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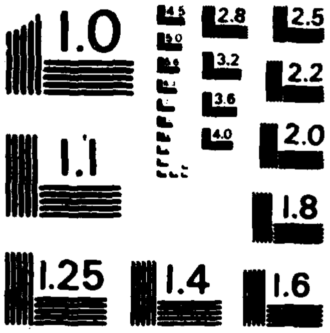

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A USER'S GUIDE TO A STEADY-STATE SHALLOW-WATER DIRECTIONAL SPECTRAL WAVE MODEL

by

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This report describes the formulation and use of a directional spectral wave model which can be used in shallow water. The model simulates the transformation of a directional wave spectrum over an arbitrary two-dimensional bathymetry allowing for the effects of atmospheric input, bottom friction, bottom percolation, nonlinear wave-wave interaction, shoaling, refraction, and equilibrium range energy limitation. The user has the option to include or exclude

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these source and sink terms in any combination desired. The formulation of each of these terms is summarized.

A description of the computer code is provided including a summary of the purpose of each subroutine and the format for data input and output of results. A sample application is provided showing the transformation of a wave spectrum from deep to shallow water over a uniformly sloping bottom.

PREFACE

This report describes the formulation and use of a computer model to calculate the transformation of wave spectra in shallow water. Various processes which may affect wave spectra in shallow water as well as input data necessary to initiate calculations are discussed. An example calculation is provided showing input data and output results. The work in this report was authorized by the Office, Chief of Engineers (OCE), Coastal Engineering Functional Area of Civil Works Research and Development, under Nearshore Waves and Currents Work Unit 31672, Harbor Entrances and Coastal Channels Program, at the Coastal Engineering Research Center (CERC) of the US Army Engineer Waterways Experiment Station (WES). Technical monitors from OCE for this program were Messrs. John H. Lockhart, Jr., and John G. Housley.

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A USER'S GUIDE TO A STEADY-STATE SHALLOW-WATER DIRECTIONAL SPECTRAL WAVE MODEL

PART I: INTRODUCTION

1. The need to predict wave conditions in shallow water has existed for many years. Recently, shallow-water wave prediction has received increased emphasis in response to the need for more accurate predictions. Reliable calculations of deepwater wave climates can now be made and provide input for propagation into shallow water. Improved shallow-water estimates will improve the economics of construction and navigation along the coasts.

2. Calculated and measured deepwater and shallow-water wave parameters are derived predominantly from wave spectra today. In the past, wave parameters were estimated considering monochromatic waves. Increased understanding of wave generation, propagation, and dissipation over the years has indicated that the spectral approach is generally more representative of prototype conditions. The availability of large, fast computers now makes directional spectral modeling economically practical. The physical processes which affect waves in deep and shallow water are generally dependent on wave frequency. Wave energy can be transferred between waves of different frequencies, and it can be distributed in different directions as well as at different frequencies. These factors require that a spectral modeling approach be adopted.

3. Spectral modeling evolved in deep water (Phillips 1957, Pierson and Moskowitz 1964, Barnett 1968, Ewing 1971 and Hasselmann, et al. 1973) and is now being extended into shallow water (Hsiao 1977 and Hughes and Jensen, in preparation). Shallow-water modeling increases in complexity over deep-water modeling due to the interaction of the waves with the bottom. Such processes as bottom friction, percolation, and bottom motion may now be important. Other processes present in deep water such as wave interaction, white capping, breaking, and wind generation are affected in shallow water since wave properties such as speed, height, and length change as a function of depth. The regional scale of a shallow-water model also will be generally smaller than that of a deepwater model and probably adjacent to a coastline. This size difference may result in more variability in space and time of the wind field in a region due to land effects which adds complexity to a problem. The various processes mentioned above are referred to as source or sink terms depending on

whether they add or subtract energy, respectively, from the wave field. It is common to refer to source and sink terms collectively as source terms. The representation of various source terms is still an area of research.

4. The formulation of this model, which evolved from Hsiao (1977), will be discussed below with a description of the present formulation of each source term. Next, a description of the computer program will be provided with definitions of subroutines, important variables, and flow of the calculations. Finally, a sample calculation will be presented showing the structure of the input data and the calculated results.

PART II: MODEL FORMULATION

5. The model is based on the assumption that the wave field can be represented by a continuous spectrum of variance or energy over a range of spectral components k_x , k_y* in wave number space or in frequency, direction (f,θ) space. The spectral density is denoted by F in $\vec{k}$ space and E in (f,θ) space. Each component can lose or gain energy, and intraspectral transfer of energy due to weak nonlinear interactions is permitted. The radiative transfer equation is used to express the spectral balance in shallow water. In wave number space, this equation is

$$\frac{DF}{Dt} = \frac{\partial F}{\partial t} + \frac{\partial F}{\partial x}\frac{dx}{dt} + \frac{\partial F}{\partial y}\frac{dy}{dt} + \frac{\partial F}{\partial k_x}\frac{dk_x}{dt} + \frac{\partial F}{\partial k_y}\frac{dk_y}{dt} = S \tag{1}$$

where $F = F(x , y , \vec{k} , t)$ and S represents source and sink terms. The term $\frac{\partial F}{\partial t}$ represents the time rate of change of the spectrum. This model assumes that a steady state exists so that $\frac{\partial F}{\partial t} = 0$. The next two terms represent change of spectral energy in space, since wave energy propagates at the group velocity, $dx/dt = C_{g_x}$ and $dy/dt = C_{g_y}$ where $C_{g_{x,y}}$ is the group velocity in the x and y directions, respectively. The last two terms on the left hand side represent change of spectral energy with wave number. The terms dk_x/dt and dk_y/dt can be expressed, respectively, as $-\partial\omega/\partial x$ and $-\partial\omega/\partial y$ by using the conservation of waves equation

$$\frac{\partial \vec{k}}{\partial t} + \nabla\omega = 0 \tag{2}$$

where

ω = radial wave frequency ($\omega = 2\pi f$)

∇ = horizontal differential operator $\partial/\partial x + \partial/\partial y$

6. Using the steady-state assumption and relations above, Equation 1 becomes

$$C_{g_x}\frac{\partial F}{\partial x} + C_{g_y}\frac{\partial F}{\partial y} - \frac{\partial\omega}{\partial x}\frac{\partial F}{\partial k_x} - \frac{\partial\omega}{\partial y}\frac{\partial F}{\partial k_y} = S \tag{3}$$

---

* For convenience, symbols and abbreviations are listed in the Notation (Appendix F).

It is now assumed that the wave frequency does not change as a function of space along the path of propagation, so Equation 3 becomes

$$C_{g_x} \frac{\partial F}{\partial x} + C_{g_y} \frac{\partial F}{\partial y} = S \qquad (4)$$

The left hand side represents refraction and shoaling, and the right hand side represents various source or sink terms. This equation can be expressed in frequency direction space by using the following relation:

$$\begin{aligned} E(f,\theta)\ df &= F(|\vec{k}|\ ,\ \theta)\ |\vec{k}|\ (d|\vec{k}|) \\ &= F(k)\ |\vec{k}|\ (d|\vec{k}|) \end{aligned} \qquad (5)$$

First, express k in polar coordinates where $|\vec{k}|$ is the radius in polar coordinates and f is radial frequency to get

$$\frac{1}{2}\ \pi\ E(\omega,\theta)\ d\omega\ d\theta = F(k,\theta)k\ dk\ d\theta$$

Then, integrate over θ from $-\pi$ to π to get $E(\omega)d\omega = 2\pi F(k)k\ dk$ and note that $d\omega/dk$ is the group velocity C_g. Thus $E = (2\pi k/C_g)F$, and Equation 4 becomes

$$C_{g_x} \frac{\partial}{\partial x} \left[\frac{(C_g E)}{k} \right] + C_{g_y} \frac{\partial}{\partial y} \left[\frac{(C_g E)}{k} \right] = 2\pi S \qquad (6)$$

which is valid for both deep and shallow water. This is the equation which is integrated numerically in this model to propagate energy from an offshore boundary to the shore.

Propagation

7. If the source terms in Equation 6 are set to zero, the solution represents propagation with refraction and shoaling of a wave component along a wave ray. In the absence of currents, the property

$$E(f,\theta)\ \frac{C_g}{k} = \text{CONSTANT} = E(F,\theta_o)\ \frac{C_{g_o}}{k_o} \qquad (7)$$

holds where the zero subscript refers to initial conditions. This equation is solved along ray paths given by

$$\frac{dx}{ds} = \cos\theta \ , \ \frac{dy}{ds} = \sin\theta$$

where s is a coordinate along the ray and

$$\frac{ds}{dt} = C$$

where C is the phase velocity. The solution is obtained row by row on the numerical grid moving from the outer boundary toward the shore. The depth contours are assumed to be locally parallel so that Snell's Law for parallel contours can be used, $k \sin\theta = k_o \sin\theta_o$. The change in wave angle $\Delta\theta$ can be calculated from this using $k \cos\theta\Delta\theta = k_o \cos\theta_o \Delta\theta_o$. A limitation on the value of $\cos\theta$ is imposed so that singularities do not occur. The refraction and shoaling method in the model, based on Snell's Law, is subject to the problems which have been evident in monochromatic refraction programs. The user should be cautious in applying the model to highly irregular bathymetry. Errors possibly introduced by refraction in these cases may not be evident due to the limitations imposed and the directional spectral form of the results.

Source Terms

8. It is evident from Equation 7 that energy is conserved in the absence of any source terms. It may be redistributed in (f,θ) space, but nothing is lost or gained. The addition of source terms allows energy to be lost, gained, or redistributed within the spectrum. The source terms available in this model are energy input from winds, energy loss from bottom friction, percolation, white capping, and breaking and redistribution of energy due to nonlinear interactions. Each of these is discussed briefly below.

Atmospheric input

9. Two mechanisms have been suggested as responsible for energy input to a wave field from the atmosphere. Phillips (1957) suggested that turbulent pressure fluctuations in the atmosphere lead to linear growth of wave energy. This is represented in the model by S_{wp} which is given by

$$S_{wp} = \alpha_g \frac{C_g}{2\pi k} \qquad (8)$$

$$\alpha_g = 0.663 \times 10^{-10} \frac{u^4}{C^3 C_g f} \left(\frac{b_2}{b_2^2 + k^2 \sin^2 \theta} \right) \left(\frac{b_1}{b_1^2 + (k \cos \theta - q)^2} \right) \tag{9}$$

$$b_1 = 0.33\ q^{1.28} \tag{10}$$

$$b_2 = 0.52\ q^{0.95} \tag{11}$$

where

$q = \frac{\omega}{u}$

θ = difference between wind and wave angles

u = wind speed

The linear growth coefficient α_g is based on the empirical work of Snyder (1974). This term has been important in deepwater modeling as a mechanism to initiate wave growth. The initial waves would then grow through another mechanism. A spectrum is input as an initial condition in this model, so this term is of minor importance. Energy from the atmosphere is input mainly through the following source term.

10. Miles (1957) suggested a growth mechanism due to a coupling between existing waves with their induced pressure fluctuations and the wind. He hypothesized that this would lead to exponential growth of waves in time and a shift of the spectral peak to lower frequencies. Hsiao and Shemdin (1983) modified this formulation based on data from the Marine Remote Sensing Experiment (MARSEN). This wave growth mechanism is represented in the model as S_{wm} which is given by

$$S_{wm} = 0.12 \frac{\rho_a}{\rho_w} \left(\frac{u}{C} \cos \theta - 1 \right) \omega E \tag{12}$$

where ρ_a and ρ_w are, respectively, the densities of air and water. Note that the magnitude of this source term is dependent on the ratio of wind speed to wave speed. Waves in a spectrum will have different speeds and directions and will approach a shallow-water wave speed $C = (gh)^{1/2}$ at different locations due to their period and the depth. Thus, the contribution of this source term can be variable across the spectrum and model region for a constant wind speed and direction.

Bottom friction

11. In shallow water there exists a boundary layer above the bed which in part is due to waves. Energy is dissipated through friction in this boundary layer when water flows over the bed. Hasselmann and Collins (1968) proposed an equation to represent this frictional loss in a spectral wave model. The frictional source term is based on their formulation and is represented in the model as

$$S_f = \frac{g C_f}{\omega^2 \cosh^2 kh} \left(2k^2 \langle |\vec{W}| \rangle + k_1 k_2 \left\langle \frac{W_1 W_2}{|\vec{W}|} \right\rangle \right) \frac{EC_g}{2\pi k} \qquad (13)$$

where C_f is a friction coefficient and $\vec{W}$ is water velocity at the top of the boundary layer. The components of vectors W and k are W_1 , W_2 and k_1 , k_2 , and $\langle \; \rangle$ is an ensemble average for a number of waves. The friction coefficient C_f is determined from empirical relations (Hsiao and Shemdin 1978) and a specified sediment diameter. Nonwave-induced bottom currents can be specified. If they are specified as zero, only wave-induced bottom currents are used. The empirically derived relation between Reynolds number, relative roughness, and friction coefficient is used to determine C_f . Values of C_f can range from 0.005 to 0.5 depending on wave and bottom characteristics. Provision is included for the presence or absence of ripples on the bottom. It is possible that during storm conditions the frictional losses might suddenly increase with the onset of ripple formation; and then if the wave conditions become more severe, the losses might decrease as the bedforms are eliminated.

Percolation

12. Wave motion in a fluid above a porous bed induces an oscillating flow within the porous media which results in dissipation of wave energy. Shemdin, et al. (1978) developed a spectral source term for this process based on Putnam's (1949) work. This source term is represented in the model as

$$S_p = -k\alpha_p \frac{\tanh kd}{\cosh^2 kh} \qquad (14)$$

where

α_p = permeability coefficient

d = depth of the permeable layer

It is assumed that the permeable layer is isotropic and of constant depth.

Values of α range from .01 to .001 m/sec for coarse to fine sand. There is not a consensus among shallow-water wave modelers on the importance of bottom effects such as friction, percolation, or bottom motion in dissipating wave energy. Studies to quantify these effects, especially for irregular waves in prototype conditions, are difficult to carry out. Aranuvachapun and Thornton (1984) provide some insight in this area using the Atlantic Remote Sensing Land-Ocean Experiment (ARSLOE) data set.

Nonlinear wave-wave energy transfer

13. Surface gravity waves can be described mathematically by a linear equation. This is a first order approximation describing some of the behavior of prototype waves but is not a complete description. In a linear approximation, waves travel over the water surface independent of each other and unchanged in space and time assuming that the depth or some source term does not affect the waves. If one extends the mathematical description to second order, a transfer of energy to the second harmonic occurs; and the surface profile of the wave changes from sinusoidal to trochoidal form. An extension to third order causes a change in phase velocity. It is apparent from these higher order nonlinear descriptions that waves will interact with each other, changing the waves present and possibly generating new waves. These effects are termed nonlinear wave-wave interactions. They can be strong or weak and occur in deep or shallow water.

14. Possibly the most striking nonlinear interaction is wave breaking which can transfer energy into higher and possibly lower frequencies than those of the breaking wave. Nonlinear interactions have been successfully used to explain the evolution and shape of the spectra calculated from the Joint North Sea Wave Program (JONSWAP) data (Hasselmann 1961, 1963a, 1963b). Third order nonlinear wave-wave interactions of the type which contributed to the shape of JONSWAP spectra can be calculated, but the calculations are so complex and time consuming that it is not practical to incorporate them into a spectral wave model. For this reason, the nonlinear source term is parameterized as a function of frequency and spectral width parameters (Hasselmann et al. 1980). This is applicable in deep water. In finite depth water, a scaling of deepwater values is used based on computations of Herterich et al. (1980). The nonlinear source term is sensitive to the energy level and shape of the spectrum. Since both of these can be expected to change in shoaling water, a parameterization based on a JONSWAP spectrum may not be the most appropriate.

Shallow-water equilibrium range limitation

15. Studies of waves in deep water have led to the concept of an equilibrium range in the spectrum where energy input is in equilibrium with energy dissipation. Phillips (1958) proposed a spectral form in this range as

$$E_p(f) = \alpha g^2 f^{-5} (2\pi)^{-4}$$

Pierson and Moskowitz (1964) modified this form to allow for a forward face on the spectrum for frequencies lower than the peak frequency f_m . Their formulation is

$$E_{PM}(f) = E_p(f)\, e^{-5/4(f/f_m)^{-4}}$$

Data from JONSWAP were used by Hasselman, et al. (1973) to propose a spectral shape under developing wave conditions which reaches an equilibrium shape under sufficient wind speed and fetch conditions. This is termed the JONSWAP spectrum and is expressed as

$$E_J(f) = E_{PM}(f)\, \gamma^{e^{-(f/f_m-1)^2/2\sigma^2}}$$

where parameters α , γ , σ , and f_m are functions of wind speed and fetch and

$$\sigma \begin{cases} \sigma_a & \text{for } f_m \geq f \\ \sigma_b & \text{for } f_m < f \end{cases}$$

16. Kitaigorodskii, et al. (1975) proposed that a similar equilibrium range might exist in finite depth water and proposed a frequency and depth dependent factor $\phi\ (\omega, h)$ which would allow transformation of a deepwater equilibrium spectrum to one in finite depth water.

17. Bouws, et al. (1985) used data from three field experiments (Texel, MARSEN, and ARSLOE to propose the following form for a wind sea spectral shape in finite depth:

$$E_{TMA}(f) = E_J(f)\, \phi(\omega,h)$$

This form, known as the TMA spectrum, was fitted to over 2,800 wind sea spectra from the above experiments by varying α and γ. They found that α and γ could be expressed empirically as functions of wind speed and peak wave number. All of these representations provide spectra which have an upper limit energy content and a certain shape based on empirical data. The equilibrium range limitation in the present model requires that

$$E(f) \leq E_p (f,\theta) \phi (\omega,h)$$

This condition is imposed prior to the source terms acting and represents an upper limit of energy as a function of frequency and depth. It can be considered as a dissipative source term where energy loss is through turbulent and viscous processes associated with white capping and large scale breaking.

Summary Remarks on Model Formulation

18. This model is based on physical principles, empirical data, and assumptions which simplify the problem enough to make it solvable. Those processes which are considered most important in the propagation and transformation of waves in shallow water are included in the model formulation. It should be recognized that the representation of these processes is the best available we have to date but should not be considered exact or permanent. The important fact that waves are limited in energy and frequency distribution in shallow water is represented in the model. Based on present knowledge, wave spectra in shallow water can be expected to remain at or below this limitation. The relative contributions of various source terms used in shallow-water wave modeling is not fully understood. Use of shallow-water models requires care because the balance between various source terms can vary with the situation modeled. Shallow-water wave modeling is not yet at the point where a model alone can be applied at a site and be expected to always give accurate wave information in a region. It is recommended, in studies where these models are used, that wave data be measured at various sites in the region. Such data can be used to calibrate and verify the model. Then the model can be used as an interpolation/extrapolation device and provide more confidence that the results are correct. More field measurements will add to the data base of shallow-water wave measurements and allow improvement in the empirically based parts of the model as well.

PART III: COMPUTER PROGRAM

19. Following is a description of the computer code which represents the model formulation discussed above. The description applies to a version of the code which is operating on the CDC CYBER 200 Series Computer System compiled with the FORTRAN compiler and executed with job control language (Appendix A). This code and computer system are available to any US Army Corps of Engineers user.

Program Structure

20. The program is separated into two parts. The first part calculates the propagation, refraction, and shoaling of all specified frequency and direction components for the specified bathymetry. The results of these calculations are saved and used in the second part of the program. As long as the bathymetry and frequency/direction band widths remain the same, the results of the first part can be used to transform various spectra over the bathymetry using various combinations of source terms. The calculations in the first part of the program are the most costly so that making them only once increases efficiency when making multiple spectral calculations.

21. The second part of the program transforms the refracted and shoaled spectrum using one or more of the following source terms:

- a. Bottom friction.
- b. Percolation.
- c. Atmospheric input.
  - (1) Miles' mechanism.
  - (2) Phillips' mechanism.
- d. Nonlinear interactions.
- e. Depth limitation.

Structuring the program this way allows one to include those source terms which are most applicable for a given problem.

22. The first part of the program consists of a main program and one subroutine to calculate wave number. The second part of the program consists of a main program and seventeen subroutines. Both parts have parameter statements in the main program and subroutines which allow dimensions of arrays to be set. The variables in the parameter statement are defined below.

Parameter Name	Definition
NTX	Number of grid cells in the x direction
NTV	Number of grid cells in the y direction
NTF	Number of frequency bands
NTA	Number of angle bands
MOUT	Number of grid cells where printout of spectra are desired

The purpose of each of the subroutines is described briefly below.

Subroutine Descriptions

TWV1

23. TWV1 reads in the parameters to specify which source terms are to be used. It calls subroutine TBND and calculates some constants. It is called once from the main program.

TBND

24. TBND reads in the type of boundary condition used as well as the directional spectra on the input boundary. It is called once from TWV1.

TLIM

25.TLIM calculates the upper bound of a wind sea spectrum as a function of depth and frequency. It is called at each grid point from the main program.

TSPF

26. TSPF locates the frequency in the spectrum at which the maximum energy occurs and calculates the significant wave height based on the total energy in this spectrum. It is called at each grid point and in turn calls TCFT.

TSPA

27. TSPA calculates the angle at which the maximum energy in the spectrum occurs. It is called at each grid point and in turn calls TCFT.

TCFT

28. TCFT calculates a quadratic fit to part of the energy spectrum to determine where the peak frequency and direction occur. It is called from TSPF and TSPA.

WAVENO

29. WAVENO calculates the wave number, given the frequency and depth, using the dispersion relation for linear waves. It is called in the main program and TFRC, TNL, and TLIM.

TDIS

30. TDIS is the first subroutine in the calculation of bottom friction. It calculates the ratios of bottom velocity components used in the formulation of bottom friction. It is called from the main program at every grid point.

TFRC

31. TFRC is the second subroutine in the bottom friction calculation. It calculates the bottom friction coefficient based on empirical data and a knowledge of the sand diameter. The bottom friction coefficient may be specified directly also. It is called from the main program at each grid point.

TNL

32. TNL calculates the nonlinear interactions using a parameterization based on exact calculations of the nonlinear interactions for a JONSWAP spectrum. A similarity relationship allows scaling to finite depth water for $k_p h \leq 0.7$. It is called from the main program at every grid point.

TPER

33. TPER calculates the percolation source term with a specified value of the permeability coefficient and depth of the sand layer. It is called from the main program at every grid point, frequency, and angle.

TFRA

34. TFRA is the third part of the bottom friction coefficient. It calculates a product of terms in the bottom friction calculation. It is called from the main program at every grid point and every frequency.

TFR

35. TFR is the final part of the bottom friction coefficient in which various terms are combined. It is called from the main program at every grid point, frequency, and angle.

TWN1

36. TWN1 is the calculation of the Miles atmospheric energy transfer mechanism. It is called from the main program at every grid point, frequency, and angle.

TWN2

37. TWN2 is the calculation of the Phillips atmospheric energy transfer mechanism. It is called from the main program at every grid point, frequency, and angle.

TWN2A

38. TWN2A calculates parameters used in the formulation of the Phillips

atmospheric energy transfer mechanism. It is called from the main program at every grid point and frequency.

TWV3

39. TWV3 prints out arrays of significant height, peak frequency, and peak direction after all calculations are finished. It is called once from the main program.

Input Data

40. There are two sets of input data, one each for the refraction and transformation parts of the program. The input data for the refraction part of the program consists of the following:

a. Up to four 80-column lines of descriptive text.

b. Namelist SIZE.

DX - Grid cell size in x direction in meters
DY - Grid cell size in y direction in meters

DELSI - Incremental distance along ray path in meters (typically one-fourth the grid cell size)

c. Namelist ANGLE.

THETA - Directions in degrees of the center of angular bands of width $\Delta\theta=\theta_2-\theta_1$ (Bands must be symmetrically placed about 0 deg which is normal to shore.)

d. Namelist FREQU.

FREQ - Center of frequency bands in hertz
DFR - Bandwidth in hertz of each band

e. Namelist DEPTH.

HT - Depth in meters at each grid point (A positive value indicates depth below mean sea level. Depths are read in columns left to right from offshore to shore.)

HTCNV - A conversion factor to convert depths to meters if depths read in are not in meters.

A typical grid orientation is shown in Figure 1. An example of an input file for this part of the program is shown in Appendix B.

41. The input data for the transformation part of the program consist of specification of the types of source terms and boundary conditions desired; the values of spectral energy as a function of frequency and direction specified on the input boundary; and three namelists supplying coefficients for the frictional, percolation, and atmospheric input subroutines and indices of grid

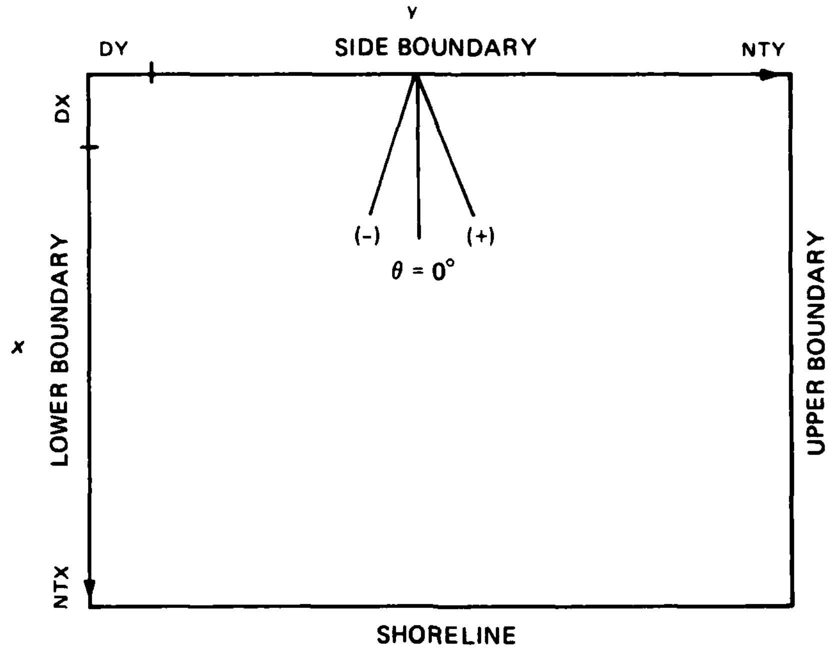

Figure 1. Orientation of model grid with convention for wave direction

points at which spectral output is desired.

42. A source term can be turned on or off by specifying T or F, respectively, for true or false. The format is (L1, 5 (1X, L2)), and in sequential order the source terms are friction, percolation, Mile's atmospheric input, Phillips' atmospheric input, nonlinear interactions, and depth limitation.

43. The types of boundary conditions are specified by the values of three parameters IDS, IDL, and IDU which represent, respectively, the side, lower, and upper boundaries as shown in Figure 1. The following values of IDS, or IDL, or IDU will result in the following action:

- a. The energy value of all spectral components (frequency and direction) at each grid point on the specified boundary will be set equal to a constant specified with the next read statement using a G13.5 format.
- b. The spectrum is equal at each point along the boundary and specified with the next read statement using a 6G13.5 format. Values are read from lowest to highest frequency at a given angle starting with the smallest angle, where the smallest angle is the largest negative value.
- c. The spectrum is read in at each point on the particular boundary using 6G13.5 format.
- d. The spectral values on the upper and lower boundaries are set

equal to the values at the adjacent grid points. No values are read in.

44. If printout of one- and two-dimensional spectra are desired, enter the x- and y-coordinate indices of the point in Format (1X, 2I3). The final data input is through three namelists called FRICT, PERCO, AND GENER.

a. Namelist FRICT.

DSC - Sand grain diameter used in the calculation of the bottom friction coefficient in meters

UM1 - The x component of steady nonwave induced bottom current in meters per second

UM2 - The y component of steady nonwave induced bottom current in meters per second

CF1 - A specified value of bottom friction coefficient (If a value of zero is specified, the program will calculate an appropriate value.)

b. Namelist PERCO.

PKC - The permeability coefficient
DC - The depth of the permeable layer in meters

c. Namelist GENER.

THWC - The direction toward which the wind is blowing in degrees with the same convention as the wave approach angle

WC - The wind speed in meters per second

An example of an input file for this part of the program is shown in Appendix C.

Output

45. The output of the refraction part of the program consists of line printer and disk file output for subsequent use by the transformation part of the program. The following information is printed out: the date and time the model was run; descriptive text describing the run; content of the three namelists--SIZE, ANGLE, FREQU; the depths at each grid point; and a conversion factor to meters if the depths are not input in meters. An example of printed output is shown in Appendix D. The user does not normally interact with the disk file output; consequently, it is not described in detail.

46. The output of the transformation part of the program consists of the following printout: the data and time the model was run, descriptive text, the water depths at each grid point, the true or false status of each of

the source terms, index values for the types of boundary conditions, the spectral values on the boundaries, the significant wave height at each grid point, and the peak frequency and peak direction at each grid point. An example of this output is shown in Appendix E. Additional output of one- and two-dimensional spectra at specified grid points is an option. This is initiated in the parameter statement of the program by specifying a value for MOUT, the number of grid points where output is desired. The locations of the grid points are specified after the spectral energy input. This is shown in Appendix C. An example of the output is shown in Appendix E.

PART IV: DESCRIPTION OF SAMPLE CALCULATIONS

47. The sample results are shown to provide the user some feeling for the effects of the source terms and various values of coefficients. A simple bathymetry was chosen which consists of a plane beach with maximum offshore depth of 50 m and minimum depth at the shore of 2.5 m. The bathymetry was approximated with a 20 by 20 grid. The grid cells were of equal dimension (500 m) in the x and y directions. Twelve angular bands of width 15 deg and symmetric around 0 deg were specified. Twenty frequency bands of width 0.01 Hz from 0.06 to 0.25 Hz were specified. A JONSWAP spectrum with the following parameters was input on the offshore boundary with the mean wave direction normal to shore: $\alpha = 0.01$, $\gamma = 3.3$, $f_m = 0.1$, $\sigma_a = 0.07$, and $\sigma_b = 0.09$. A JONSWAP spreading function was used to distribute energy over the angular bands. This spectrum was applied equally at each grid point on the offshore boundary; hence IDS = 2 . The upper and lower boundary conditions were supplied from adjacent grid points by setting IDL = IDU = 4 .

48. Results are summarized by plots of significant wave height at each grid point on a line perpendicular to shore and midway in the grid in the alongshore direction. Figures 2-9 show the effect of each source term acting alone as well as no source terms acting. Refraction and shoaling are included in all cases. A quantitative summary is provided in Table 1. Two things are obvious from these figures. First, there is little difference between the effect of each source term with exception of the depth limitation term. The effect of each source term is dependent on either a coefficient, wind velocity, or depth. For the coefficients and wind value chosen in this case, there is little difference over refraction and shoaling alone. Choice of different coefficient values can result in more significant effects. The second characteristic to note is the unrealistic behavior of the wave heights in depths where they would be expected to break if a breaking mechanism is not included.

49. In an application of the model, it is important to have prototype measurements so the model can be calibrated by adjusting coefficient values. In the absence of any prototype measurements, it is probably best to operate the model in the most conservative mode and employ only the depth limitation with refraction and shoaling. If one has knowledge of bottom characteristics or atmospheric input, the appropriate source terms can be applied. Figure 10 provides an indication of the effect of an upper limit frictional coefficient

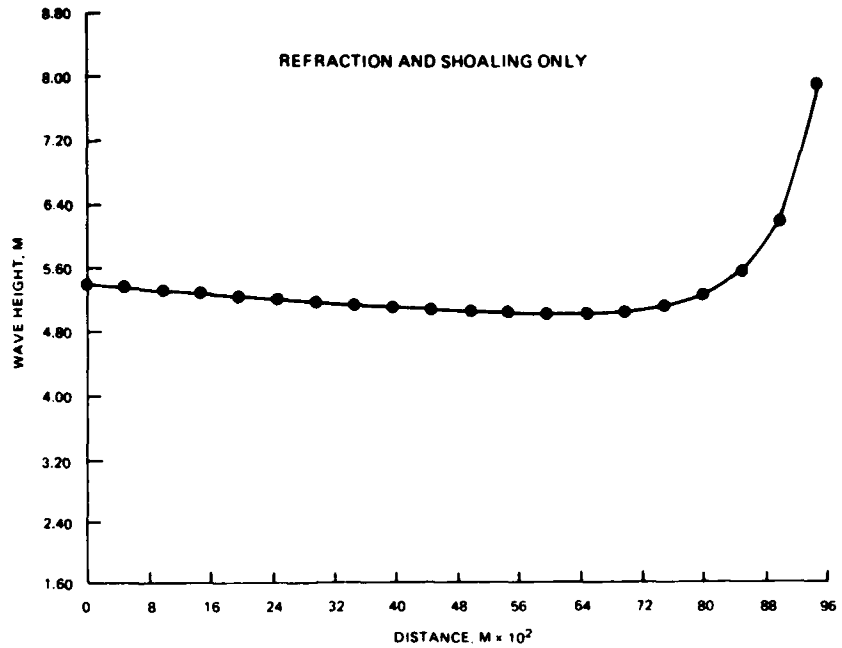

Figure 2. Wave height normal to shore with only refraction and shoaling acting

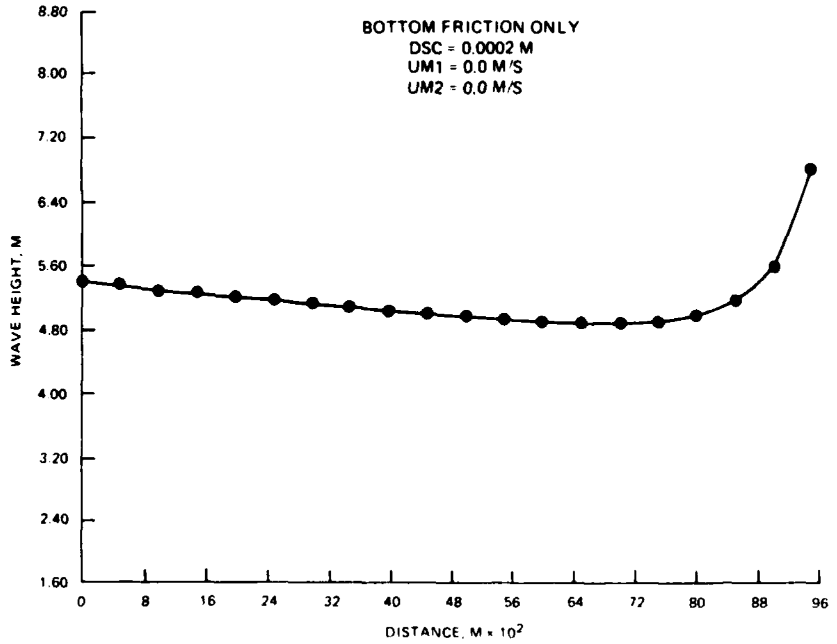

Figure 3. Wave height normal to shore with only bottom friction acting

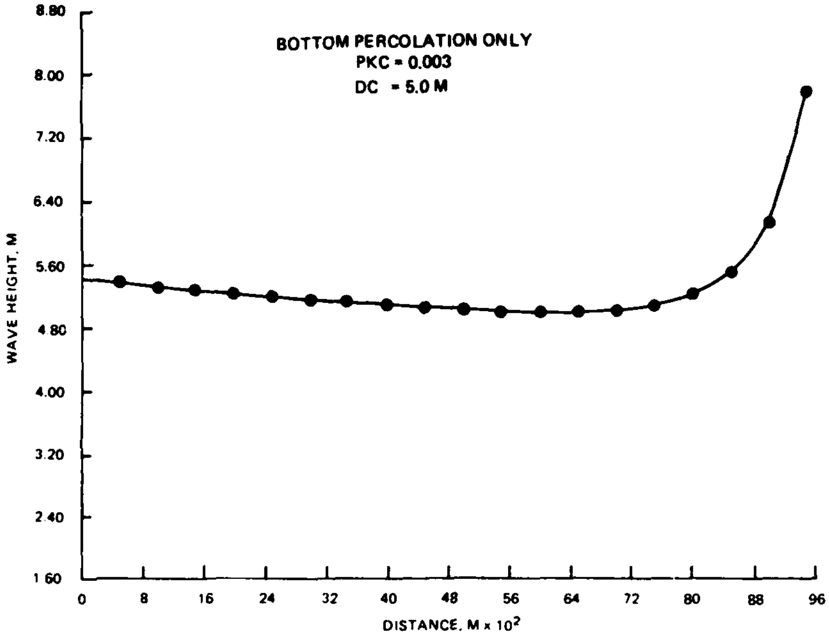

Figure 4. Wave height normal to shore with only bottom percolation acting

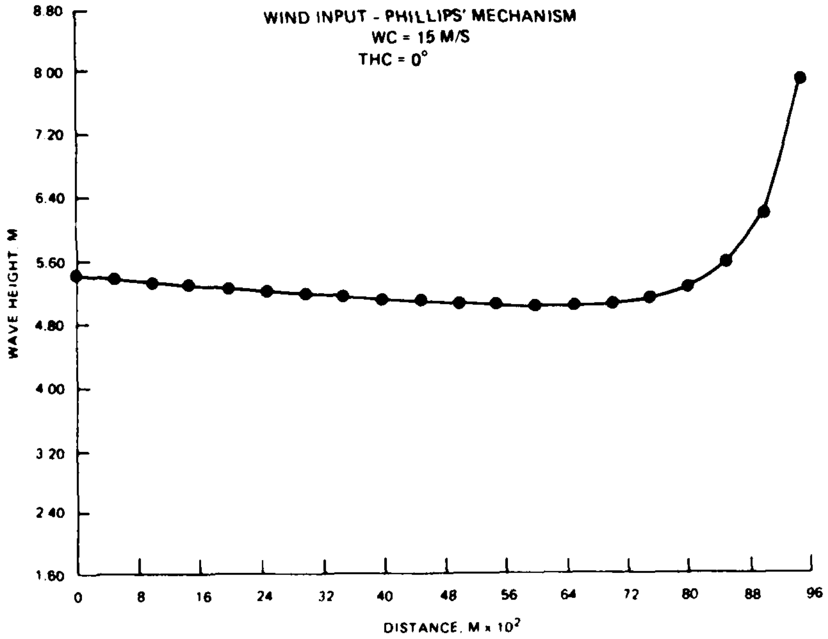

Figure 5. Wave height normal to shore with only Phillips' atmospheric input acting

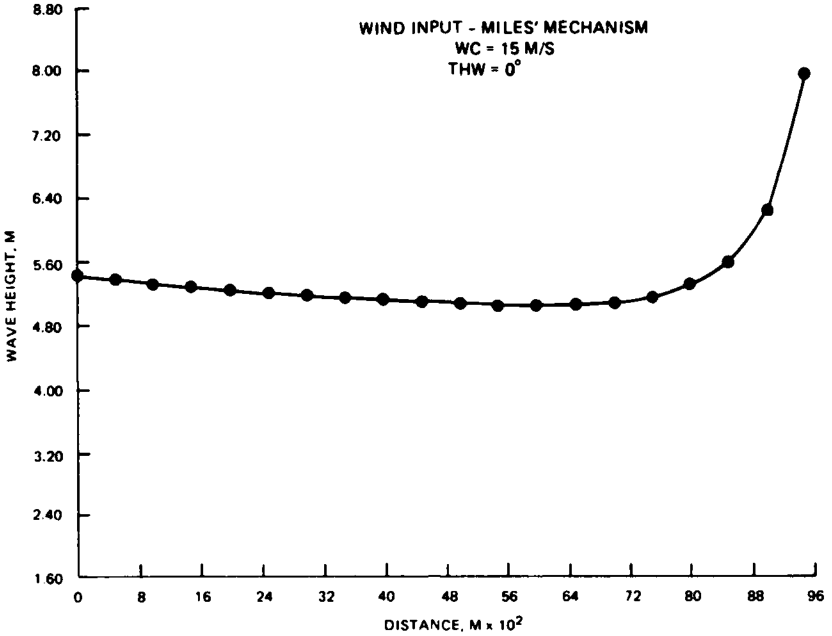

Figure 6. Wave height normal to shore with only Miles' atmospheric input acting

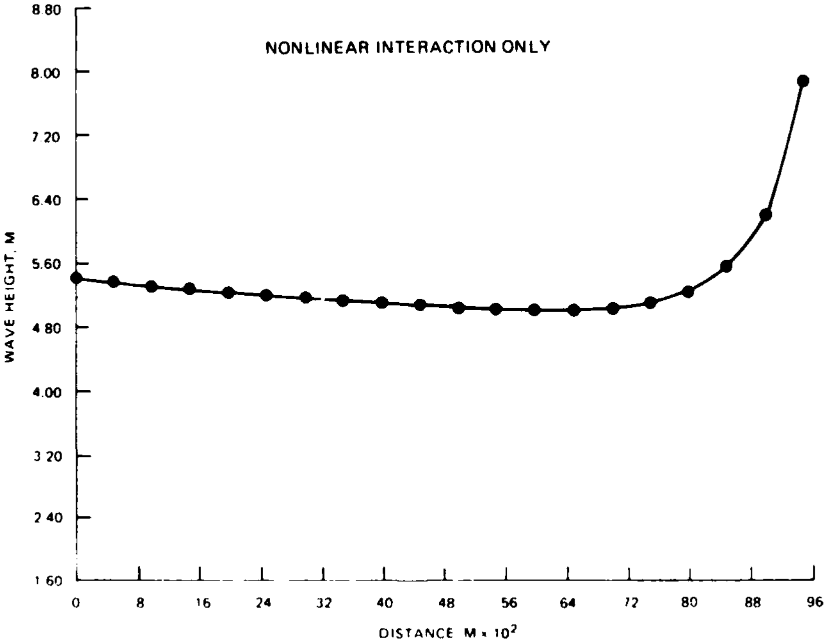

Figure 7. Wave height normal to shore with only nonlinear interaction

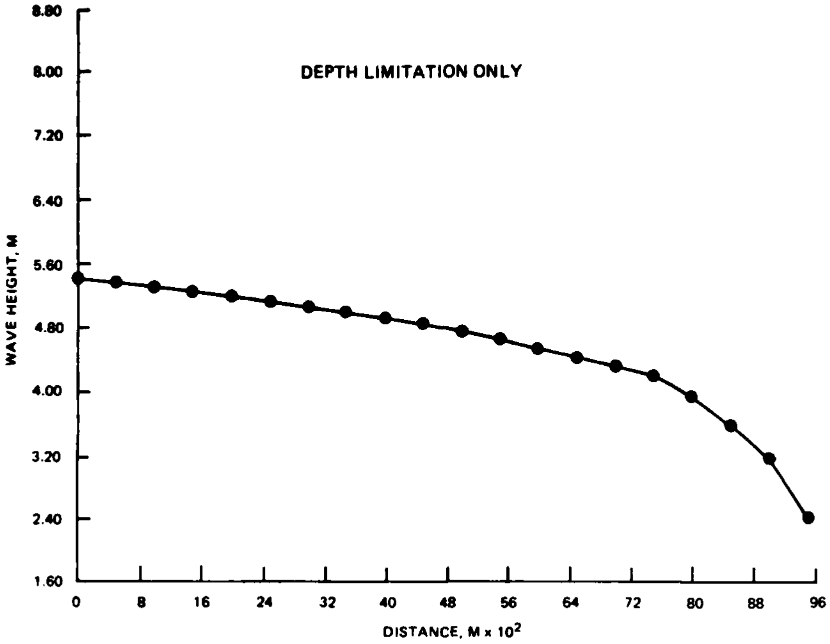

Figure 8. Wave height normal to shore with only depth limitation acting

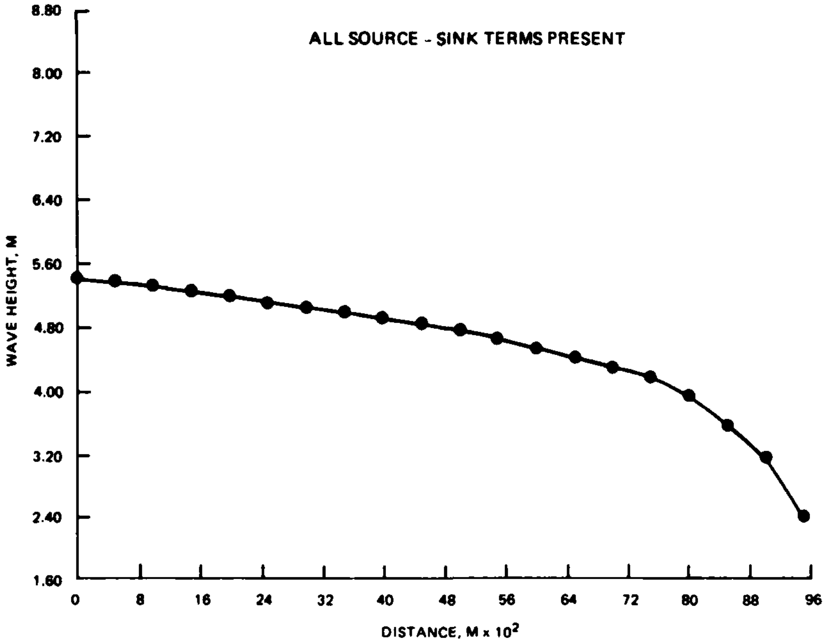

Figure 9. Wave height normal to shore with all source and sink terms acting

Table 1

Significant Wave Height* as a Function of Location and Source Terms

Grid Point	Depth	Bottom Friction	Percolation	Miles	Phillips	Nonlinear	Depth Limitation	No Source Terms
1	50.0	5.41	5.41	5.41	5.41	5.41	5.41	5.41
2	47.5	5.37	5.37	5.38	5.38	5.37	5.37	5.37
3	45.0	5.30	5.31	5.32	5.31	5.31	5.31	5.31
4	42.5	5.27	5.28	5.29	5.28	5.28	5.26	5.28
5	40.0	5.22	5.24	5.25	5.24	5.23	5.19	5.24
6	37.5	5.17	5.20	5.21	5.20	5.19	5.13	5.20
7	35.0	5.13	5.16	5.18	5.17	5.16	5.06	5.17
8	32.5	5.09	5.13	5.16	5.14	5.13	5.00	5.13
9	30.0	5.05	5.10	5.13	5.10	5.10	4.93	5.10
10	27.5	5.02	5.07	5.10	5.08	5.07	4.86	5.08
11	25.0	4.98	5.04	5.08	5.05	5.04	4.77	5.05
12	22.5	4.94	5.02	5.06	5.03	5.02	4.66	5.03
13	20.0	4.91	5.01	5.05	5.02	5.01	4.55	5.02
14	17.5	4.89	5.01	5.06	5.02	5.02	4.45	5.02
15	15.0	4.88	5.03	5.08	5.04	5.04	4.34	5.04
16	12.5	4.90	5.09	5.15	5.11	5.11	4.22	5.11
17	10.0	4.97	5.23	5.30	5.25	5.26	3.94	5.25
18	7.5	5.16	5.51	5.59	5.55	5.55	3.59	5.54
19	5.0	5.59**	6.12**	6.23**	6.17**	6.18**	3.17	6.17**
20	2.5	6.82**	7.77**	7.94**	7.86**	7.88**	2.44†	7.86**

Parameters:†† CF = 0.01 PKC = 0.003 WC = 15.0
DSC = .0002 DC = 5.0 THWC = 0.0
UM1 = 0.0 UM2 = 0.0

* In meters.
** Results in depths shallower than this probably not valid because breaking not included.
† Probably not valid, shore boundary of the model.
†† Parameters defined in paragraph 44 of main text.

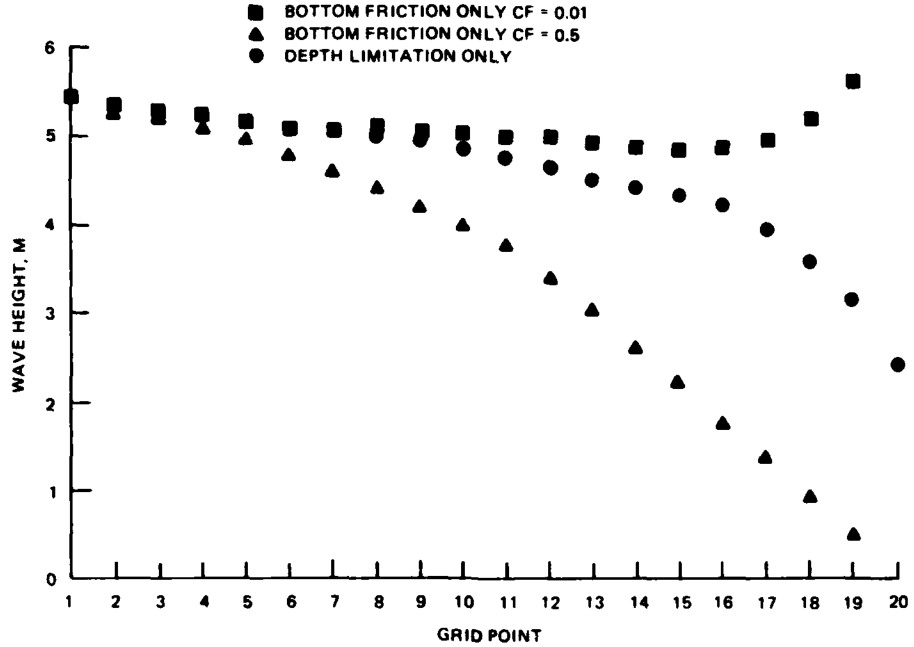

Figure 10. Wave height normal to shore for different values of bottom friction and for depth limitation only

on wave heights for this sample case. An order of magnitude increase in the percolation coefficient for this case has negligible effect. However, for a different case, such as a large extent of flat bottom with high permeability, it could be important.

50. The state of the art of modeling shallow-water waves has markedly improved as exemplified by this model. Calculation of refraction and shoaling of monochromatic waves following rays has evolved to more sophisticated numerical routines for refraction and shoaling of spectra. A variety of source terms representing possible sources and sinks of energy have been added to models to account for wave generation and dissipation in shallow water. Research continues on the most appropriate formulation for these source terms and their balance in a spectral model. The users of models such as this should exercise care to obtain adequate calibration and verification of the model, understand what source terms dominate, and use common sense in interpretation of the results.

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APPENDIX A: SAMPLE JOB CONTROL LANGUAGE

Job Control Language to Run the Refraction Program Only

FRONT END JCL

```
/JOB
/NOSEQ
PCJOB,T800,P4.
/USER
/CHARGE
GET,TMANEW2,PCDATN1,PCNEWR2.
SKIPR,PCNEWR2.
COPYBR,TMANEW2,PCNEWR2,1.
COPYBR,PCDATN1,PCNEWR2,1.
SUBMIT,PCNEWR2,T.
END OF FILE
```

CYBER 200 JCL

```
PNWJOB.
USER(U=       ,PA=       )ADY
RESOURCE(JCAT=P4,TL=800)
CHARGE(        ,        )
PATTACH,LINKPOOL.
PURGE,NEW55.
COPYL,INPUT,T1,PART=G,NUM=1.
COPYL,INPUT,D1,PART=G,NUM=1.
FORTRAN,I=T1,B=BT/#300,O=BOV.
PATTACH,FTNUTIL.
LOAD,BT,CN=TMAGO/#400,GRLP=*A.
REQUEST,NEW55/8000,RT=W.
TMAGO(TAPE5=D1,TAPE55=NEW55)
DEFINE,NEW55/8000,RT=W.
RETURN,T1,D1.
END OF FILE
```

Job Control Language to Run the Transformation Program Only

FRONT END JCL

```
/JOB
/NOSEQ
PETEJB,T700,P4.
/USER.
/CHARGE
GET,TAPE6.
RENAME,PCDATA=TAPE6.
GET,TMANEW2.
SKIPR,TMANEW2,1,C.
SKIPR,PCDATA,1,C.
GET,PNW2052.
SKIPR,PNW2052.
COPYBR,TMANEW2,PNW2052,1.
COPYBR,PCDATA,PNW2052,1.
SUBMIT,PNW2052,T.
END OF FILE
```

CYBER 200 JCL

```
TMJ.
USER(U=       ,PA=       )ADY
RESOURCE(JCAT=P4,TL=600)
CHARGE(        ,        )
PATTACH,LINKPOOL.
ATTACH,TAPE55.
COPYL,INPUT,T,PART=G,NUM=1.
COPYL,INPUT,D,PART=G,NUM=1.
FORTRAN,I=T,B=BT/#300,O=BOVLK.
LOAD,BT,CN=TMAGO/#400.
TMAGO(TAPE5=D)
RETURN,T,D.
END OF FILE
```

APPENDIX B: SAMPLE INPUT FOR REFRACTION RUN

```
SENSITIVITY OF TMANEW
JONSWAP SPECTRUM INPUT
1/200 PLANE BEACH
DECEMBER 1984
 &SIZE DX=500.0,DY=500.0,DELSI=125.0 &END
 &ANGLE
 THETA=-82.5, -67.5,-52.5,-37.5,-22.5,-7.5.7.5,22.5,37.5,52.5,67.5,82.5,
 &END
 &FREQU FREQ=0.06,0.07,0.08,0.09,0.10,0.11,0.12,0.13,0.14,0.15,
            0.16,0.17,0.18,0.19.0.20,0.21,0.22,0.23,0.24,0.25,
 DFR=20*0.01 &END
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500

--EOR--
```

APPENDIX C: SAMPLE INPUT FOR TRANSFORMATION RUN

```
T,F,F,F,F,F
2,4,4
    .94225E-02    .30739       .89999       1.1047       .82864       .28658
    .28494        .34778       .39800       .41252       .39877       .36761
    .32808        .28640       .24635       .20985       .17770       .14997
    .12639        .10651
    .11240E-01    .42749       1.5869       2.7579       3.3716       1.3849
    1.0313        1.0113       .97713       .88630       .77000       .65090
    .54095        .44510       .36430       .29755       .24308       .19892
    .16323        .13441
    .12835E-01    .54785       2.4312       5.4884       9.6882       4.5293
    2.7136        2.2572       1.9202       1.5754       1.2631       1.0003
    .78798        .62012       .48894       .38693       .30768       .24601
    .19786        .16011
    .14116E-01    .65454       3.3015       8.9912       20.656       10.596
    5.4315        4.0148       3.1173       2.3800       1.8014       1.3614
    1.0320        .78664       .60383       .46713       .36434       .28651
    .22715        .18151
    .15012E-01    .73437       4.0240       12.373       33.707       18.360
    8.5084        5.8268       4.2646       3.1080       2.2663       1.6618
    1.2288        .91747       .69215       .52767       .40643       .31619
    .24835        .19686
    .15473E-01    .77709       4.4350       14.474       42.874       24.053
    10.608        6.9968       4.9745       3.5434       2.5369       1.8328
    1.3388        .98950       .74017       .56022       .42886       .33188
    .25949        .20487
    .15473E-01    .77709       4.4350       14.474       42.874       24.053
    10.608        6.9968       4.9745       3.5434       2.5369       1.8328
    1.3388        .98950       .74017       .56022       .42886       .33188
    .25949        .20487
    .15012E-01    .73437       4.0240       12.373       33.707       18.360
    8.5084        5.8268       4.2646       3.1080       2.2663       1.6618
    1.2288        .91747       .69215       .52767       .40643       .31619
    .24835        .19686
    .14116E-01    .65454       3.3015       8.9912       20.656       10.596
    5.4315        4.0148       3.1173       2.3800       1.8014       1.3614
    1.0320        .78664       .60383       .46713       .36434       .28651
    .22715        .18151
    .12835E-01    .54785       2.4312       5.4884       9.6882       4.5293
    2.7136        2.2572       1.9202       1.5754       1.2631       1.0003
    .78798        .62012       .48894       .38693       .30768       .24601
    .19786        .16011
    .11240E-01    .42749       1.5869       2.7579       3.3716       1.3849
    1.0313        1.0113       .97713       .88630       .77000       .65090
    .54095        .44510       .36430       .29755       .24308       .19892
    .16323        .13441
    .94225E-02    .30739       .89999       1.1047       .82864       .28658
    .28494        .34778       .39800       .41252       .39877       .36761
    .32808        .28640       .24635       .20985       .17770       .14997
    .12639        .10651
```

```
   1 10
   5 10
  10 10
  15 10
  20 10
 &FRICT DSC=.0002,UM1=0.0,UM2=0.0  ,CF1=0.5 &END
 &PERCO PKC=.010,DC=5.0 &END
 &GENER WC=15.0,THWC=0.0 &END
END OF FILE
```

APPENDIX D: SAMPLE OUTPUT FOR REFRACTION RUN

```
1DSWM REFRACTION MODEL RUN AT 11/14/84  10.08.37

 SENSITIVITY OF THANEM,
 JONSWAP SPECTRUM INPUT
 1/200 PLANE BEACH
 NOVEMBER 1984



0  20 BY  20GRID
 NUMBER OF FREQUENCIES =  20
 NUMBER OF DIRECTIONS =  12
1
 &SIZE
 DX      =  .5E+03,
 DY      =  .5E+03,
 DELSI   =  .125E+03,
 &END
1
 &ANGLE
 THETA   =  -.825E+02,  -.675E+02,  -.525E+02,  -.375E+02,  -.225E+02,  -.75E+01,  .75E+01,  .225E+02,  .375E+02,  .525E+02,  .675E+
02,
   .825E+02,
 &END
1
 &FREQU
 FREQ    =  .6E-01,  .7E-01,  .8E-01,  .9E-01,  .1E+00,  .11E+00,  .12E+00,  .13E+00,  .14E+00,  .15E+00,  .16E+00,  .17E+00,  .18E+
00,
   .19E+00,  .2E+00,  .21E+00,  .22E+00,  .23E+00,  .24E+00,  .25E+00,
 DFR     =  .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E
-01,
   .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E-01,  .1E-01,
 &END
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
 25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
 50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
```

```
25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
50.000 47.500 45.000 42.500 40.000 37.500 35.000 32.500 30.000 27.500
25.000 22.500 20.000 17.500 15.000 12.500 10.000  7.500  5.000  2.500
```

APPENDIX E: SAMPLE OUTPUT FOR TRANSFORMATION RUN

```
SENSITIVITY OF TMANEW
JONSWAP SPECTRUM INPUT
1/200 PLANE BEACH
NOVEMBER 1984
1
   WATER DEPTH IN METERS

        1    2    3    4    5    6    7    8    9   10   11   12   13   14   15

20 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
19 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
18 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
17 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
16 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
15 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
14 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
13 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
12 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
11 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
10 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
 9 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
 8 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
 7 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
 6 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
 5 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
 4 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
 3 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
 2 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
 1 50.0 47.5 45.0 42.5 40.0 37.5 35.0 32.5 30.0 27.5 25.0 22.5 20.0 17.5 15.0
1
   WATER DEPTH IN METERS

       16   17   18   19   20
20 12.5 10.0  7.5  5.0  2.5
19 12.5 10.0  7.5  5.0  2.5
18 12.5 10.0  7.5  5.0  2.5
17 12.5 10.0  7.5  5.0  2.5
16 12.5 10.0  7.5  5.0  2.5
15 12.5 10.0  7.5  5.0  2.5
14 12.5 10.0  7.5  5.0  2.5
13 12.5 10.0  7.5  5.0  2.5
12 12.5 10.0  7.5  5.0  2.5
11 12.5 10.0  7.5  5.0  2.5
10 12.5 10.0  7.5  5.0  2.5
 9 12.5 10.0  7.5  5.0  2.5
 8 12.5 10.0  7.5  5.0  2.5
 7 12.5 10.0  7.5  5.0  2.5
 6 12.5 10.0  7.5  5.0  2.5
 5 12.5 10.0  7.5  5.0  2.5
 4 12.5 10.0  7.5  5.0  2.5
 3 12.5 10.0  7.5  5.0  2.5
 2 12.5 10.0  7.5  5.0  2.5
 1 12.5 10.0  7.5  5.0  2.5
```

```
      FN     PR     W1     W2     NL     LIM
       T      F      F      F      F      F


         IDS= 2       IDU= 4       IDL= 4

OBNDS
   1      .94225E-02   .30739      .89999      1.1047      .82864      .28658
          .28494       .34778      .39800      .41252      .39877      .36761
          .32808       .28640      .24635      .20985      .17770      .14997
          .12639       .10651
   2      .11240E-01   .42749      1.5869      2.7579      3.3716      1.3849
          1.0313       1.0113      .97713      .88630      .77000      .65090
          .54095       .44510      .36430      .29755      .24308      .19892
          .16323       .13441
   3      .12835E-01   .54785      2.4312      5.4884      9.6882      4.5293
          2.7136       2.2572      1.9202      1.5754      1.2631      1.0003
          .78798       .62012      .48894      .38693      .30768      .24601
          .19786       .16011
   4      .14116E-01   .65454      3.3015      8.9912      20.656      10.596
          5.4315       4.0148      3.1173      2.3800      1.8014      1.3614
          1.0320       .78664      .60383      .46713      .36434      .28651
          .22715       .18151
   5      .15012E-01   .73437      4.0240      12.373      33.707      18.360
          8.5084       5.8268      4.2646      3.1080      2.2663      1.6618
          1.2288       .91747      .69215      .52767      .40643      .31619
          .24835       .19686
   6      .15473E-01   .77709      4.4350      14.474      42.374      24.053
          10.608       6.9968      4.9745      3.5434      2.5369      1.8328
          1.3388       .98950      .74017      .56022      .42886      .33188
          .25949       .20487
   7      .15473E-01   .77709      4.4350      14.474      42.874      24.053
          10.608       6.9968      4.9745      3.5434      2.5369      1.8328
          1.3388       .98950      .74017      .56022      .42886      .33188
          .25949       .20487
   8      .15012E-01   .73437      4.0240      12.373      33.707      18.360
          8.5084       5.8268      4.2646      3.1080      2.2663      1.6618
          1.2288       .91747      .69215      .52767      .40643      .31619
          .24835       .19686
   9      .14116E-01   .65454      3.3015      8.9912      20.656      10.596
          5.4315       4.0148      3.1173      2.3800      1.8014      1.3614
          1.0320       .78664      .60383      .46713      .36434      .28651
          .22715       .18151
  10      .12835E-01   .54785      2.4312      5.4884      9.6882      4.5293
          2.7136       2.2572      1.9202      1.5754      1.2631      1.0003
          .78798       .62012      .48894      .38693      .30768      .24601
          .19786       .16011
  11      .11240E-01   .42749      1.5869      2.7579      3.3716      1.3849
          1.0313       1.0113      .97713      .88630      .77000      .65090
          .54095       .44510      .36430      .29755      .24308      .19892
          .16323       .13441
  12      .94225E-02   .30739      .89999      1.1047      .82864      .28658
          .28494       .34778      .39800      .41252      .39877      .36761
          .32808       .28640      .24635      .20985      .17770      .14997
          .12639       .10651
```

```
K    IOUT    JOUT
1       1      10
2       5      10
3      10      10
4      15      10
5      20      10


1
 &FRICT
 DSC      =   .2E-03,
 UM1      =   .0,
 UM2      =   .0,
 CF1      =   .5E+00,
 &END


--------- END OF DATA CHECK ----------


   RESULTS FOR  5 OBSERVATION POINTS FOLLOW...

   IX    IY    DEPTH (M)    PEAK FREQ.(HZ)    PEAK DIR.(DEG)    SIG. HT.(M)
    1    10       50.00              .10               .00             5.41
   1-D                                           2-D
  SPCTRM                                       SPECTRA
  -----    -----  -----  -----  -----  -----  -----  -----  -----  -----  -----  -----  ----
    .04     .01    .01    .01    .01    .02    .02    .02    .02    .01    .01    .01    .01
   1.81     .31    .43    .55    .65    .73    .78    .78    .73    .65    .55    .43    .31
   8.73     .90   1.59   2.43   3.30   4.02   4.44   4.44   4.02   3.30   2.43   1.59    .90
  23.66    1.10   2.76   5.49   8.99  12.37  14.47  14.47  12.37   8.99   5.49   2.76   1.10
  58.19     .83   3.37   9.69  20.66  33.71  42.87  42.87  33.71  20.66   9.69   3.37    .83
  31.00     .29   1.38   4.53  10.60  18.36  24.05  24.05  18.36  10.60   4.53   1.38    .29
  14.96     .28   1.03   2.71   5.43   8.51  10.61  10.61   8.51   5.43   2.71   1.03    .28
  10.71     .35   1.01   2.26   4.01   5.83   7.00   7.00   5.83   4.01   2.26   1.01    .35
   8.20     .40    .98   1.92   3.12   4.26   4.97   4.97   4.26   3.12   1.92    .98    .40
   6.23     .41    .89   1.58   2.38   3.11   3.54   3.54   3.11   2.38   1.58    .89    .41
   4.73     .40    .77   1.26   1.80   2.27   2.54   2.54   2.27   1.80   1.26    .77    .40
   3.60     .37    .65   1.00   1.36   1.66   1.83   1.83   1.66   1.36   1.00    .65    .37
   2.75     .33    .54    .79   1.03   1.23   1.34   1.34   1.23   1.03    .79    .54    .33
   2.12     .29    .45    .62    .79    .92    .99    .99    .92    .79    .62    .45    .29
   1.64     .25    .36    .49    .60    .69    .74    .74    .69    .60    .49    .36    .25
   1.28     .21    .30    .39    .47    .53    .56    .56    .53    .47    .39    .30    .21
   1.01     .18    .24    .31    .36    .41    .43    .43    .41    .36    .31    .24    .18
    .80     .15    .20    .25    .29    .32    .33    .33    .32    .29    .25    .20    .15
    .64     .13    .16    .20    .23    .25    .26    .26    .25    .23    .20    .16    .13
    .52     .11    .13    .16    .18    .20    .20    .20    .20    .18    .16    .13    .11
```

```
      SIGNIFICANT WAVE HEIGHTS IN METERS

          1    2    3    4    5    6    7    8    9   10   11   12   13   14   15

 20 5.41 5.29 5.20 5.09 4.96 4.82 4.66 4.46 4.23 3.98 3.69 3.36 3.00 2.62 2.21
 19 5.41 5.29 5.20 5.09 4.96 4.82 4.66 4.46 4.23 3.98 3.69 3.36 3.00 2.62 2.21
 18 5.41 5.29 5.20 5.09 4.96 4.82 4.66 4.46 4.23 3.98 3.69 3.36 3.00 2.62 2.21
 17 5.41 5.31 5.20 5.09 4.97 4.82 4.66 4.46 4.23 3.98 3.69 3.36 3.00 2.62 2.21
 16 5.41 5.31 5.20 5.08 4.96 4.82 4.65 4.45 4.23 3.97 3.68 3.36 3.00 2.61 2.20
 15 5.41 5.31 5.20 5.09 4.96 4.82 4.65 4.45 4.23 3.97 3.68 3.36 3.00 2.61 2.21
 14 5.41 5.31 5.20 5.08 4.96 4.82 4.65 4.45 4.23 3.97 3.68 3.36 3.00 2.61 2.20
 13 5.41 5.31 5.20 5.09 4.96 4.81 4.64 4.45 4.23 3.97 3.68 3.36 3.00 2.61 2.20
 12 5.41 5.32 5.20 5.09 4.96 4.81 4.64 4.45 4.23 3.97 3.68 3.36 3.00 2.61 2.20
 11 5.41 5.32 5.20 5.09 4.96 4.81 4.64 4.45 4.23 3.97 3.68 3.36 3.00 2.61 2.20
 10 5.41 5.32 5.20 5.09 4.96 4.81 4.64 4.45 4.23 3.97 3.68 3.36 3.00 2.61 2.20
  9 5.41 5.32 5.20 5.09 4.96 4.81 4.64 4.45 4.23 3.97 3.68 3.36 3.00 2.61 2.20
  8 5.41 5.31 5.20 5.09 4.96 4.81 4.64 4.45 4.23 3.97 3.68 3.36 3.00 2.61 2.20
  7 5.41 5.31 5.20 5.08 4.96 4.82 4.65 4.45 4.23 3.97 3.63 3.36 3.00 2.61 2.20
  6 5.41 5.31 5.20 5.09 4.96 4.82 4.65 4.45 4.23 3.97 3.68 3.36 3.00 2.61 2.21
  5 5.41 5.31 5.20 5.08 4.96 4.82 4.65 4.45 4.23 3.97 3.68 3.36 3.00 2.61 2.20
  4 5.41 5.31 5.20 5.09 4.97 4.82 4.66 4.46 4.23 3.98 3.69 3.36 3.00 2.62 2.21
  3 5.41 5.29 5.20 5.09 4.96 4.82 4.66 4.46 4.23 3.98 3.69 3.36 3.00 2.62 2.21
  2 5.41 5.29 5.20 5.09 4.96 4.82 4.66 4.46 4.23 3.98 3.69 3.36 3.00 2.62 2.21
  1 5.41 5.29 5.20 5.09 4.96 4.82 4.66 4.46 4.23 3.98 3.69 3.36 3.00 2.62 2.21
```

```
      SIGNIFICANT WAVE HEIGHTS IN METERS

         16   17   18   19   20
 20 1.78 1.35  .93  .52  .21
 19 1.78 1.35  .93  .52  .21
 18 1.78 1.35  .93  .52  .21
 17 1.78 1.35  .93  .52  .21
 16 1.78 1.35  .92  .52  .21
 15 1.78 1.35  .92  .52  .21
 14 1.78 1.35  .92  .52  .21
 13 1.78 1.35  .92  .52  .21
 12 1.78 1.35  .92  .52  .21
 11 1.78 1.35  .92  .52  .21
 10 1.78 1.35  .92  .52  .21
  9 1.78 1.35  .92  .52  .21
  8 1.78 1.35  .92  .52  .21
  7 1.78 1.35  .92  .52  .21
  6 1.78 1.35  .92  .52  .21
  5 1.78 1.35  .92  .52  .21
  4 1.78 1.35  .93  .52  .21
  3 1.78 1.35  .93  .52  .21
  2 1.78 1.35  .93  .52  .21
  1 1.78 1.35  .93  .52  .21
```

PEAK FREQUENCY IN HZ

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
20	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
19	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
18	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
17	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
16	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
15	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
14	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
13	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
12	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
11	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
10	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
9	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
8	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
7	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
6	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
5	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
4	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
3	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
2	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102
1	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.101	.102	.102	.102	.102

PEAK FREQUENCY IN HZ

	16	17	18	19	20
20	.102	.102	.102	.243	.245
19	.102	.102	.102	.243	.245
18	.102	.102	.102	.243	.245
17	.102	.102	.102	.243	.245
16	.102	.102	.102	.243	.245
15	.102	.102	.102	.242	.245
14	.102	.102	.102	.243	.245
13	.102	.102	.102	.243	.245
12	.102	.102	.102	.243	.245
11	.102	.102	.102	.242	.245
10	.102	.102	.102	.242	.245
9	.102	.102	.102	.243	.245
8	.102	.102	.102	.243	.245
7	.102	.102	.102	.243	.245
6	.102	.102	.102	.242	.245
5	.102	.102	.102	.243	.245
4	.102	.102	.102	.243	.245
3	.102	.102	.102	.243	.245
2	.102	.102	.102	.243	.245
1	.102	.102	.102	.243	.245

PEAK DIRECTION IN DEGREES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
20	.0	.0	-.0	-.0	-.0	-.0	-.0	.0	.0	.0	.0	.0	.0	.0	.0
19	.0	.0	-.0	-.0	-.0	-.0	-.0	.0	.0	.0	.0	.0	.0	.0	.0
18	.0	.0	-.0	-.0	-.0	-.0	-.0	.0	.0	.0	.0	.0	.0	.0	.0
17	.0	.0	-.0	-.0	-.0	-.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
16	.0	.0	-.0	-.0	-.0	-.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
15	.0	.0	-.0	-.0	-.0	-.0	-.0	.0	.0	.0	.0	.0	.0	.0	.0
14	.0	.0	-.0	-.0	-.0	-.0	-.0	.0	.0	.0	.0	.0	.0	.0	.0
13	.0	.0	-.0	-.0	-.0	-.0	-.0	.0	.0	.0	.0	.0	.0	.0	.0
12	.0	.0	-.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
11	.0	.0	-.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
10	.0	.0	.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0
9	.0	.0	.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0
8	.0	.0	.0	.0	.0	.0	.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0
7	.0	.0	.0	.0	.0	.0	.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0
6	.0	.0	.0	.0	.0	.0	.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0
5	.0	-.0	.0	.0	.0	.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0
4	.0	-.0	.0	.0	.0	.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0
3	.0	-.0	.0	.0	.0	.0	.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0
2	.0	-.0	.0	.0	.0	.0	.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0
1	.0	-.0	.0	.0	.0	.0	.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0	-.0

PEAK DIRECTION IN DEGREES

	16	17	18	19	20
20	.0	.1	.1	.1	.1
19	.0	.1	.1	.1	.1
18	.0	.1	.1	.1	.1
17	.1	.1	.1	.1	.2
16	.0	.1	.1	.1	.1
15	.0	.0	.1	.1	.0
14	.0	.0	.0	.0	.0
13	.0	.0	.0	.0	.0
12	.0	.0	.0	.0	.0
11	.0	.0	.0	.0	.0
10	-.0	-.0	-.0	-.0	-.0
9	-.0	-.0	-.0	-.0	-.0
8	-.0	-.0	-.0	-.0	-.0
7	-.0	-.0	-.0	-.0	-.0
6	-.0	-.0	-.1	-.1	-.0
5	-.0	-.1	-.1	-.1	-.1
4	-.1	-.1	-.1	-.1	-.2
3	-.0	-.1	-.1	-.1	-.1
2	-.0	-.1	-.1	-.1	-.1
1	-.0	-.1	-.1	-.1	-.1

APPENDIX F: NOTATION

$b_{1,2}$	Coefficients used in the formulation of the Phillips atmospheric input term
C	Wave phase velocity
C_f	Coefficient of bottom friction
C_g	Wave group velocity
d	Depth of permeable layer
E	Spectral energy in (f,θ) space
f	Wave frequency
f_m	Wave frequency at the spectral peak
F	Spectral energy in $\vec{k}$ space
g	Acceleration of gravity
h	Water depth
$\vec{k}$	Wave number vector
q	Ratio of wave frequency to wind speed
s	Coordinate distance along a wave ray
S	Source or sink term
t	Time
u	Wind speed
W	Water velocity
x	Coordinate cross-shore
y	Coordinate alongshore
α	Spectral parameter
α_g	Linear growth coefficient in Phillips' term for atmospheric input
α_p	Permeability coefficient
γ	Spectral parameter
θ	Wave direction or difference between wave and wind direction
π	Constant = 3.14159...
ρ_a	Density of air
ρ_w	Density of water
σ	Spectral constant
ϕ	Spectral parameter
ω	Wave frequency = $2\pi f$

END

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