TR-183

TECHNICAL REPORT

WAVE HINDCAST PROJECT NORTH ATLANTIC OCEAN

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ABSTRACT

A computerized system has been developed for the production of ocean wave spectra over the North Atlantic Ocean. The spectra results are fairly close to observed conditions. By means of this system a 15-month series of wave spectra has been obtained at 519 gridpoints over the North Atlantic. Each spectrum is described in terms of the spectral energy in 12 directions for 15 different frequencies.

FOREWORD

In early 1960 during discussions at David Taylor Model Basin a need was cited for a world-wide climatological hindcast of ocean wave spectra. Previous experience from manual computations of wave spectra at a single point for one year had shown that this project on an ocean-wide basis and for several years would be a formidable task and probably not feasible except by some electronic computer method. Following several more conferences during the year the U. S. Naval Oceanographic Office was assigned the task in early February 1961 of hindcasting by machine methods the ocean wave spectra for the North Atlantic Ocean for various seasons of the year. The climatological wave spectra obtained were to be recorded by some computer processing system so that the spectra could be used in other computer programs.

The basic purpose of this study, as initiated by the Bureau of Naval Weapons, was to provide a wave climatology from which carrier-deck motion spectra could be generated as a function of carrier class, speed, and heading for different geographical locations and seasons of the year. The carrier motion data in combination with separate studies to determine airplane response to command signals from the AN/STN-10 Landing Control Central would then define a landing environment and the basis for the structural design of carrier-based airplanes for fully automatic landings.

This final report gives a resume of the various phases of the task, the problems encountered with their solutions, and a summary of the final results. These results represent the culmination of about four years of determined effort by a large number of people in overcoming the many problems of a complex research project.

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Symbols and abbreviations

JNWP - Joint Numerical Weather Prediction

i, j - gridpoints on the JNWP grid

rms - root mean square

kts - knots

m - meters

u - the component of the wind, east-west

v - the component of the wind, north-south

U_g - the 1000-mb geostrophic wind component, east-west

V_{gr} - the 1000-mb gradient wind component, north-south

ζ_{700} - the 700-mb geostrophic relative vorticity

ζ_{1000} - the 1000-mb geostrophic relative vorticity

mb - millibar (pressure)

α - the indraft angle (angle of rotation from geostrophic direction-counterclockwise rotation is positive)

OWS - ocean weather ship

ft - feet

$\overline{H}_{1/3}$ - significant wave height in feet

$V_{19.5}$ - wind speed in kts at elevation of 19.5 m

$S(\omega)$ - the component spectral energy

$d\omega$ - incremental angular frequency

α_1 - a constant with value of 8.10×10^{-3}

g - the acceleration due to gravity

ω - the component angular wave frequency in radians per second

exp - exponent e

β - a constant with the value of 0.74

ω_0 - the ratio of g to $V_{19.5}$

$A^2(f)$ - the component frequency energy in $(ft)^2$

df - the incremental component wave frequency

f - the component wave frequency in cps

cps - cycles per second

V_2 - the wind speed at elevation z_2

V_1 - the wind speed at elevation z_1

C_d - the drag coefficient

K - von Karman constant with value of 0.4

ln - natural logarithm

z_2 - elevation at which V_2 is determined

z_1 - elevation at which V_1 is determined

V - wind speed at any elevation

SWOP - Stereo Wave Observation Project

$A^2(f, \theta)$ - the component frequency directional energy in $(ft)^2$

D - equivalent to $32.16/2\pi fV_{19.5}$

Δf - incremental frequency

$\Delta \theta$ - incremental direction

θ - the direction attached to the spectral component

cos - cosine

β_1 - direction from the wind direction

E - total wave spectral energy in $(ft)^2$ equal to twice the variance

$A_D^2(f, \theta)$ - the spectral energy of the component after (with) dissipation

$A_I^2(f, \theta)$ - the spectral energy of the component before (without) dissipation

C_1, C_2, C_3 - constants

WAVE HINDCAST PROJECT-NORTH ATLANTIC OCEAN (PROGRAM 501)

Introduction

The idea of numerical weather prediction dates back to the year 1922 but it remained impractical until electronic data processing computers became a reality. Even then there were staggering problems that had to be solved before the computer results could compare favorably with older, human interpretation methods and then only for the upper levels of the atmosphere.

Ocean wave forecasting on a serious basis began back in the 1940's after certain relationships among wind speeds, wind durations, and the lengths of the fetches had been empirically determined. During the 1950's prognostic wave charts giving wave heights over the oceans were being manually produced at a few weather centers for use in ship operations and routing.

The next forward step by the early 1960's was the elimination of the subjectivity of the manual wave forecasting methods by the use of electronic computers. Raw weather data from land and ship observations were fed into computers and the computers produced hemispheric charts of surface pressure and winds. With the winds as the input the computers then produced prognostic charts of wave heights and directions for periods up to 48 hours in advance. However, these forecasts had a limited application because the technique described only the significant wave height and period rather than the distribution or spectrum of heights and periods (or frequencies) - a more difficult but also a much more realistic means of describing the sea surface.

At about this stage in 1961 the U. S. Naval Oceanographic Office was given the task of producing a wave-spectra climatology for the North Atlantic Ocean.

The first objectives of the program consisted of two major parts:

1. To develop a machine method for obtaining the surface wind field over the North Atlantic Ocean from grid point pressure data.

2. To develop a machine method for providing wave spectra from the wind field as a function of geography and seasonal periods of the year.

Due to the highly specialized nature of the objectives of this program it was immediately recognized that outside private research groups that had already done corresponding work in these areas would be required. The two organizations immediately considered and with whom contracts were later negotiated were Travelers Research Center to make studies of the specification of surface winds over the ocean by machine methods and New York University to perform analytical work and prepare a program for machine computations of wave spectra from the wind field data.

Accordingly, technical specifications for the contractual work were prepared and these two organizations were invited to make contract proposals. Proposals from other organizations were also given consideration.

While the two contracts were being negotiated several studies on various topics related to both winds and waves were completed by the Oceanographic Office. These reports were later sent to the two contractors for their information and possible use in fulfilling their contracts. Continuing studies and evaluations of contractual results were also made by the Oceanographic Office throughout the period. Publications reporting these investigations are listed in the Bibliography on page 31 of this report.

Although the complete list of personnel who worked on this project would be rather lengthy, credit for the major accomplishments should go to the following:

Travelers Research Center

Mr. Albert Thomasell, Jr., Research Scientist
Mr. James G. Welsh, Research Associate

New York University

Dr. Willard J. Pierson, Jr., Professor of Oceanography
Dr. Leo J. Tick, Senior Research Scientist
Mr. Lionel I. Moskowitz, Graduate Assistant

Lockheed-California Company (N.Y.U. Subcontract)

Dr. Ledolph Baer, Principal Investigator

Travelers Research Center Contract

A contract was executed with Travelers in February 1962 to make a feasibility study for determining by machine methods a surface wind field over the North Atlantic Ocean. The input data for the work done on this contract consisted of the following:

1. Digitized sea-level pressure grid data on magnetic tape for the North Atlantic Ocean within the time period April 1955 through March 1960 obtained from the U. S. Air Force Project 433L.

2. Digitized surface to 700-mb mean temperature grid data on magnetic tape for the same period, also from Project 433L.

3. Ocean Station Vessel surface synoptic weather data on punched cards for the same period for ship locations B, C, D, and E.

4. Seasonal charts of air-sea temperature difference distribution for the North Atlantic Ocean.

5. Monthly charts of mean sea-surface temperatures for the North Atlantic Ocean.

6. North Atlantic surface-weather ship reports for 15 December through 27 December 1959.

The U. S. Air Force Project 433L data consist of manually-read sea-level pressure values and pressure height and temperature data for the 700-mb level on a diamond grid network at the JNWP gridpoints for which points i and j are both odd or both even. The data were extracted from subjective synoptic weather map analyses by the U. S. Weather Bureau. Travelers checked all the data for errors, made corrections, and, by interpolation from the diamond grid, computed values for all the standard JNWP gridpoints. The data in corrected form are on IBM 7090 magnetic tapes for the period April 1955 through March 1960.

Two methods were investigated by Travelers for the development of a wind-specification technique. The first method used the screening-regression technique to generate wind-specification equations of which six equations (Table 1) using 49 different variables (Table 2) were generated and tested. Winds from these equations are regression winds in this report. The second method, which was much more difficult to obtain, was undertaken to try for improvement of the regression winds. It consisted of an objective analysis of winds using the regression winds as an initial guess and then actual ship wind observations (assuming them to be correct) for correcting the initial guess. These wind estimates are called objective-analysis winds in this report. In addition, geostrophic and gradient winds were computed and evaluated for comparison with the regression winds.

TABLE 1
All-ship wind-specification equations with development-data-sample verification statistics*
(Travelers)

Wind-specification equation			Accumulative % explained variance	Residual error
Wind element	Coefficient	Variable		
$V =$	$+1.24052 \times 10^{1}$	1	-	7.4 knots
	$+6.38337 \times 10^{-1}$	V_g	44.4	
	$+1.42367 \times 10^{5}$	ζ_{1000}	50.0	
	$+2.80490 \times 10^{4}$	$\mathbf{V}_g \cdot \nabla T_s$	52.7	
$u =$	$+2.66762 \times 10^{-1}$	1	-	8.5 knots
	$+7.98937 \times 10^{-1}$	u_g	62.9	
	-3.46355×10^{-1}	v_{gr}	74.7	
	$+9.30208 \times 10^{4}$	ζ_{700}	75.4	
$v =$	-3.45584	1	-	8.6 knots
	$+7.82943 \times 10^{-1}$	v_g	64.7	
	$+2.41837 \times 10^{-1}$	u_g	70.5	
	$+1.23438 \times 10^{5}$	ζ_{1000}	72.3	
$V\,V_g^{-1} =$	$+1.96295$	1	-	0.4
	-3.79605×10^{-2}	V_g	15.2	
	$+3.05386 \times 10^{-4}$	V_{gr}^2	20.6	
	$+3.49295 \times 10^{3}$	ζ_{1000}	24.7	
	-2.79597×10^{-3}	v_{gr}	27.0	
$V\,V_{gr}^{-1} =$	$+1.93047$	1	-	0.4
	$+6.53799 \times 10^{3}$	ζ_{1000}	13.9	
	-3.53884×10^{-2}	V_{gr}	24.9	
	$+2.84763 \times 10^{-4}$	V_{gr}^2	29.2	
	-2.81406×10^{-3}	v_{gr}	31.2	
$\alpha =$ †	$+1.54270$	1	-	33.5°
	-1.56979×10^{10}	$\mathbf{V}_g \cdot \nabla\zeta_{1000}$	3.2	

*4417 cases, no weak winds, no measured air, sea, or temperature variables.
†$\bar{\alpha} = 15.5°$; $\sigma_\alpha = 34.1°$.

TABLE 2
Variables used for the input to the screening-regression technique (Travelers)

Variable	Unit	Description
θ	deg	Latitude
λ	deg	Longitude
T_a	°F	Air temperature
T_s	°F	Sea-surface temperature
Hour	-	Derived from hour: 00Z = 0; 12Z = 1
$\sin(6^{-1}\pi \text{ month})$	-	Derived from month: Jan. = 1; Feb. = 2; etc.
$\cos(6^{-1}\pi \text{ month})$	-	Derived from month: Jan. = 1; Feb. = 2; etc.
$\bar{T}_s$	°F	Monthly mean sea-surface temperature
$\lambda \sin(6^{-1}\pi \text{ month})$	-	-
$\lambda \cos(6^{-1}\pi \text{ month})$	-	-
$\theta \sin(6^{-1}\pi \text{ month})$	-	-
$\theta \cos(6^{-1}\pi \text{ month})$	-	-
$\theta\lambda$	-	-
$T_a - T_s$	°F	-
$(T_a - T_s)^2$	$(°F)^2$	-
$\bar{T}_{7-10}$	°F	Mean virtual temperature of the 700-1000-mb layer: $\bar{T}_{7-10} = 1.8\,[0.029197\,(Z_{700} - Z_{1000}) - 255.4]$
$\bar{T}_s - \bar{T}_{7-10}$	°F	-
$(\bar{T}_s - \bar{T}_{7-10})^2$	$(°F)^2$	-
$\delta_{12}\, Z_{1000}$	12^{-1} ft hr^{-1}	12-hr 1000-mb height change
$\delta_{12}\, Z_{700}$	12^{-1} ft hr^{-1}	12-hr 700-mb height change
$\delta_{12}\, \bar{T}_{7-10}$	12^{-1} °F hr^{-1}	12-hr 700-1000-mb mean virtual temperature change: $\delta_{12}\, \bar{T}_{7-10} = 0.525546\,(\delta_{12}\, Z_{700} - \delta_{12}\, Z_{1000})$
ζ_{1000}	sec^{-1}	1000-mb geostrophic relative vorticity*†: $\zeta_{1000} = g f^{-1} \nabla_p^2 Z_{1000}$
ζ_{700}	sec^{-1}	700-mb geostrophic relative vorticity*†: $\zeta_{700} = g f^{-1} \nabla_p^2 Z_{700}$

*f = Coriolis parameter = $2\Omega \sin\theta$.

†All space derivatives are computed by centered finite-difference approximations over 2 grid intervals.

TABLE 2 (continued)

Variable	Unit	Description
$\partial \overline{T}_s/\partial x$ $\partial \overline{T}_s/\partial y$	deg ft-1 deg ft-1	Components of monthly mean sea-surface temperature gradient ‡
$\partial \overline{T}_{7-10}/\partial x$ $\partial \overline{T}_{7-10}/\partial y$	deg ft-1 deg ft-1	Components of mean virtual 700-1000-mb temperature gradient ‡
u_g v_g	ft sec-1 ft sec-1	1000-mb geostrophic-wind components*†‡: $\mathbb{V}_g = gf^{-1} \cdot \mathbb{k} \times \nabla_p Z_{1000}$
u_{gr} v_{gr}	ft sec-1 ft sec-1	1000-mb gradient-wind components*†‡: $K_H f^{-1} V_{gr}^2 + V_{gr} - V_g = 0$
$u_{\Delta Z}$ $v_{\Delta Z}$	ft sec-1 ft sec-1	1000-mb isallobaric-wind components*†‡: $\mathbb{V}_{\Delta Z} = -gf^{-2} \nabla_p (\partial Z_{1000}/\partial t)$
V_g	ft sec-1	Geostrophic wind speed †
V_{gr}	ft sec-1	Gradient wind speed †
$V_{\Delta Z}$	ft sec-1	Isallobaric wind speed †
$\lvert \nabla_H \overline{T}_s \rvert$	°F ft-1	Monthly mean sea-surface temperature gradient †
$\lvert \nabla_p \overline{T}_{7-10} \rvert$	°F ft-1	Gradient of mean virtual temperature in the 700-1000-mb layer †
V_g^2	ft2 sec-2	†
V_{gr}^2	ft2 sec-2	†
$\mathbb{V}_{g1000} \cdot \nabla_p \zeta_{1000}$	sec-2	1000-mb advection of vorticity by geostrophic wind*†‡
$\mathbb{V}_{g700} \cdot \nabla_p \zeta_{700}$	sec-2	700-mb advection of vorticity by geostrophic wind*†‡
$\mathbb{V}_{g1000} \cdot \nabla_H \overline{T}_s$	°F sec-1	Advection of monthly mean sea-surface temperature by 1000-mb geostrophic wind*†‡
$\mathbb{V}_g \cdot \nabla_p \overline{T}_{7-10}$	°F sec-1	Advection of mean 700-1000-mb temperature by the mean 700-1000-mb geostrophic wind*†‡
K_H K_H^2 K_H^3	ft-1 ft-2 ft-3	Curvature of the 1000-mb height contours†‡: $K_H = \dfrac{\dfrac{\partial^2 Z}{\partial x^2}\left(\dfrac{\partial Z}{\partial y}\right)^2 + \dfrac{\partial^2 Z}{\partial y^2}\left(\dfrac{\partial Z}{\partial x}\right)^2 - \dfrac{\partial Z}{\partial x}\dfrac{\partial Z}{\partial y}\dfrac{\partial^2 Z}{\partial x \partial y}}{\left[\left(\dfrac{\partial Z}{\partial x}\right)^2 + \left(\dfrac{\partial Z}{\partial y}\right)^2\right]^{3/2}}$
$K_H V_{gr}^2 f^{-1}$	ft sec-1	Cyclostrophic term of gradient-wind equation*†‡
$\mathbb{k} \cdot (\nabla_H \overline{T}_s \times \nabla_p \overline{T}_{7-10})$	(°F)2 ft-2	A stability parameter †‡

*f = Coriolis parameter = $2\Omega \sin \theta$.

†All space derivatives are computed by centered finite-difference approximations over 2 grid intervals.

‡All vector components are referred to the earth's geographical coordinate system; x is positive eastward and y is positive northward.

To obtain the regression winds three screening-regression runs were made resulting in three sets of six wind specification equations. The first run used ship B data only and was used primarily as a test of machine programs. The second run used data from all four weather ships and provided the equations subsequently used for specifying the North Atlantic wind field. The third run was made to test the usefulness of the measured air- and sea-temperature functions. From the results of all three runs it appeared that the best wind estimate had a rms error of about 8.5 kts. for each wind component. The wind speed was determined mainly by the geostrophic wind speed modified slightly for curvature effects. The wind direction was given by the geostrophic-wind direction, rotated counterclockwise 15.5°. It was found from the third run that the measured air-sea temperature difference did not demonstrably show itself as any aid in specifying the indraft angle. Hence, further studies with computed variables that are merely approximations of this measured quantity were considered unnecessary.

Based on all the results of the three runs it was decided by Travelers to use the following u- and v- wind component equations computed from 4,417 samples for specifying the North Atlantic wind field:

$$(1)\ u = 0.266762 + 0.798937\ U_g - 0.346355\ V_{gr} + 9.30208 \times 10^4 \zeta_{700}$$

$$(2)\ v = -3.45584 + 0.782943\ V_g + 0.241837\ U_g + 1.23438 \times 10^5 \zeta_{1000}$$

$$(3)\ \alpha = 15.5490^\circ$$

These three equations then specify the regression winds. A test sample wind field was computed with these equations for 17-18 December 1959. The results (Fig. 1) show two large extratropical cyclones moving northeastward across the Atlantic Ocean at approximately 20 kts. In the five separate fields computed, the continuity of the cyclones was excellent, the wind pattern well organized, and the wind speeds reasonable. The large grid mesh, however, causes small scale features, such as multiple centers, to disappear and frontal shear lines have been quite blurred for the same reason.

In view of the rms error of 8.5 kts. for each of the components of the regression winds it was decided to test the possibility that a better wind specification could be obtained from the direct use of ship wind observations. Objective-analysis winds were prepared for the period 15-27 December 1959 from North Atlantic surface-weather ship reports which had been manually checked for errors. In a large-scale effort a program would have to be developed whereby this could be handled by computer. The initial-guess wind field for the objective-analysis winds was the regression wind. The ship observations were integrated with the regression winds by a conditional relaxation analysis method and then verified by the areal-mean-error method. The gridpoint values were determined by extrapolating from or interpolating between locations at which observations of the winds were available. The procedure required that the gridpoint values satisfied Poisson's equation subject to the constraints imposed by the observations and an

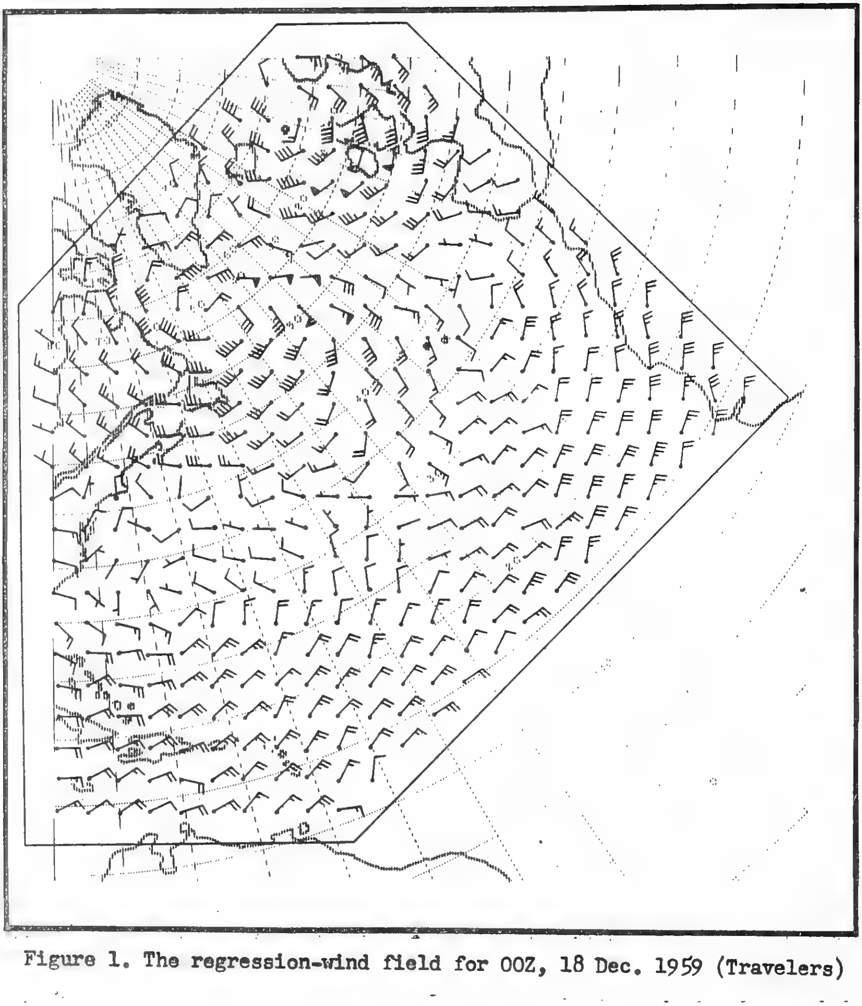

Figure 1. The regression-wind field for 00Z, 18 Dec. 1959 (Travelers)

arbitrarily defined set of boundary values consisting of the regression winds along the grid perimeter. The ship observation locations usually lie randomly within the gridblocks. The difference between the observed wind and the regression wind (initial guess) was translated to the nearest gridpoint and used to correct the initial guess there, which then became an internal boundary point. The Poisson's equation was solved by a relaxation procedure throughout which the boundary values remained unchanged.

In general the windfield which satisfied the Poisson's equation contained unreal data and required a certain amount of smoothing to eliminate small-scale wiggles from the analysis. The degree of smoothing can be variable and several values of the smoothing operator were tested. The goal of the objective-wind-analysis tests was to determine the proper smoothing factors that resulted in minimum error. Twenty-six separate wind fields were analyzed by the conditional relaxation analysis method with the regression winds serving as the initial guess and the Laplacian of the initial guess serving as a forcing function. Each analysis was smoothed and verified several times. The minimum analysis error occurred in the totally unsmoothed analysis (Fig. 2) as would be expected but the field was quite erratic. A comparison of the regression wind errors with the objective-analysis wind errors showed that the direct use of wind observations does reduce the wind specification errors but only near the location of the wind observations. There is but slight or no improvement elsewhere.

Three objective-analysis wind fields were obtained corresponding to the same times as the regression wind fields. The main discernible difference between them was that the regression winds specified larger areas of strong winds in the vicinity of the cyclone centers than did the objective-analysis winds. Otherwise they were quite similar.

The simplest method for specifying wind over the ocean is to compute the geostrophic or the gradient wind. As a third approach to see if these might be better than either the regression or the objective-analysis winds, geostrophic and gradient winds were computed from the sea-level pressure gridpoint data at Ships B, C, D, and E and compared with the ship observations. The winds were computed from centered finite-difference approximations over two JNWP grid intervals at each of the four gridpoints surrounding the ships. By curvilinear interpolation a value was then computed at the ships' locations. The results of this showed that the geostrophic and gradient wind errors were about 2 kts. higher in all categories than the regression winds. Thus, they were judged inferior to the regression winds.

To evaluate the relative quality of regression winds with objective-analysis winds one should consider not only the verification scores from tests but also the gridpoint wind fields. Since strong winds are considered more significant for ocean wave forecasting although they usually cover only a small area of the map, care must be taken in interpreting the verification scores. The scores are space averages

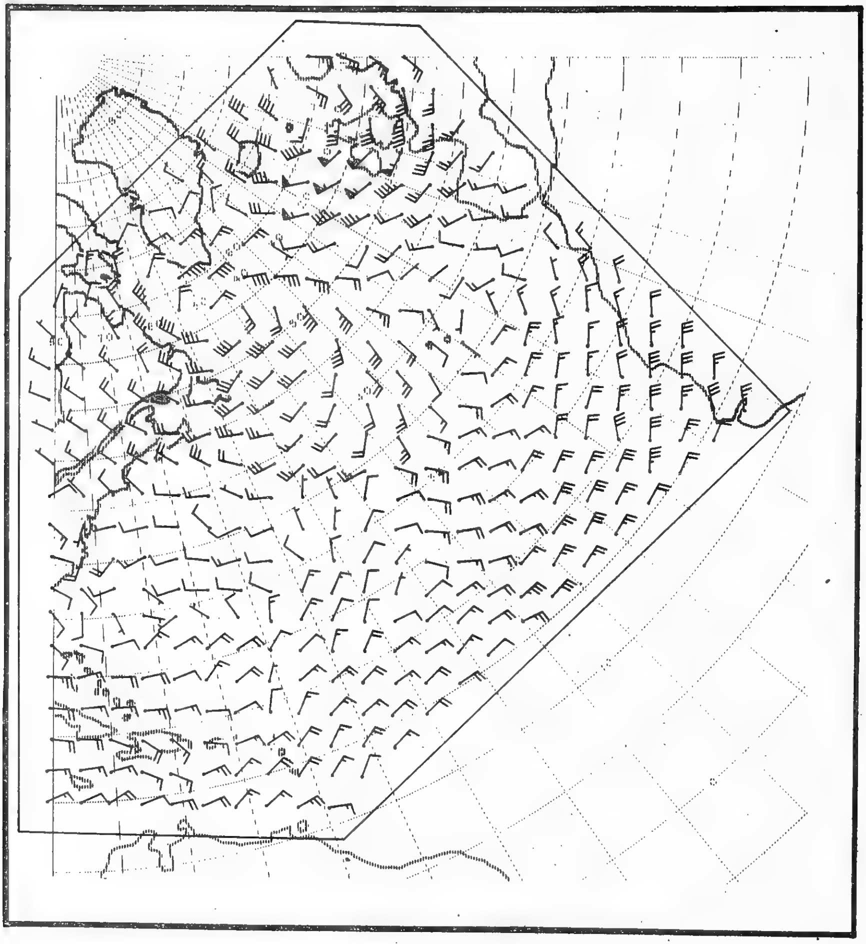

Figure 2. The unsmoothed objective-analysis-wind field for 00Z, 18 Dec. 1959 (Travelers)

of all the wind errors both strong and weak, so they reflect chiefly the errors of the less important and more abundant weaker winds. For a given wind field it would certainly be possible that a minimum error score wind would not specify the strong winds as well as a larger error score wind of some other type.

For the objective-analysis winds, the strongest winds were given by the unsmoothed analyses. The effect of smoothing, while showing improvement in the error scores up to a certain point, was to attenuate the strong winds, the greater the smoothing the greater the attenuation. The regression wind fields specified winds at least as strong as and often stronger than those of the unsmoothed objective analysis winds. Travelers recommended that the regression winds, the unsmoothed objective-analysis winds, and the smoothed-objective analysis winds all be subjected to a wave spectra test to see which one most exactly produced the observed spectra.

New York University Contract

In April 1962 a contract was executed with New York University with a subcontract to Lockheed-California to perform research in two phases:

1. To develop and verify techniques for forecasting directional wave spectra by means of computers and based on synoptic reports over the North Atlantic Ocean.

2. To produce a wave-spectrum climatology based on 12-hourly sea-level pressure data for the North Atlantic Ocean during a 5-year period beginning April 1955 and ending March 1960.

The data used in performing the work under this contract consisted of the following:

1. Approximately 800 shipborne wave-recorder records from OWS Weather Explorer and OWS Weather Reporter provided by the National Institute of Oceanography, Great Britain.

2. Digitized sea-level pressure and surface to 700-mb mean temperature grid data on magnetic tapes for the North Atlantic Ocean from April 1955 through March 1960 obtained from the U. S. Air Force Project 433L, error checked and corrected by Travelers Research Center.

3. Ship surface weather reports over the North Atlantic Ocean in Card Decks 116, 117, and British reports for the 15-month period January through December 1959, December 1958, November 1956, and December 1955 on magnetic tapes obtained from the National Weather Records Center, Asheville.

The subcontract between New York University and Lockheed-California Company was executed in mid-1962 for the purpose of providing technical support to the total project leading to an ocean wave-spectra climatology for the North Atlantic Ocean. The original objectives of the subcontract were to:

1. Compare the results obtained using the Neuman spectrum with those using the Bretschneider and Darbyshire spectra.

2. Optimize the grid size and time-step length.

3. Consider the effects of sea-air temperature differences and other stability and atmospheric turbulence criteria on the effectiveness of the wind in generating waves.

4. Build in an automatic correction capability so that any available wave observations will continually correct hindcasts used as initial conditions in the forecast.

After the project had started several problems previously unforeseen became evident so that a modification of the objectives was necessary. Priority was then given to improving the spectrum model, preparing a new wave growth function, and adding the effects of dissipation to the program.

The point of departure for starting the subcontract was the previous research on machine computations of wave spectra over the North Atlantic Ocean performed by Baer(1) for a doctoral degree at New York University. The data used for preparing a new growth function were the spectra computed at New York University from the British shipborne wave records. Various changes in machine programming to produce a better fit of spectral shapes did not require additional data.

A complete spectral analysis was made for a selected 460 out of the approximately 800 shipborne wave records and the results were published in both tabular and graphical form. The raw spectra of all 460 records have been placed on magnetic tape and are available for any further research. The four main locations in the North Atlantic where the data were taken are as follows:

Position A (62°N, 33°W)
Position I (59°N, 19°W)
Position J (52.5°N, 20°W)
Position K (45°N, 16°W)

These are the on-station positions for the weather ships in the eastern North Atlantic Ocean. Except for a few records, each was of 15 minutes duration and was reduced to a time series of 600 points. This series was analyzed by an electronic computer so that the energy spectrum was estimated at 60 points over the frequency range from zero to 0.333 cycles per second using procedures given by Blackman and Tukey(2). Final corrections and smoothing were then made on these estimates to give the corrected spectrum in units of $(\mathrm{ft})^2$. These values were tabulated for each wave record and the corrected spectrum plotted as a histogram or a regular graph (Fig. 3). The dates of the various wave records ranged from April 1955 to September 1961.

Extensive use of these wave record spectra has been made for determining estimates of the power spectra for fully-developed seas at various wind speeds and also to develop a new wave-model equation. A group of synoptically chosen spectra was analyzed to determine the mean spectra for speeds of 20, 25, 30, 35, and 40 knots. Each situation used was chosen so that both fetch and wind duration would have produced a fully-developed sea condition according to various theories. A nested family of wave spectra was obtained for these five wind speeds (Fig. 4) whereby the frequency of the maximum energy was inversely proportional to the wind speed. Also the significant height relationship to the wind speed was found to be

$$(4) \quad \bar{H}_{1/3} = 0.0182 V_{19.5}^{2}$$

From statistical tests it was further found that wind speed alone at the location and time of the wave condition did not specify the correct sea state. Rather the spectrum was a function of wind duration and fetch as well as wind speed.

Using the data for the spectra of fully-developed seas at wind speeds from 20 to 40 knots a new non-directional wave-spectrum model was developed. Over the most important range of frequencies that define the total variance of a wave spectrum, the proposed spectral model produced a better fit for the range of wind speeds from 20 to 40 knots than some previous models (Figs. 5, 6, 7, 8, 9). It was noted, however, that the proposed new spectral model was highly sensitive to wind speed, since only slight variations of speed had large effects on the shape and position of the spectral curve. This spectral model is a compromise among various other proposed spectra and has similar features to many of them.

The equation for the proposed spectral form is given by

$$(5) \quad S(\omega)d\omega = \frac{\alpha_1 g^2}{\omega^5} \exp\left[-\beta\left(\frac{\omega_0}{\omega}\right)^4\right] d\omega$$

where
$$\alpha_1 = 8.10 \times 10^{-3}$$
$$\beta = 0.74$$
$$\omega_0 = \frac{g}{V_{19.5}}$$

Since α and β are dimensionless any consistent set of units can be used in the equation. If wind speed is in knots, frequency in cycles per second and component energy in $(\text{ft})^2$, the equation reduces to

$$(6) \quad A^2(f)df = \frac{0.010707}{f^5} \exp\left[\frac{-63.21}{f^4 V_{19.5}^4}\right] df$$

This form of the spectral model will undoubtedly need further refinements when additional accurate data become available.

```
            SMOOTHED HINDCASTING SPECTRA COMPUTED MARCH 1963


     DATE = 22/12/59            AV. T=      10.8        RECORD =       JHB 3
     HOUR = 12               SIG.HGT. =     36.1   UPPER HGT. =        40.0
 TOTAL DF =122              CORR. VAR. =    81.4   LOWER HGT. =        32.5
                            NOISE LEVEL =   .0230   WIND SPEED =          0

    H   FRE. UNIT=FT.2 FILTERED -NOISE  CORR.FT.2  UPPER   LOWER

    0  .000     .1580    .1580   .1350     .1350    .2489   .0860
    1  .006     .1660    .1660   .1430     .1430    .2636   .0911
    2  .011     .2730    .2730   .2500     .2500    .4608   .1542
    3  .017     .3480    .3480   .3250     .3250    .5991   .2070
    4  .022     .2240    .2240   .2010     .2010    .3705   .1280
    5  .028     .1370    .1370   .1140     .1140    .2102   .0726
    6  .033     .3943    .3943   .3713     .5850   1.0783   .3725
    7  .039    1.7213   1.7213  1.6983    2.2549   4.1560  1.4358
    8  .044    3.6175   3.6175  3.5945    4.2804   7.8893  2.7255
    9  .050    6.4717   6.4717  6.4487    7.1574  13.1922  4.5574
   10  .056   11.0976  11.0976 11.0746   11.7723  21.6981  7.4959
   11  .061   12.5971  12.5971 12.5741   13.0457  24.0451  8.3067
   12  .067    8.4539   8.4539  8.4309    8.6476  15.9388  5.5063
   13  .072    4.4622   4.4622  4.4392    4.5546   8.3949  2.9001
   14  .078    3.9888   3.9888  3.9658    4.1046   7.5654  2.6136
   15  .083    4.2085   4.2085  4.1855    4.4007   8.1111  2.8021
   16  .089    3.1470   3.1470  3.1240    3.3218   6.1225  2.1151
   17  .094    1.7222   1.7222  1.6992    1.8749   3.4558  1.1938
   18  .100    1.0792   1.0792  1.0562    1.2024   2.2162   .7656
   19  .106    1.2808   1.2808  1.2578    1.4849   2.7368   .9455
   20  .111    1.3971   1.3971  1.3741    1.6874   3.1102  1.0744
   21  .117    1.0200   1.0200   .9970    1.2779   2.3553   .8137
   22  .122     .5160    .5160   .4930     .6618   1.2199   .4214
   23  .128     .3030    .3030   .2800     .3950    .7280   .2515
   24  .133     .2520    .2520   .2290     .3406    .6277   .2169
   25  .139     .2080    .2080   .1850     .2911    .5365   .1853
   26  .144     .2010    .2010   .1780     .2970    .5474   .1891
   27  .150     .2140    .2140   .1910     .3388    .6245   .2157
   28  .156     .1960    .1960   .1730     .3273    .6033   .2084
   29  .161     .1890    .1840   .1660     .3358    .6140   .2138
   30  .167     .1670    .1670   .1440     .3126    .5761   .1990
   31  .172     .1110    .1110   .0880     .2053    .3784   .1307
   32  .178     .1180    .1180   .0950     .2392    .4408   .1523
   33  .183     .1460    .1460   .1230     .3344    .6163   .2129
   34  .189     .1270    .1270   .1040     .3066    .5652   .1953
   35  .194     .1250    .1250   .1020     .3267    .6021   .2080
   36  .200     .1200    .1200   .0970     .3386    .6241   .2156
   37  .206     .0728    .0728   .0498     .1898    .3498   .1208
   38  .211     .0445    .0445   .0215     .0898    .1655   .0572
   39  .217     .0539    .0539   .0309     .1417    .2612   .0902
   40  .222     .0627    .0579   .0349     .1760    .3245   .1121
   41  .228     .0523    .0527   .0297     .1652    .3044   .1052
   42  .233     .0434    .0460   .0230     .1415    .2607   .0901
   43  .239     .0448    .0454   .0224     .1528    .2815   .0973
   44  .244     .0485    .0485   .0255     .1936    .3568   .1233
   45  .250     .0522    .0494   .0265     .2237    .4124   .1425
   46  .256     .0449    .0459   .0229     .2165    .3990   .1378
   47  .261     .0416    .0463   .0233     .2465    .4542   .1569
   48  .267     .0570    .0542   .0312     .3706    .6830   .2360
   49  .272     .0611    .0555   .0326     .4355    .8026   .2773
   50  .278     .0430    .0435   .0206     .3103    .5720   .1976
   51  .283     .0271    .0295   .0066     .1121    .2067   .0714
   52  .289     .0210    .0238   .0009     .0169    .0311   .0108
   53  .294     .0263    .0264   .0034     .0759    .1398   .0483
   54  .300     .0321    .0291   .0062     .1548    .2853   .0986
   55  .306     .0261    .0264   .0034     .0973    .1794   .0620
   56  .311     .0212    .0214   .0000     .0000    .0000   .0000
   57  .317     .0173    .0179   .0000     .0000    .0000   .0000
   58  .322     .0159    .0170   .0000     .0000    .0000   .0000
   59  .328     .0191    .0185   .0000     .0000    .0000   .0000
   60  .333     .0199    .0195   .0000     .0000    .0000   .0000
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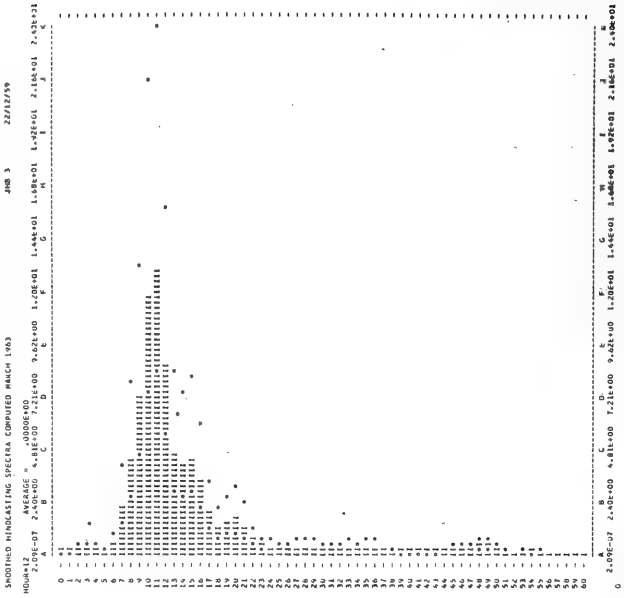

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            SMOOTHED HINDCASTING SPECTRA COMPUTED MARCH 1963


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     HOUR = 15               SIG.HGT. =     38.6   UPPER HGT. =        42.2
 TOTAL DF =163              CORR. VAR. =    93.0   LOWER HGT. =        35.2
                            NOISE LEVEL =   .0717   WIND SPEED =          0

    H   FRE. UNIT=FT.2 FILTERED -NOISE  CORR.FT.2  UPPER   LOWER

    0  .000     .1820    .1820   .1103     .1103    .2033   .0702
    1  .006     .3980    .3980   .3263     .3263    .6014   .2078
    2  .011     .6480    .6480   .5763     .5763   1.0622   .3670
    3  .017     .6750    .6750   .6033     .6033   1.1120   .3841
    4  .022     .6220    .6220   .5503     .5503   1.0143   .3504
    5  .028     .4260    .4260   .3543     .3543    .6530   .2256
    6  .033     .2820    .2820   .2103     .3313    .6107   .2110
    7  .039     .3988    .3988   .3271     .4343    .8005   .2765
    8  .044    2.3616   2.3616  2.2899    2.7268   5.0259  1.7363
    9  .050    7.5464   7.5464  7.4747    8.2962  15.2911  5.2825
   10  .056   10.4980  10.4980 10.4263   11.0832  20.4279  7.0571
   11  .061    9.2500   9.2500  9.1783    9.5225  17.5514  6.0633
   12  .067    8.1897   8.1897  8.1180    8.3266  15.3472  5.3019
   13  .072    6.9386   6.9386  6.8669    7.0454  12.9858  4.4861
   14  .078    5.6142   5.6142  5.5425    5.7365  10.5732  3.6527
   15  .083    4.5520   4.5520  4.4803    4.7106   8.6823  2.9994
   16  .089    3.7131   3.7131  3.6414    3.8719   7.1365  2.4654
   17  .094    3.8179   3.8179  3.7462    4.1336   7.6188  2.6320
   18  .100    3.2780   3.2780  3.2063    3.6501   6.7276  2.3241
   19  .106    1.7800   1.7800  1.7083    2.0167   3.7170  1.2841
   20  .111     .8350    .8350   .7633     .9373   1.7276   .5968
   21  .117     .8917    .8917   .8200    1.0510   1.9371   .6692
   22  .122    1.0000   1.0000   .9283    1.2462   2.2968   .7935
   23  .128     .8150    .8150   .7433    1.0484   1.9324   .6676
   24  .133     .6690    .6690   .5973     .8882   1.6372   .5656
   25  .139     .6380    .6380   .5663     .8909   1.6420   .5672
   26  .144     .7030    .7030   .6313    1.0533   1.9413   .6707
   27  .150     .7630    .7630   .6913    1.2261   2.2599   .7807
   28  .156     .6890    .6890   .6173    1.1678   2.1525   .7436
   29  .161     .5280    .5280   .4563     .9231   1.7013   .5877
   30  .167     .2870    .2870   .2153     .4673    .8613   .2975
   31  .172     .1780    .1780   .1063     .2479    .4569   .1579
   32  .178     .2640    .2640   .1923     .4840    .8921   .3082
   33  .183     .2570    .2570   .1853     .5037    .9283   .3207
   34  .189     .1670    .1670   .0953     .2809    .5178   .1789
   35  .194     .1330    .1330   .0613     .1963    .3618   .1250
   36  .200     .1560    .1560   .0843     .2942    .5423   .1873
   37  .206     .1710    .1710   .0993     .3782    .6971   .2408
   38  .211     .1450    .1450   .0733     .3058    .5636   .1947
   39  .217     .1240    .1240   .0523     .2397    .4418   .1526
   40  .222     .1640    .1767   .1051     .5295    .9760   .3372
   41  .228     .2550    .2275   .1558     .8665   1.5971   .5517
   42  .233     .2360    .2165   .1448     .8907   1.6417   .5672
   43  .239     .1390    .1585   .0868     .5920   1.0911   .3770
   44  .244     .1200    .1188   .0471     .3572    .6585   .2275
   45  .250     .0962    .0903   .0187     .1576    .2906   .1004
   46  .256     .0490    .0602   .0000     .0000    .0000   .0000
   47  .261     .0466    .0512   .0000     .0000    .0000   .0000
   48  .267     .0626    .0600   .0000     .0000    .0000   .0000
   49  .272     .0684    .0685   .0000     .0000    .0000   .0000
   50  .278     .0747    .0748   .0031     .0472    .0870   .0300
   51  .283     .0815    .0803   .0086     .1472    .2713   .0937
   52  .289     .0836    .0856   .0139     .2691    .4959   .1713
   53  .294     .0437    .0913   .0176     .4319    .7961   .2750
   54  .300     .0943    .0882   .0165     .4132    .7616   .2631
   55  .306     .0704    .0723   .0006     .0180    .0331   .0114
   56  .311     .0542    .0587   .0000     .0000    .0000   .0000
   57  .317     .0559    .0573   .0000     .0000    .0000   .0000
   58  .322     .0634    .0613   .0000     .0000    .0000   .0000
   59  .328     .0626    .0616   .0000     .0000    .0000   .0000
   60  .333     .0579    .0602   .0000     .0000    .0000   .0000
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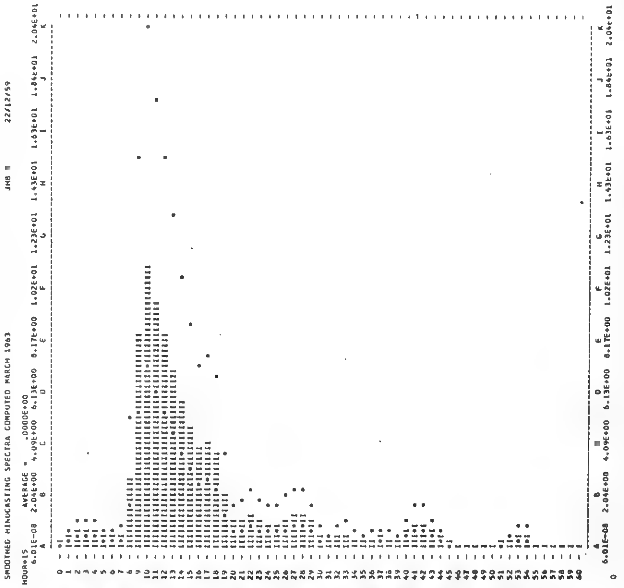


Figure 3. Tables and histograms of wave spectra computed from weather ship records of a shipborne wave recorder. 12Z and 15Z, 22 Dec. 1959 (New York University)

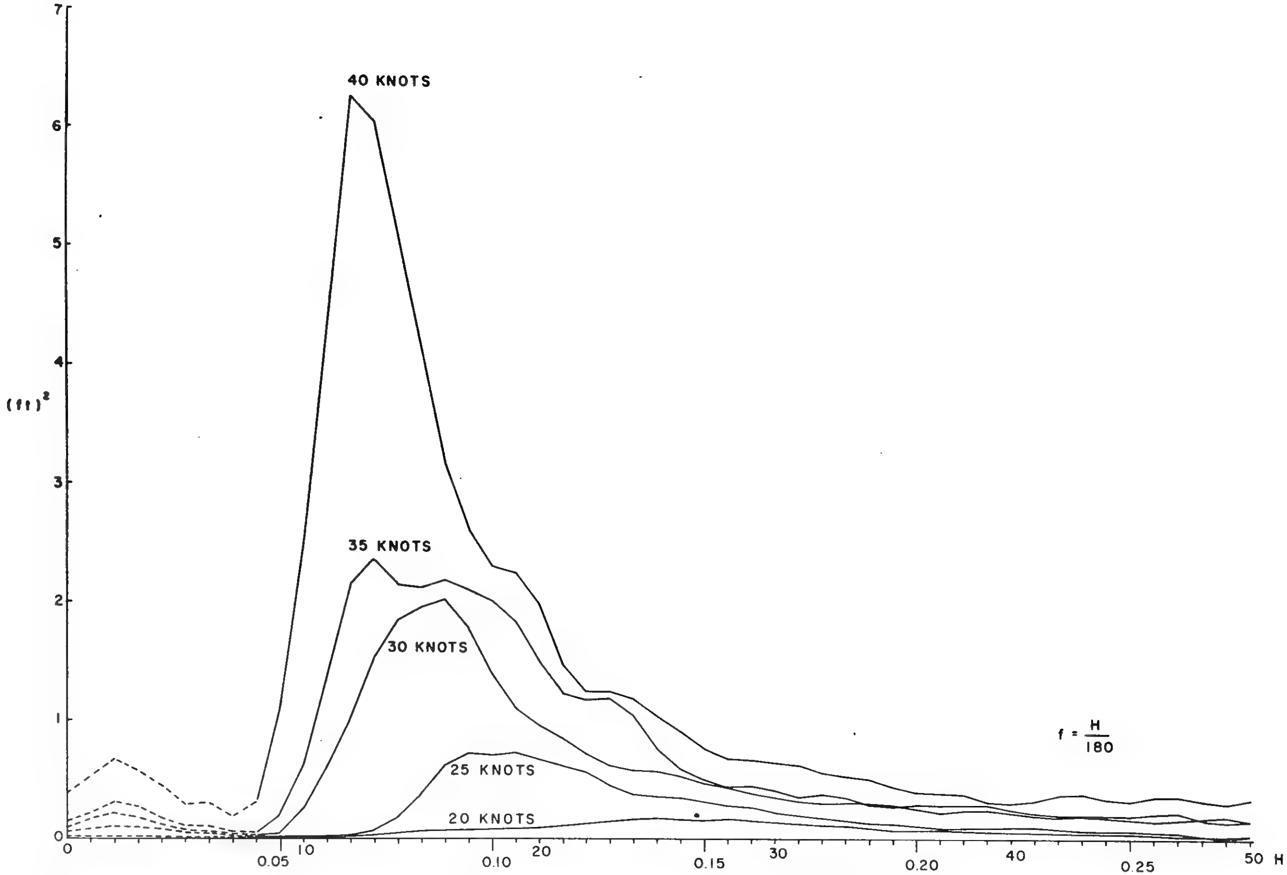
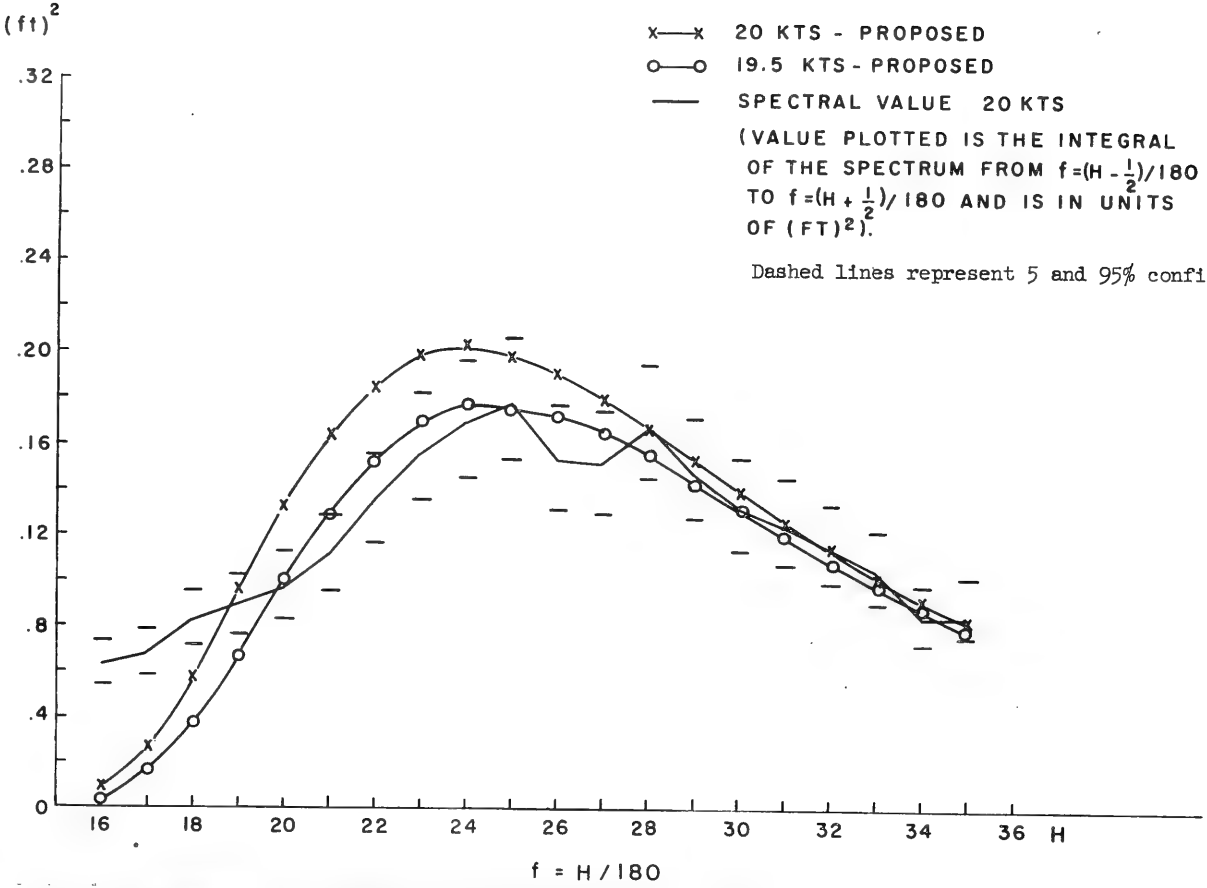


Figure 4. Graphs of synoptically chosen wave spectra (New York University)



Dashed lines represent 5 and 95% confidence limits.

Figure 5. Comparison of proposed spectrum with original data for 20-knot winds (New York University)

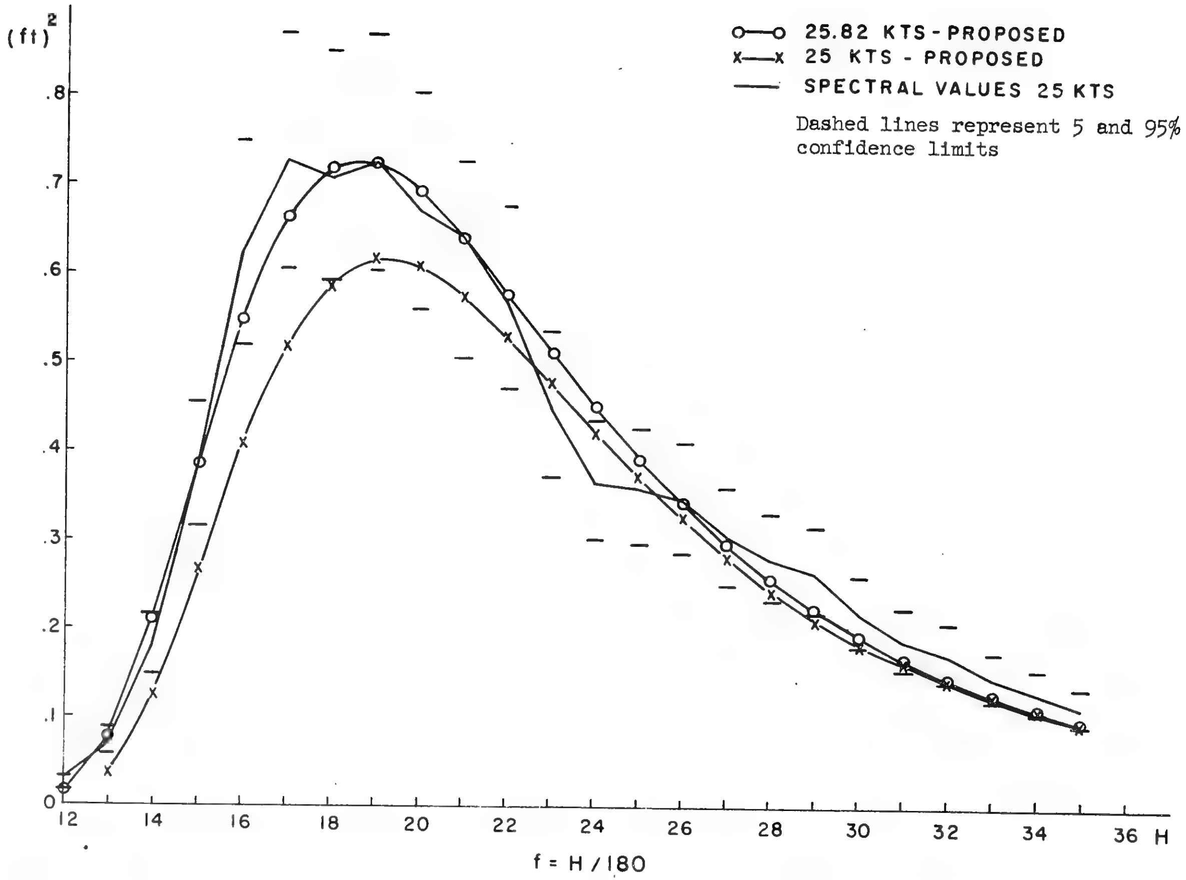


Figure 6. Comparison of proposed spectrum with original data for 25-knot winds (New York University)

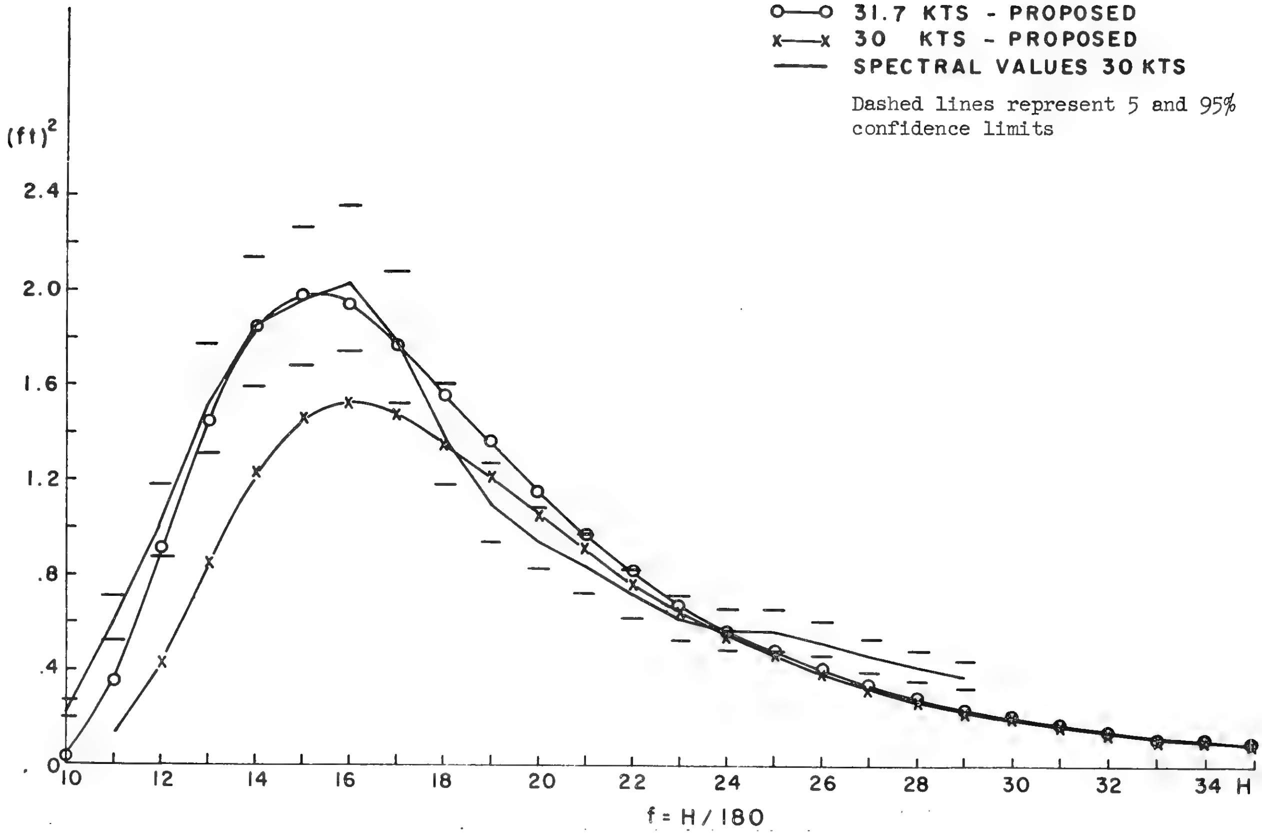


Figure 7. Comparison of proposed spectrum with original data for 30-knot winds (New York University)

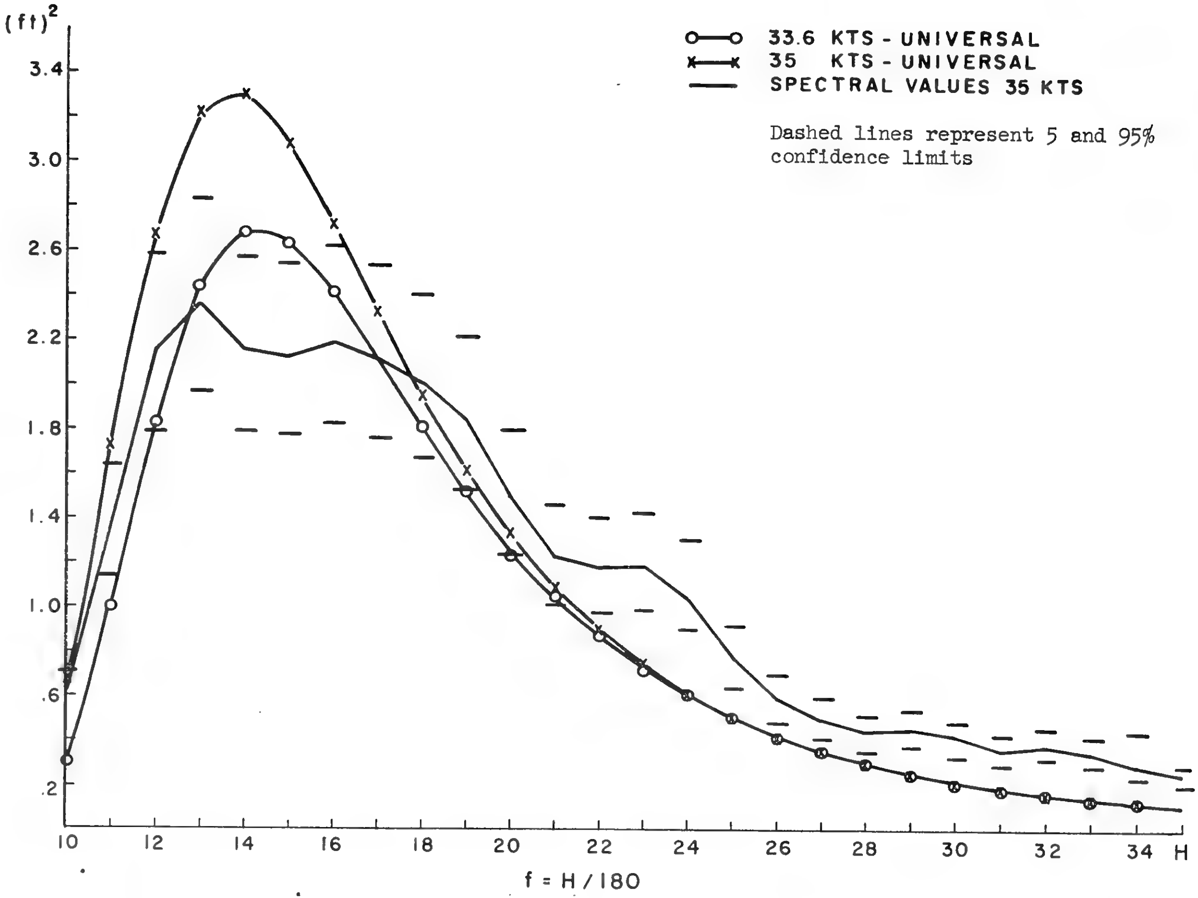


Figure 8. Comparison of proposed spectrum with original data for 35-knot wind (New York University)

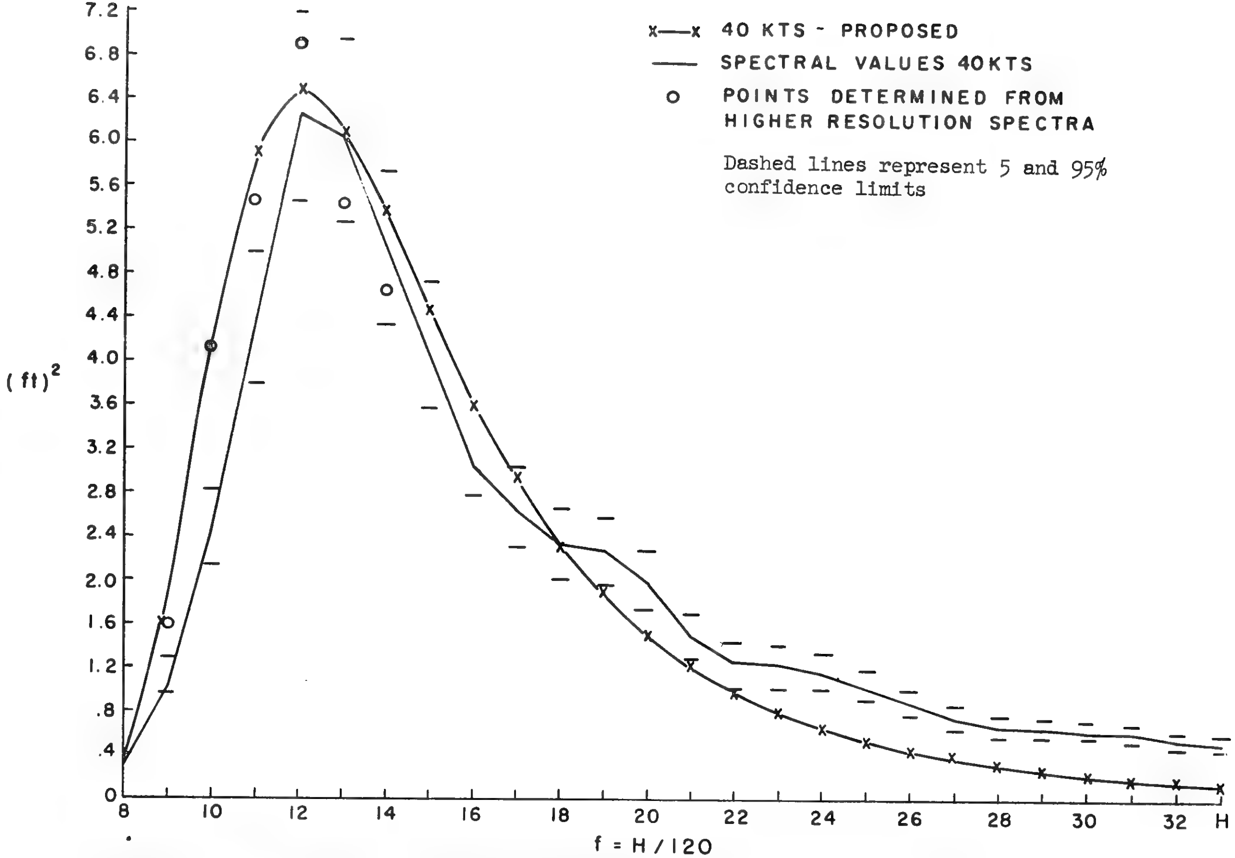


Figure 9. Comparison of proposed spectrum with original data for 40-knot wind (New York University)

Since the wind speed makes the major contribution in describing the frequency spectrum of wind generated sea, considerable work has been done on the problem of wind observations. The variation of wind with height over the sea has been studied and wind profiles obtained based on different drag coefficients. When these profiles are studied, it can readily be seen that the variation of wind with height is logarithmic. An equation for determining wind at various heights is

$$(7).\ V_2 = V_1 \left(1 + \frac{\sqrt{C_d}}{\kappa} \ln \frac{z_2}{z_1}\right)$$

where
κ = 0.4 (von Karman constant)
C_d = drag coefficient
z_2 = height at which speed V_2 is to be determined

In general the wind speed at a given height is not linear with some other level because the drag coefficients are also functions of wind speed. For example, the Sheppard drag coefficients are given by

$$(8)\quad C_d = (0.80 + 0.114V)10^{-3}$$

Whether or not the drag coefficients change with height has not yet been determined. If the air has neutral stability, the coefficient would generally be constant with height and the wind profile purely logarithmic. If the air were stable or unstable, such might not be true.

The large variability of wind observations from ships may be caused by many factors, such as the presence or absence of anemometers, the differences in the heights of the anemometers, the length of time used to average the wind, etc. There is a need for some consistent standard height for wind measurements or correction to a standard height as is done for pressure measurements so that some of the wind variability may be eliminated.

From calculations using the preceding equations together with the proper relationship between significant wave height and wind speed, it was possible to draw curves of significant heights versus wind speeds for wind speeds at various elevations (Fig. 10). These curves show that the lower the elevation the smaller the wind speed required to produce a wave of a given height.

In comparing the various theoretical spectra that have been proposed there have been considerable differences among them. It is quite likely that some of these differences may be caused by lack of attention to the variation of wind speed with height. When this factor was taken into account the various spectral models did not differ nearly as much. A very small change in wind speed leads to considerable changes in wave heights computed from the spectrum, in the total energy for fully-developed sea (3, 4), and in the location of the spectral peak. These small changes in wind may easily be present if the observed wind is at

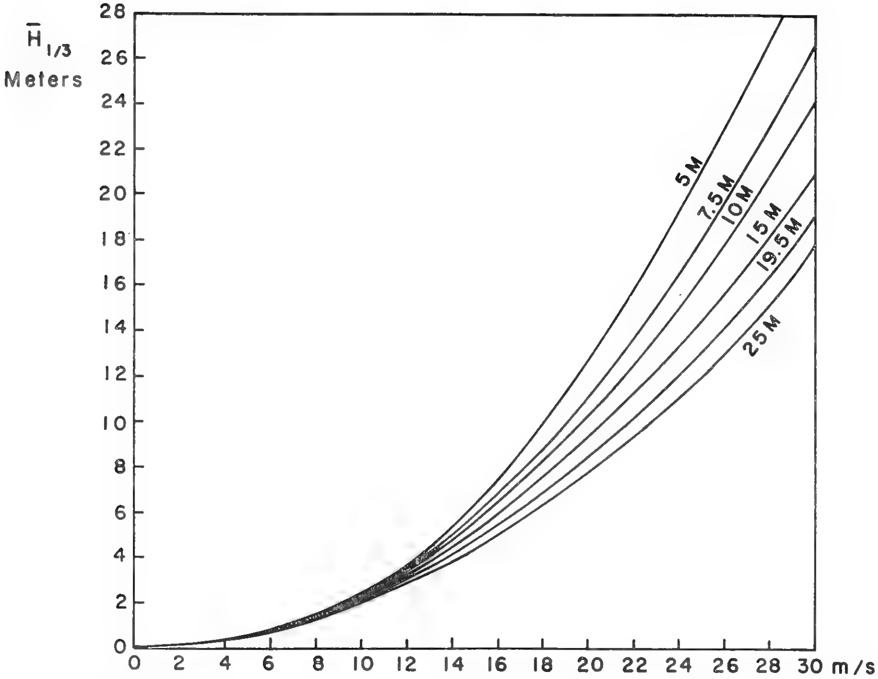


Figure 10. Significant wave height as a function of wind speed at various elevations from equation 7 and the drag coefficients proposed by Sheppard (New York University)

some elevation other than that from which the spectral model was originally derived. Thus, the lack of wind profile considerations in using ship wind reports may well result in some considerable errors of the wave spectra.

Problems Encountered - Travelers

The best wind estimates obtained by the screening regression technique contained rms errors of 8.5 knots for each wind component. Since small errors have a rather large effect on the spectral results it was felt that this technique could not be used for the wind field in computing wave spectra. The errors in the regression technique were most likely inherent because of the coarseness of the gridpoint pressure data and because the machine interpolation techniques tended to flatten out the pressure gradients in the vicinity of pressure centers.

The solution to the above serious problem was to use the regression winds as an initial estimate of the wind field and to integrate selected ship wind observations with the regression winds to obtain an objective-analysis wind. A machine program for integrating the selected ship wind observations with the initial guess regression winds was formulated by Travelers. The technique finally used by New York University was a modification of the Travelers programming. In the N.Y.U. program the ship wind observations to be used were selected for use in the initial guess field in the following priority: 1. All weather ship wind observations, 2. Observations of U. S. Navy ships with anemometers, 3. Observations of all remaining ships not located within a certain gridpoint range of the first two categories with anemometers, 4. Observations of transient ships without anemometers. Before these ship wind observations were used, the low centers on each 12-hourly synoptic map were located according to the nearest gridpoint and the corresponding wind fields at these positions were translated to the point half way between and averaged inside a circle of appropriate radius. Before the ship wind observations were entered in the priority order stated above they were all corrected to the standard height of 19.5 m when the anemometer heights could be ascertained. Only one ship wind observation, supposedly the most correct report possible for that location, was used to correct the initial guess wind at any given gridpoint.

During the time before the final procedure was adopted, there was considerable variance of opinion on the validity of many ships' wind observations as compared to the true wind field. One viewpoint was that the variance was at least 5 knots or greater and the other that it was less than 5 knots. At present there is no simple way to determine which viewpoint is correct. When wind observations are estimated on the basis of sea appearance, as is done on most ships without anemometers, the winds are usually underestimated when the sea is building up and overestimated when the waves are dying down because of the lag effects on the sea for increasing or decreasing winds. A study by the U. S. Weather Bureau(5) also found that up to about 20 knots the transient ships tend to overestimate the wind speeds and above 20 knots they underestimate them (Fig. 11). There is furthermore a lack of accuracy due to the use of the Beaufort scale which gives quite a wide range of wind speed values with no way to determine the exact speed. A study made by the Oceanographic Office listed many other reasons for wind inaccuracies of ship reports(6).

Problems Encountered - New York University

The problem of ship wind observation variability was also studied by New York University. After looking at all aspects of the problem the conclusion was reached that much of the variability may be eliminated by correcting all wind observations to a standard level of 10 m, 19.5 m, or some other level above the sea. Anemometers on ships have been found at varying heights anywhere from 10 to 25 m or more above the sea surface. If all ship wind observations were corrected to the same level by some appropriate method and these used to produce a wind field, then consistent wave spectra could be computed. For the work done by New York University the decision was made to correct all wind observations to the 19.5 m level since the model being used was based on observations made at this height.

There were several problems encountered in the computer part of the project. Two programs had to be worked out:

1. An automatic data processing program for eliminating gross errors from ship observations, sorting the ships into priority categories and eliminating all but the priority reports for each given gridpoint location, and finally correcting the wind observations to a level of 19.5 m wherever this was required. All this had to be done before the observations could be integrated into the initial regression-wind field obtained from the gridpoint pressure data.

2. A machine program for interpolating surface winds at intermediate time (6-hourly) intervals between the 12-hourly fields provided by the gridpoint pressure data.

Both problems were solved by consultation with U. S. Weather Bureau personnel where programs of a similar nature had already been produced. These programs with appropriate modifications were adapted to the New York University computer system after considerable testing.

In computing the wave spectral fields from the wind fields there were several problems that had to be solved. One of the most serious was the poor specification of the initial wave conditions. Without any prior knowledge of the shape of the spectrum at each of the gridpoints, an assumption had to be made as to how much of the spectrum was due to swell. Since the spectrum of the swell was unknown, it must of necessity be ignored originally. The best solution found was to start the machine computations for several days prior to the desired time for the wave

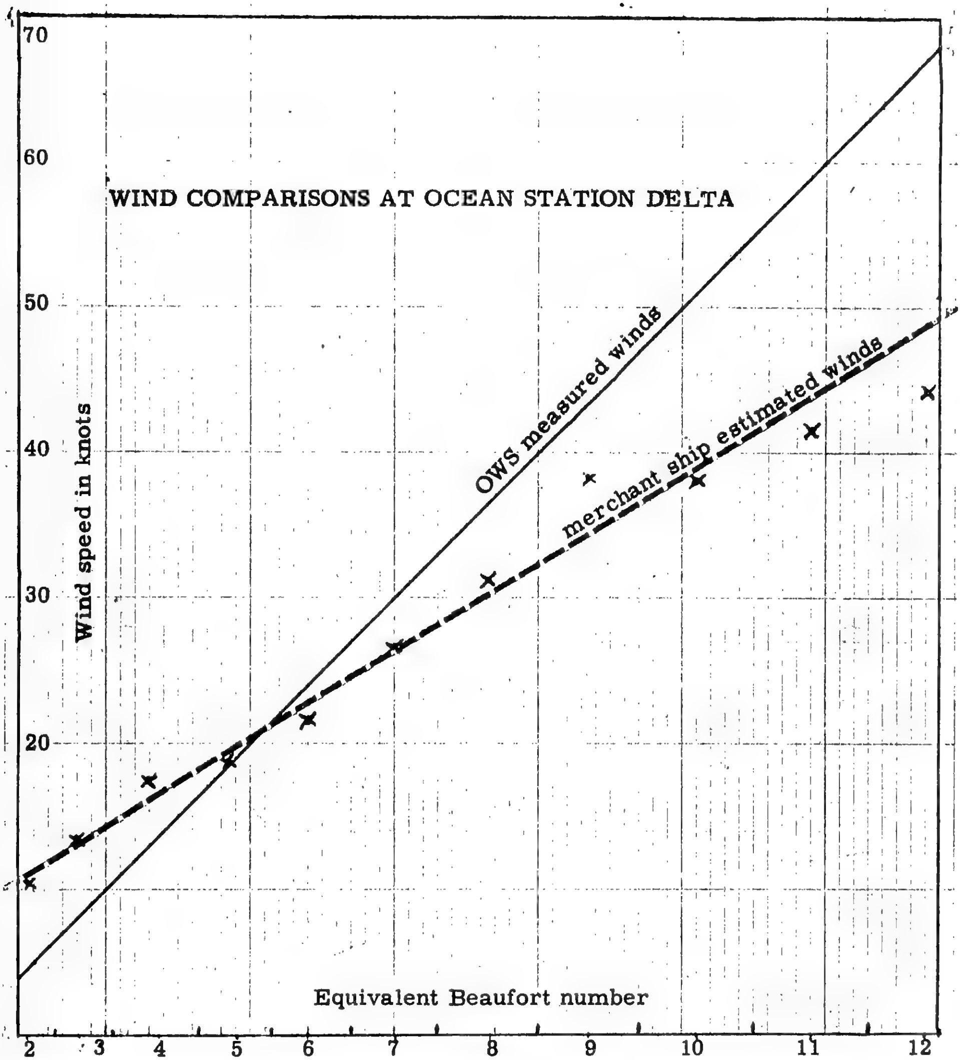


Figure 11. Wind comparisons at ocean station Delta (U.S. Weather Bureau)

hindcasts. In this way the poor initial conditions improved as time duration became a part of the output and as the swell was gradually introduced into the computations.

In addition to this problem, results obtained from the original machine program indicated that there were the following problems needing solution:

1. A better spectral model

2. A better growth function for 3-hourly intervals

3. A proper assumption for the nature of the high-frequency end of the spectrum

4. A proper dissipation function for the spectrum.

Taken together these four problems would make a formidable task for any individual effort but by a team assault they were all finally solved so that the end product gave acceptable though not perfect results.

After having tried several different spectral models, the new non-directional spectrum developed at New York University was programmed and showed very good results for the Eastern North Atlantic Ocean when compared to the wave observations taken by shipborne recorders on weather ships. Also later tests with weather ships wave observations in the Western Atlantic and with wave staff observations at Argus Island gave similarly good results.

To determine the proper growth function it was first necessary to use an equation for the maximum spectrum that could be generated, assuming an infinite fetch, infinite duration, and certain directional effects found in other studies.(7) The form of the equation used was

$$(9) \quad A^2(f, \theta) = \frac{C_1}{2\pi f^5} \exp\left[-C_2 D^4\right] \Delta f \Delta\theta \left\{1.0 + \left[0.5 + 0.82 \exp(-0.5D^{-4})\right] \cos(0.0349065\, \beta_1) + 0.32 \exp(-0.5D^{-4}) \cos(0.069813\, \beta_1)\right\}$$

for $90^\circ \geq |\beta_1|$ and zero otherwise and

where $D = \dfrac{19.08}{2\pi f V_{19.5}}$

β_1 = direction from the wind direction
Δf = incremental frequency
$\Delta\theta$ = incremental direction
f = frequency in cycles per second
$V_{19.5}$ = wind speed in knots at 19.5 m height
C_1 and C_2 = constants

To compute the growth function, a curve fitting program was designed for the computer so that the end product was a 3-hourly final growth table showing wind speeds at 2-knot intervals from 10 to 60 knots versus the E-values (Table 3). Here E is in units of $(\text{ft})^2$ and represents a number twice the variance of the spectral density. The new growth assumes that a partially developed spectrum has the same shape as the fully-developed spectrum for the lower wind speed that would produce the same significant height waves. This assumption yields a much more reasonable spectrum during periods of wave growth and propagation than do other assumptions.

Another study at New York University led to the conclusion that the high-frequency end of the wave spectrum could be simply represented within the limits of forecast accuracy as a function of wind speed alone. Thus, the machine program could be modified to assume full development for all waves with periods less than 7 seconds. A further consequence of this idea was the assumption that all waves with periods below 7 seconds dissipated immediately if the wind decreased. With these assumptions the machine programming was considerably simplified.

In a test of the original machine program it was found that the waves at a point did not dissipate as fast as they should because the programmed dispersion was too low. To remedy this an empirical dissipation function was developed and tested. The form of the dissipation function was

$$(10)\quad A_D^2(f, \theta) = A_I^2(f, \theta) \cdot \left\{\exp\left[C_3\, f^4 E^{0.5}\right]\right\}^{K(\beta_1)}$$

where $A_D^2(f, \theta)$ = spectral energy of component after (with) dissipation

$A_I^2(f, \theta)$ = spectral energy of component before (without) dissipation

f = center frequency of spectral component

θ = center direction of spectral component

C_3 = 345.0, a constant

$E = \iint A_I^2(f, \theta)\,df\,d\theta$ = total energy in spectrum

$\beta_1 = |\theta - \text{wind direction}|$

and $K(|\beta_1| \leq 75^\circ) = 0$

$K(75^\circ < |\beta_1| \leq 105^\circ) = 1.5$

$K(105^\circ < |\beta_1| \leq 135^\circ) = 3.0$

$K(135^\circ < |\beta_1| \leq 165^\circ) = 4.5$

$K(165^\circ < |\beta_1| \leq 180^\circ) = 6$

By using this empirical dissipation factor a solution was found for the problem of shifting wind directions and decreasing wind speeds.

Thus, when the original program had been modified by using a new spectral model, a new growth function, a new dissipation factor, and a specification only for the long period end of the spectrum, then the results compared favorably with wave observations in most of the situations.

Results

Since the project began in 1961 a total of 27 reports, papers, and manuscripts have been written as a result of the hindcast project, all except one by project or contract personnel. These are listed by authors in chronological order at the end of this report.

The major purpose of the project - to produce by machine methods a wave spectrum climatology over the North Atlantic Ocean - has in general been realized. A series of magnetic tapes containing four times daily wind directions and speeds and wave spectra hindcasts for each of 519 gridpoints over the North Atlantic Ocean for 15 months, including the entire year 1959, has been made available. A new spectral form for fully-developed seas at wind speeds from 20 to 40 knots has been developed. This spectral form appears to be an improvement over previously proposed spectral forms. New machine programs have been developed for the production of wind fields from pressure gridpoint data and ships' weather reports. A better understanding of wind speed profiles and drag coefficients has been indicated from the studies made. A new, improved machine program for producing hindcasts or forecasts of wave spectra at gridpoints over the North Atlantic Ocean has been made available. A study of the representativeness of the weather over the North Atlantic for the year 1959 compared with seven other years from 1957 to 1964 indicates that the 1959 weather was generally normal except for the month of December which was above normal but not anomalous.

Conclusions and Recommendations

1. The most serious problem in the present production of accurate machine hindcasts or forecasts of wave spectra appears to be the inability to produce adequate wind fields. Over large expanses of the oceans there is a complete lack of weather observations and even in the shipping lanes, the ships may often be poorly spaced. Discontinuities of the winds, such as along fronts, present a special problem since computer analysis techniques tend to smooth out the discontinuities.

2. The procedures for the observation of winds and waves should be improved and standardized. The winds should be automatically recorded at perhaps several different elevations on weather ships. Anemometers should be located so that the effect of the ship on the wind is eliminated. For various types of ships a standard level above the sea surface should be used for the height of the anemometer, such as 10 m or 19.5 m depending on the ship size and superstructure. Shipborne wave recorders should be installed at least on the U. S. weather ships and possibly on some of the Navy ships so that more adequate wave data can be obtained in the Western North Atlantic. The winds should be recorded and averaged for the same length of time as used for the wave observations, say 15 or 20 minutes. A measurement of gustiness, if any, should also be included in the observation. The length of the wave records should depend on the wind speed. For example, when the wind speed is over 35 knots at an elevation of 19.5 m, it would be advisable to take continuous recordings of the waves.

TABLE 3
Final growth table (3-hour) for new spectra model
(Lockheed)

WIND SPEED (KNOTS)

E ZERO*	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	64	68	72	80
0	0.5	1	1.5	1.7	1.9	2.5	3	3.7	4.5	5.3	6	6.5	7	8	9	9	9	9	9	9	9	10	11	12	13	14	16	22	24	25
.5	0.5	1	1.5	1.7	1.9	2.5	3	3.7	4.5	5.3	6	6.5	7	8	9	9	9	9	9	9	9	10	11	12	13	14	16	22	24	25
2		1	1.5	1.7	1.9	2.5	3	3.7	4.5	5.3	6	6.5	7	8	9	9	9	9	9	9	9	10	11	12	13	14	16	22	24	25
4			1.5	1.7	1.9	2.5	3	3.7	4.5	5.3	6	6.5	7	8	9	9	9	9	9	9	9	10	11	12	13	14	16	22	24	25
8				1.7	1.9	2.5	3	3.7	4.5	5.3	6	6.5	7	8	9	9	9	9	9	9	9	10	11	12	13	14	16	22	24	25
12							3	3	3.5	5.0	7	8	8	9	9.5	9.5	9.5	10	11	11	12	14	15	16	17	18	20	26	28	29
18									3.5	4.0	8	10	9	9	11	11	12	13	14	18	19	20	20	21	22	23	24	30	32	33
25										4.0	6	9	10	10	12	13	15	16	19	21	23	23	24	24	25	25	28	34	36	37
32											6	6	8	10	13	15	17	19	21	23	25	26	27	28	29	29	32	38	40	43
40												6	6	9	11	15	17	22	26	28	29	31	32	32	33	35	37	42	44	49
50													6	6	10	14	20	24	29	31	32	34	34	35	36	37	42	46	50	55
60														6	8	13	19	24	30	34	35	36	37	38	39	40	46	50	56	61
75															8	10	18	22	29	35	38	40	42	43	44	45	51	54	59	67
95															0	8	10	19	25	32	41	45	47	48	49	50	55	59	63	69
110																0	10	16	22	30	41	48	50	52	53	54	60	65	69	72
130																		10	14	21	38	50	54	55	58	58	65	70	75	78
150																		10	12	18	32	42	52	60	62	63	71	76	81	85
180																			12	14	25	36	49	60	67	69	77	82	87	91
210																				14	20	29	40	52	65	75	84	95	95	98
240																					15	22	31	44	60	69	90	105	103	108
270																						16	26	35	50	60	84	99	112	118
300																						16	20	30	40	54	78	93	120	130
330																							20	30	40	50	72	87	114	140
360																							20	30	40	50	65	80	108	130
390																								30	40	50	65	80	102	120
420																								30	40	50	65	80	95	110
450																									40	50	65	80	95	110
500																										50	65	80	95	110
550																											65	80	95	110
600																											65	80	95	110
650																												80	95	110
700																												80	95	110
750																													95	110
800																													95	110
900																														110

*All units are $(ft)^2$

3. Evaluations of the newly developed spectral form, the various new machine programs for integrating ship observations with an initial guess regression wind, for handling wave growth and decay, for specifying the wave spectrum at high frequencies, and for interpolating between 12-hourly observations all show that the results agree with observed wave spectra within the expected accuracy in view of the many variables involved. This is not to say that further improvement is impossible because there is still much work remaining to be done. It is believed that the 15 months of wave spectra which have been obtained for 519 points over the North Atlantic Ocean represent a definite step forward and the machine techniques used in obtaining these data are a breakthrough in this field of endeavor.

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Appendix - List of wave hindcast project manuscripts, reports, and related papers in chronological order. All are unclassified.

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1961. A comparison of computed surface winds with observed ship weather station winds. I. O. M. No. 6-62. U. S. Naval Oceanographic Office, Washington, D. C. (Unpublished)

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1961. A comparison of 3-, 6-, and 12-hourly wind observations for calculating significant heights of waves from wave spectra. I. O. M. No. 7-62. U. S. Naval Oceanographic Office, Washington, D. C. (Unpublished)

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1961. A comparison of three methods for determining the surface winds over the sea. I. O. M. No. 8-62. U. S. Naval Oceanographic Office, Washington, D. C. (Unpublished)

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1962. Further studies of fully developed seas at ship METRO, 1958. I. M. R. No. 0-47-62. U. S. Naval Oceanographic Office, Washington, D. C. (Unpublished)

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BUNTING, DONALD C.
1962. The variability of surface wind speeds observed by fixed weather ship stations. I. M. R. No. 0-57-62. U. S. Naval Oceanographic Office, Washington, D. C. (Unpublished)

BURKHART, MARVIN D.
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1965. A comparison of wind speeds and wave heights over the North Atlantic Ocean during the years 1957 - 1964. I. M. R. No. O-40-65. U. S. Naval Oceanographic Office, Washington, D. C. (Unpublished)

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13. ABSTRACT

A computerized system has been developed for the production of ocean wave spectra over the North Atlantic Ocean. The spectra results are fairly close to observed conditions. By means of this system a 15-month series of wave spectra has been obtained at 519 gridpoints over the North Atlantic. Each spectrum is described in terms of the spectral energy in 12 directions for 15 different frequencies. (U)

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