CHAPTER 14

OCEAN WAVE STATISTICS FROM FNWC SPECTRAL ANALYSES

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ABSTRACT

Climatological wave data that may be shoaled and refracted from a deep-water wave station can be compiled in two forms from spectral ocean wave analyses produced by the Fleet Numerical Weather Central at Monterey, California: (1) significant wave statistics, which are similar to statistical tables currently in use, and (2) spectral element statistics, which give the frequency of occurrence of energy densities contained in a matrix of 15 frequency bands and 12 direction bands. Experimental formats of both types of statistical compilations are presented, their properties are examined, and the coastal engineering applications of these statistics are discussed.

BACKGROUND

For certain purposes coastal engineers require frequency-of-occurrence statistics on ocean waves compiled for a selected deep-water wave station located offshore from the coastal sector of interest. These wave climatology tables characteristically give the statistical frequency with which height-period-direction (H-T-ψ) data elements occur per average month or average year. They are of particular value in beach erosion studies because of the fact that the H-T-ψ elements can be shoaled and refracted from deep water to any location in intermediate or shallow depths up to the breaker point. The gradient of the statistical wave field in deep water is generally sufficiently small along the coast that wave statistics prepared for a given deep-water wave station may be carried into shoal water depths for many miles in either direction from the station.

Frequency-of-occurrence statistics are derived from synoptic weather maps by the wave-hindcast method. Heretofore, the analysis of weather maps for wave generation parameters (wind velocity, fetch, and wind duration) has been performed manually. Because of the large amount of labor involved, climatological data of this type are not available for most coasts of the open oceans. Statistical tables have been compiled by the hindcast method for the Atlantic, Gulf, and Pacific coasts of the United States, however, and these have had wide use (tables currently in use were prepared by Saville, 1954; Newmann and James, 1955; Bretschneider and Gaul, 1956; Marine Advisers, 1961, and National Marine Consultants, 1960, 1961). The effort involved in making manual hindcasts has also limited these compilations to three years of weather maps. The yearly variability of the statistical wave field at a given open ocean wave station in middle and higher latitudes is known to be appreciable; accordingly, a three-year data base for long-term average statistics must be considered minimal.

In December 1974 the Fleet Numerical Weather Central (FNWC) of the United States Navy at Monterey, California put into routine operation a spectral ocean wave computer model that produces "real-time" computations, termed analyses, of the deep-water wave field in spectral form 12-hourly for a grid-point field covering the major oceans of the Northern Hemisphere (waves are not computed for the Southern Hemisphere). The wave field is computed in 3-hour time steps from the surface wind field, which in turn is derived from the observed sea-level pressure field. The grid-point spacing is approximately 150 nautical miles. Details concerning the FNWC Spectral Ocean Wave Model, including comparisons between FNWC wave computations and open-ocean observations, are given by Lazanoff and Stevenson (1975).

In addition to issuing daily wave analyses and forecasts, FNWC has begun running historical weather maps through their spectral wave program and is in the process of storing the 6-hourly wave field for the Northern Hemisphere oceans on magnetic tapes. Present plans call for the production of 20 years of 6-hourly analyses for the period 1955-1974. When the project is completed, which will require many months, the archived wave data will provide the potential to extend the present wave statistics coverage geographically to most coasts and islands of the open North Pacific, North Atlantic, and North Indian Oceans, and to increase the time base nearly an order of magnitude as well.

Wave statistics for coastal engineering use have not previously been produced from FNWC spectral wave computations. In this paper, formats for presenting frequency-of-occurrence statistics are illustrated and applications of the statistics are discussed. Additional information is given by Reynolds (1976).

DEVELOPMENT OF THE TABLES

The approach taken by the authors to develop wave-occurrence statistics from FNWC spectral analyses was to mock up suitable formats manually from a short series of FNWC computer printouts for a given wave station. This permitted experimentation with the format design, including the selection of suitable scales. The wave station chosen is a FNWC grid point located at latitude 50.9°N and longitude 145.6°W near Ocean Weather Station Papa in the open Gulf of Alaska (a deep-water site along an open ocean coast could have been chosen). A summer month and a winter month, August 1974 and February 1975, were selected for extremes in seasonal wave activity and with the expectation of a dominance of swell during one month and sea in the other. The statistical tables for February only are presented here. The equivalent tables for August can be found in Reynolds (1976). It may be noted that the August wave statistics reveal much lower wave activity, shorter wave periods, and a higher incidence of swell versus sea than occurred in February. Because of missing synoptic analyses, the data for February that are shown in the tables were drawn from 45 12-hourly computer printouts totalling 22½ days of time.

SYNOPTIC SOURCE DATA

Familiarity with the FNWC wave analysis printout is required for a full understanding of the design and characteristics of the tables presented herein. A sample printout for the selected wave station for 00Z on 31 August 1974 is shown in Table 1.

The 15 wave-frequency values shown across the top of the printout (Item 1) each represent the central frequency of a given FNWC frequency band. The central frequencies are seen to cover a period range from 6.1 seconds (0.164 Hz) to 25.7 seconds (0.039 Hz). The limits and width of each frequency band are given in Table 2. The 12 wave-direction values shown in the right-hand column in degrees (Item 2) and in the left-hand column in coded form (Item 3) each represent the central direction of a 30° directional band. The geographical directions are seen to be irregular. They vary from grid point to grid point because of the global map projection used by FNWC (Lazanoff and Stevenson, 1975).

The block of 180 numbers forming the body of the table (Item 4) constitutes the frequency-direction (f-ψ) spectrum of the wave field. Each number represents the wave energy density, expressed as variance (ft^2), contained in the frequency and direction bands indicated. The sums of the columns (Item 5) represent the wave energy contained in the 15 frequency bands irrespective of wave direction and constitute the familiar f-spectrum. The sums of the rows (Item 6) give the wave energy contained in the 12 direction bands irrespective of wave frequency, and collectively represent the less familiar ψ-spectrum.

The sums of the component variance values contained in the f-ψ spectrum, the f-spectrum, and the ψ-spectrum (Items 4, 5, and 6) are identical, and for the waves being considered are seen to total 3.145 ft^2 (Item 7). It is of interest to note that two well-defined wave trains from different sources are revealed in the printout. The larger set is a swell train with a dominant period of about 15.0 seconds (0.067 Hz band) and a dominant direction from the West (259° band); the other set is sea of about 9.7 second period (0.103 Hz) from the South (199°).

At this point, some comment is needed regarding the wave frequency bands (Item 1) represented in the printout. The 15 bands have been carefully selected by FNWC to minimize computing time and yet cover the full frequency range for ordinary gravity waves with suitable bandwidths. It may be noted in Table 2 that the bands below a frequency of 0.080 Hz are of constant width (0.0055 Hz), but that at higher frequencies the bandwidth has been widened by multiples of 2, 3, 4, and 18. A consequence of this design is that in order to properly compare the magnitude of two energy density values, the values must be adjusted to a common frequency bandwidth. Choosing the common or standard bandwidth to be Δf = 0.0055 Hz, this can be done by multiplying the energy density values in the printout by the appropriate energy density factors listed in Column 4 of the table. By way of example, the secondary peak of the f-spectrum (Item 5 of Table 1) appears to lie at a frequency of about 0.133 Hz, whereas this maximum actually lies at about 0.103 Hz (the primary peak of the f-spectrum lies at about 0.067 Hz). The energy content of these two frequency bands are seen from the printout to have values of 0.41 ft^2 per Δf = 0.0165 Hz (from Table 2) and 0.33 ft^2 per Δf = 0.0110 Hz, or about 0.14 ft^2 and 0.16 ft^2 respectively, when adjusted to the common bandwidth of Δf = 0.0055 Hz. The component variance values of the f-ψ spectrum (Item 4) must be similarly adjusted for direct comparison of their energy contents.

It should be further noted that if the variance values composing the f-spectrum shown in the printout (Item 5) were plotted on a linear frequency scale, the resulting graph would be exaggerated at the high-frequency end of the spectrum because of the choice of variable frequency bandwidths. Nevertheless, the sum of these variance values, 3.145 ft^2, correctly represents the total energy content computed for the waves present. For a correct graphical representation of the frequency spectrum (to the accuracy permitted by the widths of the frequency bands), the variance values must first be adjusted to a common frequency bandwidth through use of the energy density factors. No such difficulty arises with the ψ-spectrum because of the use of equal directional bandwidths.

The FNWC decision to represent the frequency spectrum by unequal bandwidths affects the way in which statistical tables may be formatted and the statistics compiled, and requires care by the user in order to assure correct interpretation of the data. This is commented upon further in the discussion of the individual tables.

Returning to the spectral printout in Table 1, the waves computed to be present at the station at the designated time are seen to be described in considerable detail by 180 ΔV-Δf-$\Delta\psi$ elements, each being a component, ΔV, of the total variance of the wave field (V) contained in a specific frequency band, Δf, and direction band, $\Delta\psi$. These wave data are referred to herein as <u>spectral element data</u>. The wave information in the printout may also be summarized by designating the significant height, $\bar{H}_{1/3}$, the period of maximum energy density, T_{max}, and the direction of maximum energy density, ψ_{max}. For the wave field shown in the printout, $\bar{H}_{1/3}$ = 6.8 feet ($\bar{H}_{1/3} = 4V^{1/2}$ where V = 3.145 ft^2), T_{max} lies in the frequency band centered at 15.0 seconds (or 0.67 Hz), and ψ_{max} lies in the direction band centered at 259 degrees. Thus, the wave field can be described in a gross way by a single $\bar{H}_{1/3}$-T_{max}-ψ_{max} data unit. Wave data in this form will be referred to as <u>significant wave data</u>.

It is evident that wave statistics derived from a time series of FNWC spectral analyses may be compiled as (1) significant wave statistics, consisting of one $\bar{H}_{1/3}$-T_{max}-ψ_{max} data unit per FNWC analysis, and as (2) spectral element statistics, composed of 180 ΔV-Δf-$\Delta\psi$ data units per FNWC analysis (or fewer than 180 units when variance values of 0.00 ft^2 are excluded from the statistical tabulation). Example formats of each are given in the following sections.

In the statistical tables and the discussion herein, wave frequency and wave period are used interchangeably, in a reciprocal sense, according to convention; frequency is used when reference is made to the FNWC spectral model and period when operational wave products are of interest.

SIGNIFICANT WAVE TABLE

The significant wave statistics compiled for the selected station for February 1975 from FNWC spectral wave analyses are presented in Table 4. Because of the sparcity of the data in the individual direction bands, the entries for all 12 directions have been combined into a single table for illustration purposes in this paper; tables intended for practical use would display each direction component separately. The values in the table represent the number of 12-hourly synoptic analyses occurring during the 22½ day data period. The height scale, coded for brevity (code given in Table 3), is linear with an increment of 2 feet. Regarding the period scale, wave occurrences were compiled from the printouts by the FNWC frequency bands shown in Table 2, but for purposes of convention each column of Table 4 is labelled for the period equivalent to the central frequency of each FNWC frequency band. The equivalent period bandwidths are seen from Table 2 to be variable and to lie mostly in the range of 1 to 2 seconds.

The design of Table 4, except for the use of frequency as a base instead of period, is essentially identical to existing frequency-of-occurrence tables, but with one important exception. In compiling wave statistics derived from the manual analysis of weather maps, wherein wave trains generated in individual wind areas are computed and propagated separately, it has been the general practice to record each set of waves as an independent occurrence whenever two or more trains are present simultaneously at the wave station. This results in tables containing more hours of wave occurrence in a month than actually occurs, particularly when separate tables for sea and swell are compiled. This presents the user with the problem of how to adjust the data to 100% occurrence. In addition, higher wave heights must occur in nature than these tables generally indicate because multiple wave trains are a common occurrence at open ocean wave stations. In the FNWC Spectral Ocean Wave Model, the growth of sea and the propagation of swell are complexly interrelated and individual wave trains are not differentiated in the f-ψ spectrum. Accordingly, the statistics compiled from the

FNWC spectral analyses reflect wave heights associated with the statistical occurrence of multiple wave trains, and the super-occurrence problem does not exist.

In using significant wave tables compiled from FNWC spectral analyses, it may be desirable for some purposes to distinguish swell from sea and to estimate the relative age of the swell, i.e., whether it has travelled over a short, moderate, or long decay distance. Because swell steepness diminishes with increasing travel distance from the generating area, some measure of the steepness of the wave field, γ_s, can be used for this purpose. In this study, γ_s is defined in terms of $H_{1/3}$ and T_{max} by analogy to monochromatic waves as shown in Table 5. The relationship selected between wave age and γ_s is given in the lower part of the table. Thus, young swell has a statistical steepness in the range of about 1/40 and 1/100, has travelled 0 to 250 nautical miles from the location where it was generated, and has been reduced in significant height by a factor of 1.0 to 0.5. It may be observed that because significant wave tables are a matrix of values of $H_{1/3}$ and T_{max}, they are also tables of γ_s and accordingly of wave age. This permits wave-age boundaries to be superimposed, as in Table 4.

It may be recalled that the term "wave age" was introduced by Sverdrup and Munk (1947) to describe the growth stages of sea during wave generation. They defined it as the ratio of wave speed to surface wind speed, C/U, and related it to wave steepness. In extending use of the term to swell, which has considerable practical merit, wave age is defined differently than for sea but remains related to the steepness of the wave field.

The zone labelled "sea" in Table 4 contains all synoptic occurrences where sea is the dominant component of the wave field present, regardless of the wind speed generating the sea or of its stage of growth. The zone is seen to have a cutoff such that wave heights greater than a certain value do not occur for a given period. Young seas, because they are of maximum steepness, should lie along this data envelope, whereas fully arisen seas should fall near the inner margin adjacent to the zone labelled "young swell". A well-defined data cutoff should be expected whenever a significant number of synoptic entries represent seas, but may not be evident in statistics where swell is dominant.

SPECTRAL ELEMENT TABLES

Spectral element statistics compiled for the selected station for February 1975 from FNWC synoptic wave analyses are shown in Table 6. The entries in the table were read directly from the 180 component variance values contained in each of the 45 12-hourly printouts available for the month (eg., Item 4 of Table 1). The entries for all 12 direction bands have been combined into a single table for purposes of comparison with Table 4.

Table 6 is identical to Table 4 with respect to the period scale and the manner of representing frequency of occurrence (i.e., by the number of 12-hourly analyses); however, the significant-height scale is replaced by a variance scale chosen to give a reasonable spread to the data. The variance scale is coded (Table 3) to simplify the table. It should be noted that the units of variance in Table 6 are ft^2/FNWC frequency bandwidth.

Tables 6 and 4 were derived from the same FNWC printouts and the total energy content represented by their entries is identical. Nevertheless, there are no values common to both distributions, and consequently, there are no means by which the data in the two tables can be equated numerically. Neither can one table be derived from the other. These circumstances arise from the fact that although the energy in the waves at a given place and time can be separated analytically into spectral components and can subsequently be reconstituted to yield a significant wave height representing that sea surface, the same spectral components when distributed in a statistical table with components from other synoptic analyses can no longer be identified and reassembled to produce the significant height.

A comparison of these two tables offers some interesting contrasts, however, and gives some feeling for the coarseness of significant wave data as a descriptor of ocean wave climatology. The spectral element table contains some fifty times more data than the significant height table; specifically, 2126 variance entries (> 0 ft^2) versus 45 height entries. The variance entries are distributed in a wider range of period bands, from 6.1 to 25.7 seconds versus 9.7 to 18.0 seconds, and extend into what are ordinarily considered very long periods. Further, the entry of maximum energy is centered in the 20.0 second band for the spectral element statistics versus the 16.4 second band for the significant wave statistics. It should additionally be noted that the wave activity in February 1975 was appreciable; this is indicated in Table 4 by the small number of occurrences of waves under 10 feet (Code 05 and under), but is not apparent in Table 6 where most of the entries are in the lowest energy categories.

A peculiarity of Table 6 is that a given energy category or code number does not represent the same energy density for all frequency bands. This is due to the variable widths of the FNWC frequency bands. For example, Code 03 represents an energy level of 0.50-0.74 ft^2/0.0055 Hz bandwidth in the 12.0 second band but 0.50-0.74 ft^2/0.0110 Hz bandwidth in the adjacent 10.9 second band, giving the 10.9 second band about half the energy density of the 12.0 second band. Accordingly, energy density values cannot readily be compared across the table. This circumstance would complicate the use of this type of table and would likely result in incorrect interpretation of the statistics.

This difficulty may be avoided by reducing the component variance values to the standard frequency bandwidth, Δf = 0.0055

Hz, through multiplication by the energy density factors given in Table 2. This operation may be applied either to the 180 variance values in each FNWC printout, or with a slight reduction in statistical accuracy to the statistics compiled directly from these values. Table 7 was derived from Table 6 by the latter method. The variance scale of Table 7 thus has the units of ft^2/ 0.0055 Hz standard bandwidth for all periods in the table.

Table 7 has the desirable quality that a given energy code number represents the same energy level for all frequency bands. On the other hand, the table contains less total energy than Table 6. This is due to the fact that in adjusting the energy of the FNWC frequency bands to the standard bandwidth in the periods from 6.1 to 10.9 seconds, segments of the frequency spectrum lying outside the 0.0055 Hz bandwidth centered about each period are in effect excluded.

A feature of the spectral element tables of particular interest that is best seen in Table 7 is the well-defined energy cutoff extending diagonally across the table. The cutoff represents the energy-saturated frequencies of sea spectra associated with the strongest winds occurring during the month. The cause and nature of the cutoff can be more readily visualized from consideration of Table 8 which shows the spectral entries such as might be extracted from a single FNWC printout for a fully arisen sea of 50 knots (in the absence of swell). The entries in this table show the energy density per 0.0055 Hz and 30° bandwidths (as in Table 7) for the condition in which the mean wind direction coincides with the center of the direction band (this condition gives the maximum variance values possible for the 50-knot sea). The reader may recognize this distribution as a frequency spectrum graph in tabular form that has been rotated 180° about both the energy density and frequency axes. If one now imagines a graph of nested frequency spectra for fully arisen seas generated over a range of wind speeds, the spectra are seen in the higher frequencies to occupy a relatively narrow band on the graph, with the outermost spectrum being associated with the strongest wind and representing the energy cutoff in the equivalent statistical tables. If non-fully developed spectra for the same wind speeds are added to the imagined graph, the unsaturated portions of each will lie inside this band, as will also the saturated low-frequency tails of fully arisen spectra associated with weaker winds.

It is evident from these considerations that the entries in Table 7 lying inside the cutoff zone may represent (1) saturated frequency components associated with fully arisen seas produced by weaker winds, (2) unsaturated components of seas produced by strong or weak winds, or (3) swell. There is no way to associate these entries with sea or swell however, whether or not this might be desired for practical purposes. All that can be said in this vein is that the entries lying in a band along the data envelope clearly represent dominantly sea. It should be mentioned here that the energy cutoff in Table 7 is not fully analogous to the height cutoff in Table 4; occurrence entries representing sea may be found anywhere inside the data envelope of Table 7 but lie only in the zone labelled "sea" in Table 4.

The wave statistics for February are presented in still another form in Figure 1. This figure was constructed by cumulating the occurrences in Table 7 from high to low energy density within each period band (cumulative table not shown), and plotting the cumulated values against the period. The curves in the graph are isopleths of energy density coded according to Table 3. Figure 1 combines the advantage of Table 6 in that the total energy represented is correct, and Table 7 in which the energy densities are referenced to the standard 0.0055 Hz bandwidth. This graphical presentation gives the user a distinctly better visual impression of the statistical distribution than do the two tables; however tables directly provide the numerical values a user needs.

Figure 1 is of particular interest not so much as a format in which spectral element statistics may be presented but because of the possibility which it suggests for describing climatological wave data by a mathematical function, at least for some ocean regions and seasons. The energy-occurrence curves in the figure are seen to resemble nested wave frequency spectra for fully arisen seas associated with a range of wind speeds, with the dashed curve being the counterpart of the T_{max} curve for the spectra. The fact that the pattern of this small-sample distribution is so well defined suggests that the long-term average pattern for February is similar at this station. It may be expected, on the basis of continuity, that similar wave climatology patterns occur in adjacent months and over adjacent regions of the North Pacific Ocean; accordingly, it seems possible that all of these distributions might be described by a function having variable coefficients that provide for seasonal and geographical gradients. From a practical standpoint, the availability of wave climatology models for ocean regions would greatly improve data packaging, allow greater versatility in data manipulation, and improve the prediction of infrequently occurring wave conditions.

Consideration of the spectral characteristics of sea and swell further suggests that in ocean regions and seasons where swell is dominant, the wave climatology may not be amenable to mathematical description. A graph similar to Figure 1 prepared for August (not shown) when the swell-to-sea ratio is substantially higher at the selected station is inconclusive on this point because of the low frequency of wave occurrence in that month. It should be recalled that Figure 1 is a data composite of all 12 direction bands. If long-term average statistics for February were displayed for each direction band, it is reasonable to expect that a pattern similar to that in the figure would appear for all or some of the component directions.

USES OF THE STATISTICS

Significant wave statistics tables derived from FNWC spectral analyses are similar in construction to climatology tables currently in use, except for tabulation of the wave data by variable period increments. This design feature may appear untidy but should not restrict the uses of the statistics.

The coastal engineering applications which would be made of these tables appear to be identical to those of existing wave climatology tables. Reasons for favoring use of the FNWC-derived significant wave statistics, however, are that they are free of the familiar super-occurrence problem in which tables contain more total hours of wave occurrence than actually occurs, and that they take into account simultaneous occurrence of wave trains arriving at a wave station and therefore contain higher wave heights.

With regard to spectral element statistics, there are considerable uncertainties concerning their uses and apparently no experience available to provide guidance. The following comments are therefore limited to the more obvious things that can and cannot be done with these statistics.

The ΔV-Δf-$\Delta\psi$ values composing spectral element tables compiled for a deep-water wave station can be shoaled and refracted in the same manner as the spectrum of a given set of waves (described by Pierson, Neumann, and James, 1955); thus, the spectral element climatology can be determined for a selected shoal-water site (except near the surf zone since the breaker height cannot be identified in the spectral statistics). These statistics cannot be converted into wave height statistics, however, and so cannot be used to compute design wave heights, wave forces, breaker-height statistics, or littoral-drift rates by current methodology; these quantities must still be calculated using the more gross significant wave statistics.

The principal uses for wave statistics in spectral element form, both in coastal waters and the open ocean, appear to lie in the realm of resonant reaction of structures to waves. Practical applications can readily be visualized involving piling platforms, spar platforms, tethered breakwaters, floating causeways, surface vessels, and surface-effects craft. The nature of the transform from spectral wave information to structures response and how the transform can be applied quantitatively appear to be little understood, however.

Although specific uses for spectral element climatology are not now developed, the marked differences which these statistics display from the significant wave statistics derived from the same synoptic source data, along with the possibility of modelling these spectral distributions mathematically, compels further attention to these data.

REFERENCES

Bretschneider, C. L., 1958. Revisions in wave forecasting: deep and shallow water. Proc. of Sixth Conf. on Coast Engr., Chap. 3, pp. 30-67.

Bretschneider, C. L., and R. D. Gaul, 1956. Wave statistics for the Gulf of Mexico (for 5 wave stations). Army Corps of Engrs., Beach Erosion Board, Tech. Memo. 85-89 (5 reports).

Lazanoff, S. M., and N. M. Stevenson, 1975. An evaluation of a hemispheric operational wave spectral model. Fleet Numerical Weather Central, Tech. Note 75-3, 103 pp.

Marine Advisers, Inc., 1961. A statistical survey of ocean wave characteristics in Southern California waters. Prepared for Army Corps of Engrs., Los Angeles Dist., 30 pp. + tables.

National Marine Consultants, Inc., 1960. Wave statistics for seven deep water stations along the California coast. Prepared for Army Corps of Engrs., Los Angeles and San Francisco Dist., 20 pp. + tables.

National Marine Consultants, Inc., 1961. Wave statistics for three deep water stations along the Oregon-Washington coast. Prepared for Army Corps of Engrs., Portland and Seattle Dist., 17 pp + tables.

Neumann, G., and R. W. James, 1955. North Atlantic Coast wave statistics hindcast by the wave spectrum method. Army Corps of Engrs., Beach Erosion Board, Tech. Memo. 57, 23 pp. + tables.

Pierson, W. J., Jr., G. Neumann, and R. W. James, 1955. Practical methods for observing and forecasting ocean waves. Navy Hydro. Off., H.O. Pub. 603, 284 pp.

Reynolds, F. M., 1976. Climatological wave statistics derived from FNWC synoptic spectral wave analyses. Naval Postgrad. Sch., Monterey, Calif., M. S. Thesis, 141 pp.

Saville, T., Jr., 1954. North Atlantic Coast wave statistics hindcast by Bretschneider-revised Sverdrup-Munk method. Army Corps of Engrs., Tech. Memo. 55, 18 pp. + tables.

Sverdrup, H. U., and W. H. Munk, 1947. Wind, sea, and swell: theory of relations for forecasting. Navy Hydro. Off., H.O. Pub. 601, 44 pp.

DTG=74083100 TAU= 0
SUBPROJECTION 3 GRID PT 0.00 LAT 50.900 LONG 214.400
WIND SPEED 6.30 WIND DIR 205. USTAR .22

FREQ / DIR	.164	.153	.133	.117	.103	.092	.083	.078	.072	.057	.061	.056	.053	.044	.039		
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	319.5
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.02	289.5
3	0.00	0.00	.02	.01	.02	.04	.07	.04	.15	.85	.35	.11	.01	0.00	0.00	1.65	259.5
4	.01	0.00	.02	.02	.02	0.00	0.00	.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.09	229.5
5	.01	.20	.27	.37	.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.14	199.5
6	.01	.12	.10	0.00	0.00	0.00	.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.24	169.5
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	139.5
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	109.5
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	79.5
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	49.5
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.5
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	349.5
	.03	.33	.41	.40	.33	.04	.08	.05	.15	.85	.35	.11	.01	0.00	0.00	3.145	

TABLE 1: FNWC SPECTRAL PRINTOUT OF WAVE FIELD
FOR GRID POINT 164 OF SUBPROJECTION 3 FOR 00Z ON 31 AUGUST 1974

Table 2: FNWC FREQUENCY/PERIOD PARAMETERS
(Modified from Lazanoff and Stevenson, 1975)

Central frequency (Hz)	Frequency band (Hz)	Frequency bandwidth (Hz)	Energy density factor	Central period (sec)	Period band (sec)	Period bandwidth (sec)
0.164*			1/18	6.1		
0.153	0.142-0.164	0.0220	1/4	6.5	7.2- 6.1	1.1
0.133	0.125-0.142	0.0165	1/3	7.5	8.0- 7.2	0.8
0.117	0.108-0.125	0.0165	1/3	8.6	9.3- 8.0	1.3
0.103	0.097-0.108	0.0110	1/2	9.7	10.3- 9.3	1.0
0.092	0.086-0.097	0.0110	1/2	10.9	11.7-10.3	1.4
0.083	0.080-0.086	0.0055	1	12.0	12.5-11.7	0.8
0.078	0.075-0.080	0.0055	1	12.9	13.4-12.5	0.9
0.072	0.069-0.075	0.0055	1	13.8	14.4-13.4	1.0
0.067	0.064-0.069	0.0055	1	15.0	15.7-14.4	1.3
0.061	0.058-0.064	0.0055	1	16.4	17.2-15.7	1.5
0.056	0.053-0.058	0.0055	1	18.0	19.0-17.2	1.8
0.050	0.047-0.053	0.0055	1	20.0	21.2-19.0	2.2
0.044	0.042-0.047	0.0055	1	22.5	24.0-21.2	2.8
0.039	0.036-0.042	0.0055	1	25.7	27.6-24.0	3.6

*Lower limit of frequency band

Note: Periods are derived from the FNWC frequencies.

Table 3: COOE FOR EXPRESSING SIGNIFICANT WAVE HEIGHT AND SPECTRAL ENERGY OENSITY IN THE CLIMATOLOGY TABLES

Significant wave table

Code	$\bar{H}_{1/3}$ (ft)
01	0.0 - 1.9
02	2.0 - 3.9
03	4.0 - 5.9
04	6.0 - 7.9
05	8.0 - 9.9
06	10.0 - 11.9
07	12.0 - 13.9
08	14.0 - 15.9
09	16.0 - 17.9
10	18.0 - 19.9
11	20.0 - 21.9
12	22.0 - 23.9
13	24.0 - 25.9
14	26.0 - 27.9
15	28.0 - 29.9
16	30.0 - 31.9
17	32.0 - 33.9
18	34.0 - 35.9
19	36.0 - 37.9
20	38.0 - 39.9
21	40.0 - 41.9
22	42.0 - 43.9

Spectral element tables

Code	ΔV (ft^2)
01	0.01 - 0.24
02	0.25 - 0.49
03	0.50 - 0.74
04	0.75 - 0.99
05	1.00 - 1.24
06	1.25 - 1.49
07	1.50 - 1.74
08	1.75 - 1.99
09	2.00 - 2.49
10	2.50 - 2.99
11	3.00 - 3.49
12	3.50 - 3.99
13	4.00 - 4.49
14	4.50 - 4.99
15	5.00 - 5.49
16	5.50 - 5.99
17	6.00 - 6.49
18	6.50 - 6.99
19	7.00 - 7.49
20	7.50 - 7.99
21	8.00 - 8.49
22	8.50 - 8.99

ALL DIRECTIONS FEBRUARY 1975

CENTRAL PERIOD (SECONDS)

SIGNIFICANT HEIGHT (CODED)	6.1	6.5	7.5	8.6	9.7	10.9	12.0	12.9	13.8	15.0	16.4	18.0	20.0	22.5	25.7
01															
02													OLD		
03									1		2		SWELL		
04						1				1					
05										1	MOD				
06					2	1					SWELL				
07					6	1									
08					2		2								
09						1			YOUNG						
10						2	2		SWELL						
11						1		3							
12							2	1		1					
13						SEA			3	1					
14								1	1	1					
15										1					
16											2				
17												1			
18											1				
19															
20															
21															
22															

TABLE 4: SIGNIFICANT WAVE STATISTICS

Table 5: DEFINITIONS OF WAVE STEEPNESS AND WAVE AGE
(Applicable to deep water only)

WAVE STEEPNESS, γ

Monochromatic waves

$$\gamma_m = \frac{H}{L} = \frac{H}{\frac{g}{2\pi} T^2} = \frac{H}{5.12\ T^2}$$

H = wave height
L = wave length
T = wave period

Spectrum waves

$$\gamma_s = \frac{\bar{H}_{1/3}}{\frac{g}{2\pi} T^2_{max}} = \frac{\bar{H}_{1/3}}{5.12\ T^2_{max}}$$

$\bar{H}_{1/3}$ = significant wave height

T_{max} = period of max energy density

WAVE AGE (in terms of γ_s)

Wave age	γ_s	Significant height reduction* (H_D/H_F)	Decay distance* (naut mi)
Sea			
	1/40	1.00	0
Young swell			
	1/100	0.50	250
Moderate swell			
	1/250	0.25	1600
Old swell			

H_F = sea height in the generating area

H_D = swell height at decay distance D

*Approximate values for swell generated in an average extratropical cyclonic storm from the SMB wave forecasting graphs (Bretschneider, 1958).

ALL DIRECTIONS FEBRUARY 1975

CENTRAL PERIOD (SECONDS)

ENERGY DENSITY/FNWC FREQ. BANDWIDTH (CODED)	6.1	6.5	7.5	8.6	9.7	10.9	12.0	12.9	13.8	15.0	16.4	18.0	20.0	22.5	25.7
01	142	135	122	123	123	153	143	158	129	108	76	60	37	11	13
02	141	115	137	40	41	33	39	37	29	27	17	12	2	1	
03			1	65	49	33	30	17	17	16	9	9	8	1	1
04				65	51	18	19	16	7	7	6	3		1	1
05				2	29	19	20	13	13	9	6		1	1	
06						20	9	8	7	4	4				
07						18	4	8	4	2	1				
08						16		3	6	3	2				
09						1		3	3	4	1	1	3		
10									5			2			
11										6		3			
12											5	1		1	
13										1	2		1		
14															
15											1	1			
16												1			
17															
18															
19												1			
20															
21													1		
22															

TABLE 6: SPECTRAL ELEMENT STATISTICS
ENERGY DENSITY (CODED) PER FNWC FREQUENCY BANDWIDTH
AND 30° DIRECTION BANDWIDTH

ALL DIRECTIONS FEBRUARY 1975

CENTRAL PERIOD (SECONDS)

ENERGY DENSITY/0.0055 HZ BANDWIDTH (CODED)	6.1	6.5	7.5	8.6	9.7	10.9	12.0	12.9	13.8	15.0	16.4	18.0	20.0	22.5	25.7
01	283	250	260	228	164	186	143	158	129	108	76	60	37	11	13
02				67	100	51	39	37	29	27	17	12	2	1	
03					29	39	30	17	17	16	9	9	8	1	1
04						34	19	16	7	7	6	3		1	1
05							20	13	13	9	6		1	1	
06							9	8	7	4	4				
07							4	8	4	2	1				
08								3	6	3	2				
09								3	3	4	1	1	3		
10									5			2			
11										6		3			
12											5	1			
13										1	2		1		
14															
15											1	1			
16												1			
17															
18															
19												1			
20															
21													1		
22															

TABLE 7: SPECTRAL ELEMENT STATISTICS

ENERGY DENSITY (CODED) PER 0.0055 Hz STANDARD FREQUENCY BANDWIDTH AND 30° DIRECTION BANDWIDTH

ALL DIRECTIONS FEBRUARY 1975

CENTRAL PERIOD (SECONDS)

ENERGY DENSITY/0.0055 HZ BANDWIDTH (CODED)	6.1	6.5	7.5	8.6	9.7	10.9	12.0	12.9	13.8	15.0	16.4	18.0	20.0	22.5	25.7
01	1	1													
02			1												
03				1											
04					1										
05															
06															
07						1									1
08															
09							1								
10															
11								1							
12									1						
13															
14														1	
15										1					
16															
17											1				
18															
19												1	1		
20															
21															
22															

TABLE 8: SPECTRAL ENTRIES FOR A 50-KNOT FULLY ARISEN SEA
FOR A GIVEN LOCATION AND SYNOPTIC TIME
0.0055 HZ AND 30° BANDWIDTHS

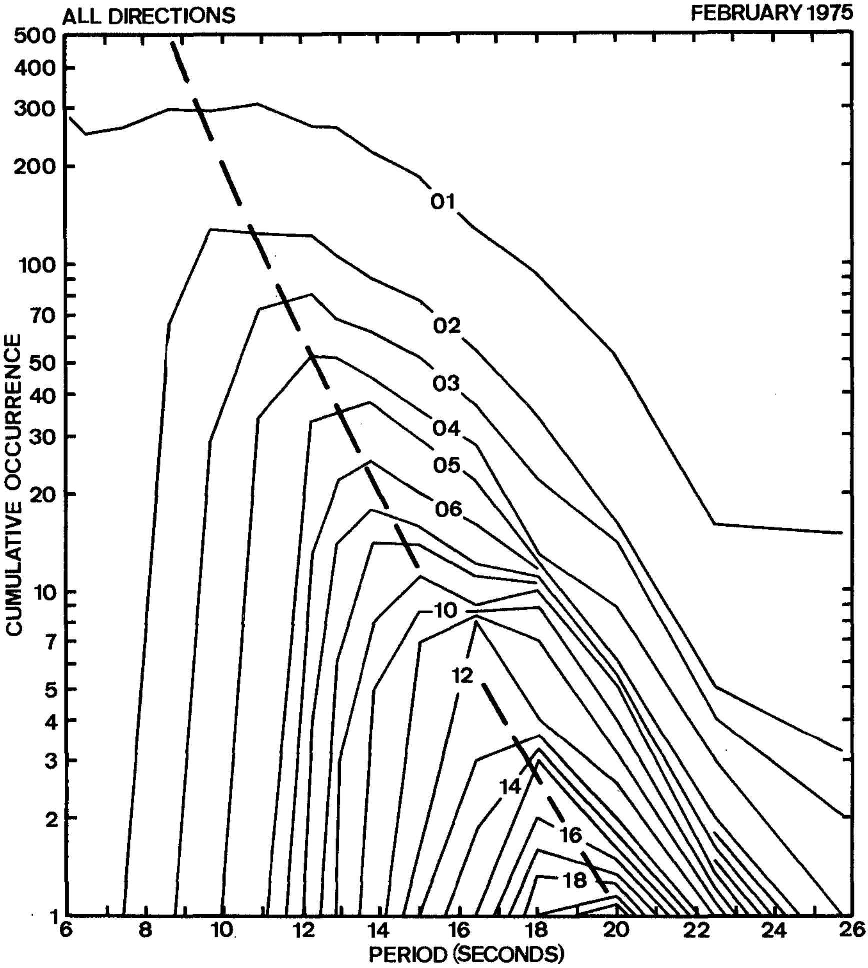

FIGURE 1: CUMULATIVE SPECTRAL ELEMENT STATISTICS
CURVES ARE ENERGY DENSITY (CODED) PER 0.0055 Hz BANDWIDTH AND 30° DIRECTION BANDWIDTH