; 135 E) during the hours (8:00–10:00 a. m.) of the observation days in July, August, September, and October, 1958 through 1965, provided in "The Results of Marine Meteorological and Oceanographical Observations" issued bi-annually from the Japan Meteorological Agency. It was assumed that the variation of the sea temperature be negligible within the area and the range of time set up above. Now 24 typhoons occurred during 1958 through 1965 and travelled over or by the area of Tango were selected from "The Chart of Typhoon-Courses" published annually from the Japan Meteorological Agency, to study the changes of the sea temperature distributions of the layer down to 200 m observed in the mornings of two days before and after a typhoon passing. The determination of the day before or after a typhoon passing can be made quite arbitrarily depending on the researcher's purpose. Here, the present author defined the day before a typhoon passage (t_b) to be the day when a typhoon approached within the zone bounded by two concentric circles of radius 5 lat. and 15 lat. with center at Tango as illustrated in Fig. 1 and the day after a typhoon passage (t_a) to be the day when she passed away within the zone. However, this definition was not applied for the several typhoons who lacked in observations within the above zone before or after their passages. For these cases, t_b and t_a simply means the day when the last or the first of the observations made at Tango before or after a typhoon passage was available. Typhoon center positions on t_b and t_a for each individual typhoons are made clear in Supplemented Fig. 1 and in Fig. 2.

The difference ($\delta T = T_b - T_a$) in the sea temperatures of T_b and T_a does not wholly represent a typhoon passing effect, but contains the effect of some non-typhoon disturbances which may also take part in changing the temperature. Thus, δT should be separated into two and written· $\delta T = \delta T_t + \delta T_n$, where δT_t is a change purely caused by a typhoon and δT_n is the one by a non-typhoon disturbance. An estimation of δT_n together with δT enables us to obtain the change δT_t by rewriting the above equation in $\delta T_t = \delta T + (-\delta T_n)$, applying $(-\delta T_n)$ as a correction factor to δT.

Using all available morning sea temperature observations and the interpolated values for the days lacking of the observations, of July, August, September, and October, 1958 through 1964 (1965 was excluded just because of inavailability of the data book at hand), we computed the five-day average of sea temperature for 0 m, 20 m, 30 m, 50 m, 75 m, and 100 m levels exclusive of typhoon appearing days within the circle zone of 5 lat. radius around Tango and obtained the sea temperature variation curves with time



1958
O (Tango)
< 5° lat
5°~10° lat
>10° lat
Dates
(5808) (5809) 5811 5813 5817 5812 5822
7/5 10 July 15 20 25 30 8/5 10 Aug 15 20 25 30 9/5 10 Sept 15 20 25 30 10/5 10 Oct 15 20 25 30
1959
(5906) (5914) (5915) (5916) (5918)
1960
(6006) (6007) (6009) 6011 (6010) (6012) 6014 (6013) (6015) (6016) 6018 (6020) (6024) 6025
1961
(6111) (6110) (6115) (6117) (6120) 6118 (6122) (6123) 6124 6126



( ) — unanalysed typhoon ■~■ — days before and after a typhoon passage t_b, t_a when analysis was made

△ — a die of typhoon ▨ — class-intervals exclusive of typhoon appearing days in a 5 lat. circle zone around Tango

Fig. 2. Typhoon center positions in relative to Tango and with time, dates with data available, and the five day class intervals exclusive of typhoon appearing days

and by levels with which afterwards the change (δT_n) by non-typhoon causes was estimated. In order to exclude a typhoon effect in consructing the above curves, the state of typhoon appearings in the vicinity of Tango was carefully examined for each year with the help of Fig. 2 which showed moving typhooon center positions in relative to Tango and with time. In taking the average, no average value was given to a class interval of averaging, if it contained any typhoon appearing days. Fig. 2 also presents days with data available, and five--day class interval of averaging. The related numerical values were all presented in Supplemented Table 2.

3. Results and Discussion

(a) *Typhoon Development and the Sea Surface Water Temperature*

The correlation was studied between the central pressure change per day and the surface water temperature change per day that were obtained by taking the difference between today's central pressure and surface water temperature and the yesterday's ones. And the results were shown in Fig. 3—a. and Fig. 3—b, for the case of the central pressure change versus the during-typhoon surface water temperature change and for that of the central pressure change versus the before-typhoon surface water temperature change, respectively, under the classification of the surface water temperature expressed by the average of today's and yesterday's temperatures. It is generally known that the generated typhoons in the tropical region of the Pacific take two types of courses; one moving toward north almost straight or with recurvatures in the western region of the Pacific, and the other travelling toward west and eventually landing on the southern part of the China continent. For the present study that purposes for the understanding of the sea effect on a typhoon, those with the former type of course were automatically more selected, merely because they stayed longer over the sea and could contribute more data for the present analysis. However, in contradiction with the above benefit of selecting these typhoons, the fact that the surface water temperature generally decreases as we go north from south, which made scarce of the data giving the cases of the central pressure change versus the surface water temperature increment which reflected upon the rareness of the plots in the first and fourth quardrants of Fig.3—a and Fgi 3—b. Therefore, it was impossible to discover a correlation coefficient, and accordingly no knowledge was obtained on how much pressure decrease would be produced by a given amount of surface water temperature increase.

However, an appreciation was possible on the contribution of the sea surface water temperature itself to a typhoon development. Typhoons experienced intensification more frequently in the region of higher surface

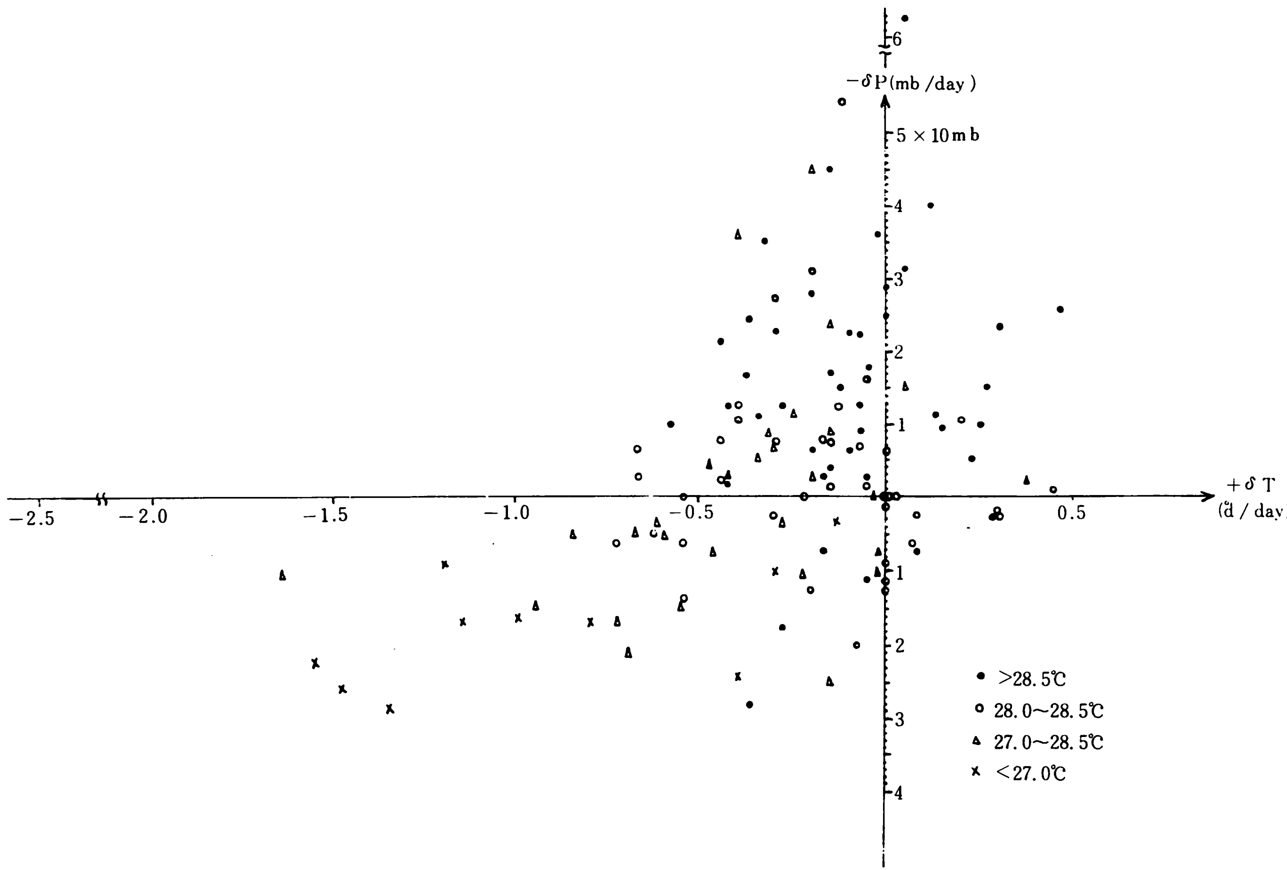


Fig. 3—a. Correlation between the change of central pressure of typhoons(mb/day)and that of the during-typhoon sea surface water temperature (°C/day) under the classification of the sea surface water temperature

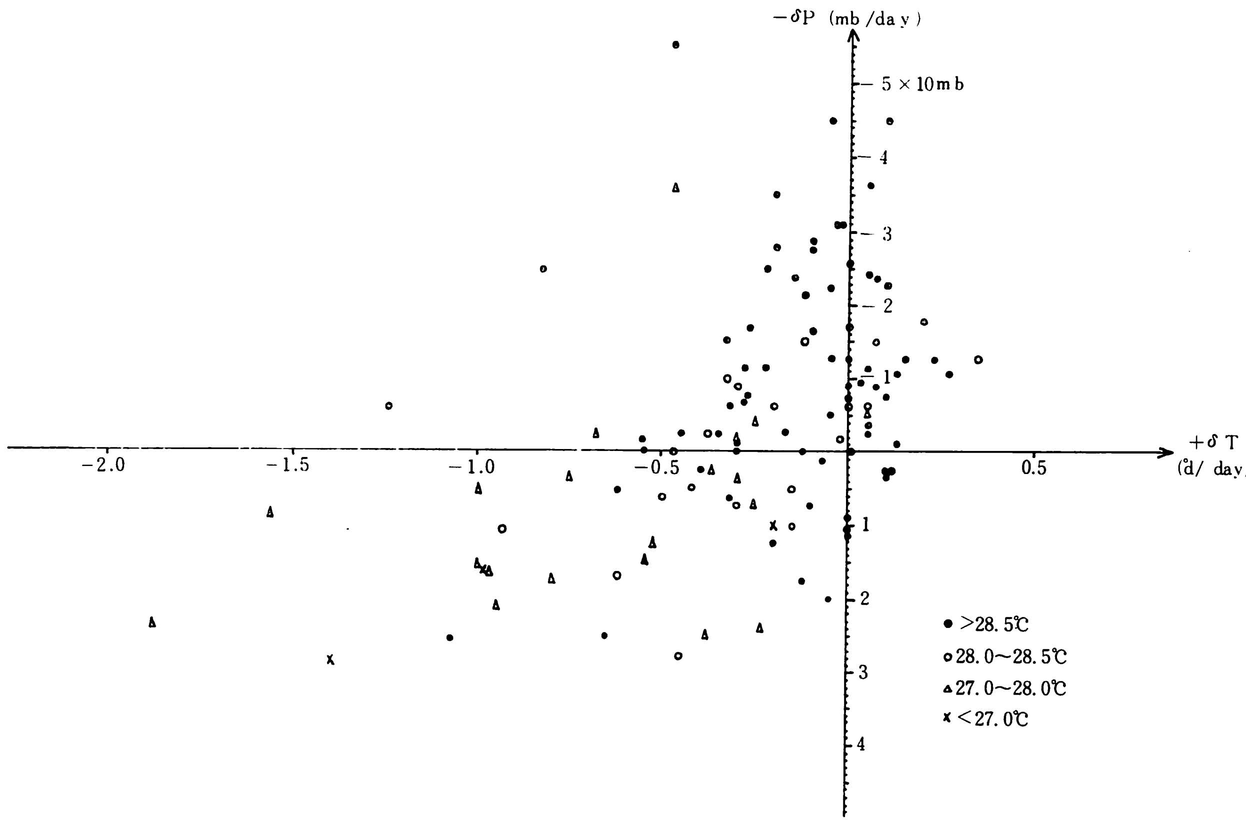


Fig. 3—b. Correlation between the change of central pressure of typhoons(mb/day)and that of the before-typhoon sea surface water temperature (°C/day) under the classification of the sea surface water temperature

water temperature and less in the lower temperature areas, as understood from the statistics of Table 2 with help op the distribution pattern of the plots of Figs. 3—a and Fig. 3—b according to the classification of the surface water temperature. Most of the typhoons intensified themselves over the sea with the surface water temperature above 28.5 °C and none below 27° C which are fairly consistent with the results given by T. OGATA.[3)]

Table 2. Dependency of typhoon development on the during-typhoon sea surfce water temperature (T_1) , and on the before-typhoon sea surface water temperature (T_2)

Sea surface water temperature	Total frequency	Frequency of developing	Frequency of decaying	Frequency of maintaining
28.5 C	42(73)	37(54)	5(16)	0(3)
28.0—28.5 C	41(18)	21(9)	16(8)	4(1)
27.0—28.0 C	30(20)	14(5)	15(15)	1(0)
27.0 C	11(3)	0(0)	14(3)	0

Note. Numbers in parentheses are the statistics for the case of the dependency of typhoon development on T_2

Now it is interesting to know that the before-typhoon surface water temperature (T_2) is warmer than the during-typhoon surface water temperature (T_1) for the most part of the analysis period of almost all typhoon cases (See Supplemented Table 1) . The difference (T_2-T_1) averaged over all days of all typhoons cases came out 0.45 °C Thus, assuming this amount to be an average surface water temperature decrease in the half way of a typhoon passage, we can give 0.9 °C as an estimate of the surface water temperature decrease in a complete typhoon passage. Although it can be questioned whether or not this amount contains the temperature change caused by non-typhoon factors such as the seasonal weather revolution, the movement of water masses, etc., we can accept it as a temperature decrease purely caused by a typhoon-passage, granting that these factors were cancelled out in the stage of taking the average.

(b) *Typhoon Intensity and the Vertical Sea Temperature Distribution*

In Fig. 5 are presented with heavy lines the vertical sea temperature distributions down to 200 m in depth over Tango in the mornings of the day before typhoon comings (t_b) and the day after typhoon passings (t_a). One can doubt whether the difference between the temperatures on t_b and that on t_a really expressed the whole change caused by a typhoon disturbance. It may contain some change produced by the disturbances other than typhoons. In order to obtain the pure effect of a typhoon on the sea, an elimination of the non-typhoon effects which might act for a typhoon passing period were carried out with use of the five day sea temperature variation curves of Fig. 4 constructed in the way as explained in Section 2. The curves for 150

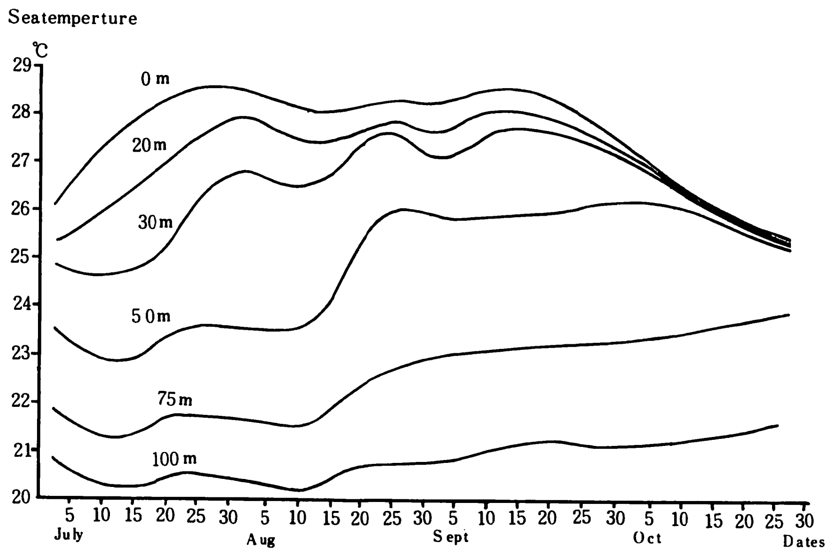
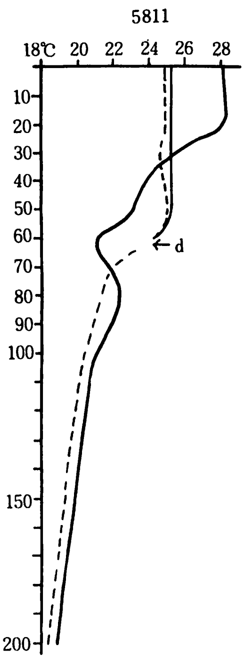
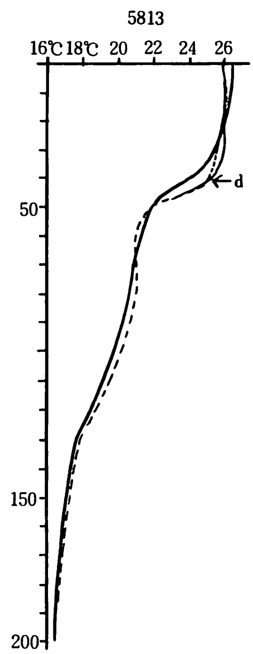


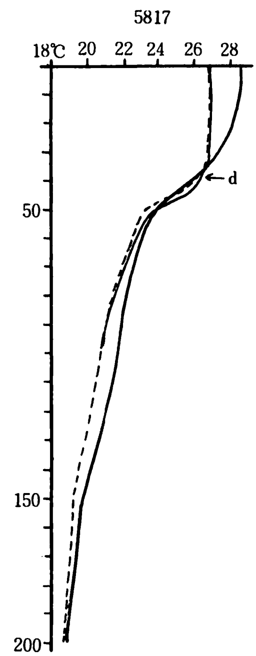
Fig. 4. The five day average of sea temperature variation curves with time and by levels

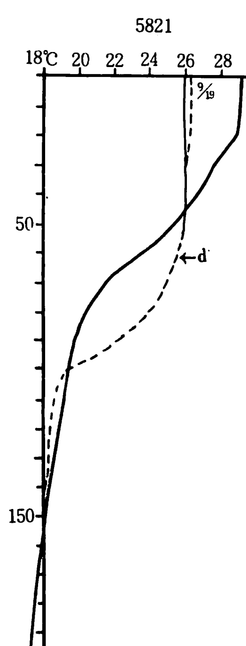
m and 200 m in depths were not constructed simply because there is little variation expected with time for them. The curves for O m and 20 m levels rapidly increase from early July to the late of July, then keep almost constant till the middle of September, and now rapidly decrease in the late of September and in October. The curves for 30 m and 50 m levels look different from the above two curves in that they experience an existence of a slight decrease in the middle of July and a delaying of the starts of the rapid increases which appears in late July for 30 m and in the middle of August for 50 m, but their decreasing tendency toward late summer is alike with that for 0 m and 20 m. The curves for the deep layers 75 m and 100 m show entirely different patterns having a slight temperature gradient for entire analysis period with low temperature in July to August and high in September to October. We may think all these curves reveal the reliable average patterns of the sea temperature variation under the calm weather condition without typhoons over the sea of Tango, if we are allowed to disregard the errors expected from the insufficient number of data, from the inadequacy of taking the averaging class, and from the incompleteness of eliminating typhoons.

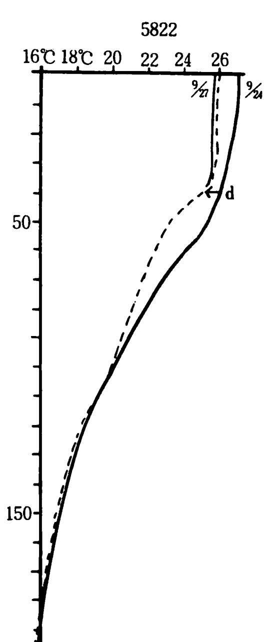
The change to be resulted from non-typhoon disturbances during the period between t_b and t_a was read from the above curves and used to obtain

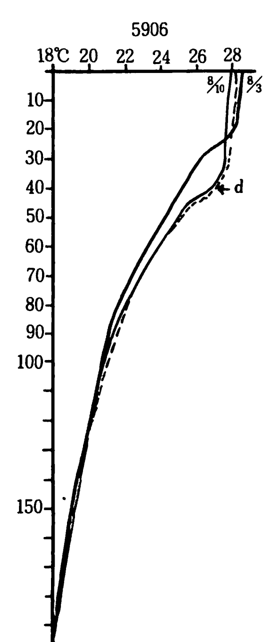

5811
18℃ 20 22 24 26 28
10 20 30 40 50 60 70 80 90 100 150 200
d

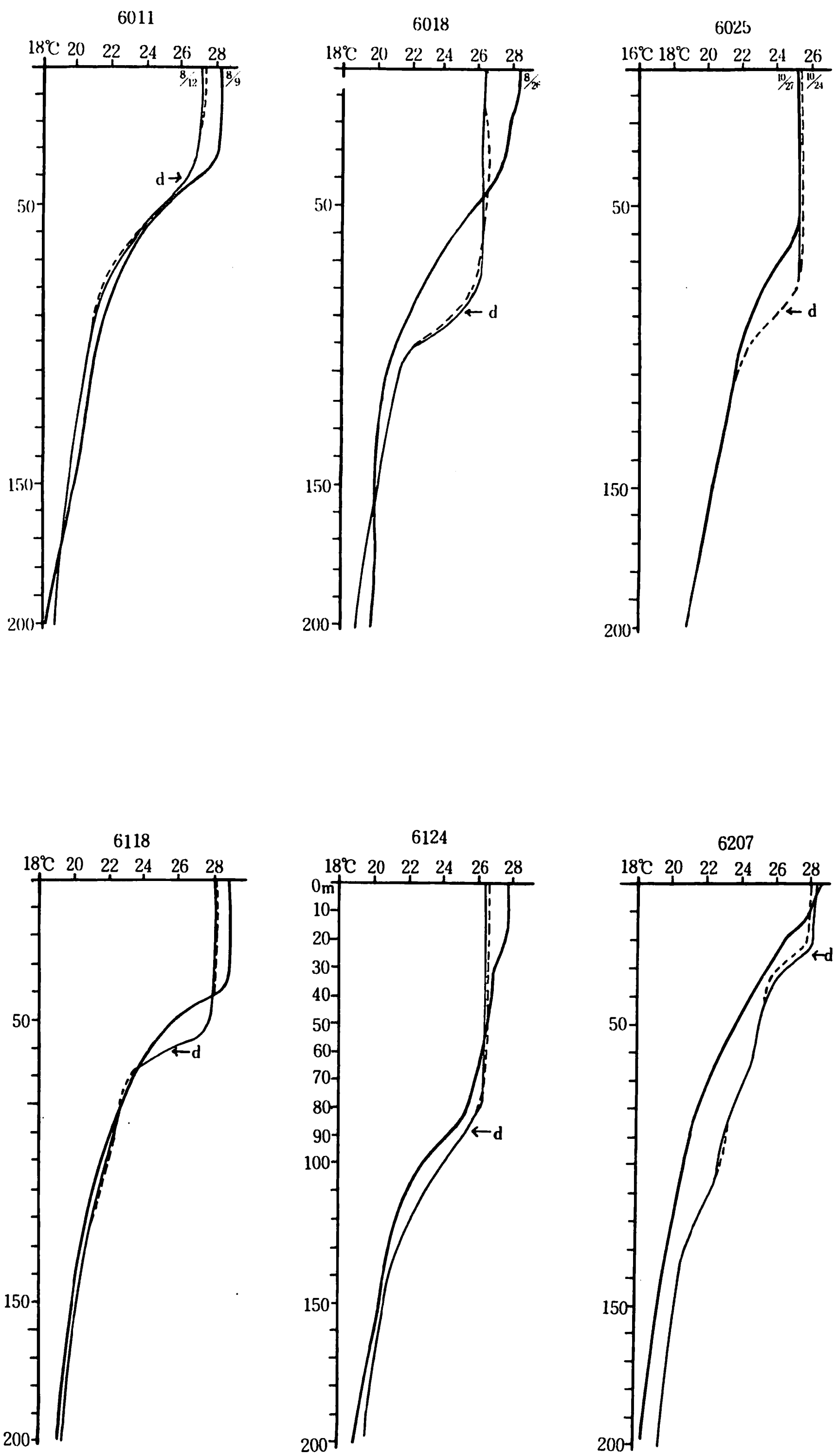

5813
16℃ 18℃ 20 22 24 26
50 150 200
d


5817
18℃ 20 22 24 26 28
50 150 200
d


5821
18℃ 20 22 24 26 28
9/19
9/13
50 150 200
d


5822
16℃ 18℃ 20 22 24 26
9/27
9/24
50 150 200
d


5906
18℃ 20 22 24 26 28
8/10
8/3
10 20 30 40 50 60 70 80 90 100 150 200
d


6011
18℃ 20 22 24 26 28
8/12
8/9
d
50
150
200
6018
18℃ 20 22 24 26 28
8/21
d
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150
200
6025
16℃ 18℃ 20 22 24 26
10/27
10/24
d
50
150
200
6118
18℃ 20 22 24 26 28
d
50
150
200
6124
18℃ 20 22 24 26 28
0m
10
20
30
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6207
18℃ 20 22 24 26 28
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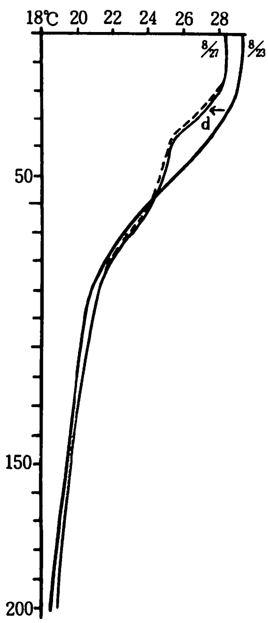
200

6214



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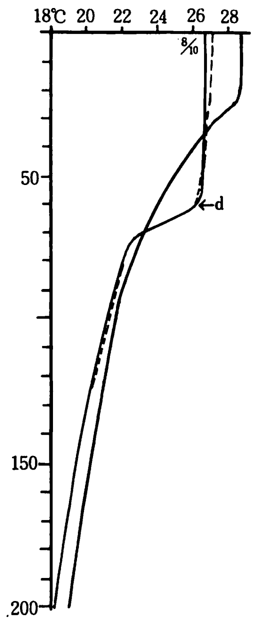

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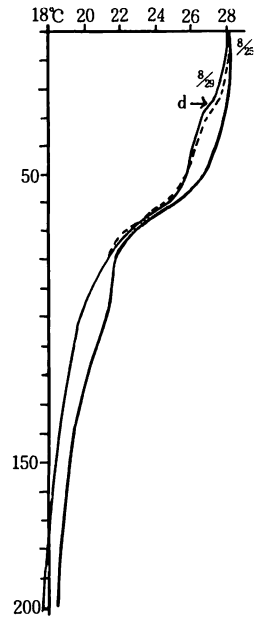

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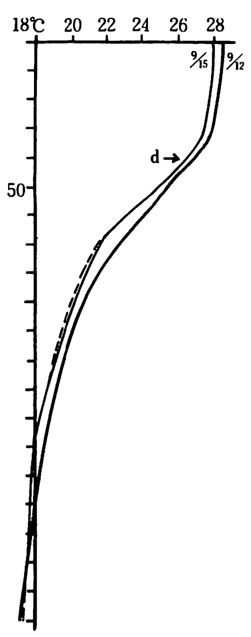

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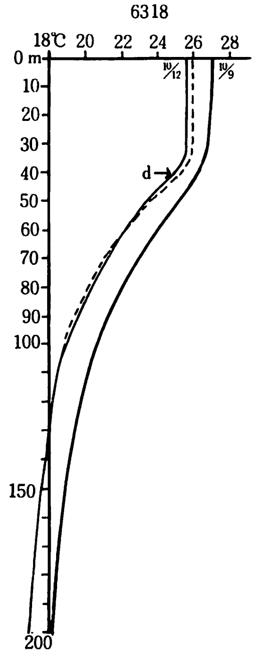

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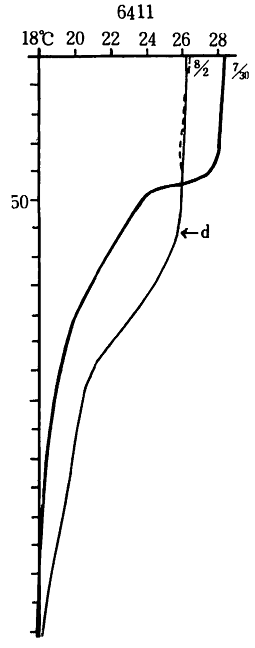

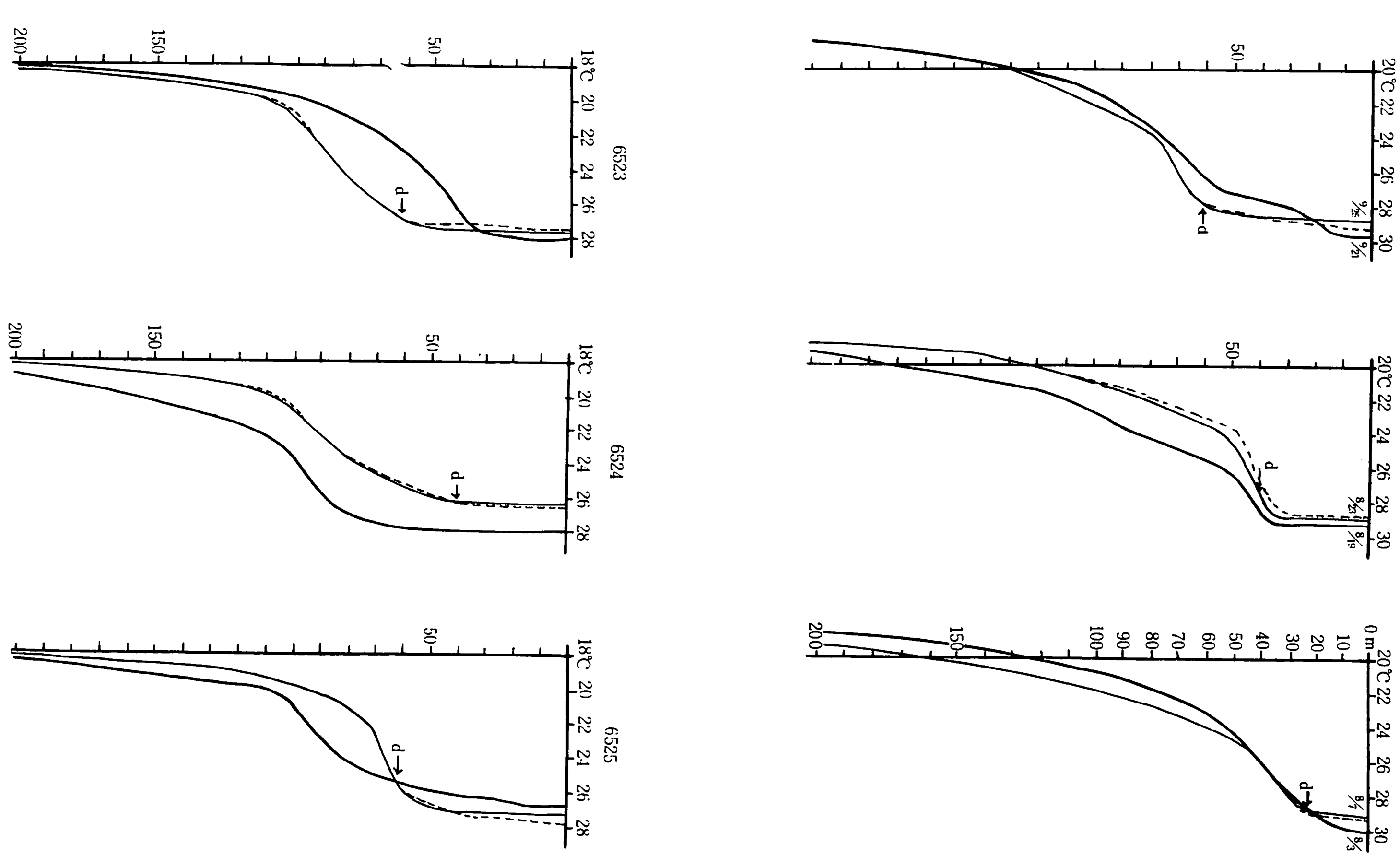

Fig. 5. Changes of the vertical temperature distributions in typhoon passages (T_b. T_a, CT_a)

Notes : Heavy lines indicate the temperatures before-typhoon passings (T_b), the lighter ones after-typhoon passings (T_a), and the dotted lines the corrected temperature after-typhoon passings (CT_a)

a temperature after a typhoon passage which would have been established if any non - typhoon factors had not involved in changing the temperature while a typhoon passing. Here, we called this temperature a corrected sea temperature after a typhoon passage (CT_a). The vertical distribution of CT_a are indicated by dotted lines in Fig. 5 and their numerical values are given in Supplemented Table 3 together with the correction δT_n of non-typhoon effects. Now, by comparing CT_a curves with those of T_b, we can depict some clear features of the sea temperature change in a typhoon passage:

1) T_b is higher than CT_a at the sea surface for all but one case, Typhoon 6526

2) T_b is higher than CT_a in the surface layer with the depth varying from one typhoon to other but the opposite situation occurs in the deeper layer for 18 typhoons: Typhoons 5811, 5813, 5817, 5821, 5906, 6011, 6025, 6118, 6124, 6207, 6214, 6309, 6311, 6411, 6420, 6515, 6523, and 6526

3) T_b is constantly higher than CT_a in all layers for five typhoons; Typhoons 5822, 6318, 6315, 6517, and 6524

4) T_b is lower than CT_a in the surface layer but the opposite in the deeper layer for Typhoon 6526

The average of the temperature decrease (T_b—CT_a) at the surface amounts to 1.0 °C. The amount 1.0 °C is quite close to 0.9 °C that was derived as a typhoon effect of decreasing the surface water temperature in the preceding Paragraph (a), which backs up the validity of the method of estimating the during - and before - typhoon surface water temperature using the 10 day Mean Surface Water Temperature Distribution Maps in Paraqraph (a) .

The tendency of the lowering of the depth of thermocline layers after a typhoon passage[4] suggests that a typical vertical pattern of the sea temperature distributions T_b and T_a must look like an illustration of Fig. 6 with T_a lower in the surface layer and higher in the succeeding deep layer and with the temperature difference converging to zero in the deeper layer. A major portion of the heat energy loss by a typhoon passage expressed in the area A of Fig. 6 goes out to the atmosphere of the typhoon and the rest is used to warm up the succeeding layer B. In this present analysis of 24 typhoons, 18 out of them formed up the distributions fairly similar to the above typical pattern with conspicous lowerings of depths of the thermocline layer after a typhoon passage.

Postulating that the depth of the thermocline layer after a typhoon passage which is marked by an arrow d in Fig. 5 indicates a limit of the sea-typhoon interaction, the heat per unit area Q (cal/cm2) supplied to a typhoon while its passing over Tango was calculated by the formula;

$$Q=C_p \rho d\ (T_b-CT_a)$$

, where C_p and ρ are specific heat (cal / gr°C) and density (gr / cm3) , respectively. It is interesting to know from Fig. 7 that the quantity Q is fairly correlated to the central pressure of the typhoons averaged over the typhoon passing period and expressed in term of 1000 mb minus central pressure, classifying into two; one group passing relatively close to and the other group relatively far from Tango, with neglection of some exceptional cases like Typhoons 5822 and 6526. Typhoon 5822 was extraordinarily strong with the minimum central pressure 890 mb and Typhoon 6526 was one of the weakest with 995 mb who marched over

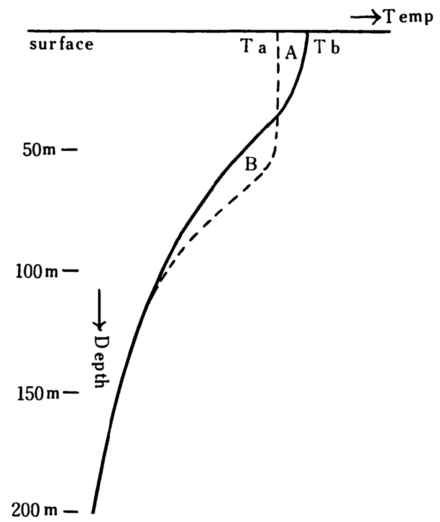

Fig. 6. A model of the change of the vertical temperature structure in a typhoon passage

Table 3. The water temperature change at the surface and the heat (Q) supplied to a typhoon in its passing over Tango and some typhoon elements

Typhoons	Temp. change at surface (°C)	Heat (x 100cal/cm2)	1000mb— central pressure	Passing * period-1 (hours)	Passing ** period-2 (days)	Typhoon size in radius (lat.)
5811	3.1	75.1	50	33	3	4.3
5813	0.5	8.3	26	88	4	2.0
5817	1.6	40.9	21	71	5	3.0
5821	2.9	72.6	53	56	6	5.7
5822	1.1	23.5	110	53	3	5.8
5906	0.3	−11.7	30	30	7	NA
6011	0.9	37.5	13	31	3	7.0
6018	2.0	−1.5	35	7	5	2.0
6025	0.0	−40.3	29	18	3	NA
6118	0.7	−2.2	77	32	3	NA
6124	1.1	2.7	67	32	3	4.0
6207	0.2	−8.1	28	56	4	3.0
6214	0.9	23.2	30	57	4	1.4
6309	1.7	15.2	42	85	6	4.8

6311	−0.1	−2.4	12	108	4	1.4
6315	0.6	17.8	2	33	3	NA
6318	1.1	41.0	60	28	3	4.0
6411	2.0	45.1	40	41	3	NA
6420	0.5	−27.5	60	60	4	NA
6517	0.5	23.6	47	52	4	2.4
6515 * * *	0.8	7.6	45	0	4	NA
6523	0.5	−44.9	52	47	5	3.8
6524	1.6	65.0	53	26	5	5.9
6526	−0.9	−45.9	10	48	4	2.0
Average	1.0	13.4		47.4	4.1	3.7

* the period between t'_b and t'_a defined in Fig. 1

* * the period between t_b and t_a defined in Fig. 1

* * * not included when taking average because of Zero for Passing - period - 1

Tango following the path of the strong pre-going Typhoon 6524. According to Fig. 7, the stronger the typhoon the more heat is supplied from the sea, for instance, a typhoon with central pressure 950 mb absorbs heat 6000 (cal/cm^2) for a typhoon passage twice as much as a typhoon with 975 mb does, confining the discussion to the group of the close passing-typhoons with help of the tendency line e-e of Fig. 7. This fact convinces us of the critical role of the sea in determining whether a typhoon will be large or small.

Determining the average size of a typhoon and the days lapsed during the typhoon passage with data on the typhoons used in this analysis, the average heat supplied to an average typhoon per day was estimated. We obtained the numerical values, as shown in Table 3, 3.7 lat. (410 km) in radius for the typhoon-size, and 47.4 hours (1.97days) and 4.1 days for the period from a time (t'_b shown in Fig. 1) of a typhoon coming in the circle zone of 5 lat. radius around Tango to a time (t'_a) of her passing away out of this zone and for the period from t_b to t_a, respectively. Assuming 4.1 days to be an over-estimation of the typhoon affecting period on the sea of Tango and 1.97 days to be its under-estimation, we came to the conclusion that a typhoon with the average size 3.7 lat. in radius is supplied with the heat of $7 \sim 15 \times 10^{25}$ erg/day through the underlying sea surface. These values are rather small but are in agreement in order - magnitude with the estimate 73×10^{25} erg/day given in the unfinished work of Dr. J. kondo (National Research Center for Disaster Prevention, Scientific and Technical Agency, Japan) who

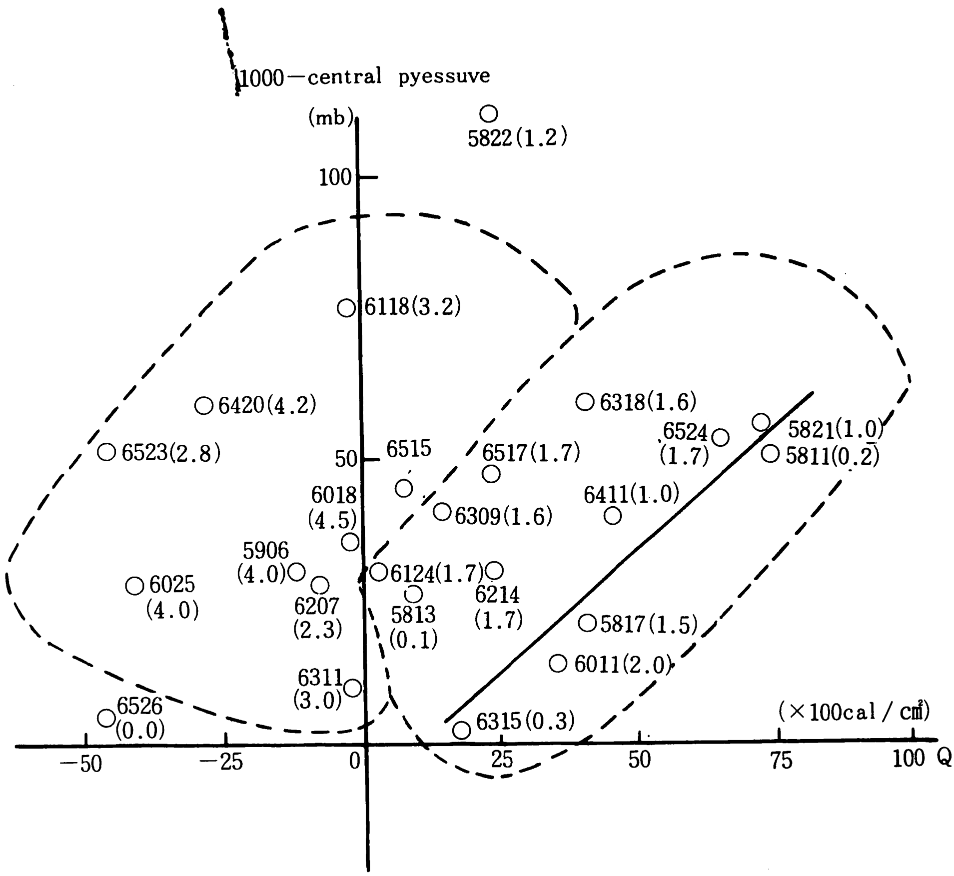

Fig. 7. Correlation between the central pressure of typhoons and the heat supplied from the sea in their passages

derived it in the calculation of the transfer of sensible heat and the latent heat of evaporation for several large typhoon cases.

4. References

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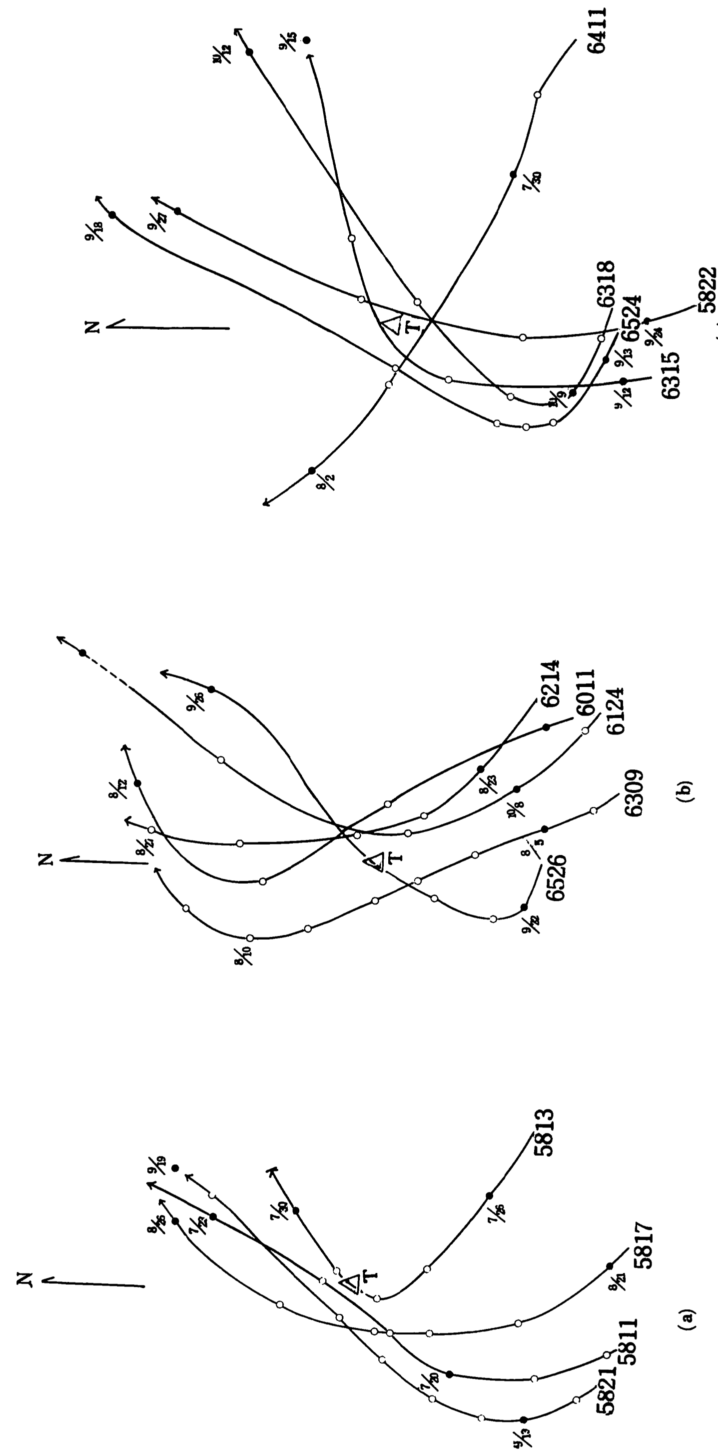
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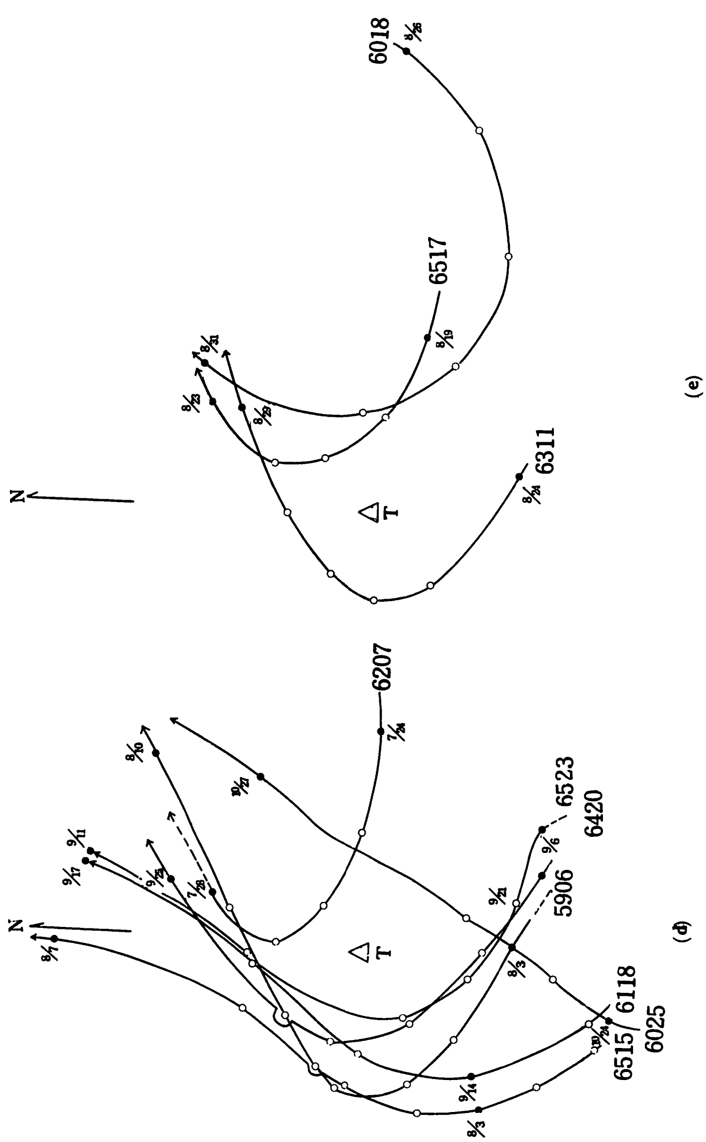

Supplemented Fig. 1. Courses of the typhoons used for analysis of vertical sea temperature structure

T……… a location of Tango

○,●……… typhoon center positions each day at 9:00

●) (●…… typhoon center positions on the days before and after her passage (tb,ta)

→………… typhoon dying point

→●……… typhoon center positions on tb. or ta in the domain farther than 15 lat. from Tango

(a) , (b) , (c) relatively close passing typhoons to Tango

(d) , (e) … relatively far passing typhoons from Tango

Supplemented Table 1. Difference between the before-typhoon sea surface temperature (T_2) and the during-typhoon sea surface temperature (T_1)

	6006								**6009**		
T_2 (°C)	29.90	29.80	29.90	29.90	29.90	30.00	29.60	28.35	28.85	28.75	28.60
T_1 (°C)	28.18	28.13	28.20	28.20	28.20	28.50	28.78	28.10	28.85	28.85	29.15
T_2-T_1	1.72	1.67	1.70	1.70	1.70	1.50	0.82	0.25	0.00	−0.10	−0.55
continued	**6018**					**6123**					
	28.50	28.38	28.05	27.68	27.13	28.65	28.48	28.15	28.15	28.00	27.00
	28.95	28.83	28.25	27.95	27.40	28.28	27.93	27.55	27.25	27.03	26.90
	−0.45	−0.45	−0.20	−0.27	−0.27	0.37	0.55	0.60	0.90	0.97	0.80
	6124					**6128**					**6207**
	29.10	29.10	28.60	28.18	27.80	28.00	27.53	27.28	27.05	26.85	27.70
	28.50	28.30	28.18	27.50	27.35	27.83	27.43	26.95	26.55	26.25	28.10
	0.60	0.80	0.42	0.68	0.45	0.17	0.10	0.33	0.50	0.60	−0.40
				6212						**6214**	
	27.75	27.45	26.70	29.40	29.25	28.70	28.25	27.73	27.05	29.22	29.00
	27.75	28.13	27.85	28.95	28.93	28.50	28.13	27.93	27.50	28.85	28.55
	−0.00	−0.68	−1.15	0.45	0.32	0.20	0.12	−0.20	−0.45	0.37	0.45
			6217						**6222**		
	28.68	28.33	29.05	29.05	28.95	29.10	29.10	28.98	28.75	28.83	28.90
	28.65	27.98	28.50	28.43	28.13	28.00	28.00	28.00	28.80	28.78	28.63
	0.03	0.35	0.55	0.62	0.82	1.10	1.10	0.98	−0.05	0.05	0.27
							6224				
	29.00	28.95	28.75	28.68	28.40	27.43	28.80	28.80	29.03	29.10	28.65
	28.48	28.40	28.40	28.40	28.33	27.60	28.40	28.25	27.85	27.53	27.33
	0.52	0.55	0.35	0.28	0.07	−0.17	0.40	0.55	1.18	1.57	1.32
				6228				**6304**			
	28.18	28.03	26.47	28.33	27.33	26.35	24.95	28.38	28.08	27.83	27.03
	27.30	26.70	25.50	27.58	26.73	25.73	24.38	28.05	27.90	27.43	26.28
	0.88	1.33	0.97	0.75	0.60	0.62	0.57	0.33	0.18	0.50	0.75
	6307			**6309**						**6314**	
	29.05	28.50	28.30	28.85	28.80	28.85	28.90	28.78	28.48	28.80	28.85
	28.40	28.18	28.18	28.83	28.90	28.88	28.73	28.45	28.30	28.90	28.53
	0.65	0.32	0.12	0.02	−0.10	−0.03	0.17	0.33	0.18	−0.10	0.32

Continued

		6317				**6318**				
28.85	28.80	29.28	29.08	28.25	26.37	29.10	29.05	28.85	28.58	28.20
29.00	29.23	28.68	28.35	27.43	25.88	29.20	29.13	28.93	28.55	28.10
−0.15	−0.43	0.60	0.73	0.82	0.49	−0.10	−0.08	−0.08	0.03	0.10
	6319						**6411**			**6515**
27.20	28.95	28.95	29.05	29.05	28.73	27.80	28.60	28.58	28.28	28.15
27.15	29.50	29.43	29.13	28.70	27.97	26.33	28.70	28.75	28.83	28.78
0.05	−0.55	−0.48	−0.08	0.35	0.76	1.47	−0.10	−0.17	−0.55	−0.63
			6517			**6520**				**6523**
28.20	28.55	28.65	28.80	28.63	28.13	29.33	29.05	28.43	27.48	29.20
28.68	28.40	28.23	28.90	28.73	28.18	29.03	28.68	28.05	27.35	28.93
−0.48	0.15	0.42	−0.10	−0.10	−0.05	0.30	0.37	0.38	0.13	0.27
			6524						**6528**	
29.08	28.75	28.53	29.05	29.05	28.78	28.83	28.90	28.80	28.95	28.90
28.48	28.75	28.88	28.70	28.55	28.10	27.85	27.90	27.88	28.05	27.85
0.68	0.00	−0.35	0.35	0.50	0.68	0.98	1.00	0.92	0.90	1.05
			6529			**6615**				
29.00	28.35	27.73	29.20	29.20	28.13	29.35	29.40	29.43	29.30	
27.23	25.75	24.95	28.05	27.98	25.50	28.55	28.50	28.65	28.25	
1.77	2.60	2.78	1.15	1.22	2.63	0.80	0.90	0.78	1.05	
6616										
28.75	28.45	28.43	28.70	28.83	29.03	29.48				
28.60	28.05	28.00	28.20	28.65	28.60	28.30				
0.15	0.40	0.43	0.50	0.18	0.43	1.18				

Supplemented Table 2. Five day average of the sea temperature (°C) exclusive of typhoon appearing days by levels of depth and by years

Surface level

Averaging period	1958	1959	1960	1961	1962	1963	1964	Average
7 / 1— 5	26.08	26.30			25.84			26.07
6—10	26.88	27.18			26.52			26.86
11—15	27.10	27.02			27.82	28.10	27.74	27.56
16—20	27.20	27.26	28.04		27.86	28.64	27.96	27.82
21—25		28.26	28.16	28.44	28.22	29.10	27.94	28.35
26—30		28.42	28.32			29.12	28.44	28.57
31— 8/ 4		28.55	28.88		27.88	29.06		28.59
8 / 5— 9	27.84		28.18		28.44			28.15
10—14	27.70				28.40		28.52	28.20
15—19	28.22	28.28	27.40		28.42	27.10		27.88
20—24				28.46		28.06		28.26
25—29				28.96			27.62	28.29
30— 9/ 3	27.76	29.02			27.70	28.02	28.28	28.15
9 / 4— 8	28.88	28.92	27.26		28.08	28.50	28.88	28.42
9—13	28.98	29.24	27.24	29.02	28.38		29.22	28.68
14—18			27.74		28.44		29.56	28.58
19—23	26.52		28.16	27.58	28.96	27.86		27.81
24—28			28.20	27.52	28.28	28.00		28.00
29—10/ 3	26.44		27.52		27.52	27.78	27.78	27.40
10/ 4— 8	25.56		26.66	27.74	27.20	27.84	27.70	27.11
9—13	25.34		26.68		26.76		27.28	26.51
14—18	25.52		25.74	27.33	26.08		26.66	26.26
19—23	25.16		25.50		26.26		25.88	25.70
24—28	24.96	25.48			25.76		25.62	25.45
20m—level								
7 / 1— 5	25.84	25.20			24.74			25.33
6—10	25.92	25.28			25.74			25.65
11—15	26.40	24.96			26.04	26.90	26.36	26.13
16—20	26.98	25.50	26.94		26.82	27.74	27.02	26.83
21—25		25.66	26.44	28.20	26.70	27.76	27.50	27.04
26—30		27.02	27.48			28.40	28.06	27.74
31— 8/ 4		27.75	28.10		27.66	29.02		28.13
8 / 5— 9	26.70		28.10		27.70			27.50
10—14	27.28				27.80		27.24	27.44
15—19	27.34	27.86	27.24		28.12	27.06		27.52
20—24				28.22		27.42		27.82
25—29				28.42			27.36	27.89
30— 9/ 3	26.06	28.60			27.00	27.70	27.24	27.32
9 / 4— 8	27.92	28.74	26.84		27.94	28.00	27.78	27.87
9—13	28.68	29.04	27.12	29.06	28.22		28.10	28.37
14—18			27.64		28.32		28.68	28.21
19—23	26.66		27.74	27.30	28.80	27.82		27.66
24—28			28.06	27.24	28.18	27.92		27.85
29—10/ 3	26.44		27.50		27.46	27.66	27.68	27.35
10/ 4— 8	25.56		26.64	27.42	27.14	27.70	27.66	27.02
9—13	25.36		26.54		26.74		27.28	26.48
14—18			25.64	26.70	26.04		26.62	26.10
19—23			25.52		26.14		25.70	25.63
24—28			25.76		25.14		25.70	25.63
24—28					25.76		25.44	25.39

Continued 2

30m level

	1958	1959	1960	1961	1962	1963	1964	Average
7 / 1− 5	25.52	24.72			24.24			24.83
6−10	24.90	24.52			24.70			24.71
11−15	24.48	24.42			24.70	24.58	24.44	24.52
16−20	24.66	24.26	25.16		25.82	26.50	24.60	25.16
21−25		24.40	24.62	26.90	25.66	26.56	25.06	25.53
26−30		25.90	25.24			26.78	26.92	26.21
31− 8/ 4		26.10	26.44		27.24	27.72		26.88
8 / 5− 9	26.28		27.16		26.22			26.55
10−14	25.94				26.52		26.46	26.31
15−19	26.34	27.54	26.56		27.36	26.90		26.94
20−24				28.03		27.26		27.65
25−29				28.24			27.22	27.73
30− 9/ 3	25.94	28.02			26.40	26.84	26.90	26.82
9 / 4− 8	27.48	28.36	26.54		27.32	27.06	27.42	27.36
9−13	27.86	28.72	26.74	28.86	27.72		27.76	27.94
14−18			27.46		27.88		28.12	27.82
19−23	26.42		27.52	27.26	28.46	27.72		27.48
24−28			27.78	27.02	27.96	27.74		27.65
29−10/ 3	26.48		27.22		27.46	27.60	27.60	27.27
10/ 4− 8	25.52		26.58	27.14	27.06	27.70	27.66	26.94
9−13	25.34		26.40		26.70		27.28	26.43
14−18	25.50		25.60	26.7	26.02		26.60	26.08
19−23	25.14		25.50		26.12		25.62	25.60
24−28	24.94				25.76		25.38	25.36

50m level

	1958	1959	1960	1961	1962	1963	1964	Average
7 / 1−5	24.60	23.84			22.14			23.53
6−10	22.90	23.72			22.52			23.05
11−15	22.60	23.34			22.92	21.90	22.74	22.70
16−20	22.74	23.40	23.66		23.88	23.48	22.56	23.29
21−25		22.82	23.06	24.48	23.96	24.10	22.60	23.50
26−30		23.30	23.56			23.86	23.56	23·57
31− 8/ 4		23.70	23.76		22.98	23.74		23.55
8 / 5− 9	23.18		24.66		22.62			23.49
10−14	23.16				22.62		24.00	23.26
15−19	23.88	24.64	23.66		23.88	26.62		24.54
20−24				24.44		26.66		25.55
25−29				26.44			25.98	26.21
30− 9/ 3	25.58	25.50			25.27	25.40	26.02	25.55
9 / 4− 8	25.84	24.84	26.22		25.84	26.06	25.92	25.79
9−13	25.46	26.02	25.96	25.60	26.40		26.36	25.97
14−18			25.18		26.58		26.28	26.01
19−23	25.30		24.34	26.86	26.76	26.12		25.88
24−28			25.10	26.73	26.38	26.76		26.24
29−10/ 3	25.52		25.04		27.30	26.32	26.54	26.14
10/ 4− 8	25.06		25.82	26.52	26.48	27.08	27.66	26.44
9−13	25.32		26.26		26.46		26.40	26.11
14−18	25.50		25.50	26.60	25.94		25.66	25.84
19−23	25.00		25.48		26.00		25.44	25.48
24−28	24.83	25.34			25.66		25.26	25.29

Continued 3

75m level

	1958	1959	1960	1961	1962	1963	1964	Average
7 / 1— 5	22.50	22.42			20.85			21.93
6—10	20.96	22.54			21.04			21.51
11—15	21.04	21.72			21.46	20.34	21.12	21.14
16—20	21.12	22.16	22.34		22.58	21.22	20.64	21.68
21—25		21.54	21.54	22.62	22.66	21.92	20.20	21.75
26—30		21.90	21.80			21.84	21.36	21.73
31— 8/ 4		21.85	22.00		21.18	21.56		21.65
8 / 5— 9	21.46		22.48		21.00			21.65
10—14	21.28				20.96		21.18	21.14
15—19	22.82	22.38	21.74		21.44	23.06		22.29
20—24				22.24		22.82		22.53
25—29				22.86			22.60	22.73
30— 9/ 3	22.10	22.38			22.15	23.52	23.78	22.79
9 / 4— 8	21.92	21.70	25.50		23.70	24.02	22.92	23.29
9—13	21.48	22.32	24.64	22.88	24.52		23.00	23.14
14—18			22.06		24.42		22.78	23.09
19—23	22.88		21.38	23.98	24.32	23.28		23.17
24—28			22.04	25.03	23.58	24.14		23.70
29—10/ 3	21.98		22.30		23.76	23.08	23.34	22.89
10/ 4— 8	22.26		22.94	25.44	23.66	23.10	22.88	23.38
9—13	22.44		24.44		23.02		22.84	23.19
14—18	22.22		23.50	26.50	24.36		22.60	23.84
19—23	22.42		23.60		25.20		22.98	23.55
24—28	22.04	24.40			25.38		23.78	23.30

100m level

	1958	1959	1960	1961	1962	1963	1964	Average
7 / 1— 5	20.84	21.26			20.12			20.74
6—10	19.90	21.54			20.16			20.53
11—15	20.08	20.94			20.42	19.30	19.82	20.11
16—20	20.08	20.76	21.30		21.40	19.50	19.60	20.44
21—25		20.64	20.76	21.06	21.44	20.54	19.08	20.59
26—30		20.84	20.64			20.76	19.66	20.48
31— 8/ 4		20.72	20.64		20.12	20.26		20.44
8 / 5— 9	20.36		21.12		20.02			20.50
10—14	20.44				19.92		19.72	20.03
15—19	21.30	20.90	20.56		20.22	20.72		20.74
20—24				20.70		21.14		20.92
25—29				21.20			20.44	20.82
30— 9/ 3	20.44	20.84			20.12	20.14	20.12	20.33
9 / 4— 8	20.22	20.10	21.96		21.38	21.38	20.90	20.99
9—13	19.62	20.56	21.80	21.52	22.48		21.10	21.18
14—18			20.50		22.22		21.28	21.33
19—23	20.32		19.96	21.96	22.12	20.62		21.00
24.28			20.94	22.53	21.88	21.82		21.79
29—10/ 3	20.14		20.60		21.84	20.88	21.38	20.97
10/ 4— 8	19.80		20.86	23.40	21.58	21.06	21.02	21.29
9—13	19.70		21.36		21.24		21.34	20.91
14—18	19.68		22.48	24.40	21.82		21.46	21.97
19—23	19.32		21.34		23.02		21.16	21.21
24—28	19.20	22.00			23.08		21.32	21.40

Supplemented Table 3. Observation records of the sea temperature by levels (T_b, T_a), correction factors (δT_n), and corrected temperatures after a typhoon passage (CT_a)

Typhoons	Levels	Before typhoons (T_d)	After typhoons (T_a)	Correction (δT_n)	Corrected (CT_a)	Change (δT_t)
5811	m	7/20	7/23	C	C7/23	C
	0	28.1	25.2	−0.2	25.0	3.1
	10	28.2	25.2			
	20	28.2	25.2	−0.4	24.8	3.4
	30	25.5	25.2	−0.8	24.4	1.1
	50	23.4	25.2	−0.2	25.0	−1.6
	76	22.3	21.5	0.0	21.5	0.8
	100	21.1	20.3	0.0	20.3	0.8
	150	19.9	19.3		19.3	0.6
	200	19.0	18.5		18.5	0.5
5813		7/26	7/30		C7/30	
	0	26.3	25.8	0.0	25.8	0.5
	10	26.2	25.9			
	20	25.8	25.9	−0.3	25.6	0.2
	30	25.4	25.9	−0.4	25.5	−0.1
	50	21.7	21.6	0.0	21.6	0.1
	75	20.5	20.8	0.0	20.8	−0.3
	100	19.7	20.0	0.0	20.0	−0.3
	150	18.9	19.0		19.0	−0.1
	200	18.4	18.3		18.3	0.1
5817		8/21	8/26		C8/26	
	0	28.5	27.0	−0.1	26.9	1.6
	10	28.6	27.0			
	20	28.2	27.0	−0.1	26.9	1.3
	30	27.3	27.0	−0.1	26.9	0.4
	50	23.8	23.8	−0.5	23.3	0.5
	75	22.4	21.8	−0.2	21.6	0.8
	100	21.9	20.7	0.0	20.7	1.2
	150	19.8	19.3		19.3	0.5
	200	18.9	18.7		18.7	0.2
5821		9/13	9/19		C9/19	
	0	29.1	26.0	0.2	26.2	2.9
	10	29.1	26.0			
	20	28.9	26.0	0.2	26.2	2.7
	30	27.6	26.0	0.1	26.1	1.5
	50	25.4	26.0	0.0	26.0	−0.6
	75	20.9	24.5	0.0	24.5	−3.6
	100	19.3	19.2	0.0	19.2	0.1
	150	18.0	18.0		18.0	0.0
	200	17.2	17.1			0.1

Continued 2

Typhoons	Levels	(Tb)	(Ta)	(δTn)	(CTa)	(δTt)
5822		9/24	9/27		C9/27	
	0	27.0	25.6	0.3	25.9	1.1
	10	26.9	26.6			
	20	26.7	25.6	0.2	25.8	0.9
	30	26.4	25.6	0.2	25.8	0.6
	50	25.4	23.2	0.0	23.2	2.2
	75	22.2	21.4	0.0	21.4	0.8
	100	20.2	20.0	0.0	20.0	0.2
	150	19.0	18.9		18.9	0.1
	200	17.7	17.6		18.6	0.1
5906		8/3	8/10		C8/10	
	0	28.6	27.9	0.4	28.3	0.3
	10	28.4	27.8			0.6
	20	28.1	27.7	0.4	28.1	0.0
	30	26.1	27.6	0.2	27.8	−1.7
	50	24.2	24.9	0.0	24.9	−0.7
	75	22.1	22.4	0.0	22.4	−0.3
	100	20.8	21.0	0.2	21.0	−0.2
	150	19.2	19.0		19.0	0.2
	200	18.1	18.0		18.0	0.1
6011		8/9	8/12		C8/12	
	0	28.1	27.1	0.1	27.2	0.9
	10	28.1	27.1			
	20	28.1	27.0	0.0	27.0	1.1
	30	28.0	26.9	0.0	26.9	1.1
	50	24.9	25.0	−0.2	24.8	0.1
	75	22.4	22.0	−0,2	21.8	0.6
	100	21.1	20.6	0.0	20.6	0.5
	150	18.9	19.6		19.6	−0.7
	200	18.1	18.7		18.7	−0.6
6018		8/26	8/31		C8/31	
	0	28.4	26.4	0.0	20.4	2.0
	10	28.3	26.4			
	20	27.9	26.3	0.1	26.4	1.5
	30	27.6	26.3	0.4	26.7	0.9
	50	25.8	26.2	0.1	26.3	−0.5
	75	23.0	26.0	−0.2	25.8	−2.8
	100	21.2	22.1	0.0	22.1	−0.9
	150	20.0	20.1		20.1	−0.1
	200	19.9	18.8		18.8	1.1