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A STATISTICAL STUDY OF WAVE CONDITIONS AT FOUR OPEN-SEA LOCALITIES IN THE NORTH PACIFIC OCEAN

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SUMMARY

The present study of wave conditions in the Pacific Ocean was undertaken by the Scripps Institution of Oceanography to investigate the following characteristics of the sea and wind which are considered to be of primary importance in the structural design of flying boats and seaplanes: (a) Wave height and frequency of occurrence, (b) wave length-height ratio and frequency of occurrence, (c) wave velocity and its relation to wave lengths, (d) wind velocity, and (e) wave shape.

For each of four open-sea localities representing conditions for the main regions of the Pacific Ocean, the percentage frequencies of wave heights and wave length-height ratios have been calculated by use of weather maps and methods developed for forecasting sea and swell. These data have been presented in graphical and tabular forms. Also included in the present paper is the following information: Discussions of the relation between wave velocity and wave length, tabulation of wind-velocity distributions, discussions of wave shape, and examples of the use of the figures. Comparison between computed and observed heights was found to be satisfactory.

INTRODUCTION

For a study of open-sea conditions, comprehensive observations are lacking, and the few observations available are confined to wave height only. Consequently, it was necessary to compute wave heights and lengths from weather maps by using the methods previously developed for forecasting sea and swell. Daily computations were carried out for each of four representative localities of the Pacific Ocean for the 3-year period 1936-38. These computations form the basis for the summaries of wave conditions which appear in the present report.

For each of the stations the percentage frequencies of wave heights and wave length-height ratios have been calculated, and the data have been presented in graphical and tabular forms. By frequency of occurrence in the case of wave heights is meant the percentage of total time the wave height lies within a specified interval. A practical lower limit for specified intervals of wave height is 1 to 2 feet. By frequency of occurrence in the case of length-height ratio is meant the percentage of total time the length-height ratio lies within a specified interval. The lower limit of length-height ratio is of primary importance. The wind-velocity distributions have also been tabulated. Discussion of the relation between wave velocity and length and a discussion of wave shape are included in the report. Explanations and numerical examples for the use of the figures are given in the appendix.

The authors wish to express their appreciation to Dr. H. U. Sverdrup, without whose guidance, suggestions, and assistance this study would never have been accomplished.

DEFINITIONS OF TERMS

Sea	waves that are being generated by the local wind and are traveling nearly with the wind
Swell	waves that have been generated by distant winds and are traveling through regions of weaker winds or calms and are decreasing in height
Height	vertical distance from trough to crest of a wave
Length	horizontal distance from crest to crest of waves
Steepness	ratio of height to length of a wave (the steepness, however, is conveniently expressed by the inverse quantity, the length-to-height ratio)
Period	time interval between the appearance of two consecutive crests at a given place
Wave velocity	velocity with which the wave form travels

WAVE VELOCITY AND SHAPE

Wave Velocity

The wave velocity C, the length L, and the period T are so related that it is possible to express any one of them as a function of either of the others. For example:

$$C = \sqrt{\frac{gL}{2\pi}}$$

$$C = \frac{gT}{2\pi}$$

If C is in feet per second, T in seconds, and L in feet,

$$C = 2.26\sqrt{L}$$

$$C = 5.12T$$

or, with C in knots, T in seconds, and L in feet,

$$C = 1.34\sqrt{L}$$

$$C = 3.03T$$

Wave Shape

With a length-height ratio L/H greater than 100 the shape of a wave is nearly sinusoidal. As the length-height ratio decreases, the troughs become wider and flatter and the crests narrower and steeper until the wave form becomes unstable when the ratio L/H equals 7. If only a single train of waves were present, these shapes would be apparent to an observer. However, when the waves are steep (length-height ratio less than 30) there is always more than one train present, and the shape of the individual waves is masked by the resulting superposition of waves of different heights and lengths.

STATE OF THE SEA AND SIGNIFICANT WAVE HEIGHT

The appearance of the sea surface is too complicated to be pictured by a train of waves of equal heights and lengths.

In the generating area the individual waves are masked. Waves are traveling in different directions at small angles with the wind, and the consequent crisscrossing of waves leads to the checkerboard pattern of crests and troughs which is described as "short-crestedness." Even this pattern is always in a state of rapid change because the single waves are of different heights and lengths and travel with different velocities. Short and long waves and high and low waves cross each other in ever-changing combinations and produce the confused "sea" typical of the generating area.

As wave trains leave the generating area the shorter waves fall behind and are quickly dissipated and only the longer waves travel over great distances as "swell" which becomes smoother the farther it advances. But even the longest swell is not regular. It is composed of trains of waves of slightly different periods and these waves interfere with each other. When crests coincide they reinforce each other and groups of relatively high waves appear, whereas when the crests of one train coincide with the troughs of another a partial cancellation takes place and the resulting waves are low. Thus, groups of high waves and regions of low waves alternate.

Superimposed upon the swell there may appear new confused waves generated by local wind. The term "state of the sea" is applied to the combined effect of simultaneously present sea and swell.

Because of the irregular appearance of the sea surface, it is necessary to describe the waves that are present by means of some statistical term. This term should give emphasis to the higher waves because they are operationally more important than the lower ones, although the actual number of lower (and shorter) waves may be greater. For this reason, it is not advisable to state the mean wave height for, say, a $\frac{1}{2}$- or 1-hour observation period, but it is better to use the average height of the highest one-third of all observed waves. This average is used herein and is called the "significant wave height." This measure, as well as the mean, is not an exact measure because it depends upon the extent to which small waves have been recorded. If every ripple is counted as a "wave," both the mean height and the average height of the one-third-highest waves are reduced. Tests indicate that the average height of the one-third-highest waves is less dependent upon the scope of the observations than is the mean height and is, therefore, a more consistent measure. Furthermore, a casual observer tends to pay more attention to the higher waves and reports a wave height which lies closer to the significant wave height than to the mean.

The meaning of the terms as well as the variability in wave height can be illustrated by means of two examples. Figure 1 shows the frequency distribution of wave heights according to a German report (reference 1) in which observations of "sea" in a generating area in the North Sea are discussed. Since the wind velocity was only 12 knots, the waves were small with short periods. The significant wave height which a casual observer could be expected to record and which is used in this report as a basis for calculating frequencies was 1.6 times the mean height of all waves. The highest waves present were approximately $1\frac{1}{2}$ times the significant wave height. The periods of the waves also varied within wide limits. The average period of the highest one-third of the waves was about 1.3 times greater than the value of the mean period of all the waves.

Figure 2 is a reproduction of a graph taken from a statistical analysis of "swell" recorded off the Scripps Institution of Oceanography (reference 2) by means of a pressure recorder. The lower waves were somewhat less dominating than in the preceding example, and the significant wave height was 1.5 times the mean wave height.

Figure 3 shows a comparison of the wave-height characteristics of sea (from reference 1) and swell (from reference 2). The significant wave height has been given a relative value of 1.0. Therefore, if the significant wave height is known, the heights of the highest, of the mean, and of the low waves can be computed, as well as the percentages of waves higher or lower than any stated value. The following table contains the relative values of these wave heights and the corresponding percentages of higher waves.

COMPARISON OF WAVE-HEIGHT CHARACTERISTICS FOR SEA AND SWELL

Wave	Relative height		Occurrence of higher waves (percent)	
	Sea	Swell	Sea	Swell
Significant (highest one-third)	1.00	1.00	12.5	12.5
Highest	1.52	1.63	<1	<1
Average	.62	.66	45	52
Low	.25	.25	88	90

By using this table, it is seen, for example, that if swell has a significant wave height of 10 feet, the highest waves are 16.3 feet, with higher waves occurring less than 1 percent of the time; the mean waves are 6.6 feet, with higher waves occurring 52 percent of the time; and the low waves are 2.5 feet, with higher ones occurring 90 percent of the time. Figure 3 and this table represent preliminary results and should be used only as guides until a larger number of records of sea and swell has been analyzed statistically. The figure and the table are needed for the correct interpretation of the results which are discussed in the following part of the report, because this discussion deals only with the significant wave heights.

METHOD OF ANALYSIS OF WAVE CHARACTERISTICS

General

Daily weather maps for the years 1936-38 were used in computing the wave characteristics (reference 3). With certain indicated exceptions, the methods of forecasting, graphs, theories, and formulas of wave motion and shape were taken from reference 4. The information on wind conditions was obtained from reference 5.

The frequency of wave heights and of length-height ratios, the general state of the sea, and the frequency of wind velocities were determined for the following open-sea localities in the Pacific Ocean (see fig. 4):

Station A . . . . 50.0° N. 150° W.

Station B . . . . 32.5° N. 150° E.

Station C . . . . 32.5° N. 140° W.

Station D . . . . 28.0° N. 177.5° W.

Determination of Significant Wave-Height Frequencies

For each station the significant wave heights were computed for a 3-year period. Plates I to VI, reference 4, were used in calculating the heights and periods at the four stations.

The daily weather maps were used to determine at least one wave height and period for each 24 hours. All waves generated by winds of 9 knots or less were evaluated as less than 2 feet and the actual height was not calculated. The highest waves present at any time were used in drawing a smooth curve of wave height against time for each year.

The yearly curves of wave height were then summarized for certain ranges. For waves smaller than 10 feet, 2-foot intervals were used because of the greater frequency of occurrence of waves of these heights. The remaining intervals were taken as 10 to 15 feet, 15 to 20 feet, and greater than 20 feet. In this report the lower limit is included in the interval, for example, 15-foot waves are included in the range of 15 to 20 feet. The length of time in which the wave height occurred in each range was determined to the nearest 0.1 day. The frequency of occurrence of waves in a given range was expressed as the ratio between the number of days with waves in that range and the total number of days in the months under consideration.

The annual and seasonal frequencies of occurrence of wave heights for each station appear in tables I to IV. Three seasons were used: Winter (Jan., Feb., Mar., Dec.), transitional (Apr., May, Oct., Nov.), and summer (June, July, Aug., Sept.).

The cumulative percentage distribution of wave height for each station is shown in figures 5 to 8.

Station B was the only station where typhoons appeared frequently enough to be taken into consideration. Because no completely satisfactory method has been developed for forecasting the wave heights from typhoons, these waves were omitted from the analysis, but the number of days was recorded when sea or swell greater than 2 feet originating from typhoons might be expected at station B. This time was subtracted from the total time, and the frequency of wave heights was calculated on the basis of the percentage remaining, as shown in table II and figure 6.

Determination of Length-Height Ratios

In order to determine the L/H ratio, the length was obtained from the computed period by using the formula $L = gT^2/2\pi$. The height was obtained from the wave-height curve. Since the height curve was drawn for the highest waves present, the L/H ratios are associated with the highest waves with the following exceptions: (1) No ratios of L/H were calculated for waves less than 2 feet in height and (2) when the swell was higher than the sea but the sea was greater than 4 feet, the ratio L/H for the sea was used since it gave the lower value. This ratio was computed rather than the one pertaining to a higher swell because it is believed that the lower value is of greater importance to seaplane operations.

When plotted against time, the L/H curve did not appear as a single continuous curve but resolved into a series of curves, each representing the dominant wave train. For example, the L/H ratio for a swell coming from a distant storm may be 100 and be increasing as the decaying swell decreases in height; but when a local wind generates waves which become equal to or higher than the swell, a new train of waves appears and the significant L/H ratio changes discontinuously from greater than 100 to 25 or less.

None of the computed values of the ratio L/H was less than 15. Theoretically, the wave form becomes unstable and breaks when the ratio L/H is 7, but observations indicate the lower limit to be about 12.

A frequency distribution of length-height ratios was obtained for each given wave-height range above 2 feet. The results appear in tables V to VIII. Figures 9(a) to 9(d) show the percentage distributions of length-height ratios at the four stations.

STATE OF THE SEA

Three categories were used in describing the state of the sea: (1) All waves less than 2 feet, (2) waves greater than 2 feet with sea predominant, and (3) waves greater than 2 feet with swell predominant. A monthly frequency-distribution graph was constructed for each station as shown in figures 10(a) to 10(d). When sea is predominant, the waves are short and irregular with steep crests, and when swell is predominant, the waves are long and low and are nearly sinusoidal in shape.

WIND VELOCITY

By using reference 5, frequencies of wind force on the Beaufort scale were tabulated for each of the four stations. The following charts were used:

(1) Charts 3 to 14, which show percentage of winds of Beaufort force 0 to 3, or percentage of winds of Beaufort force 4 or higher if dominant 60 percent or more of the time

(2) Charts 31 to 34, which show percentage of wind observations that show Beaufort force 0

(3) Charts 35 to 46, which show percentage of winds of Beaufort force 7 or higher

(4) Charts 47 to 50, which show percentage of winds of Beaufort force 8 or higher

These data were used to plot points representing frequencies of occurrence of the foregoing wind velocities for each month. Smooth curves were drawn between the points and these curves were used to obtain the frequencies of occurrence of various intervals of Beaufort force shown in table IX.

RESULTS

The height frequencies and length-height ratio frequencies for the four stations are presented in tables I to VIII and figures 5 to 10. The height tables (tables I to IV) give the annual and seasonal percentage frequencies of waves of different heights. The tables of length-height ratio (tables V to VIII) give the percentage frequencies of L/H ratios for different ranges in wave height and for all waves greater than 2 feet.

Figures 5 to 8 present the same data as the height tables in a different form. The curve represents the cumulative frequency of wave heights so that it is possible to read directly the percentage of waves below or above a given height. Figures 5(a) to 8(a) give the curves for a whole year and figures 5(b) to 8(b), the seasonal curves.

Figure 9 represents the data in the tables of length-height ratio as cumulative-frequency curves. From these curves of L/H it is possible to determine for any wave height the percentage of time that the L/H ratio will be at or below a given value. Figure 10 shows the percentage of time for each month that waves will be less than 2 feet or that sea and swell will be predominant when the waves are greater than 2 feet.

The graphs in figures 5 to 10 are intended to summarize the wave characteristics in such a manner that the essential features can be seen at a glance. If graphs are used for computing frequencies under stated conditions, as discussed under EXPLANATIONS AND EXAMPLES, it is recommended to replot the curves on graph paper. The information needed for the replotting is contained in tables I to VIII.

It is again emphasized that tables I to VIII and figures 5 to 10 show the significant wave heights only. If the significant wave height is known approximately, information as to the occurrence of higher or lower waves can be obtained by using figure 3 or the table COMPARISON OF WAVE-HEIGHT CHARACTERISTICS OF SEA AND SWELL.

COMPARISON OF COMPUTED WITH OBSERVED VALUES

In order to obtain some check on the validity of the computed wave heights and frequencies, these values were compared with wave observations entered on the charts of reference 6. The observations were taken during the period 1924-38. On each monthly chart the observations are grouped for 2° squares and presented in the form of histograms. Columns representing the percentage of frequency for the following height ranges are shown: 0 to 3 feet, 3 to 8 feet, 8 to 20 feet, and greater than 20 feet. When a station was located within one of the 2° squares, the percentage values of that square were used. When the station lay between two squares, the values from both were averaged, and when the station was located on a corner, the values from the four surrounding squares were averaged.

By using the values for 3, 8, and 20 feet, a cumulative percentage graph was plotted for each of the four stations. From these graphs and the cumulative graphs of computed wave height, the percentage frequency for every 2-foot height range up to 20 feet was read, so that the observed values would be comparable to the computed ones. Figure 11 shows frequency of occurrence of observed and computed wave heights for each of the four stations.

At stations A and D the heights with maximum frequencies are identical for the observed and computed curves, but at stations B and C the computed heights with maximum frequencies are 1.0 foot and 1.5 feet lower, respectively, than the observed heights. The shapes of the curves in all cases, however, show close agreement, and the discrepancies at stations B and C may be due to the wide height ranges in which the original observed data were grouped.

CONCLUDING REMARK

A statistical study of wave conditions at four open-sea localities in the north Pacific Ocean showed that the method of calculating the percentage frequencies of wave heights and wave length-height ratios gives satisfactory results in the comparison between computed and observed values.

Scripps Institution of Oceanography
La Jolla, Calif., July 1, 1946

APPENDIX

EXPLANATIONS AND EXAMPLES

Figures 5 to 8

Figures 5 to 8 show the cumulative percentage frequencies of given wave heights. Figures 5(a) to 8(a) contain one curve for the entire year and figures 5(b) to 8(b) contain three curves, for winter (Dec., Jan., Feb., Mar.), summer (June, July, Aug., Sept.), and the transitional months (Apr., May, Oct., Nov.).

To find the cumulative percentage frequency of all wave heights up to and including a given height, enter the graph at the base with the given wave height, follow a vertical to its intersection with a curve, and read the percentage frequency on the vertical scales.

EXAMPLE: At station A, find the frequency of waves less than 4 feet in summer.

Answer: 61 percent.

To find the percentage frequency of occurrences of wave heights within stated limits, find first the percentage frequencies at the given limits and next subtract the percentage obtained by using the lower limit from the percentage obtained by using the upper limit.

EXAMPLE: At station A, find the frequency of waves between 3 and 5 feet in winter.

Answer:

Frequency of 5-foot waves,	28 percent
Frequency of 3-foot waves,	11 percent
Percentage of waves between 3 and 5 feet,	17 percent

Figure 9

Figure 9 contains a set of curves for length-height ratios 20, 30, 40, 60, 100, and 200. Each curve shows the frequency of occurrence of all length-height ratios (as function of the wave height) lower than that entered on the curve.

To find the frequency with which waves of given height have a length-height ratio less than a stated value, enter the graph at the base with the given wave height, follow a vertical to the curve marked with the stated value of the L/H ratio, and read the percentage on the vertical scales.

EXAMPLE: At station A, find the frequency of 6-foot waves having L/H ratio of 40 or lower.

Answer: 55 percent.

To find the frequency of waves of given height having L/H ratio between stated limits, enter the graph at the base with the given wave height, follow a vertical to its intersection with the curves representing the given limits of the L/H ratio, read the percentages, and subtract the lower from the higher.

EXAMPLE: At station A, find the frequency of 4-foot waves falling in the range of L/H ratio of 60 to 100.

Answer: Frequency of 4-foot waves of L/H ratio 100 or less,	85 percent
Frequency of 4-foot waves of L/H ratio 60 or less,	70 percent
Frequency of 4-foot waves in range of L/H ratio of 60 to 100	15 percent

If a height range is given instead of a height, the answers are obtained by entering the base of the graph with the average wave height in the range.

Figures 5(a) to 8(a) and Figure 9 Combined, or

Figures 5(b) to 8(b) and Figure 9 Combined

To find the frequency of occurrence of waves in a given height range and a given range of the L/H ratio, obtain the frequency of occurrence of waves of a given height from figures 5(a) to 8(a) or figures 5(b) to 8(b), and obtain the frequency when these waves lie in a given range of the L/H ratio from figure 9. Multiply the two percentages and divide the product by 100.

EXAMPLE: At station A, find the annual frequency of occurrence of waves between 6 and 8 feet with an L/H ratio between 20 and 40.

Answer: From figure 5(a) the frequency of occurrence of waves between 6 and 8 feet is found to be 17 percent. From figure 9(a) the frequency of 7-foot waves (the average of 6- and 8-ft waves) in the range 20 to 40 of the L/H ratio is found to be 61 percent. Multiply 17 by 61, divide by 100, and the result is that waves between 6 and 8 feet having an L/H ratio between 20 and 40 occur with a frequency of 10 percent.

Figure 10

Figure 10 shows the monthly frequencies of (1) waves lower than 2 feet; (2) waves higher than 2 feet, swell predominant; and (3) waves higher than 2 feet, sea predominant. The lower curve shows the monthly frequencies of waves lower than 2 feet and the upper curve shows the combined monthly frequencies of waves lower than 2 feet and higher than 2 feet with swell predominant.

To find the frequency of occurrence of waves lower than 2 feet in a given month, enter the base with that month, follow a vertical to its intersection with the lower curve, and read off the percentage frequency on the vertical scales.

EXAMPLE: At station A, find the percentage frequency of waves lower than 2 feet in July.

Answer: 28 percent.

To find the frequency of occurrence of waves higher than 2 feet, swell predominant in a given month, enter the graph at the base with that month, follow a vertical to its intersection with both curves, read the corresponding percentages, and subtract the smaller from the larger.

EXAMPLE: At station A, find the percentage frequency of waves greater than 2 feet in April.

Answer: From upper curve, 45 percent
From lower curve, 11 percent
Frequency of waves greater than 2 feet with swell predominant, 34 percent

To find the frequency of occurrence of waves greater than 2 feet, sea predominant in a given month, enter the base with that month, follow a vertical to its intersection with the upper curve, read the percentage on the vertical scale, and subtract this reading from 100.

EXAMPLE: At station A, find the frequency of occurrence in October of waves higher than 2 feet, sea predominant.

Answer: From upper curve, 36 percent
Frequency of occurrence of waves higher than 2 feet, sea predominant,
100 percent - 36 percent = 64 percent.

REFERENCES

1. Ehring, H.: Kennzeichnung des gemessenen Seegangs auf Grund der Haüfigkeitsverteilung von Wellenhöhe, Wellenlänge und Steilheit. T.B. 4, 1940, pp. 152-155. (Translation: U. S. Hydrographic Office, S.I.O. Wave Project, Rep. No. 54, Contract NObs 2490.)

2. Anon.: Proposed Uniform Procedure for Observing Waves and Interpreting Instrument Records. S.I.O. Wave Project, Rep. No. 26, Dec. 12, 1944.

3. Daily Synoptic Series, Historical Weather Maps, Northern Hemisphere Sea Level. U. S. Weather Bureau, for 1936-1938.

4. Anon.: Wind Waves and Swell. Principles in Forecasting. U. S. Hydrographic Office, H.O. Misc. No. 11,275. (Published in revised form: Sverdrup, H. U., and Munk, W. H.: Wind Sea and Swell - Theory of Relations for Forecasting. H.O. Pub. No. 601, 1947.)

5. Anon.: Atlas of Climatic Charts of the Oceans. U. S. Weather Bureau, No. 1,247, Oct. 1, 1938.

6. Anon.: Waves in the North Pacific Ocean. U. S. Hydrographic Office, H.O. Misc. No. 11,117.

TABLE I.- FREQUENCY OF OCCURRENCE OF SIGNIFICANT WAVE HEIGHT

EXPRESSED IN PERCENT - STATION A

Period \ Wave-height range	Less than 2 feet	2-4 feet	4-6 feet	6-8 feet	8-10 feet	10-15 feet	15-20 feet	Greater than 20 feet	Total
Winter (Dec., Jan., Feb., Mar.)	4.3	15.7	20.4	18.0	17.1	16.9	5.4	2.2	100.0
Transitional (Apr., May, Oct., Nov.)	7.4	16.0	20.8	21.2	14.0	17.0	2.8	.8	100.0
Summer (June, July, Aug., Sept.)	31.7	29.3	22.8	11.3	3.5	1.4	---	---	100.0
Annual	14.5	20.4	21.4	16.8	11.5	11.7	2.7	1.0	100.0

TABLE II.- FREQUENCY OF OCCURRENCE OF SIGNIFICANT WAVE HEIGHT

EXPRESSED IN PERCENT - STATION B

Period \ Wave-height range	Less than 2 feet	2-4 feet	4-6 feet	6-8 feet	8-10 feet	10-15 feet	15-20 feet	Greater than 20 feet	Hurricane frequency	Total
Winter (Dec., Jan., Feb., Mar.)	8.6	26.5	21.0	17.0	11.6	12.0	1.9	1.4	----	100.0
Transitional (Apr., May, Oct., Nov.)	26.0	33.1	19.7	8.2	3.9	2.5	.1	.2	6.3	100.0
Summer (June, July, Aug., Sept.)	51.4	25.5	7.0	3.7	1.6	----	---	---	10.8	100.0
Annual	29.6	28.4	15.5	9.3	5.6	4.6	.7	.6	5.7	100.0

TABLE III.- FREQUENCY OF OCCURRENCE OF SIGNIFICANT WAVE HEIGHT

EXPRESSED IN PERCENT - STATION C

Period \ Wave-height range	Less than 2 feet	2-4 feet	4-6 feet	6-8 feet	8-10 feet	10-15 feet	15-20 feet	Greater than 20 feet	Total
Winter (Dec., Jan., Feb., Mar.)	16.8	29.5	20.8	14.9	9.1	6.3	2.3	0.3	100.0
Transitional (Apr., May, Oct., Nov.)	35.9	35.3	16.8	4.3	3.4	3.6	.7	---	100.0
Summer (June, July, Aug., Sept.)	38.4	36.1	16.5	6.9	2.1	---	---	---	100.0
Annual	30.3	33.7	18.0	8.7	4.9	3.3	1.0	.1	100.0

TABLE IV.- FREQUENCY OF OCCURRENCE OF SIGNIFICANT WAVE HEIGHT

EXPRESSED IN PERCENT - STATION D

Period \ Wave-height range	Less than 2 feet	2-4 feet	4-6 feet	6-8 feet	8-10 feet	10-15 feet	15-20 feet	Greater than 20 feet	Total
Winter (Dec., Jan., Feb., Mar.)	10.75	31.6	20.4	13.8	9.4	10.3	3.25	0.5	100.0
Transitional (Apr., May, Oct., Nov.)	30.3	39.8	16.1	7.4	3.1	2.9	.3	.1	100.0
Summer (June, July, Aug., Sept.)	28.2	45.2	21.0	4.6	.9	.1	----	---	100.0
Annual	23.0	38.9	19.2	8.6	4.5	4.4	1.2	.2	100.0

TABLE V.- FREQUENCY OF LENGTH-HEIGHT RATIO FOR GIVEN WAVE-HEIGHT RANGE

EXPRESSED IN PERCENT - STATION A

L/H \ Wave-height range	Less than 2 feet	2-4 feet	4-6 feet	6-8 feet	8-10 feet	10-15 feet	Greater than 15 feet	All greater than 2 feet
0-20		-----	1.7	2.2	6.6	9.3	18.7	3.9
20-30		6.7	10.8	23.3	41.5	52.5	58.5	24.3
30-40		20.6	34.6	36.1	28.4	23.4	19.1	28.4
40-60	Not	35.0	27.7	21.4	16.6	9.6	3.7	23.2
60-100		19.1	17.5	11.4	4.35	4.9	-----	12.4
100-200	calculated	14.3	7.1	5.1	2.4	.3	-----	6.5
>200		4.3	.6	.5	.15	-----	-----	1.3
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE VI.- FREQUENCY OF LENGTH-HEIGHT RATIO FOR GIVEN WAVE-HEIGHT RANGE

EXPRESSED IN PERCENT - STATION B

L/H \ Wave-height range	Less than 2 feet	2-4 feet	4-6 feet	6-8 feet	8-10 feet	10-15 feet	Greater than 15 feet	All greater than 2 feet
0-20		4.0	2.7	5.1	9.4	11.1	11.9	4.9
20-30		10.8	19.6	30.7	39.3	54.0	84.4	22.6
30-40		21.7	32.1	34.3	35.9	22.5	2.2	27.0
40-60	Not	35.0	28.3	20.4	12.8	6.2	1.5	26.7
60-100		17.4	15.0	8.3	2.0	4.7	-----	13.0
100-200	calculated	10.6	2.3	1.2	.6	1.5	-----	5.6
>200		.5	-----	-----	-----	-----	-----	.2
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE VII.- FREQUENCY OF LENGTH-HEIGHT RATIO FOR GIVEN WAVE-HEIGHT RANGE

EXPRESSED IN PERCENT - STATION C

L/H \ Wave-height range	Less than 2 feet	2-4 feet	4-6 feet	6-8 feet	8-10 feet	10-15 feet	Greater than 15 feet	All greater than 2 feet
0-20		0.4	0.6	0.3	0.8	0.8	19.7	0.8
20-30		10.5	9.6	19.8	39.8	54.8	64.6	16.4
30-40		35.9	38.5	45.5	38.1	34.7	14.0	37.5
40-60	Not	29.4	27.9	22.6	16.2	9.7	1.7	25.9
60-100		6.7	9.6	7.5	4.9	-----	-----	7.0
100-200	calculated	9.8	10.9	4.1	.2	-----	-----	8.1
>200		7.3	2.9	.2	-----	-----	-----	4.3
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE VIII.- FREQUENCY OF LENGTH-HEIGHT RATIO FOR GIVEN WAVE-HEIGHT RANGE

EXPRESSED IN PERCENT - STATION D

L/H \ Wave-height range	Less than 2 feet	2-4 feet	4-6 feet	6-8 feet	8-10 feet	10-15 feet	Greater than 15 feet	All greater than 2 feet
0-20		0.8	0.6	3.0	3.3	0.8	5.4	1.2
20-30		5.6	7.3	14.4	23.0	30.4	62.5	10.4
30-40		39.8	37.2	40.7	30.4	36.7	25.4	38.4
40-60	Not	31.7	37.0	23.7	23.7	23.9	6.7	30.8
60-100		6.7	5.6	11.3	14.5	7.4	-----	7.3
100-200	calculated	10.3	11.2	6.9	5.1	.8	-----	9.1
>200		5.1	1.1	-----	-----	-----	-----	2.8
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE IX.- FREQUENCY OF WIND VELOCITY

Station	Beaufort force / Knots / Period	0	1-3	4-5	6-7	8 and >8
		<1	1-10	11-21	22-33	34 and >34
A	Winter	1.7	25.5	36.8	25.8	10.2
	Transitional	.6	29.9	41.8	19.5	8.2
	Summer	3.1	44.1	39.3	11.4	2.1
	Annual	1.8	33.2	39.3	18.9	6.8
B	Winter	2.1	26.4	40.2	22.3	9.0
	Transitional	2.9	40.4	37.2	14.7	4.8
	Summer	3.9	55.4	35.0	3.5	2.2
	Annual	3.0	40.7	37.5	13.5	5.3
C	Winter	2.0	45.0	39.2	10.3	3.5
	Transitional	3.1	61.6	29.0	4.9	1.4
	Summer	4.3	68.0	26.0	1.5	.2
	Annual	3.1	58.2	31.4	5.6	1.7
D	Winter	3.1	43.1	39.3	11.6	2.9
	Transitional	2.1	57.4	34.0	5.3	1.2
	Summer	3.4	67.6	25.8	3.0	.2
	Annual	2.9	56.0	33.0	6.6	1.5

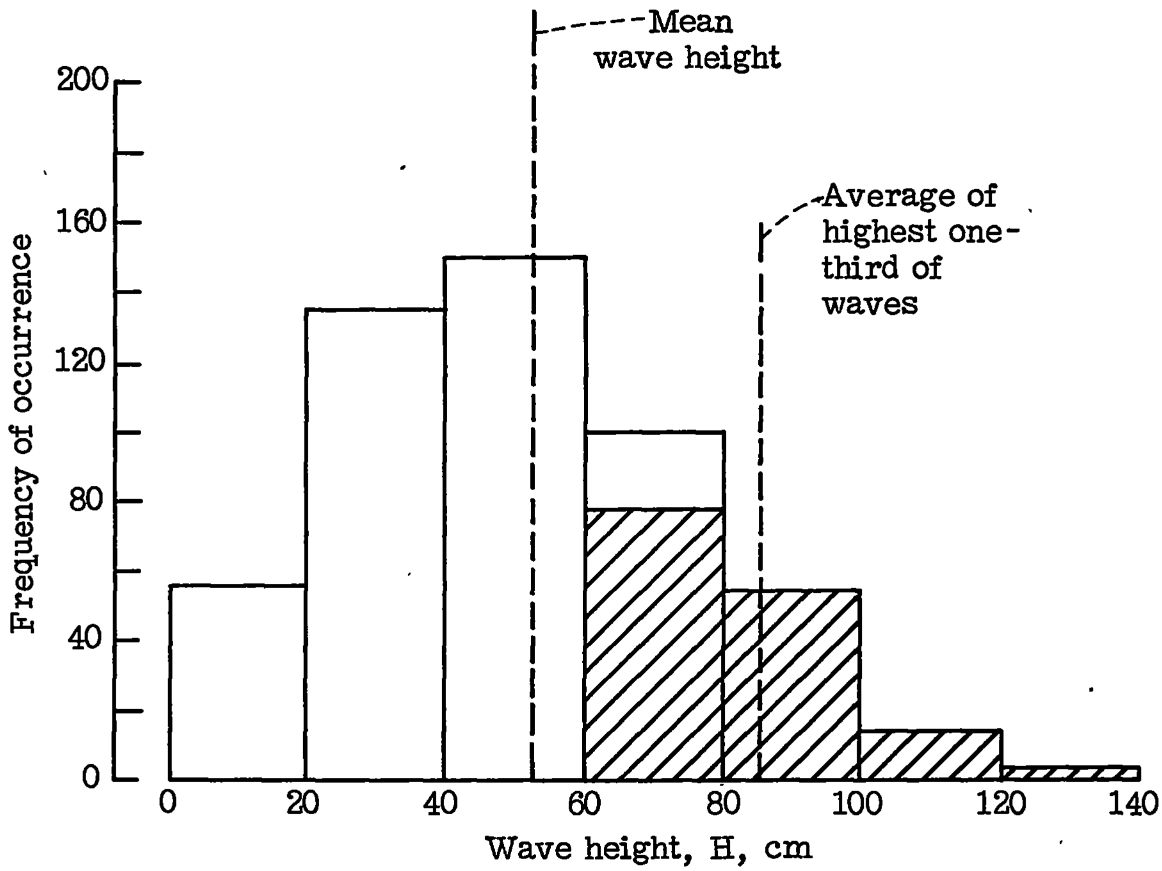


Figure 1.- Frequency distribution of wave heights of sea from German analysis of 517 waves (reference 1). Shaded area refers to highest one-third of waves.

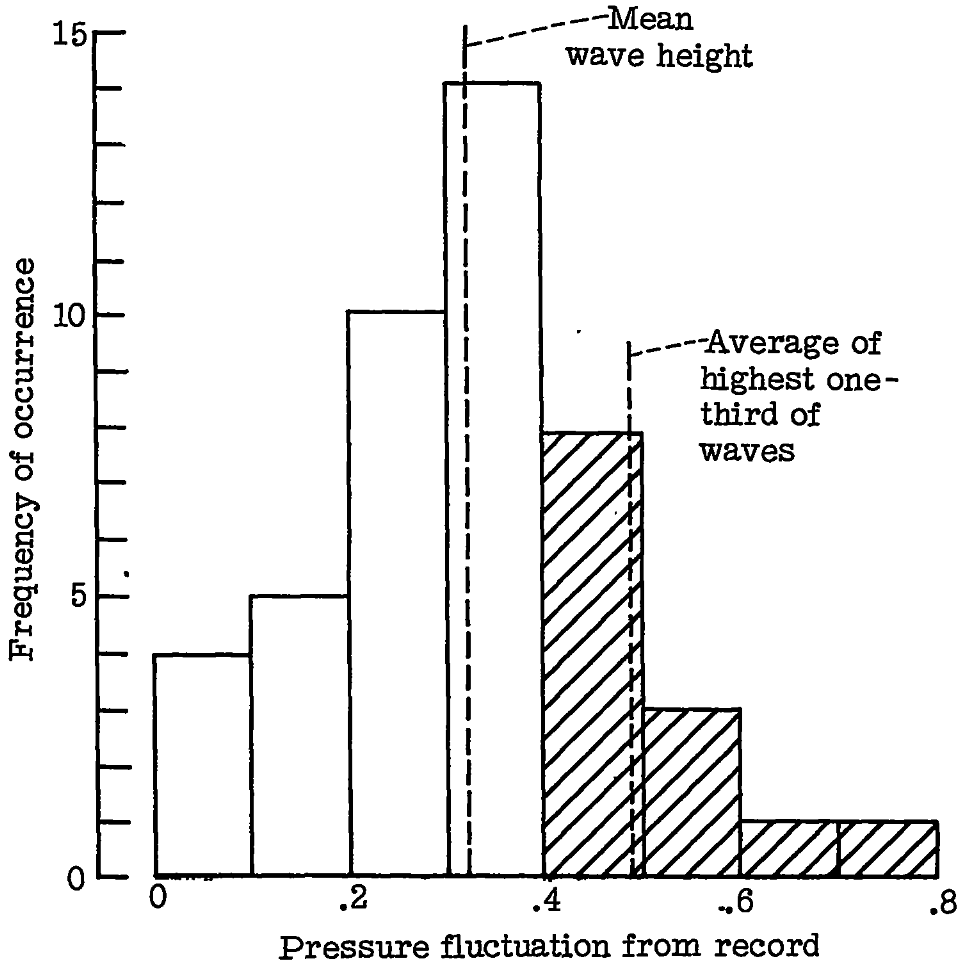


Figure 2.- Frequency distribution of pressure-recorded wave heights of swell taken from an analysis of 46 waves (reproduced from reference 2). Shaded area refers to highest one-third of waves.

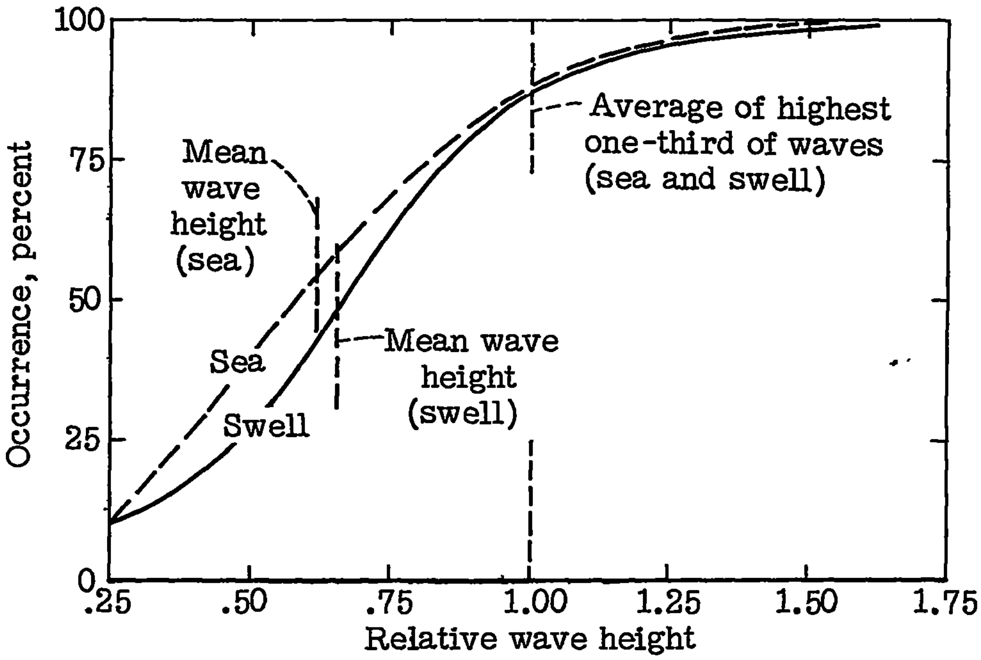


Figure 3.- Percentage of occurrence of relative wave height for sea (reference 1) and swell (reference 2).

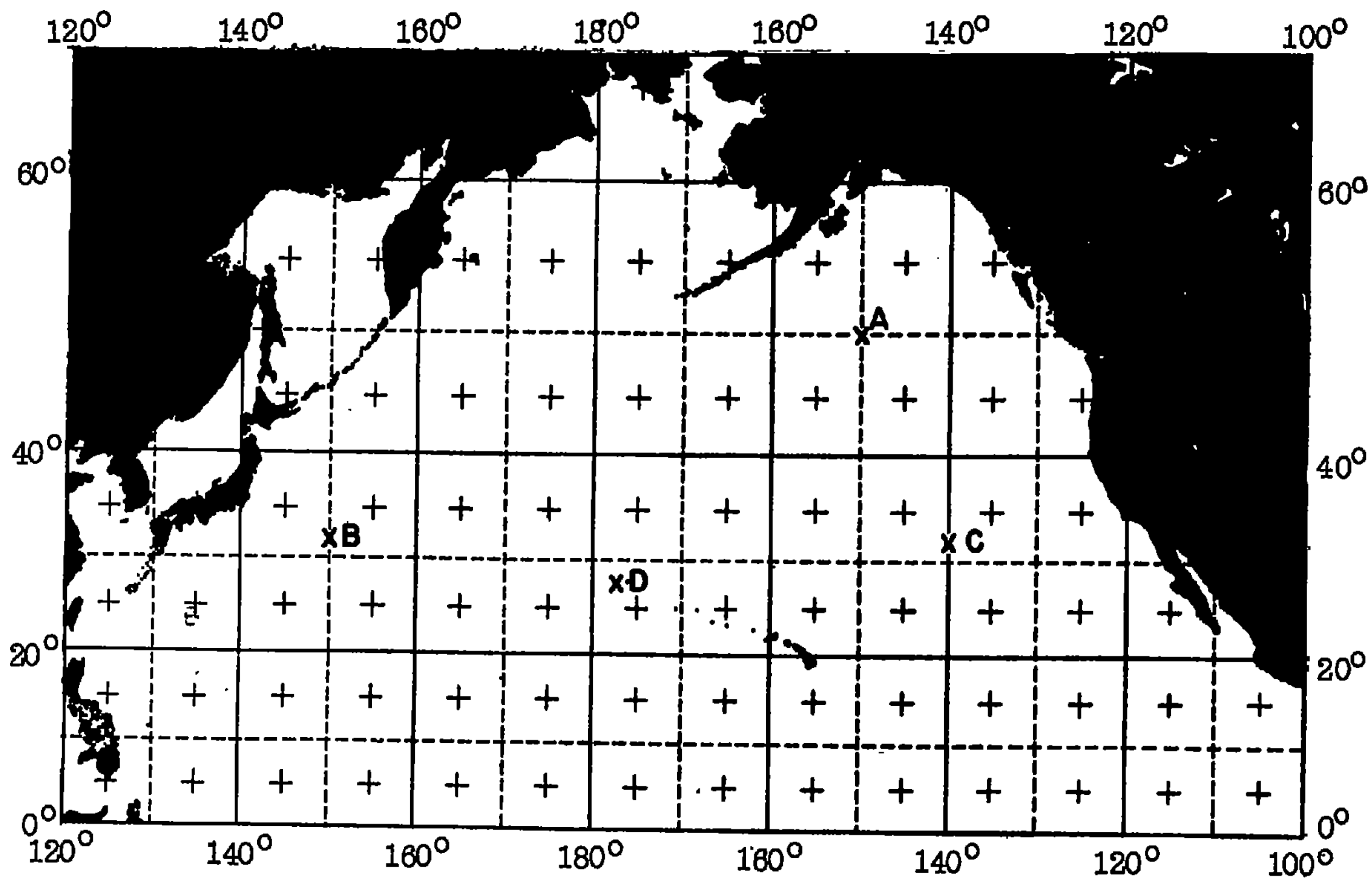


Figure 4.- Open-sea localities in the Pacific Ocean for which wave studies were made.

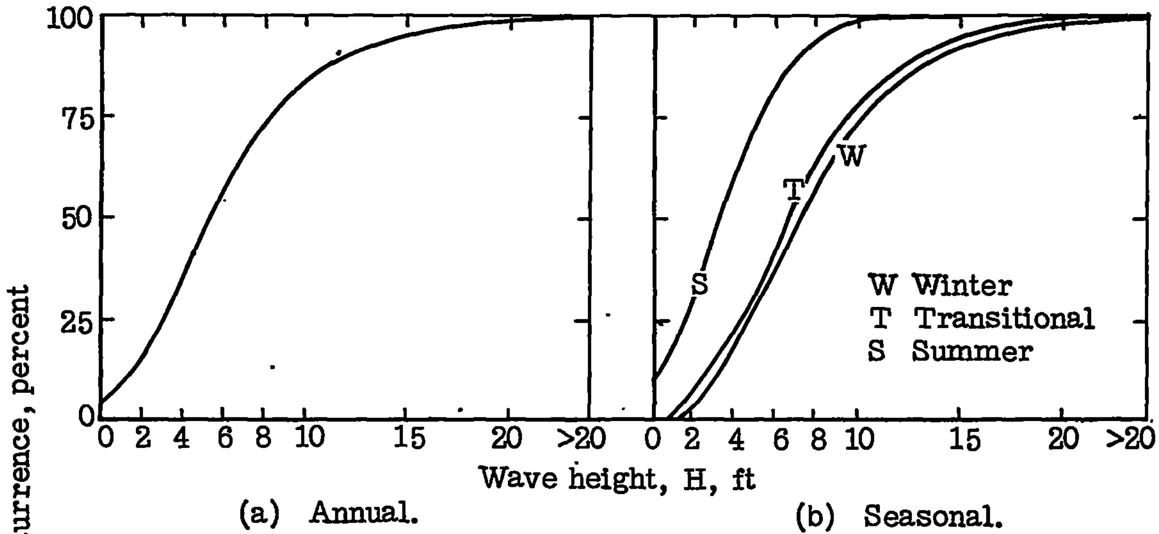


Figure 5.- Cumulative percentage distribution of wave height. Station A.

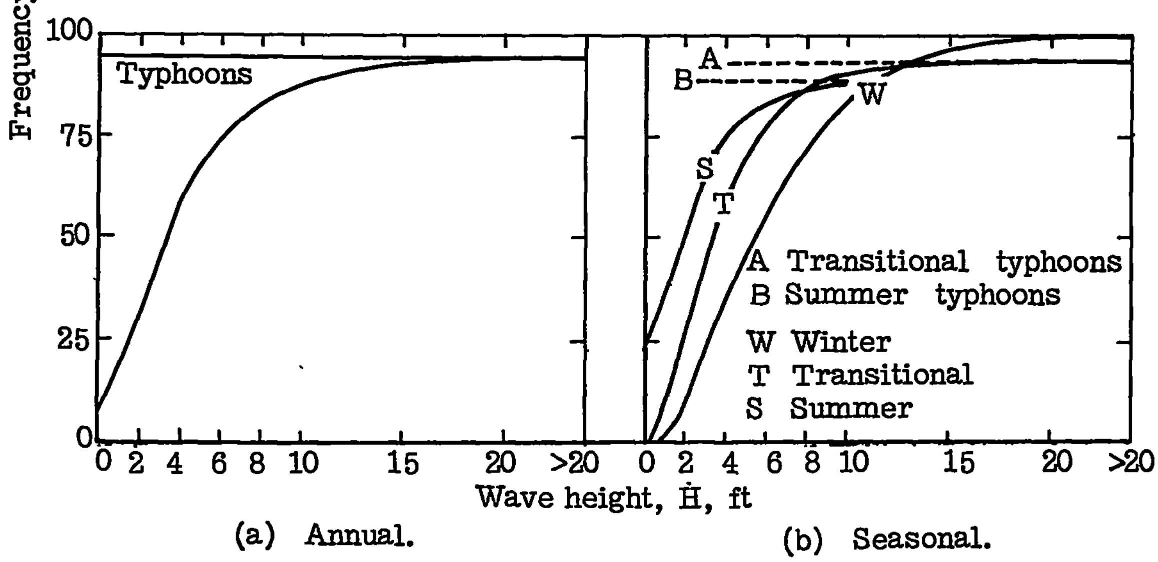
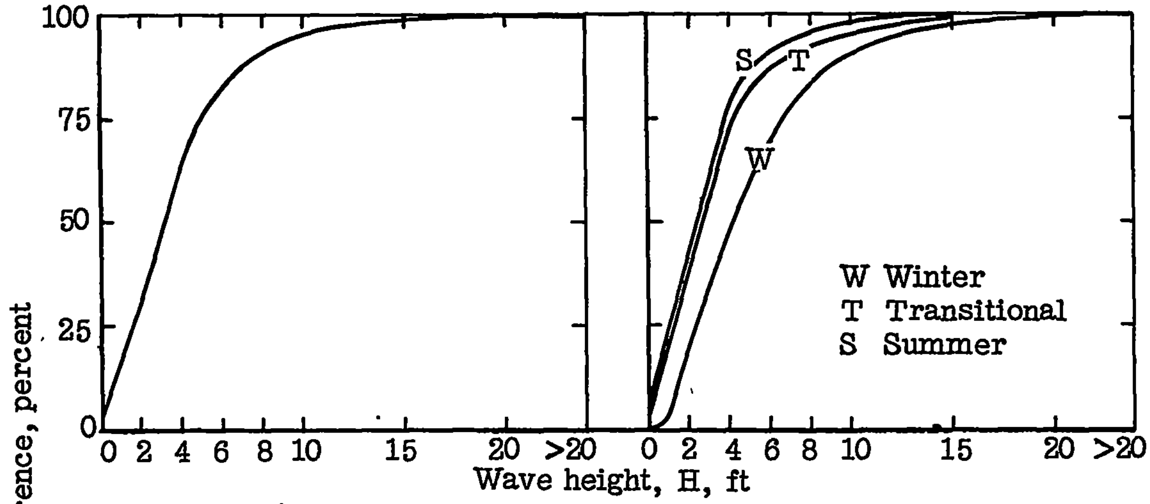
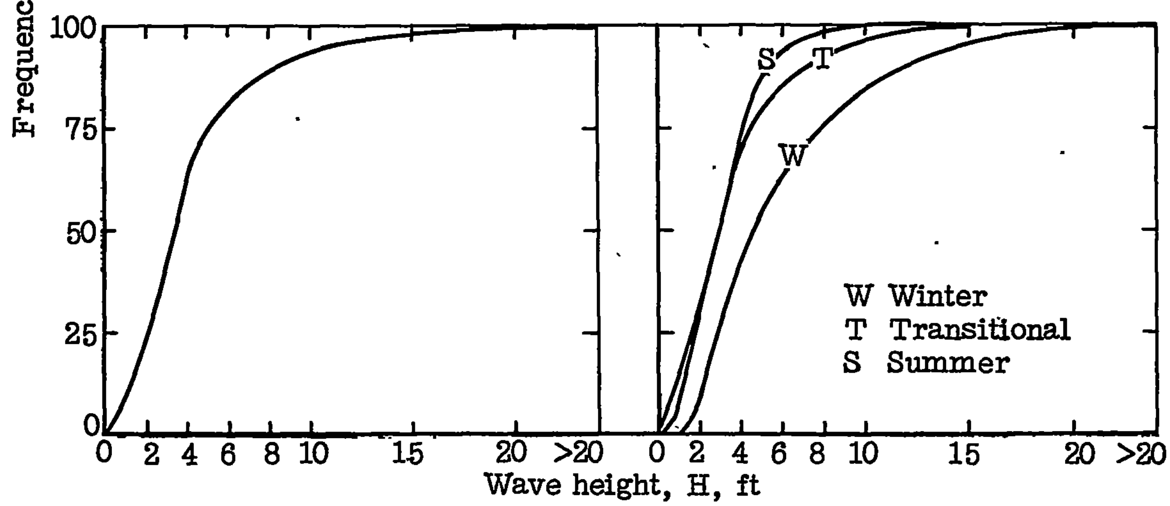


Figure 6.- Cumulative percentage distribution of wave height. Station B.



(a) Annual. (b) Seasonal.

Figure 7.- Cumulative percentage distribution of wave height. Station C.



(a) Annual. (b) Seasonal.

Figure 8.- Cumulative percentage distribution of wave height. Station D.

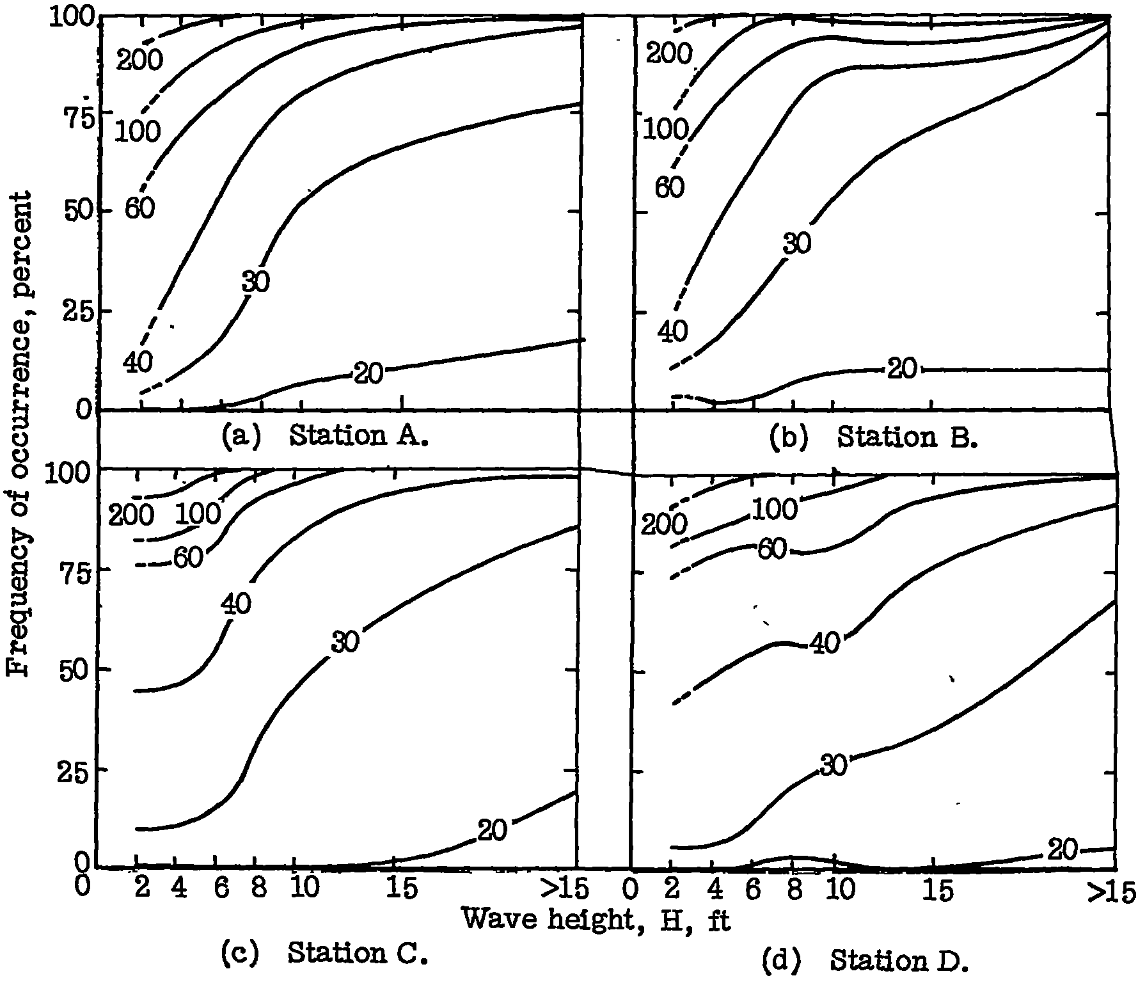


Figure 9.- Percentage distributions of length-height ratios at the four stations investigated.

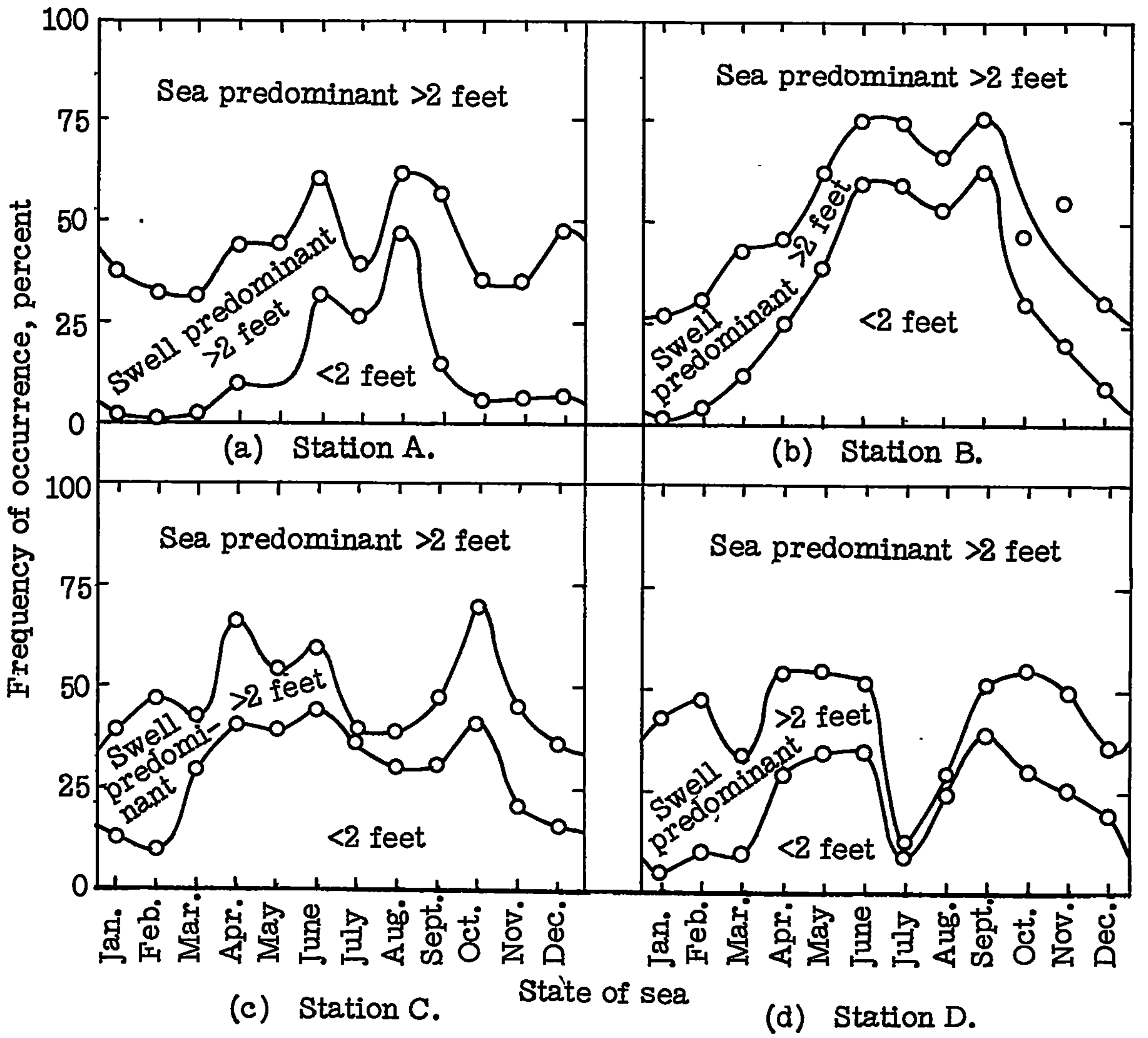


Figure 10.- Monthly frequency-distribution graph for each station.

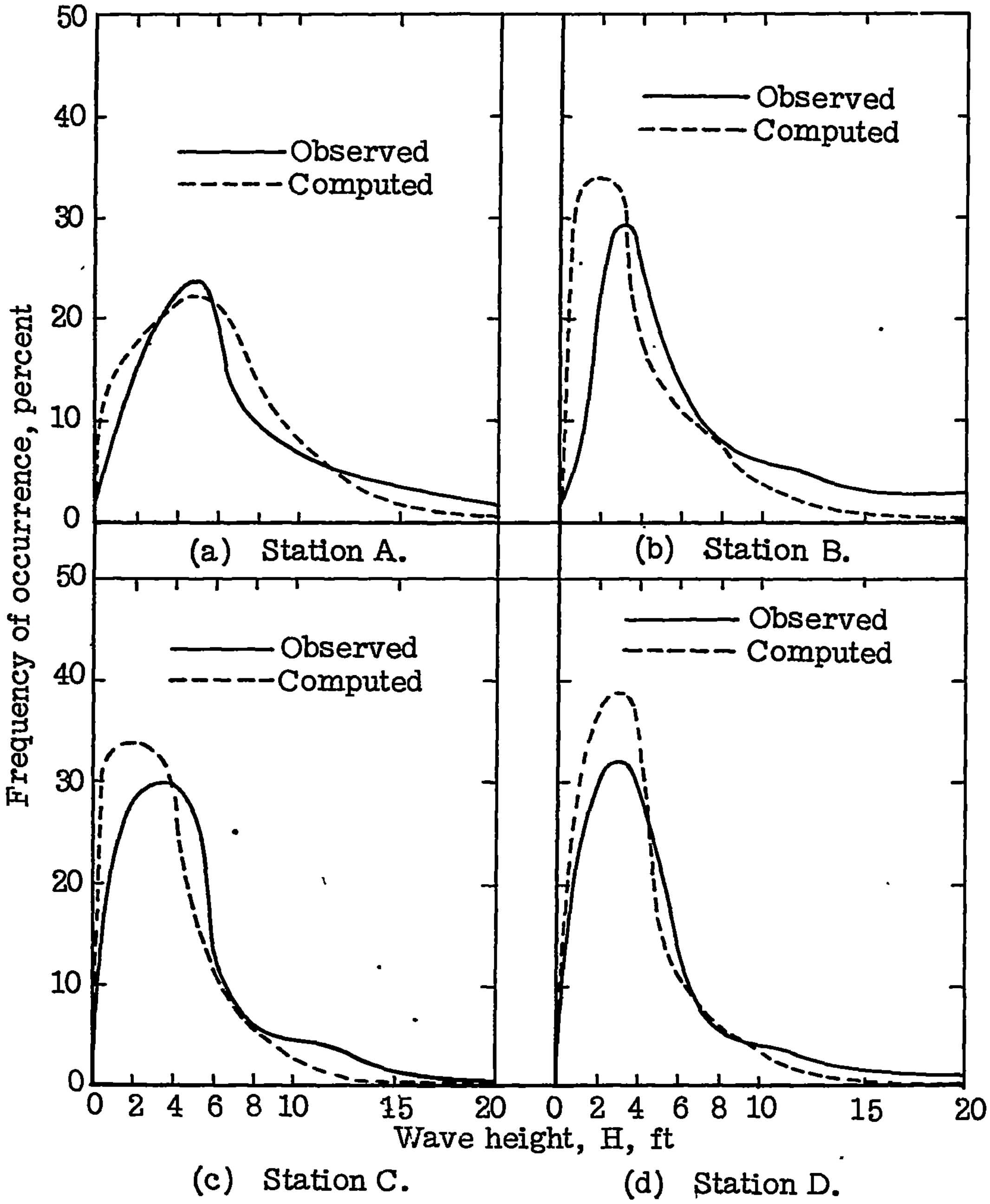


Figure 11.- Frequency of occurrence of observed and computed wave heights for each of the four stations. Curves drawn for a 2-foot-height interval.