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The Wave Spectrum and Windspeed as Descriptors of the Ocean Surface

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ABSTRACT

Of the various parameters and phenomena used in describing sea surface conditions, the two most widely used are the wave spectrum and the windspeed. The wave spectrum states how the surface wave energy is distributed with wave frequency. The windspeed is the key parameter for allowing an estimate of the wave spectrum to be made where it is otherwise unobtainable. Remote sensing techniques have been developed to help describe what is occurring at the sea-air interface. However, we must first be able to correlate the remotely sensed data with the sea surface descriptors. This requires an understanding of the wave spectrum concept and the accuracy of oceanic windspeed estimates. In this report the wave spectrum concept is discussed briefly and a systematic approach is taken to describe various ways by which windspeeds at sea are determined. The various techniques for determining windspeeds at sea can be classified in three categories: (a) direct measurements from instrumented platforms, (b) estimates from noninstrumented platforms, and (c) estimates inferred from other data. Such a classification serves to document systematic errors associated with various methods of obtaining windspeed observations.

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CONTENTS

Abstract ii

INTRODUCTION 1

WAVE SPECTRUM 1

WINDSPEED 5

INSTRUMENTED PLATFORMS 5

- System Accuracy 5
- Instrument Sheltering 5
- Height Above Sea Surface 6
- Atmospheric Stability 6
- Platform Motion 6
- Platform Velocity 7
- Data Averaging 7

ESTIMATES FROM UNINSTRUMENTED PLATFORMS 7

- Visual Wave Height and Windspeed Estimates 7
- Whitecap Density 9
- Navigational Estimates 9

ESTIMATES INFERRED FROM OTHER DATA 9

- Synoptic Weather Maps 9
- Ocean Wave Records 10

CONCLUSION 10

REFERENCES 10

THE WAVE SPECTRUM AND WINDSPEED AS DESCRIPTORS OF THE OCEAN SURFACE

INTRODUCTION

From a historical standpoint, airborne remote sensing for oceanography began in January 1785 with man's first balloon flight over the English Channel starting in Dover, England and ending in the forest of Guines, France. Of course, the only remote sensor system available at that time, and for a long time to come, was the human eye. Probably, the only observable phenomena seen on the sea surface by the observers were surface waves and whitecaps. Of course, the balloon flight itself was more important at that time than any observations made.

Today, there is a multitude of sensor systems capable of remotely surveying ocean surface phenomena. These include ground-based HF doppler radar (over-the-horizon radar) as well as other systems aboard aircraft and satellites. Within only a few short years application of remote sensing technology to the field of oceanography has increased greatly. In fact, our understanding of the technology involved has increased at a faster rate than our knowledge of the oceans. Remote sensing of oceanographic phenomena from aircraft is an excellent means of providing microscale information of the ocean surface. Remote sensing from ground-based radar and satellite altitudes has provided mesoscale information from the world's oceans.

Except, perhaps, for sensor systems which will view the ocean in the infrared region of the electromagnetic spectrum, the appearance or condition of the sea surface will have to be well understood in order to correctly evaluate and interpret remotely sensed information. It is unfortunate that many researchers including meteorologists and oceanographers take for granted that the information (surface truth) regarding sea surface descriptors (e.g., wave spectra, windspeed estimates, etc.) will be unquestionably accurate. In most cases there will have been only a single estimate or observation of a sea surface descriptor, thereby necessitating the acceptance of its accuracy. Unfortunately, obtaining reliable information on sea surface descriptors is difficult, and many people are unaware of the various possible sources of error contained in the descriptor data.

Two of the dynamical descriptors of the sea surface are the wave spectrum and windspeed. Although these descriptors are not inherent properties of the sea surface, they are used to help define the physical processes occurring at the sea-air interface. In this report the main emphasis will be on showing how the wave spectrum and windspeed are used as descriptors of the sea surface, their interrelationship, and sources of error contained in the primary observable, i.e., the windspeed.

WAVE SPECTRUM

The endless sea is in constant motion. The motion of the sea surface is random, with the waves continually changing their appearance, i.e., height, length, and extent. The

superposition theory of St. Denis and Pierson (1) describes the sea surface as an infinite number of sinusoidal waves with different heights, periods, and phases all travelling in different directions. Figure 1 shows how the addition of only a few periodic sinusoids can combine to produce a resulting irregular wave pattern. Fortunately, the sea surface can be described in fairly simple terms. The total energy of the sea surface is the sum of the energies of the infinite number of small regular waves which make up the sea. It can be shown that the energy per square foot of a simple sinusoidal wave is $\rho g h^2/8$. It follows then, that

$$\text{Total Energy} = \frac{\rho g}{8} \left(h_1{}^2 + h_2{}^2 + h_3{}^2 + h_4{}^2 + \ldots\right), \qquad (1)$$

where ρg (the unit weight of water) is constant and $h_n{}^2$'s are the squares of the crest-to-trough wave heights of each individual component wave in the sea. The contribution to the total energy of each component wave of different length λ or period T, or more convenient, frequency f (which equals 1/T), is known as the wave spectrum.

There are people today who still have the idea that the sea surface may be described by a single representative wave height or sea state code number which covers a broad range of wave heights. In the majority of cases these descriptors of the sea surface still have to be used because there is no means of obtaining wave spectral information. It is only slightly more than 20 years ago that the spectrum concept was applied to ocean waves by Neumann (3). Prior to the development of the Neumann spectrum, the significant wave method was the main technique for describing the sea surface. Developed by Sverdrup and Munk (4) in the early 1940's, this method yielded information on the significant wave height which is defined as the average of the 1/3 highest waves in a sequential record of waves. From a spectrally analyzed wave record it is possible to determine statistically a significant wave height as well as other wave information if the total area under the spectrum is known. However, a spectrum will show how the energy of the sea surface is distributed with wave frequency. This type of information could enable a naval architect (as an example) to understand how a ship should respond in a seaway with a given spectrum.

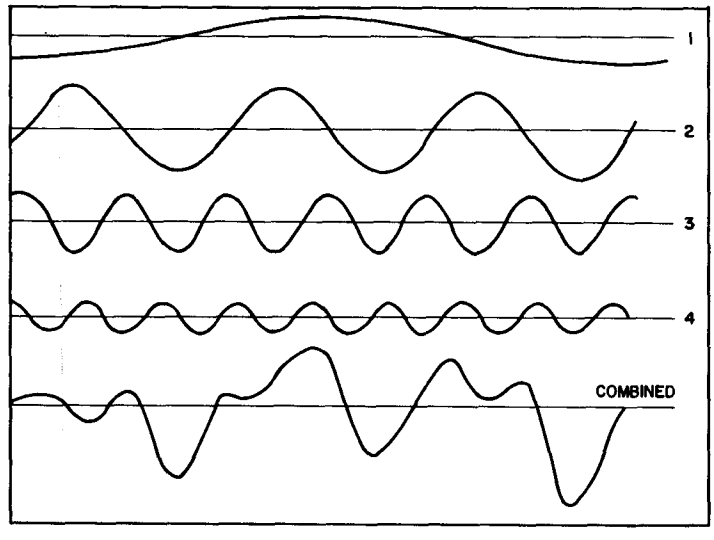

Fig. 1 — Wave pattern combining four regular waves (2)

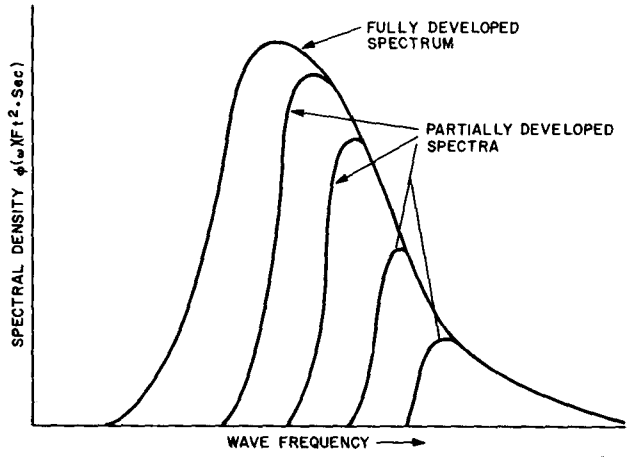

Fig. 2 — Wave spectral growth for a constant windspeed as a function of fetch or duration

Most of the various spectral forms developed to date have expressed the wave spectrum in terms of the windspeed V, wave frequency ω or f, fetch X, and wind duration t, that is,

$$\Phi\ (\omega) = \Phi\ (\omega, V, X, t). \tag{2}$$

For the deep ocean an objective method for determining fetch (the distance over water that a wind of constant speed and direction will blow) does not exist. In addition, each of the spectral forms is supposedly representative of a fully developed sea. That is,

$$\Phi\ (\omega) = \Phi\ (\omega, V), \tag{3}$$

which implies that either the fetch or wind duration or both are sufficiently large enough such that the wave spectrum will not vary statistically unless the windspeed changes. A wave spectrum will continue to grow, as shown in Figure 2, for a constant windspeed until a point in time is reached when energy supplied by the wind to the waves will be offset by the energy dissipated in waves breaking. The sea will grow only if the windspeed increases.

The Neumann fully developed spectrum is expressed as

$$\Phi\ (\omega) = C_1\ \omega^{-6} \exp\left(-C_2\ V^{-2}\, \omega^{-2}\right), \tag{4}$$

where

C_1, C_2 are constants

ω is the angular frequency

V is the windspeed in knots.

The presently accepted empirical spectrum derived by Pierson and Moskowitz (5) is expressed as

$$\Phi(\omega) = C_3\, g^2\, \omega^{-5} \exp\left[-C_4 \left(\frac{g}{V\omega}\right)^4\right], \tag{5}$$

where

C_3, C_4 are constants

g is the acceleration of gravity

V is the windspeed in knots

ω is the angular frequency.

Equations (4) and (5) are both of the same form as Eq. (3). The reasons contributing to their differences are numerous; however, one can now see more easily just how important a parameter the windspeed is. It is the only necessary input parameter required to describe the sea surface wave conditions for a fully developed sea. The situations not fully developed are quite different and require information on fetch and/or wind duration, but, even in those cases, the windspeed plays an equally important role.

Another spectral form for describing the surface of the sea uses the significant wave height and period in place of the windspeed. Such a spectral form was developed by Bretschneider (6) and is expressed as

$$\Phi(\omega) = C_5\, H_s^2\, T_s^{-4}\, \omega^{-5} \exp\left(C_6\, T^{-4}\, \omega^{-4}\right), \tag{6}$$

where

C_5, C_6 are constants

H_s is the significant wave height

T_s is the significant wave period

ω is the angular frequency.

It is more difficult to obtain information on H_s and T_s than it is to get information on the windspeed. If we know the windspeed we can determine H_s and T_s from simple relationships given in Refs. 7 and 8.

Since all that we now need is a windspeed value to determine a specific sea surface condition, the accuracy of the windspeed value becomes ever more important. A windspeed difference of 5 knots (2.57 ms^{-1}) is sufficiently large enough to yield statistically different fully developed spectra (using Eq. (5)). Unfortunately, in the deep ocean, sea surface windspeed values are not easy to obtain; in most cases they can only be estimated. The following section discusses in more detail various methods for obtaining sea surface windspeed estimates in the deep ocean and many of the errors involved in obtaining the estimates.

WINDSPEED

In the previous section we discussed briefly the concept of the wave spectrum as a descriptor of the sea surface and the importance of the windspeed in determining a spectrum. Various factors affecting windspeed observations and estimates at sea are listed below.

Direct measurements from instrumented platforms

1. Instrumental accuracy
2. Instrument sheltering
3. Height above sea surface
4. Atmospheric stability
5. Platform motion
6. Platform velocity
7. Data averaging

Estimates from uninstrumented platforms

1. Visual wave height and windspeed estimates
2. Whitecap density
3. Navigational estimates

Estimates inferred from other data

1. Synoptic weather maps
2. Ocean wave records

Any one factor or combination of factors would be sufficient to produce errors of large magnitude in the windspeed. The list shows that the factors affecting windspeed estimates at sea can be classified in three categories: (a) direct measurements from instrumented platforms, (b) estimates from noninstrumented platforms, and (c) estimates from other data. No specific wind-measuring instruments are discussed. Instead, they are placed in a single family under the common category of Instrumented Platforms. Only the most common factors affecting the measurement of windspeeds will be included within the categories.

Instrumented Platforms

System Accuracy — Regardless of the type of anemometers used in obtaining windspeed information at sea, little need be said of the need for the instruments to be calibrated, free from salt encrustation and rust, and operating as intended. This, of course, holds for any instrumentation being used for a specific purpose. A clean, unfouled instrument will allow data to be obtained. If the system is calibrated, the data can be analyzed further; otherwise, the data will be descriptive.

Instrument Sheltering — A mast-mounted anemometer situated in the downwind flow of the wind may be shadowed by the mast. A lower value of the windspeed will usually be recorded in this case. This may also happen in cases where an anemometer is not located at the highest point on a mast, tower, or light station. It may even be possible for an anemometer positioned in the upwind streamflow to be influenced by turbulence produced by the supporting structure. The turbulence may produce the recording of windspeed values greater than the actual wind.

Height Above Sea Surface — The height of an anemometer above the sea surface is important to know since the "surface wind" used for describing the sea surface conditions has generally been accepted as the wind measured at the 19.5-m level. Windspeeds determined from an anemometer not at the 19.5-m level should be adjusted to that level. The variation of windspeed with height (discussed further in the next paragraph) was shown in Ref. 7 to be one of the primary reasons why various wave forecasting techniques produced different results when given the same windspeed input data. When the windspeed was was adjusted to the 19.5-m level (8), at least in the case of the Neumann and P-M spectra (5), the results from the two methods became more compatible.

Atmospheric Stability — Atmospheric stability plays an important role in determining how windspeed varies as a function of height above the sea surface. Although a topic of major research in itself, atmospheric stability may be approximated by the air-sea temperature difference;

$$(\theta_a - \theta_s) \begin{array}{l} < 0 \text{ unstable} \\ = 0 \text{ neutral} \\ > 0 \text{ stable,} \end{array}$$

where θ_a is the air temperature (°C) and θ_s is the sea surface temperature. Under neutral stability conditions one could expect a logarithmic wind profile in simplified form given by Eq. (7);

$$V_2 = V_1 \left(1 + \frac{\sqrt{C_D}}{k} \ln \frac{Z_2}{Z_1}\right), \tag{7}$$

where

V_2 and V_1 are windspeeds at two elevations Z_2 and Z_1

$k = 0.4$ (Von Karman's constant)

C_D, the drag coefficient, is a function of windspeed.

Equation (7) thus allows one to determine a windspeed at some arbitrary elevation Z_2 within the planetary boundary layer, given a windspeed at elevation Z_1. The height to which Eq. (7) may be considered valid depends on the thickness of neutrally stratified air. This may range from a fraction of a meter to perhaps 1500 m in the extreme. Under stability conditions other than neutral, the vertical wind profile no longer obeys a purely logarithmic law and becomes more difficult to describe. With regard to wave forecasting procedures, the adjustment of windspeed data to the 19.5-m level is becoming more widespread for reasons given in the preceding paragraph.

Platform Motion — Platform motion, excluding forward translation covered in the following paragraph, produces the effect of truncating high and low windspeed estimates. Each of the three motions — heave (vertical displacement), roll, and pitch — experienced by a platform or vessel at sea produce the effect of changing the anemometer height. The rougher the sea the greater the effect each produces. A cup anemometer aboard a floating platform would tend to read higher than the true windspeed when the platform is rolling. This is because the sensor accelerates more easily than it decelerates. If the platform is a buoy or small vessel, a Bernoulli effect slightly above the sea surface may introduce a perturbation in the wind field. This effect can be readily understood when one visualizes

a fluid flowing through a pipe containing a constriction. The fluid must speed up in passing through the constriction and slow down when exiting the constriction. Another effect of platform motion is that under very high wind conditions large waves may completely shelter an anemometer on a buoy or vessel, thereby producing an erroneous wind recording. In this case an anemometer may record practically no wind at all when indeed there is a very strong wind blowing.

Platform Velocity — Platform velocity, not necessarily pertinent to anchored buoys, is important because the wind vector must now be derived based on platform velocity (speed plus direction). Since platform velocity such as ship speed and direction is only a closely approximated parameter, it is nonetheless not exact and, therefore, the derived wind vector is inexact.

Data Averaging — Probably more effort in research on winds at sea pertains to time series analysis of windspeed records than any other aspect of windspeed determination. Some of the conclusions of Baer and Withee (9) are quite startling regarding windspeed observations from buoys. They conclude that to keep from exceeding a windspeed error of 2.5 knots with data intervals of 6 hrs, an averaging device acting over a time of at least 4 hr would be required as a filter. Such filtering could miss small-scale phenomena (such as fronts, squalls, and thunderstorms, etc.) that produce rapid changes in the wind, but would yield reliable information on the mean wind.

The above discussion was concentrated on windspeed observations at sea obtained from an anemometer aboard an instrumented platform (vessel, buoy, etc.) on the sea surface. The following section will discuss windspeed estimates from noninstrumented platforms.

Estimates From Uninstrumented Platforms

Visual Wave Height and Windspeed Estimates — Although most ships have some type of anemometer, many of them have none at all. In this case an experienced observer would estimate the windspeed from the visual appearance of the sea conditions. The observer would estimate the (significant) wave height and correlate his estimate with some windspeed vs wave height scale. Regardless of how experienced the observer may be, he cannot estimate wave height as accurately as is needed in determining the windspeed. However, where windspeed is otherwise not obtainable, the visual estimates are all that do exist and should be used, but with care.

Probably the oldest and best known of the windspeed vs wave height relationships is the Beaufort wind scale originally designed by Admiral Sir Francis Beaufort in 1805. It was based on the effects of various windspeeds on the amount of canvas that a full-rigged frigate of the period could carry. Table 1, a condensed modern version of the original Beaufort scale, describes the sea surface appearance as a function of windspeed.*

*This version of the Beaufort scale is condensed from the July 1970 issue of the *Mariner's Weather Log*, Vol. 14, No. 4. Another version may be found in *Physics of the Marine Atmosphere* by H. U. Roll, Academic Press, New York 1965.

Table 1

Beaufort Number	Definition	Windspeed (Knots)	Description of Effects on Sea Surface
0	Calm	Under 1	Sea is mirror smooth.
1	Light air	1-3	Ripples present, but without foam crests.
2	Light breeze	4-6	Small wavelets, crests are glassy but do not break.
3	Gentle breeze	7-10	Large wavelets; crests begin to break; only an occasional whitecap.
4	Moderate breeze	11-16	Small waves, becoming longer. Frequent whitecaps.
5	Fresh breeze	17-21	Moderate waves, many whitecaps.
6	Strong breeze	22-27	Large waves begin to form. White foam crests are more extensive. Streaks develop.
7	Moderate gale	28-33	Sea builds up. Streaks very noticeable in wind direction.
8	Fresh gale	34-40	Moderate high waves, well-defined streaks.
9	Strong gale	41-47	High waves, dense streaks.
10	Whole gale	48-55	Very high waves; sea surface takes on a white appearance.
11	Storm	56-63	Exceptionally high waves; sea covered with large patches of foam.
12	Hurricane	64+	Air filled with spray and foam; sea completely white; driving spray.

Whitecap Density — Two approximations of the windspeed can be made from its visual appearance. The first approximation can tell you what the wind speeds *are not* and the second approximation can tell you what the minimum value of the windspeed *is*. Both situations pertain to the presence of whitecaps. It is widely known that whitecaps will be produced by the wind at about 12-13 knots. Hence, if there are no whitecaps present it may be concluded that the wind is less than this minimum value and not greater. Exceptions to this generality are shallow-water areas and situations in which a current system may be moving counter to the wave motion. Both conditions may cause the waves to steepen and produce some wave-breaking.

The second approximation, estimating a minimum windspeed when whitecaps are already present, is made possible when the wind is in excess of 25 knots. At this and higher windspeeds, the whitecaps are hurled downwind in the form of long streaks. This effect is best noticeable visually in the windspeed range of 30-50 knots. The actual onset of these streaks has been found to occur at about 20 knots (10), but is not very evident and may be the result of gusts. Above 50 knots many more whitecaps are produced which may obscure the thin white streaks. This phenomenon is more easily observed from aircraft than from a ship, whereas the first situation (i.e., no whitecaps) can be better disconcerned from aboard a ship.

Navigational Estimates — From the aircraft heading, speed, and drift it is relatively easy to calculate via vector addition a windspeed and direction. However, these values are normally computed at specific times, are only as accurate as the input parameters, and are pertinent only at the altitude the airplane is flying. By no means are they necessarily representative of the sea surface winds. Not only does windspeed vary with height, but the wind direction also varies with height. For an aircraft flying at 5,000 ft the wind direction at the sea surface might be significantly different than the wind direction at flight altitude. A 30-45 degree difference in direction should not be surprising. In the case of a squall a 180-degree difference might be observed. (Over land, a complete reversal of wind direction may occur within (say) 100 m.) Inertial navigation systems may be able to yield continuous windspeed (and direction) information, but, again, valid only at flight altitude.

Whereas this and the previous section considered in-situ windspeed estimates, the following section concerns windspeed derived from other means.

Estimates Inferred From Other Data

Synoptic Weather Maps — The 6-hourly surface weather maps of the Northern Hemisphere purport to show windspeed and direction from ship report data. This is, indeed, done but the windspeed is depicted only to the nearest *5* knots and is usually representative of the 10-m level. To determine the observed windspeed to the nearest knot (by whichever means it was obtained), it would be necessary to obtain a copy of the transmitted weather report or a copy of the ship's log. Windspeed information from weather maps should be used with care. Techniques have been proposed for depicting the windspeed in greater detail (11) but have not been put into practice.

In areas where sufficient ship reports are lacking, windspeeds may be computed from the sea surface pressure pattern. Windspeeds thus determined are subject to the accuracy of the map analysis. In addition, the geostrophic windspeeds computed have been found to be approximately 30% higher than observed winds at sea and, therefore, must be reduced by this factor.

Ocean Wave Records — Windspeed estimates may be inferred from visual wave information as described previously. It is also possible to infer windspeed estimates from recorded wave height data. If a wave height profile vs time or distance is available, a wave spectrum may then be calculated using standard time series analysis techniques. The area under the spectrum, the total variance, is related to the significant wave height by

$$H_s = 4\sqrt{\sigma^2} = 4\sigma, \tag{8}$$

where

H_s is the significant wave height

σ^2 is the total variance

σ is the rms wave height displacement.

If observed windspeed data are unavailable, the windspeed may be estimated by

$$H_s = 1.82 \times 10^{-2}\ V^2,$$

which is the relationship of the windspeed (in knots) to the significant wave height (in feet) of a fully developed sea determined in Ref. 7. The windspeed thus computed is valid only for fully developed seas. When this method is used in a situation not fully developed and cases where swell waves, generated elsewhere and propagated into the area of interest, the resulting windspeed estimate should be used cautiously.

CONCLUSION

Remote sensing of the ocean surface via passive and active microwave techniques from ground-based aircraft and satellite sensor systems will complement the present methods for obtaining windspeed and wave height data over all the world's oceans. A more dense network of ocean wind data is necessary especially on an operational basis if we are to learn more about the oceanic heat balance and apply the wind data to improving weather and ocean wave predictions. When use is made of oceanic windspeed data, care should be given to understand how the data were obtained and their apparent accuracy. This report has attempted to describe and categorize many of the factors affecting windspeed estimates at sea in hope that users will not blindly accept the validity of the windspeed data.

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13. ABSTRACT

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