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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 (II)—

by

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Abstract

The present author treated tentatively the relation between the wind speeds in the wind wave scale 3 and the surface water temperatures in an open sea using the data of oceanographical observations taken at the Ocean Weather Station "X" (39°N, 153°E) in the North Pacific Ocean in view of the foaming of sea water, and the following results were obtained:

1) The general features of the frequency distribution of wind speeds in the wind wave scale 3 were discussed (Section 3).

2) He defined a quantity R_θ, which is physically significant, in order to discriminate the degree of foaming in actual seas how often the white-caps appear, where θ represents the degree of surface water temperature. Using its values calculated from oceanographical data, he could ascertain that the higher the surface water temperature becomes, the lower the degree of foaming of sea water. This relationship coincided fairly well with the results of his previous report [1] (Section 4).

1. Introduction

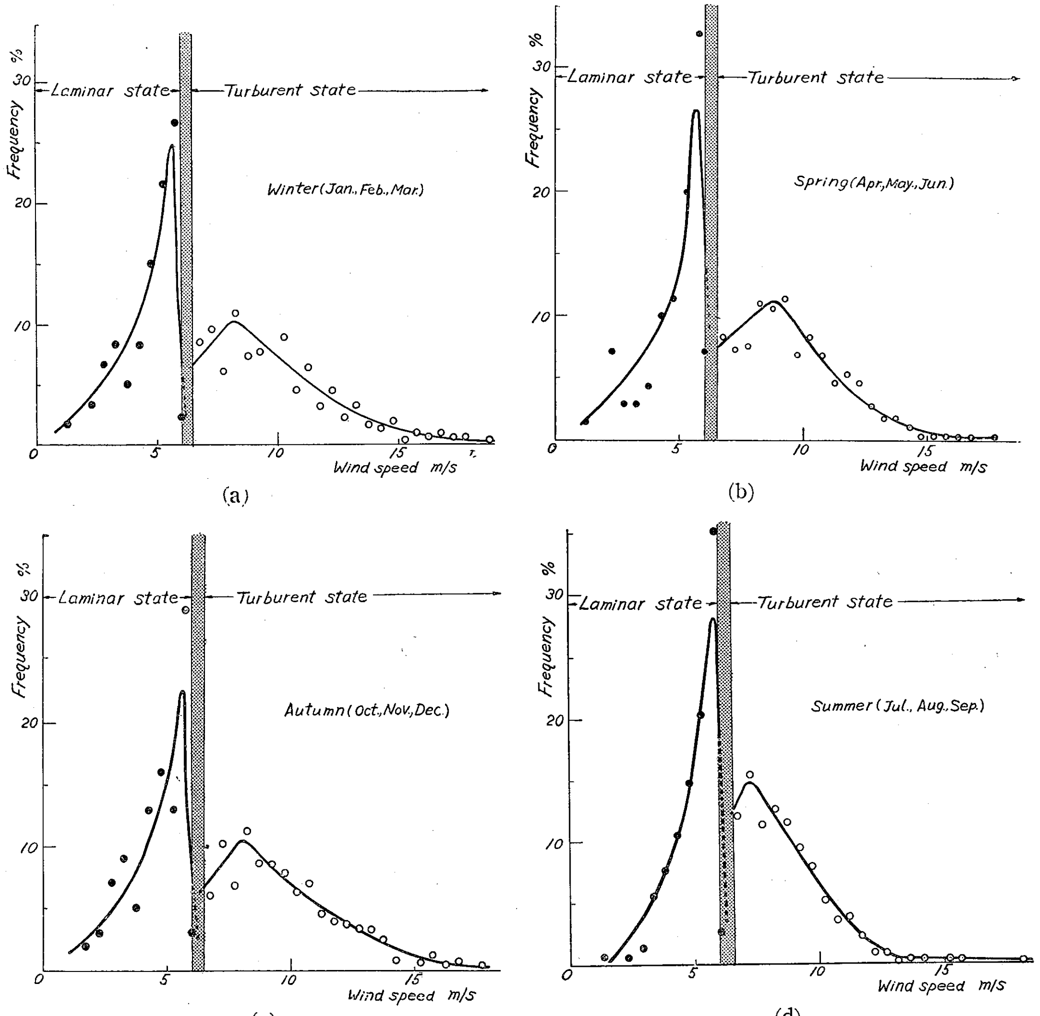
In a previous paper [1], the present author introduced a quantity S (equal to τh_0), which is physically significant, in order to indicate the degree of forming in actual seas, where τ and h_0 represent the half life and the initial height of foam layer, respectively. Using the values of the quantity S calculated from the results of his laboratory experiments, he could ascertain that the relation between S and water temperature is none other than that which is expected as the relation between the foaming and the surface water temperature in open sea, that is, within 6 m/s of wind speed on the open sea surface, it was theoretically and experimentally found that the higher the temperature of sea water becomes, the smaller the ability of foaming.

In the present paper, he will treat the same property of sea water in open sea from another standpoint, to ascertain whether this trend holds good in the case of sea water.

2. The data of observation used [2]

At the Ocean Weather Station "X" (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, the data of the wind wave scale 3 for three of the seven years i.e. 1948, '49 and '50 are treated. The data used were those of every 3 hours in this period, i.e. 03, 06, 09, 12, 15, 18, 21, and 24h of the day. The scale 3 denotes the state of the sea when the wave on the sea surface is partly covered with 'white-caps'. *This white foaming of sea water in 'white-caps' is a remarkable and important indication in discriminating the wind wave scale.*

3. Frequency distribution of wind speed in the wind wave scale 3.



(a) (b)

(c) (d)

Fig. 1. Frequency distribution of the wind speed at the wind wave scale 3, at the Ocean Weather Station "X" (39°N, 153°E), in 1948, '49 and '50.

Table 1. Wind speed and surface water temperature in wind wave scale 3, case of laminar state at the Ocean Weather Station "X" (39°N, 153°E), 1948, '49 and '50.

(a). Winter and Spring.

	S. water temp. °C Wind speed m/s	7~9	9~11	11~13	13~15	15~17	17~19	19~21	Total	%
Winter	1.0~1.5	—	—	1	—	—	—	—	1	1.67
	1.5~2.0	—	—	—	—	—	—	—	—	—
	2.0~2.5	—	—	2	—	—	—	—	2	3.34
	2.5~3.0	—	1	3	1*	—	—	—	4	6.66
	3.0~3.5	—	4	1	1*	—	—	—	5	8.33
	3.5~4.0	—	1	2	1*	—	—	—	3	5.00
	4.0~4.5	1	2	2	4*	—	—	—	5	8.33
	4.5~5.0	—	3	6	1*	—	—	—	9	15.0
	5.0~5.5	2	7	4	1*	—	—	—	13	21.6
	5.5~6.0	2	5	9	1*	—	—	—	16	26.6
	6.0	1	—	1	1*	—	—	—	2	2.34
	Total	6	23	31	8*	—	—	—	60	98.86
Spring	1.0~1.5	—	—	—	—	1	—	—	1	1.43
	1.5~2.0	—	—	—	—	—	—	—	—	—
	2.0~2.5	—	2	—	2	1	—	—	5	7.14
	2.5~3.0	—	—	1	1	—	—	—	2	2.85
	3.0~3.5	—	—	—	1	—	1	—	2	2.85
	3.5~4.0	—	—	—	2	—	1	—	3	4.28
	4.0~4.5	—	1	2	2	—	2	—	7	9.98
	4.5~5.0	—	2	—	5	—	1	1*	8	11.4
	5.0~5.5	—	4	3	4	2	1	—	14	20.0
	5 5~6.0	—	1	6	8	6	2	2*	23	32.8
	6.0	—	—	2	2	—	1	—	5	7.14
	Total	—	10	14	27	10	9	3*	70	99.87

*: excepted one

(b). Summer and Autumn.

	S. water temp. °C Wind speed m/s	11~13	13~15	15~17	17~19	19~21	21~23	23~25	25~27	Total	%
Summer	10. ~1.5	—	—	1	—	—	—	—	—	1	0.70
	1.5~2.0	—	—	—	—	—	—	—	—	—	—
	2.0~2.5	—	—	—	—	1	—	—	—	1	0.70
	2.5~3.0	—	—	—	—	—	1	1	—	2	1.41
	3.0~3.5	—	—	1	—	2	2	—	3	8	5.64
	3.5~4.0	—	—	1	—	1	6	1	2	11	7.75
	4.0~4.5	—	—	2	1	2	3	3	3	15	10.6
	4.5~5.0	—	—	1	1	1	7	4	7	21	14.8
	5.0~5.5	—	—	2	1	3	5	4	14	29	20.4
	5.5~6.0	—	—	3	5	5	8	8	21	50	35.2
	6.0	—	—	2	—	—	—	1	1	4	2.8
	Total	—	—	13	8	15	32	22	51	141	100.0
Autumn	1.0~1.5	—	—	—	—	—	—	—	—	—	—
	1.5~2.0	—	1	1	—	—	—	—	—	2	2
	2.0~2.5	1*	2	—	—	1	—	—	—	3	3
	2.5~3.0	1*	1	3	2	1	—	—	—	7	7
	3.0~3.5	—	1	3	2	2	1*	—	—	8	8
	3.5~4.0	—	1	—	3	1	—	—	—	5	5
	4.0~4.5	—	3	2	5	3	—	—	—	13	13
	4.5~5.0	—	5	4	4	3	—	—	—	16	16
	5.0~5.5	1*	5	2	4	2	—	—	—	13	13
	5.5~6.0	3*	8	6	11	4	—	—	—	29	29
	6.0	—	—	2	1	—	—	—	—	3	3
	Total	6*	27	23	32	17	1*	—	—	99	99

An analytical treatment of the data was preformed, considering transfigurations of sea surface features due to wind actions. An abrupt transfiguration of the sea features takes place when the wind speed equals or exceeds 6.6 m/s (MUNK [3], WOODCOCK [4]). In other words, it changes from a smooth sea to a rough sea covered with 'white-caps', that is, when the wind speed exceeds this critical value, the feature of the sea changes from a laminar to a turbulent state. And so, for convenience' sake, we shall henceforth divide all the data as follows:

Speed ranges (m/s) 1, ≤6 m/s: these are temporarily called laminar state,
" " 2, ≥6.5 m/s: these are temporarily called turbulent state.

The seasonal data of laminar and turbulent states are shown in Table 1 (a, b) and Table 2 (a, b), respectively. Here, the data containing only one of the 3 years were omitted as not representing the general featurs of the whole period, the data omitted being shown by an asterisk(*). The frequency distributions of the wind speed in the wind wave scale 3 were shown in Fig. 1 (a, b, c, d), which show the case of laminar and turbulent states separately. In the case of laminar state, the modes of wind speeds for 4 seasons were almost equal for

Table 2. Wind speed and surface water temperature in wind wave scale 3, case of turbulent state at the Ocean Weather Station "X" (39°N, 153°E), 1948, '49 and '50.

(a). Winter and Spring.

m: median value

Wind speed m/s \ S. water temp. °C		Winter						Spring							
	m	7~9	9~11	11~13	13~15	Total	%	9~11	11~13	13~15	15~17	17~19	19~21	Total	%
6.5~ 7.0	6.75	2	10	15	1*	27	8.61	5	11	11	4	9	5	45	8.35
7.0~ 7.5	7.25	2	14	14	—	30	9.58	2	16	13	5	1	1	38	7.21
7.5~ 8.0	7.75	2	7	10	2*	19	6.06	1	12	14	3	5	5	40	7.59
8.0~ 8.5	8.25	—	22	12	3*	34	10.85	9	11	19	3	11	5	58	11.0
8.5~ 9.0	8.75	3	16	4	1*	23	7.35	12	13	9	6	11	5	56	10.62
9.0~ 9.5	9.25	1	11	12	2*	24	7.66	8	14	14	4	20	—	60	11.4
9.5~10.0	9.75	2	14	8	3*	24	7.66	6	5	10	5	7	3	36	6.83
10.0~10.5	10.25	1	12	15	1*	28	8.95	12	10	10	3	4	5	44	8.35
10.5~11.0	10.75	1	8	5	1*	14	4.47	7	7	12	2	7	1	36	6.83
11.0~11.5	11.25	2	6	12	4*	20	6.38	4	8	2	1	6	3	24	4.55
11.5~12.0	11.75	—	5	5	1*	10	3.19	9	13	2	2	2	—	28	5.31
12.0~12.5	12.25	—	9	5	—	14	4.47	6	9	6	—	3	—	24	4.55
12.5~13.0	12.75	—	2	5	—	7	2.24	3	5	4	—	2	—	14	2.65
13.0~13.5	13.25	2	3	5	2*	10	3.19	2	3	3	—	1	—	9	1.71
13.5~14.0	13.75	—	4	1	1*	5	1.59	1	5	—	—	2	1	9	1.71
14.0~14.5	14.25	1	—	3	—	4	1.28	2	1	—	—	2	—	5	0.95
14.5~15.0	14.75	1	3	2	—	6	1.92	1	—	—	—	—	—	1	0.19
15.0~15.5	15.25	1	—	—	—	1	0.32	—	1	—	—	—	—	1	0.19
15.5~16.0	15.75	—	1	2	—	3	0.96	1	—	—	—	—	—	1	0.19
16.0~16.5	16.25	1	1	0	—	2	0.64	—	1	—	—	—	—	1	0.19
16.5~17.0	16.75	1	2	—	—	3	0.96	—	1	—	—	—	—	1	0.19
17.0~17.5	17.25	—	1	1	—	2	0.64	—	—	—	—	—	—	—	—
17.5~18.0	17.75	—	1	1	—	2	0.64	—	1	—	—	—	—	1	0.19
18.0~18.5	18.25	—	—	—	—	—	—	—	—	—	—	—	—	—	—
18.5~19.0	18.75	—	1	—	—	1	0.32	—	—	—	—	—	—	—	—
19.0~19.5	19.25	—	—	—	—	—	—	—	—	—	—	—	—	—	—
19.5~20.0	12.75	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Total		23	153	137	22*	313	99.9	—	—	—	—	—	—	527	100.7

(b). Autumn and Summer.

		Autumn								Summer							
Wind speed m/s \ S. water temp. °C		11~13	13~15	15~17	17~19	19~21	21~23	Total	%	15~17	17~19	19~21	21~23	23~25	25~27	Total	%
	m																
6.5~7.0	6.75	3*	4	6	6	12	3	31	6.07	6	3	9	10	12	18	68	21.1
7.0~7.5	7.25	3*	6	6	26	11	3	52	10.2	4	5	8	25	21	24	87	15.5
7.5~8.0	7.75	3*	2	4	17	11	1	35	6.86	2	2	11	18	11	20	64	11.9
8.0~8.5	8.25	1*	7	11	14	24	1	57	11.20	1	3	15	18	14	20	71	12.7
8.5~9.0	8.75	2*	7	5	14	16	2	44	8.63	1	2	5	20	19	18	65	11.6
9.0~9.5	9.25	1*	8	9	17	10	—	44	8.63	—	4	11	14	7	17	53	9.45
9.5~10.0	9.75	1*	7	9	9	15	—	40	7.84	—	4	5	9	13	14	45	8.02
10.0~10.5	10.25	1*	6	6	11	9	—	32	6.27	—	—	2	9	4	14	29	5.16
10.5~11.0	10.75	—	4	9	12	10	1	36	7.06	—	—	3	10	2	5	20	3.57
11.0~11.5	11.25	—	2	5	13	3	—	23	4.51	—	3	3	3	6	7	22	3.92
11.5~12.0	11.75	—	3	6	6	5	—	20	3.92	—	—	2	2	5	4	13	2.32
12.0~12.5	12.25	—	3	6	7	3	—	19	3.73	—	—	3	1	1	1	6	1.07
12.5~13.0	12.75	—	2	6	6	2	1	17	3.33	—	—	1	1	3	1	6	1.07
13.0~13.5	13.25	—	6	4	4	3	—	17	3.33	—	—	—	—	—	1	1	0.18
13.5~14.0	13.75	—	3	4	5	1	—	13	2.55	—	—	—	2	1	—	3	0.54
14.0~14.5	14.25	—	—	1	2	1	—	4	0.78	—	—	1	1	—	—	2	0.36
14.5~15.0	14.75	—	4	—	2	1	—	7	1.37	—	—	—	—	—	—	—	—
15.0~15.5	15.25	—	—	2	1	—	—	3	0.59	—	—	—	1	—	—	1	0.18
15.5~16.0	15.75	—	2	1	1	2	—	6	1.18	—	—	—	1	—	1	2	0.36
16.0~16.5	16.25	—	1	1	—	—	—	2	0.39	—	—	—	—	—	—	—	—
16.5~17.0	16.75	—	3	—	1	—	—	4	0.78	—	—	—	—	—	—	—	—
17.0~17.5	17.25	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
17.5~18.0	17.75	—	1	—	1	—	—	2	0.39	—	—	—	—	—	—	—	—
18.0~18.5	18.25	—	—	—	—	—	—	—	—	—	—	2	—	—	—	2	0.36
18.5~19.0	18.75	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
19.0~19.5	19.25	—	1	—	—	—	—	1	0.20	—	—	—	—	—	—	—	—
19.5~20.0	19.75	—	—	1	—	—	—	1	0.20	—	—	—	—	—	—	—	—
Total		15*	82	102	175	139	12	510	100.0	14	26	79	146	119	165	560	99.86

Table 3. Seasonal values of the mode of wind speed in turbulent state at the Ocean Weather Station "X" (39°N, 153°E).

Season	Winter	Spring	Summer	Autumn	Annual mean value
Wind speed of max. freq. (m/s)	8.3	9.0	7.3	8.0	8.15
Its freq. (%)	10.3	11.3	15.0	10.6	11.72

each, the values being 5.7 m/s of wind speed. In the case of turbulent state, however, the values of the modes differed slightly (Table 3) and the frequency distributions of wind speed were of the type of chisquare distribution as shown in Fig. 1 (a, b, c, d).

From the above tables and figures, it is seen that the moderate seas in this district mostly occur in summer.

4. Relation between the surface water temperature and the appearance of the wind wave scale 3

In a previous report [1], it was shown that the relation between the foaming and the surface water temperature in an open sea, and both the newly defined quantity S (a measure of the degree of the foaming condition on sea surface) derived from the present author's experimental values and the probabilities of the appearance of 'white-caps' which were calculated from the data of oceanographical observations, have an almost similar tendency with regard to the change of surface water temperature in an open sea.

In that report, it was also discussed from another viewpoint whether or not the above-mentioned relation holds good. Now, the relation between the wind stress and the wind speed has been discussed by many researchers and it seems appropriate to consider that the stress of wind blowing over sea surface is proportional to the square of its speed, that is,

$$\tau = K\rho_a V^2, \tag{1}$$

where τ is the stress of wind, V its speed, ρ_a the density of air, and K a constant; the value of K is 0.0008 when the flow is laminar, and 0.0026 when the flow is turbulent.

For analysing the data, the author sorted out the data according to the values of wind speeds in a similar manner to that previously mentioned, and in order to determine whether or not the case of the wind wave scale 3 appears more often at any wind speeds, he introduced the quantity R_θ when the surface water temperature is θ°C,

$$R_\theta = \frac{K_l \cdot (\Sigma n_l) \cdot \overline{v_l^2}}{K_t \cdot (\Sigma n_t) \cdot \overline{v_t^2}}, \tag{2}$$

where n is the number of appearance of the scale 3, $\overline{v^2}$ the mean square of wind speed at the sea surface, and suffixes l and t indicate the laminar and turbulent states, respectively; this was introduced on considering both the frequency of appearance of the wind wave scale 3 and the action of the wind.

Then the numerator and the denominator of Equ. (2) can be written as follows:

$$(\Sigma n_l) \cdot \overline{v_l^2} = (\Sigma n_l) \cdot \frac{\Sigma v_l^2}{\Sigma n_l} = \Sigma v_l^2, \tag{3}$$

$$(\Sigma n_t) \cdot \overline{v_t^2} = (\Sigma n_t) \cdot \frac{\Sigma v_t^2}{\Sigma n_t} = \Sigma v_t^2, \tag{4}$$

further,

$$\frac{K_l}{K_t} = \frac{0.0008}{0.0026} \fallingdotseq 0.308\,. \tag{5}$$

Then, by Equs. (3), (4) and (5), Equ. (2) becomes

$$R_\theta = 0.308 \times \frac{\Sigma v_l^2}{\Sigma v_t^2}\,. \tag{6}$$

Now, we shall consider the physical meaning of R_θ.

i) The case of $R_\theta > 1$.

This means that the white-caps appear more often in the case of laminar state than in turbulent state, in other words, the larger R_θ becomes, the larger the foaming ability of sea water.

ii) The case of $R_\theta = 1$.

This means that the degree of appearance of the white-caps in laminar state is the same as that in turbulent state, in other words, it also means that in either of laminar and turbulent states, the sea water has similar foaming ability, thus there is little effect of wind speed upon sea surface features.

iii) The case of $R_\theta < 1$.

This means that the white-caps appear more frequently in the case of turbulent state than in laminar state in other words, the smaller R_θ becomes, the smaller the frequency of appearance of the white-caps, and so the surface sea water does not easily foam when its temperature is high even though it is violently disturbed by the action of wind.

Table 4. Calculated values of R_θ.

Season		Summer			Autumn		
°C S. water temp.	Median	$\sum v_l^2$	$\sum v_t^2$	R_θ	$\sum v_l^2$	$\sum v_t^2$	R_θ
13～15	14	—	—	—	616	10,300	0.0185
15～17	16	310	752	0.126	510	11,600	0.0136
17～19	18	234	1,990	0.036	770	16,400	0.0145
19～21	20	347	6,340	0.0169	358	12,500	0.0086
21～23	22	729	11,290	0.0200	—	—	—
23～25	24	578	9,500	0.0188	—	—	—
25～27	26	1,390	13,000	0.033	—	—	—

The result of actual calculation of R_θ from the data of Tables 1 and 2 by use of Equ. (5), is shown in Table 4, where the cases containing data less than 10 observations were omitted, for they do not represent the general tendency. The calculations were limited to two seasons, summer and autumn, because in the other two seasons, winter and spring, the wind speeds were generally very large, and so the state of flow could hardly be regarded as laminar. The effect upon the sea surface is mostly due to wind speed, its effect being proportional to the square of its speed, and the effect of surface water temperature is not large. In general, the calculated values of R_θ are smaller than unity,

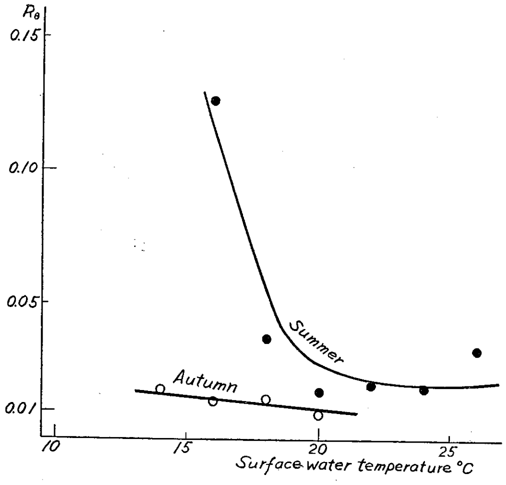


Fig. 2 Relation between the surface water temperature and R_θ at the Ocean Weather Station "X" (39°N, 153°E), 1948, '49 and '50.

which belongs to the case iii) mentioned above. The relations between R_θ and the surface water temperature are shown in Fig. 2.

For the above two seasons, R_θ decreases with increasing surface water temperature. And this tendency is especially remarkable in summer; namely, in this case R_θ decreases rapidly with increasing surface water temperature between 16° and 20°C and then it remains nearly constant afterwards. This is an interesting fact from the standpoint of physical oceanography. In autumn, R_θ is smaller than in summer and decreases almost linearly with increasing surface water temperature.

Therefore, we may generally say that the degree of appearance of the wind wave scale 3 decreases with increasing surface water temperature; in other words, there is a tendency such that the ability of foaming of sea water decreases with increasing surface water temperature as was previously mentioned.

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