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A Study on the Foaming of Sea Water

—A Tentative Analysis of Wind Wave Data in View of the Foaming of Sea Water—

by

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Abstract

The present author treated tentatively the relation between the wind wave scales and the surface water temperatures in an open sea using the data of oceanographical observations taken at the Northern Fixed Point (39°N, 153°E) in the North Pacific Ocean with a view to the foaming of sea water, and the following results were obtained:

1) The general features of the annual variation in wind waves were discussed (Section 3).

2) The probability (P_3) of the appearance of the wind wave of scale 3 has a tendency to decrease with increasing surface water temperature, that is to say, the lower the surface water temperature becomes, the stronger the foaming ability (Section 4).

3) A quantity $S(=\tau h_0)$ was deifined, which is physically significant, in order to indicate the degree of foaming in actual cases, where τ and h_0 represent the half life and the initial height of foam layer, respectively. Using the values of the quantity calculated from the results of his laboratory experiments, the auther could ascertain that the relationship mentioned above holds good approximately (Section 5).

1. Introduction

It is a well-known fact that sea water has more intense foaming power than fresh water[1], and the phenomena concerning the foaming of sea weter, for example the foaming on ocean surface produced by wind actions, or the foaming in current rips or "Shiome" and so on, give us many important problems in oceanography. But, up to the present there have been few scientific researches on them. The present author has examined experimentally and theoretically the foaming of sea water and made some reports on the type of the decay of foam layer[2], the size distribution of bubbles in the foam layer[3] and so on[4].

He now intends to discuss the relation between the results obtained from laboratory experiments, and those of marine meteorological and oceanographical observations in actual seas. In the present paper he is going to analyse the wind wave data with a view to the foaming of sea water.

2. The data of observation used[5]

At the Northern Fixed Point (39°N, 153°E) in the North Pacific Ocean, marine meteorological and oceanographical observations have been carried out by the

Central Meteorological Observatory of Japan for seven years since October 1947.

As a tentative analysis, he treated the data for three of the seven years i. e. 1950, '52 and '53.

3. The annual variation of wind waves

It is necessary for prospected analyses to have a knowledge of the general features of wind waves in the region concerned, and so an examination thereof is our first task.

The wind-wave scales observed there for 3 years range from 0 to 7 in wave scale (0~9). For convenience' sake, we shall divide them into the following three classes

		wind-wave scale
Class 1:	rather calm sea	0, 1 and 2
Class 2:	〃 moderate sea	3 and 4
Class 3:	〃 rough sea	5, 6 and 7

The scale 3 or 4 in the above table corresponds to such a state that the sea surface is partly or totally covered with "white caps". It is to be noticed that remarkable white foam with which the surface of waves is covered partially or totally is an important indication in discriminating the wind wave scales, especially of scale 3 or 4. As shown in Table 1 and Fig. 1, at the Northern Fixed Point, about 60% of the total number in a year belongs to moderate sea, and about 40% to rather calm sea, while the number of rough sea is very small, attaing only to 3% of the total.

Generally speaking, stormy weather frequently appears in this district, for above-mentoned "moderate sea" rather corresponds to stormy weather than the calm, though there are few cases of phenomenal weathear. Calm sea

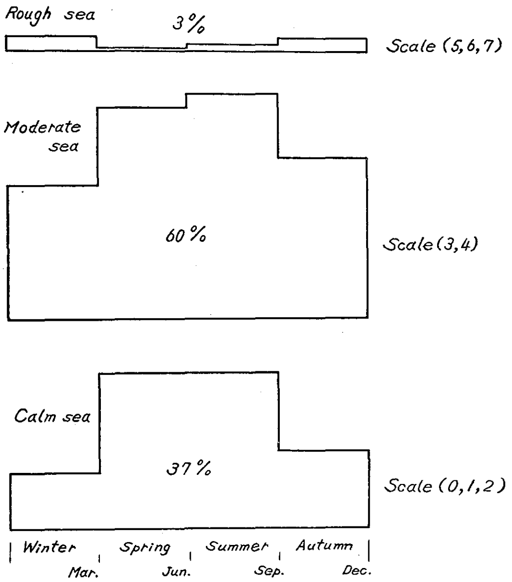

Fig. 1. Frequency diagram of wind wave.

Table 1. Seasonal variation of wind wave at the Northern Fixed Point (39°N, 153°E).
Number of case

Wind wave scale / Season	0	1	2	3	4	5	6	7	total
Winter (Jan.~Mar.)	0	5	15	30	15	4	1	0	70
Spring (Apr.~Jun.)	0	8	45	55	16	1	0	0	125
Summer (Jul.~Sep.)	0	17	36	60	16	1	0	1	131
Autumn (Oct.~Dec.)	1	7	19	40	14	2	2	0	85
Total	1	37	115	185	61	8	3	1	411
		153		246			12		411
Percentage		37%		60%			3%		100%

appears comparatively frequently in spring or summer, and rough sea in winter or autumn.

4. Relation between wind waves and the surface water temperature

Now, in order to obtain the relationship between the wind wave scales and surface water temperatures, the monthly average values of the surface water temperatures and of wind wave scales during the above-mentioned period were plotted as shown in Fig. 2. From this figure it seems to be the case that the lower the surface water temperature, the larger the number of the scale, that is to say, the surface water temperature falls with increasing wind force. A similar relationship has already been pointed out by P. Bintig [6] from many data of oceanographical observations in the West Biskaya and elsewhere. The present author examined only whether or not this relation

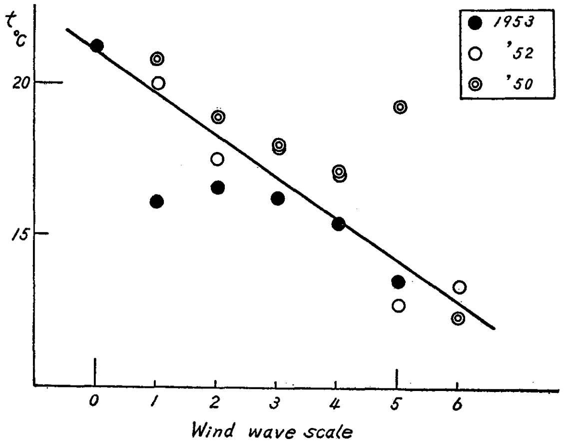

Fig. 2. Relation between surface water temperature (t) and wind wave scale.

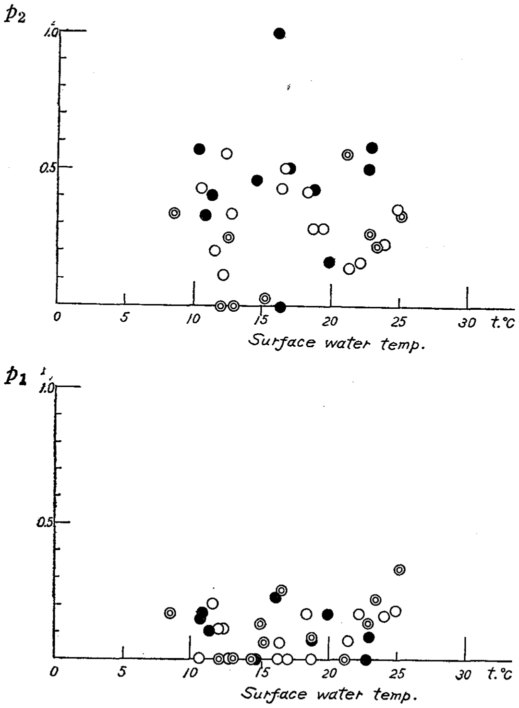

Fig. 3. Probability (p_1, p_2) and surface water temperarture.

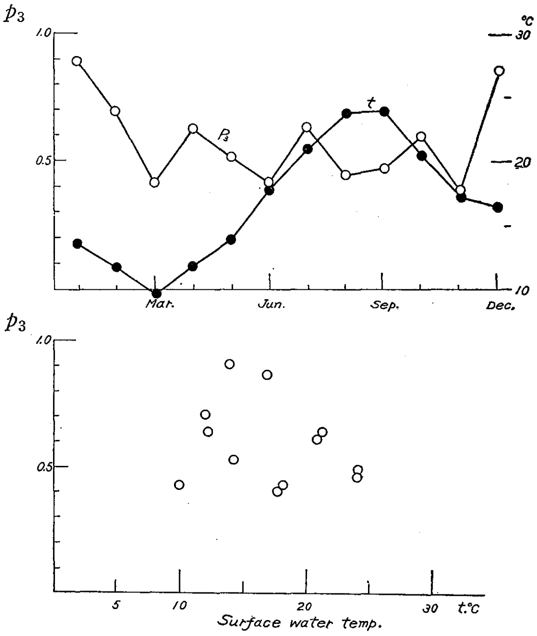

Fig. 4. Seasonal variations of p_3 and its relation to surface water temperature (t), where ●: t ○: p_3.

holds good for any wind wave. Now, consider the probability p_n or the frequency of appearance of any wind wave scale n during a certain month, where n is a positive integer (0, 1, 2, 3, etc). Thus, p_3 denotes the probability that "white-caps" are just formed by wind actions, and consequently the size of p_3 may be used as a good measure to represent the degree of appearance of "white-caps." The results of calculations with the actual data are summarized in Table 2.

Table 2. Seasonal variation of surface water temperature and the probability. (p_1, p_2 and p_3)

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1950	Surface water temp.	12.0	13.0	8.45	12.5	15.2	21.2	22.9	23.4	25.2	19.4	16.6	14.5
	p_1	0.00	0.00	0.17	0.13	0.059	0.00	0.13	0.22	0.33	0.072	0.25	0.00
	p_2	0.00	0.00	0.33	0.25	0.029	0.56	0.27	0.22	0.33	0.29	0.50	0.00
	p_3	1.00	1.00	0.50	0.62	0.65	0.44	0.60	0.56	0.33	0.64	0.25	1.00
1952	Surface water temp.	12.7	11.5	10.5	12.1	12.3	16.4	21.4	24.9	24.0	22.2	18.3	18.7
	p_1	0.00	0.20	0.00	0.11	0.11	0.062	0.074	0.18	0.15	0.17	0.17	0.00
	p_2	0.33	0.20	0.43	0.11	0.56	0.44	0.14	0.36	0.23	0.17	0.42	0.29
	p_3	0.70	0.60	0.57	0.78	0.33	0.50	0.79	0.46	0.62	0.67	0.42	0.71
1953	Surface water temp.	16.2	10.8	10.3	11.3	14.6	16.1	18.8	23.0	22.8	19.9	17.0	–
	p_1	0.00	0.17	0.14	0.10	0.00	0.22	0.071	0.083	0.00	0.17	0.0	–
	p_2	0.00	0.33	0.57	0.40	0.46	1.00	0.43	0.58	0.50	0.17	0.50	–
	p_3	1.00	0.50	0.30	0.50	0.54	0.31	0.50	0.33	0.50	0.50	0.50	–
Average	Surface water temp.	13.65	11.77	9.75	11.97	14.03	17.90	21.03	23.77	24.00	20.50	17.30	16.60
	p_1	0.00	0.12	0.10	0.11	0.057	0.095	0.092	0.16	0.16	0.13	0.14	0.00
	p_2	0.11	0.17	0.44	0.28	0.35	0.66	0.28	0.39	0.35	0.21	0.47	0.14
	p_3	0.90	0.70	0.42	0.62	0.52	0.42	0.63	0.45	0.48	0.60	0.39	0.86

The probabilties p_1, p_2 and p_3 were plotted against the surface water temperatures as abscissa as shown in Figs. 3 and 4. It is interesting to note that p_3 seems to have a tendency to decrease with increasing surface water temperatures, while both p_1 and p_2 are comparatively small and have no regular tendency. As regards this point further analysis will be made in the following.

As is well known, the state of the sea varies with the speed of wind blowing over it, that is to say, when the wind speed equals or exceeds 4 in Beaufort's scale (this includes the range 5.5~7.9 m/sec) or the corresponding scale 3 of the wind wave, an abrupt change in the state of the sea takes place. In other words, it changes from a smooth sea to a rough sea covered with "white-caps." Again, according to the results of laboratory experiments conducted by H. ROUSE and W. H. MUNK [7] at the Institute of Hydraulic Research, University of Iowa, and the photographs of the sea surface taken by the U. S. Navy and others the critical wind speed is about 6.3~7 m/sec, that is, when the wind speed exceeds this critical value, the state of the sea surface changes its pattern, which means physically the transition from laminar to turbulent flow. Hence, in the present analysis, only the winds with speed below 6 m/sec were treated.

For convenience' sake, we shall divide the data as follows:

Speed (m/sec) 0∼3, 3∼6 (every 3 m/sec),
Temperature (°C) 7∼10, 10∼13 and so on (every 3°C).

Then we shall have a relation between the probability (P_3) of appearance of "white-caps" and the surface water temperature (t) for speed range 3∼6 m/sec. Plotting P_3 against t using the observed data, we can see that P_3 decreases with increasing t, while the probability of appearance of both wind wave scales 1 and 2 has no apparent relation with t (see Fig. 5 and Table 3).

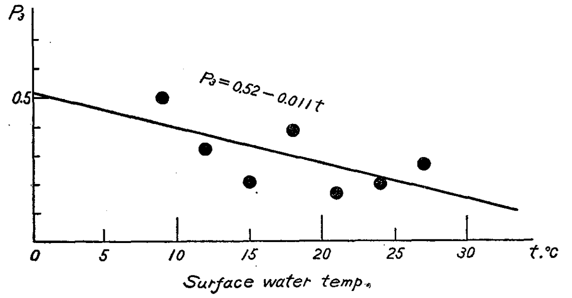

Fig. 5. Variations of P_3 with temperature. Wind speed 3∼6 m/sec. Standard deviation: about 0.080.

Table 3. Number of case of scale and its probability, wind wave range 3∼6 m/sec.

Range of surface water temp. °C	Wind wave scale	1	2	3	4	total	
	Number of case	0	1	1	0	2	
7∼10	Probability	0	0.50	0.50	0	1.00	
	Number of case	4	9	6	0	19	
10∼13	Probability	0.21	0.47	0.32	0	1.00	
	Number of case	2	6	2	0	10	
13∼16	Probability	0.20	0.60	0.20	0	1.00	
	Number of case	0	10	7	1	18	
16∼19	Probability	0	0.56	0.39	0.05	1.00	
	Number of case	4	10	3	0	18	
19∼22	Probability	0.22	0.56	0.17	0	1.00	except 1 case (scale 7, prob. 0.05)
	Number of case	3	9	3	0	15	
22∼25	Probability	0.20	0.60	0.20	0	1.00	
	Number of case	4	7	4	0	15	
25∼28	Probability	0.27	0.47	0.27	0	1.01	
total case		17	53	26	2		
		70		28			
ratio		1		0.4			

Thus, assuming a linear relation, we obtain the following formula graphically,

(1) $P_3=0.52-0.011\,t$ (Standard deviation: about 0.080).

5. Comparison of the observed and the experimental data

Now, we shall consider the phenomena relating to the foaming of sea water on the open sea surface. The sea surface is affected by blowing wind, and when the wind speed is gradually increasing, only small ripple waves appeare first here and there, and then these waves develop larger and larger, and spread over the sea surface. If the speed increases further, incipient " white-caps " at last begin to be seen here and there; this is the state of sea of wave scale 3, and then these " white-caps " develop well and cover the total sea surface; this is the state of sea of wave scale 4.

Table 4. Experimental value of h_0 or τ at various temperatures, sea water : 19.26 ‰ Cl.

Water temperature °C	29	21	14	4
h_0 mm	22.5	23.8	17.4	16.2
τ sec	4.8	5.5	10.0	10.0

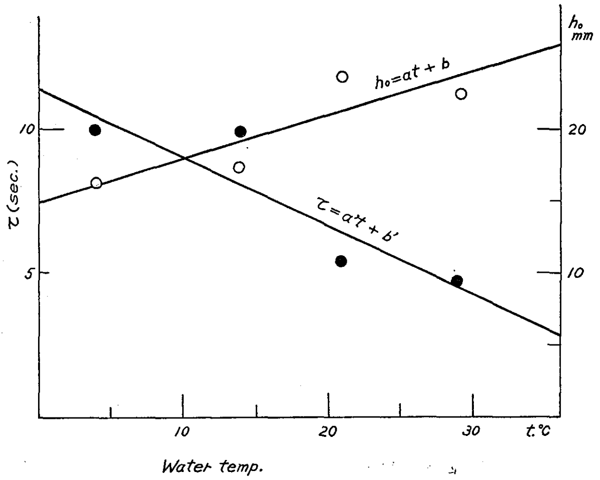

Fig. 6. Relation between water temperaure and τ or h_o, (Sea water : 19.26‰ Cl),
τ—● : half life of Foam layer,
h_o—○ : initial height of Foam layer.

Now, we shall examine the process of foaming in the foam layer on the sea surface in detail. It is necessary for the existence of the white foam on the sea surface that the life of each bubble making up the foam is of sufficient length to insure that another bubble having quantities equal to or more than those of the initial one is produced before the initial one disappears; in other words, the foam layer must have an adequate foaming ability.

Now, for the first approximation, let us suppose that when the chlorinity of sea water is contstant the life and the foaming ability of the foam layer are proportional to the half life (τ) and the initial height of the foam layer (h_0) respectively, then we have the following equation.

$$(2) \quad D(\text{degree of foaming condition of the sea surface})=f(\tau\cdot h_0),$$

or

$$D=K\cdot\tau h_0=K\cdot S,$$

where K is a constant.

The experimental data of τ and h_0 are tabulated in Table 4 [2], and the relation between t and τ or h_0 is shown in Fig. 6. Now, assuming a linear relationship between t and τ or h_0, we have the following equations graphically,

$$\text{(3)}\qquad h_o = at+b = 0.31\,t+15,$$

$$\text{(4)}\qquad \tau = a't+b' = -0.24\,t+12,$$

where a, b, a', ane b' are constants.

Then,

$$\text{(5)}\qquad S = h_0\tau = (at+b)(a't+b') = aa't^2+(ab'+a'b)t+bb'$$
$$= -0.074t^2+0.01t+170,$$

which represents a parabola, since $aa'<0$, the parabola being concave towards the t-axis and having only one maximum.

By differentiating equation (5) with respect to t, we have

$$\text{(6)}\qquad \frac{dS}{dt} = 2\times aa't+(ab'+a'b),$$

Equate $\frac{dS}{dt}$ to zero, then

$$\text{(7)}\qquad t_{max} = \frac{-(ab'+a'b)}{2\cdot aa'},$$

where t_{max} is the value of t for which S becomes maximum, or

$$t_{max} = \frac{-0.01}{2x(-0.074)} = 0.14°\text{C}.$$

Thus, the curve $S(t)$ is a decreasing function of t over a wide range of t (Table 5).

Table 5. Values of $h_0\ \tau$ at various times (calculated).

t(sec)	0	0.1	2	5	10	15	20	25	30
$h_0\ \tau$	170	170	170.9	169.5	164.6	155.9	143.5	127.5	107.7

The above-mentioned relation between S and t is none other than that which is expected as the relation between the foaming and the surface water temperature in the open sea. This relation is shown diagrammatically in Fig. 7. For the comparison between the result of laboratory experiments and that of oceanographical observations, the values calculated from equation (1) are plotted in Fig. 7. From this figure we can see that the two curves have similar tendency in regard to surface temperature, especially within the range of 10∼20°C.

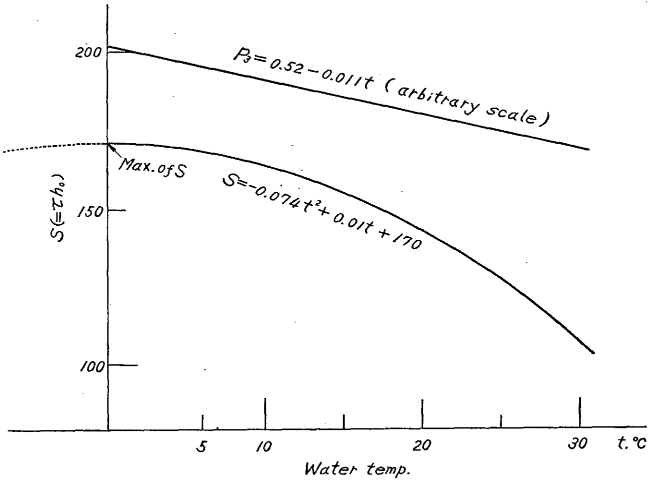

Fig. 7. Variation of S or P_3 with temperature.

6. Concluding remarks

As mentioned above, the quantity S derived from the author's experimental values and the probability of appearance of "white-caps" have an almost similar tendency with regard to the variation of surface water temperature, and so it will be possible to analyse the observed data of wind waves in an open sea according to the experimental results obtained in the laboratory. Probably, it corresponds to the constant vibrating condition of the ampule containing filtered sea water in the experiment, to limit the range of wind speed blowing over the sea surface.

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