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# WAVE INFORMATION STUDIES OF US COASTLINES

WIS REPORT 19

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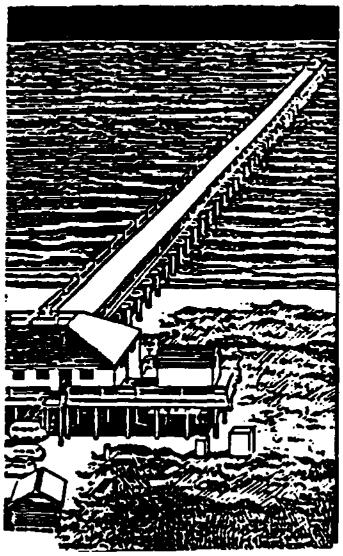
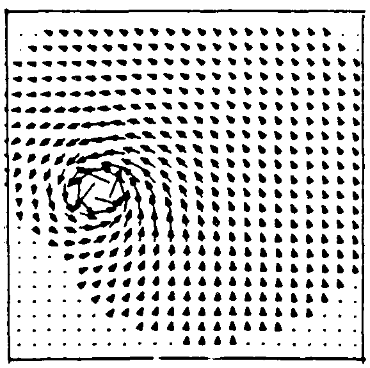
# HURRICANE HINDCAST METHODOLOGY AND WAVE STATISTICS FOR ATLANTIC AND GULF HURRICANES FROM 1956-1975





by

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Coastal Engineering Research Center

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Wave conditions at locations along the US Atlantic and Gulf of Mexico coastlines are hindcast during hurricanes occurring between 1956 and 1975. A total of 68 hurricanes occurred in the period, 43 affecting the Atlantic coast and 25 the gulf coast. The hindcast methodology is discussed and verification presented for storms where observations are available. Results are presented as the highest wave occurring at each location and significant wave height versus return period for each location.

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## Preface

A study to produce a wave climate for US coastal waters was initiated at the US Army Engineer Waterways Experiment Station (WES). The Wave Information Study (WIS) was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Coastal Field Data Collection Program, which is managed by the WES Coastal Engineering Research Center (CERC). Mr. John Lockhart, Jr., HQUSACE, is the Technical Monitor for the Coastal Field Data Collection Program. Mr. J. Michael Hemsley, CERC, is Program Manager, and Dr. Jon M. Hubertz, Coastal Oceanography Branch (COB), CERC, is WIS Project Manager.

This report, the nineteenth in a series, presents hurricane hindcast methodology and summary wave statistics for the Atlantic and Gulf of Mexico coasts for the period 1956-1975. This report and the information it summarizes were prepared by Dr. Charles E. Abel (deceased), Ms. Barbara A. Tracy, Dr. C. Linwood Vincent, and Dr. Robert E. Jensen, COB, CERC, with technical editorial assistance from Dr. Hubertz and general assistance from the members of the WIS staff.

The study was conducted under the direct supervision of Dr. Edward F. Thompson, Chief, COB, CERC, and Mr. H. Lee Butler, Chief, Research Division, CERC; and under the general supervision of Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., Chief and Assistant Chief, CERC, respectively. The word processing of this report was accomplished by Ms. Victoria L. Edwards, COB. This report was edited by Ms. Lee T. Byrne, Information Technology Laboratory, WES.

COL Dwayne G. Lee, EN, is the Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

## Contents

# Conversion Factors, Non-SI to SI (Metric) Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| feet | 0.3048 | metres |
| knots (international) | 0.5144444 | metres per second |
| miles (US statute) | 1.609347 | kilometres |

# HURRICANE HINDCAST METHODOLOGY AND WAVE STATISTICS FOR ATLANTIC AND GULF HURRICANES FROM 1956-1975

## Introduction

1. Hurricanes are defined as tropical cyclones with winds of 74 mph* or greater. These storms occur in the warmwater areas of the Atlantic and Pacific Oceans and the Gulf of Mexico and often cross onto populated land along the Atlantic and gulf coasts of the United States. More rarely, they have affected southern California and Hawaii. The winds, waves, and water levels at the coast associated with these storms have resulted in loss of lives and large property losses. The large waves produced by hurricanes at sea are a threat to navigation and to the coastline. Swell wave propagation from a hurricane impacts the coast even if the hurricane never makes landfall. The presence of swell at the coast typically begins before the fully developed hurricane wind waves reach the coast. The design wave statistics for the gulf and southern Atlantic coast are generally derived from hurricane events. These waves are also a significant component of the wave climate in the Middle Atlantic and New England States. Those involved in coastal engineering in these areas need to consider hurricane wave information at the site of interest. The wave height and period information from historic storms is a critical element in structural designs that need to withstand these storms and in determining flood protection.

2. Measured data would be the most logical source of hurricane wave information, but most measuring devices are damaged or destroyed by the storms making field data scarce. An alternative method of providing wave information is use of a numerical wave hindcast model. Spectral and wave height comparisons between available field measurements and hindcast data show this method agrees to within ±10 percent for wave height and ±15 percent for wave period. The hindcast values can be used to compile extremal statistics for extreme wave conditions at all specified coastal locations. The numerical wave hindcast model uses wind as input and calculates the waves created by the physical interaction of the wind with the water. Wind-generated surge is not included, and computations are done on the mean-low-water datum.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

3. The Wave Information Study (WIS) was established to create a data base of wave information for the coasts of the United States. Twenty years of continuous wave data are available at coastal locations for the period from 1956-1975. The wave information excluded tropical storm generated waves. The hurricane weather systems with their large pressure gradients and changes in wind direction over relatively small areas create special problems when a wave hindcast model is being used. It was decided to hindcast hurricanes separately and use a model that could represent the dynamics of these complex wind systems. This report discusses how the hurricane wave information and wave statistics were compiled for the hindcast period. The Atlantic and gulf coasts were completed first because most hurricanes occur there. A study is underway to add the Pacific hurricanes to the same data base. Data were saved for the same stations used in the WIS Atlantic Phase II hindcast and in the WIS gulf hindcast. Figure 1 shows the Atlantic grid that was used. Figure 2

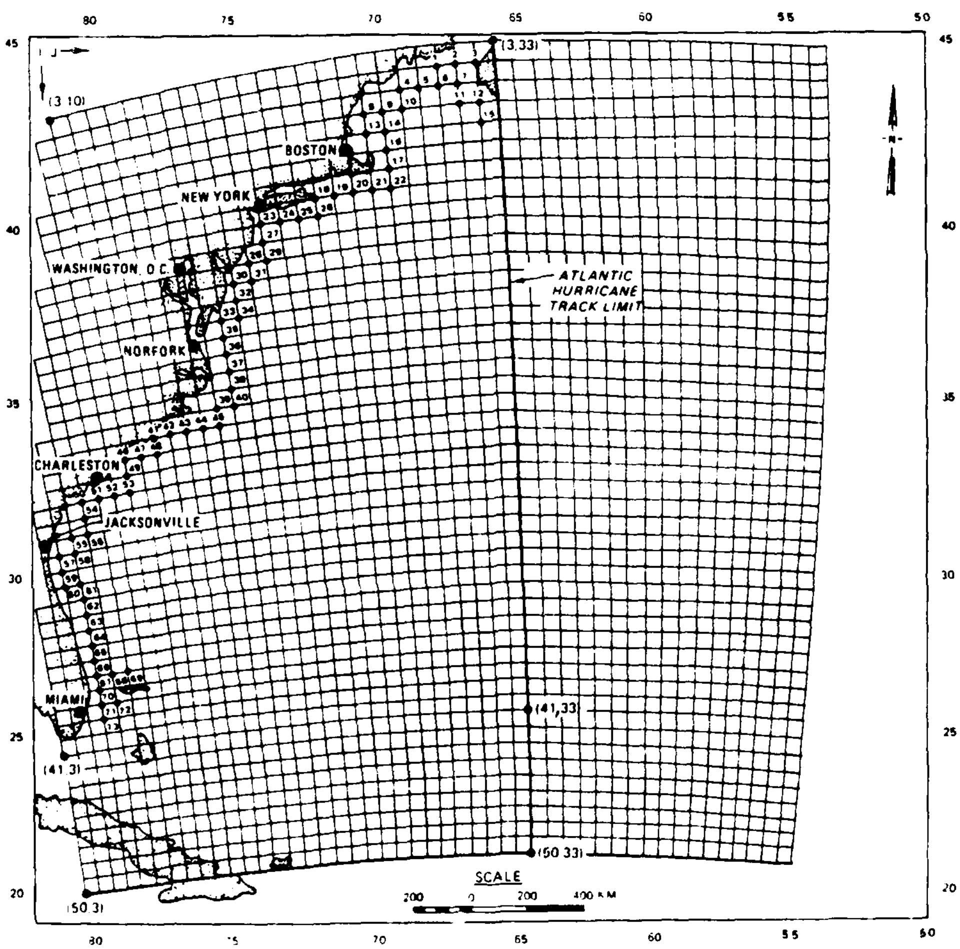



Figure 1. Numerical grid on which the Atlantic hurricanes were hindcast. Locations at which data are available are indicated by numbers along the coastline

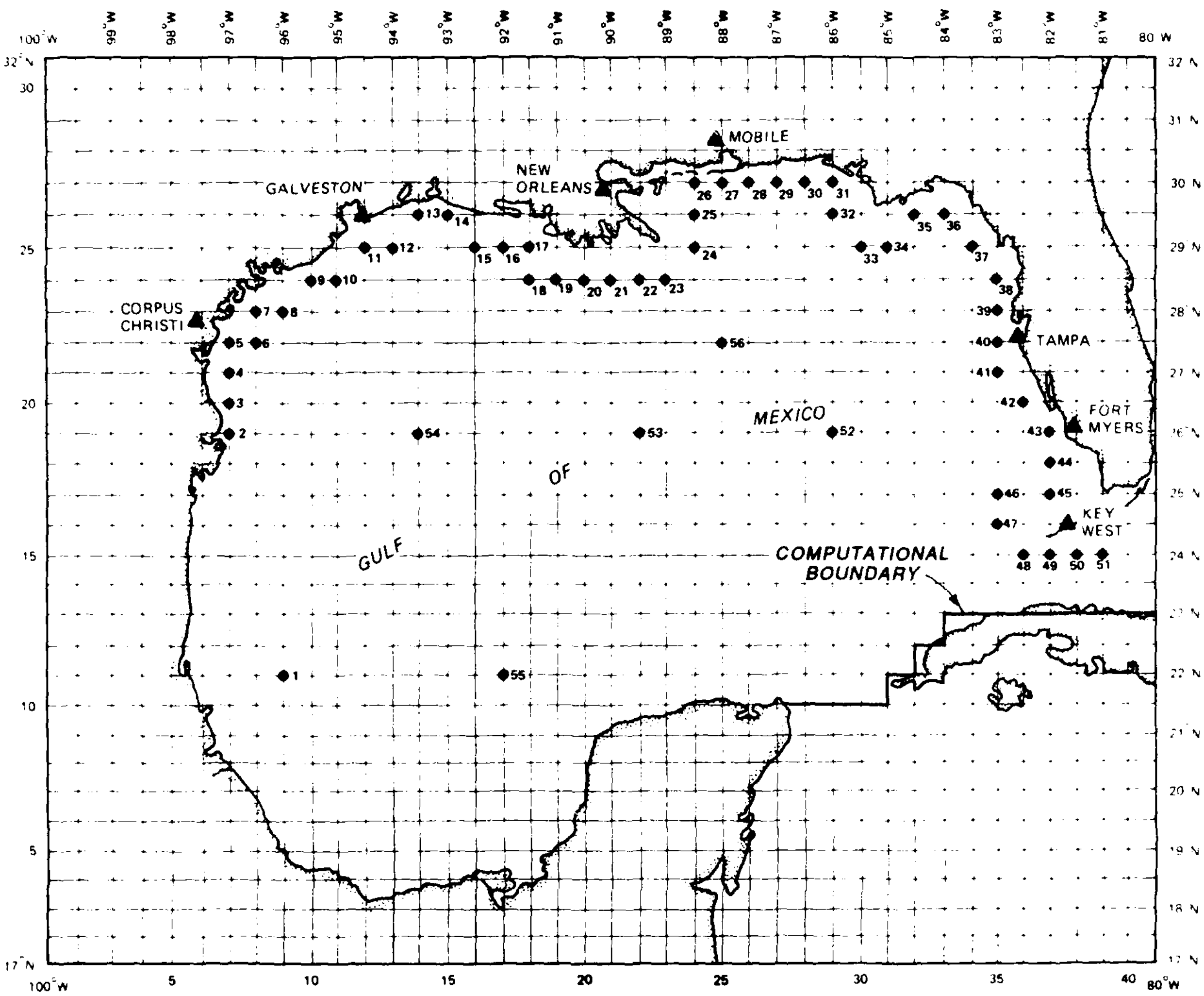



Figure 2. Numerical grid on which gulf hurricanes were hindcast. Locations at which data are available are indicated by numbers along the coastline

shows the gulf grid. Appendix C lists the latitude, longitude, and depths of the Atlantic and gulf stations where data have been saved.

## Storm Selection

4. The period from 1956-1975 was selected to correspond to the hindcast period used in the previous WIS Atlantic and gulf hindcasts. Figure 3 shows a histogram of all the hurricanes for the North Atlantic from 1900-1975. An analysis of the number of storms per year shows that the 75-year data set averages 4.7 storms per year and the 1956-1975 subset averages 5.3 storms per year. In both the full data set and the 20-year subset, the mode of the

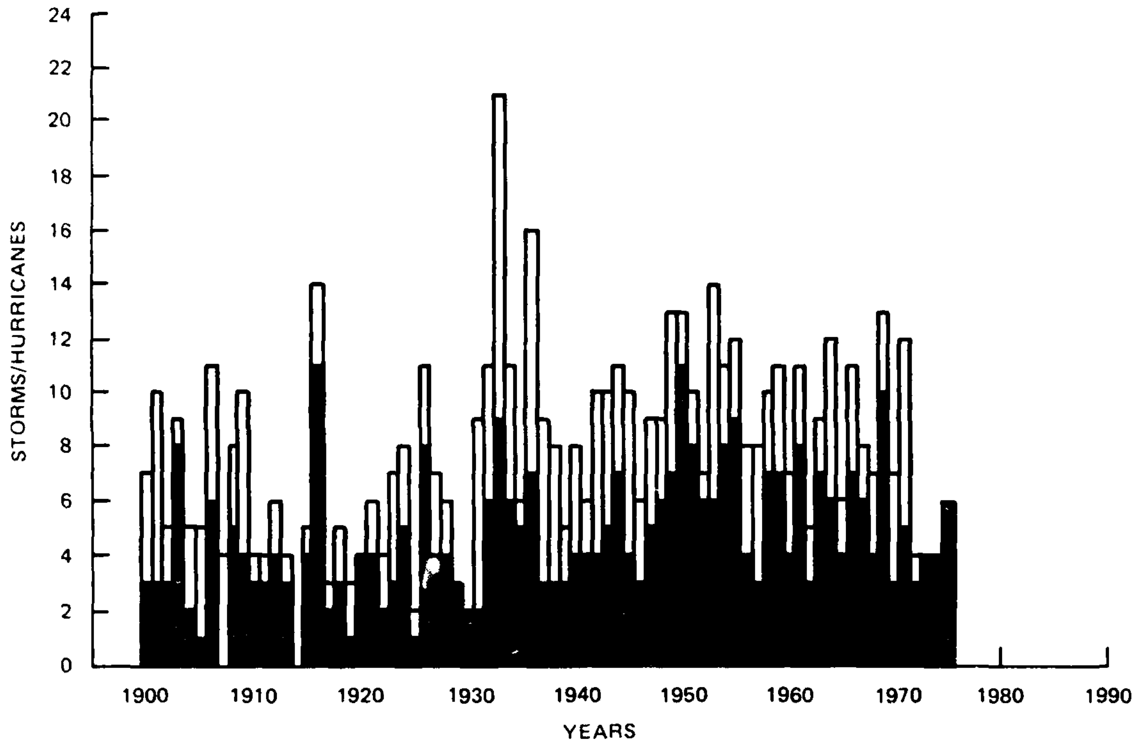



Figure 3. Occurrence of hurricanes (shaded) and tropical storms (unshaded) for the period 1900-1976

number of storms per year falls between four and five. The average of lowest pressures for the storms listed in "NWS Climatology for the Atlantic and Pacific Coasts of the United States" (National Weather Service (NWS) 1987) for the period 1900-1974 is 964 mb. The average for the period from 1956-1974 is 965 mb. These two values indicate that the severity of the storms in the smaller data set corresponds to the severity of the storms in the whole data base.

5. Storm selection was limited to storms that met two criteria. The storm was required to reach hurricane strength and have a track in the following specified areas. The gulf storms were required to have their tracks in the Gulf of Mexico and to have some effect on the US gulf coast. The Atlantic storms were required to have a track crossing into the WIS Atlantic Phase II hindcast grid (Figure 1). Atlantic storms outside this area were not considered since they did not strongly influence the coast of the United States. One tropical storm was included in the Atlantic hindcast because of its unusual looped track and possible influence on the coastline. Figure 4 shows the superimposed tracks of the hurricanes that were included in the hindcast in the Atlantic and gulf. Some gulf coast areas have not had a

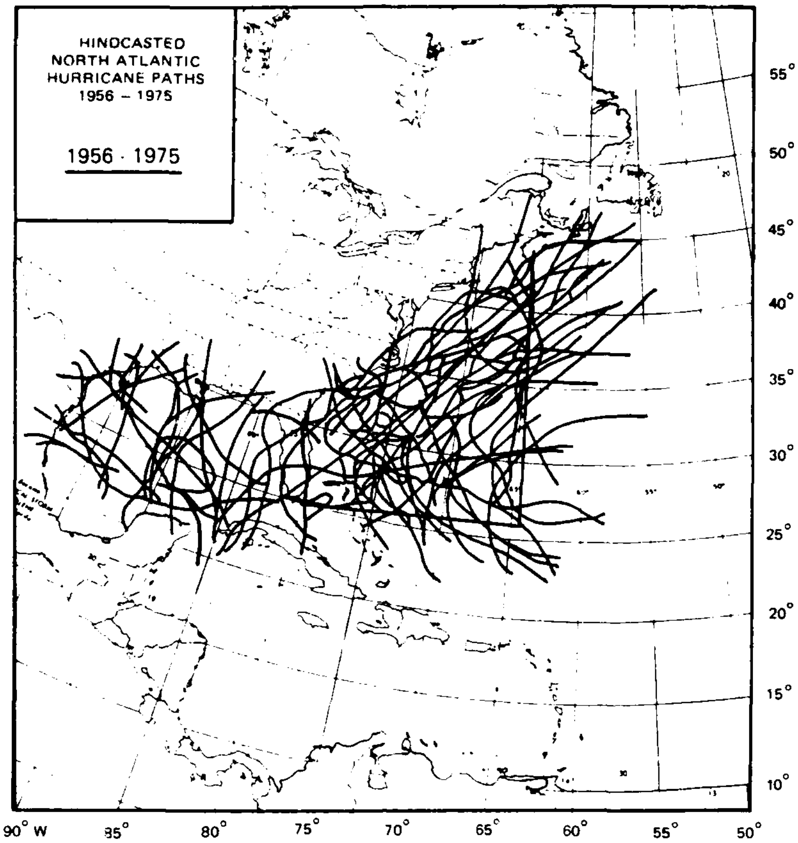



Figure 4. Tracks of hurricanes hindcast in the Atlantic and Gulf of Mexico

direct hit during the 1956-1975 period. The Florida peninsula is vulnerable for both Atlantic or gulf storms and has many storms that move from the Atlantic to the gulf and vice versa. A storm that existed in both the Atlantic and the gulf will have the Atlantic portion of its track hindcast with the Atlantic storm and the gulf portion of its track hindcast separately as gulf storm. Tables 1 and 2 list information on all the hurricanes hindcast for the Atlantic and gulf respectively. Hurricanes are listed by number, name, and a year-month identifier. Many times the severity of a hurricane is measured by the damage it produces. Table 3 gives a list of the top-ranking storms in relation to damage caused. The monthly Weather Review provides storm tracks and details associated with individual storms.

## Wind Hindcast Method

6. The primary input for an ocean wave hindcast involving hurricane waves is an accurate representation of the hurricane wind field. A model was

developed that uses the meteorological storm parameters available from past hurricanes to calculate the surface stress and the wind vectors in the planetary boundary layer (PBL) of a tropical cyclone. Storm parameters consist of information about the storm's speed and direction of movement, the pressure in the storm's eye and at the edge of the storm, the size of the storm, the distance from the eye's center to where the maximum winds occur, and any information on atmospheric steering currents. This report will not deal with the mechanisms for the inception and growth of a hurricane; Ooyama (1969) provides background material on that subject. Models that create a hurricane wind field need to account for the complex flow patterns in the atmosphere close to the Earth's surface that are associated with these storms. One of these is discussed next.

7. The hurricane wind model used in this study is a modification by Cardone of Chow's (1971) vortex model. Chow's model gave a good qualitative description of the PBL's wind field, but some modification was needed to produce good agreement between numerically created wind and actual hurricane wind data. The Cardone model contains an efficient numerical scheme to solve the equation of horizontal motion vertically averaged through the depth of the PBL. Chow's model is capable of providing a solution for the high-resolution grid needed for a hurricane's wind field and gives emphasis to the physical boundary layer flow mechanisms that contribute to hurricane development. The equations of motion are solved for a moving tropical cyclone using a fixed pressure field in the boundary layer. A nested grid system (Figure 5) with spacings on the order of 5 km in the central grid near the hurricane center is used. It is assumed that vertical advection of momentum can be neglected because it is small compared with horizontal advection, and shearing stress is assumed to vanish at the top of the PBL. Pressure is defined as the sum of the large-scale pressure field representing a constant geostrophic flow and a pressure field represerting the tropical cyclone. The storm pressure field is not necessarily axisymmetric and moves at a specified speed. The equations of motion are solved, and the wind-field solution is completed by specifying values for the drag coefficient, the horizontal eddy viscosity coefficient, and the boundary conditions at the outermost grid boundary. The outermost boundary is assumed to be a balance between the Coriolis force, the pressure gradient force, and the surface frictional force. The solution uses a finite difference formulation. The computational scheme is discussed in Chow (1971).

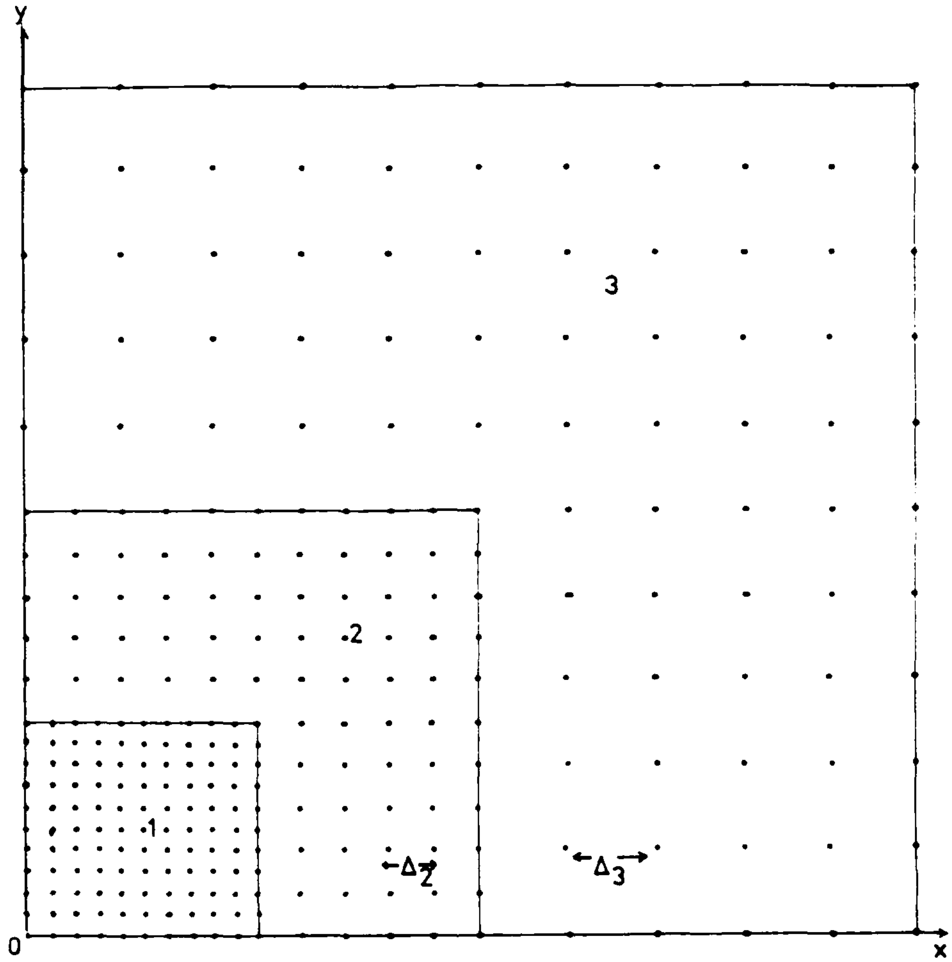



Figure 5. Schematic of the variable spacing, moving grid system of the wind model. Only the intermost three meshes are shown

Diagonal and ordinary upstream differencing was used for the spatial derivatives, and the computational grid consisted of a series of nested rectangular grids, each with constant grid spacing. If the innermost grid has a spacing of 5 km, the others are 10, 20, 40, and 80 km, and the grid covers 1,600 by 1,600 km using a 21 by 21 grid. The computation scheme begins with a set of wind components computed from the storm's pressure field. The time-related components are integrated forward in time at each grid point until the acceleration is small. Chow concluded that friction and storm motion seem to combine nonlinearly to produce a strongly asymmetric inflow pattern. Storm motion seems to be responsible for the front-back asymmetry in wind speed, and the asymmetric pressure field is responsible for the left-right asymmetry in wind speed. Myers and Malkin (1961) deduced these same characteristics from their work using similar vector equations of motion.

8. Cardone's initial modification of Chow's scheme allowed more specific information on each storm as input. The previous input variables were pressure change, radius of maximum winds, storm velocity, and the ambient geostrophic pressure gradient (steering flow). The angle between the storm track and the steering flow was added, as was an option to specify the pressure change and radius of maximum winds by storm quadrant that allows up to 11 input parameters. Storm track latitude and longitude along with the previously mentioned parameters and a PBL depth of 650 m provide the model's numerical description of the hurricane. Aircraft measurements reported by Moss and Rosenthal (1975) support a PBL depth of 650 m rather than the 1 or 2 km used previously.

9. Two shortcomings of Chow's formulation were his assumption that the height of the boundary layer was 1 or 2 km and his use of a drag coefficient that depended linearly on the wind speed. Research and field observations on hurricanes have led to the conclusion that the PBL is on the order of 500 m and has a variable height at any given time; this height is dependent on the stage of the storm's development. Deardoff (1972) developed the PBL fluxes of momentum, heat, and moisture as functions of layer-averaged mean PBL properties. Cardone adopted Arya's (1977) updated parameterization of Deardoff's work. Equations are solved for the horizontal wind components in the direction of surface shear and perpendicular to it. Input values to solve for these components included the mean layer virtual potential temperature, the specific humidity, a roughness parameter that has been normalized by the PBL height, and a potential temperature scale function expressed in terms of heat flux. The PBL height is used as an independent variable, and various similarity constants are calculated (Arya 1977) for stable and unstable conditions using wind speed and the potential temperature input values as stability indicators. When a hurricane exists in near-neutral conditions, the constants are determined by linear interpolation between the stable and unstable value. The drag coefficient was computed using the PBL height, roughness parameter, and the potential temperature variable and was computed differently depending on the land or water roughness conditions. To avoid using an iterative scheme to solve for the roughness parameter, boundary height, and wind speed, the temperature difference over water and the boundary layer height were considered to be invariant over the storm area. These assumptions seem valid even near

the coast. Values can be calculated once for a given storm state and saved in tabular form.

10. The best test of accuracy of the computed wind field is to compare the results with actual data. Much hurricane data are lost because instruments cannot withstand the force of the storm, but some data are available; therefore comparisons can be made. Cardone, Pierson, and Ward (1976) and Cardone, Ross, and Ahrens (1977) conducted tests on evaluation of the constants to be used in their parameterization by using the wind data available from an oil rig directly in the path of Hurricane Camille. Their formulation was set up to recreate the hurricane wind field as accurately as possible. Their results were verified, as was the accuracy of the computer code. Figures 6 through 9 show plots of actual observations with the computer simulation results. Hurricanes Camille, Belle, Delia, and Anita are shown. These hurricanes represent different severities as well as both the Atlantic and gulf storms. The model results show a smoother growth pattern than the observed winds. The large grid spacing and the need for a smooth solution to the physical equations produce a smoother growth pattern than would be

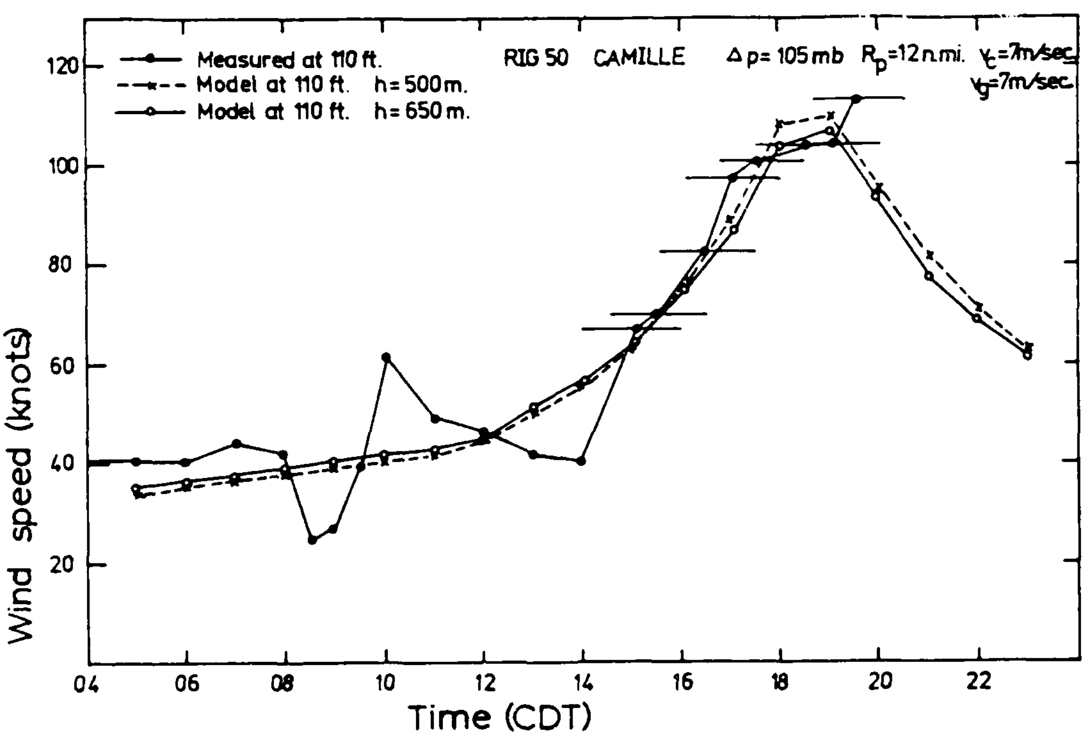



Figure 6. Comparison of measured and modeled wind speed during Hurricane Camille, 17 August 1969. Site is near the Mississippi River delta at Southwest Pass

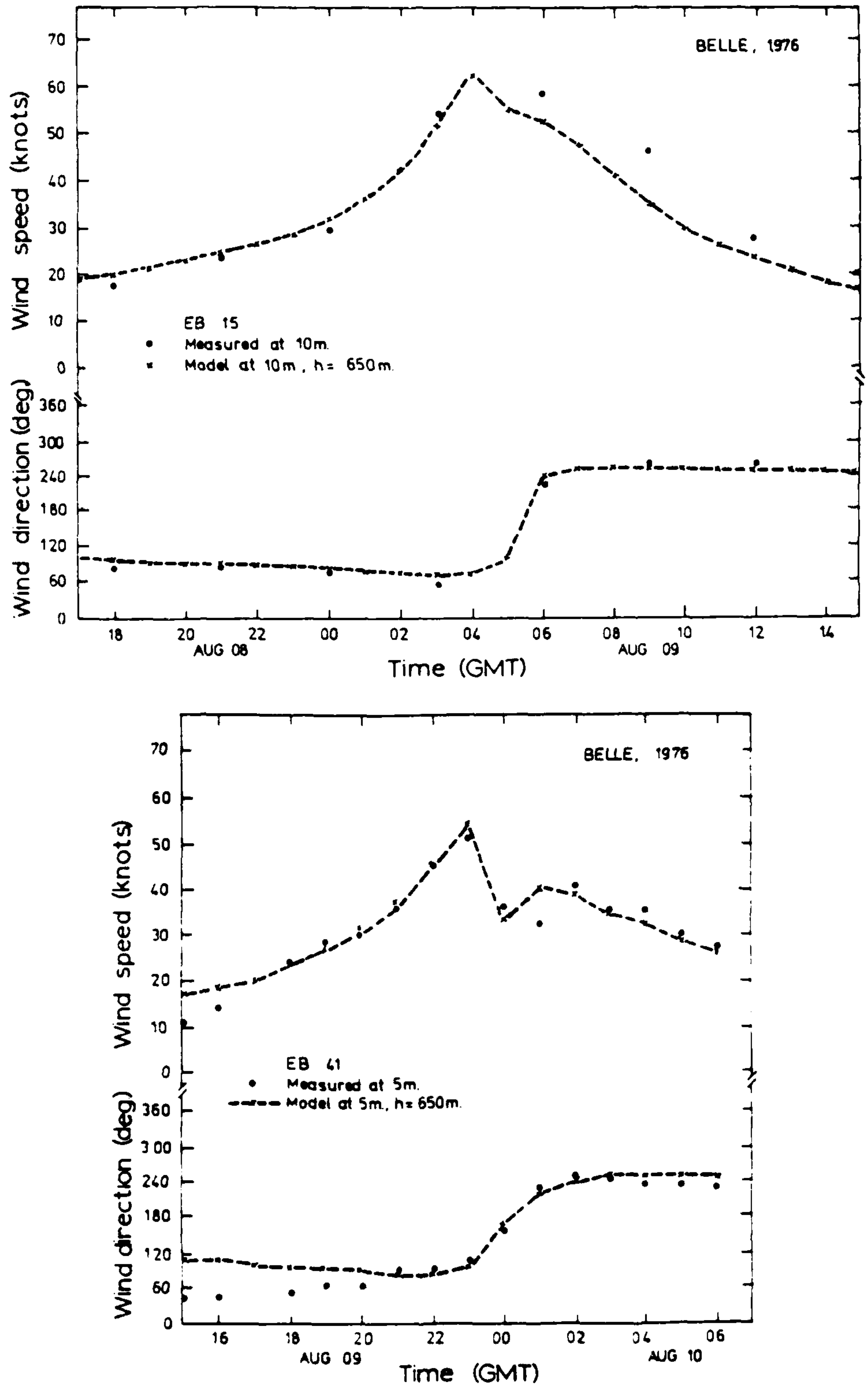
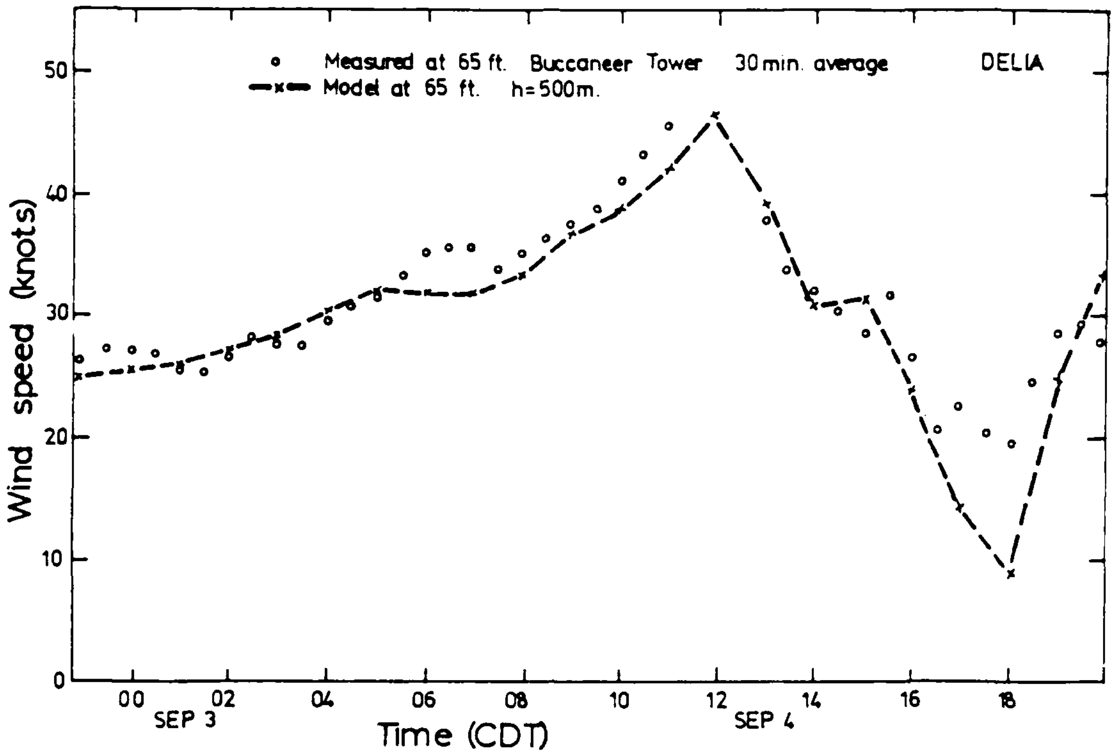



Figure 7. Comparison of measured and modeled wind speed and direction during Hurricane Belle, August 1976. Measurements are from buoys EB15 and EB41 offshore of South Carolina and New Jersey respectively



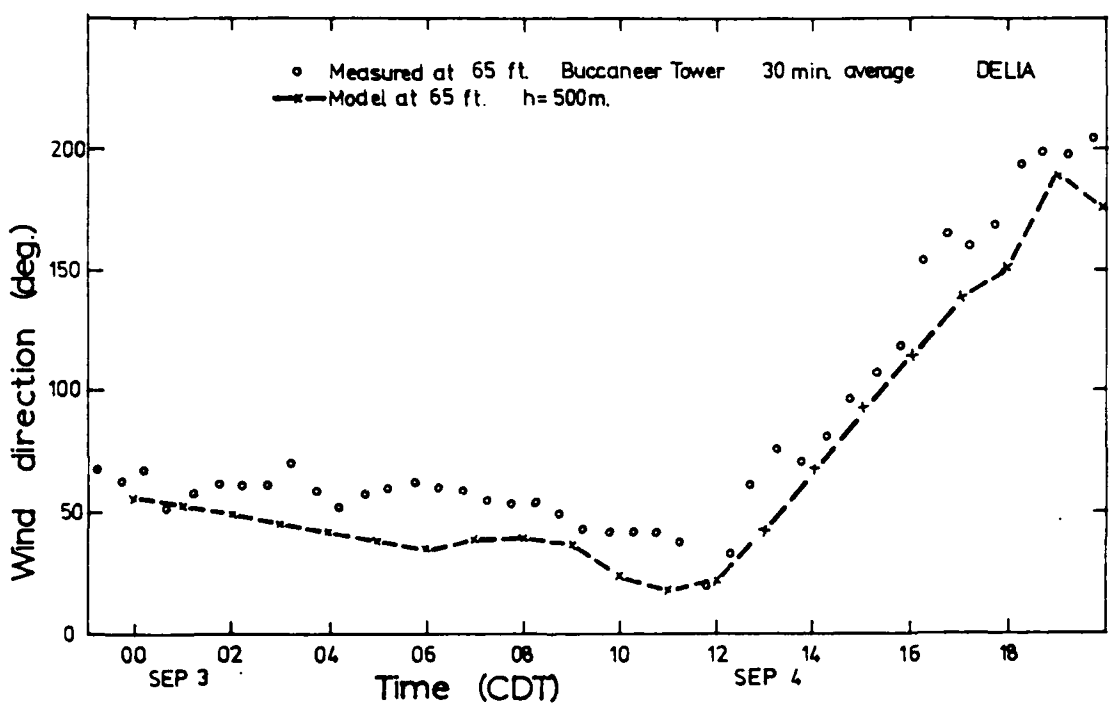




Figure 8. Comparison of measured and modeled wind speed and direction during Hurricane Delia, September 1973. Site is south of Texas-Louisiana border

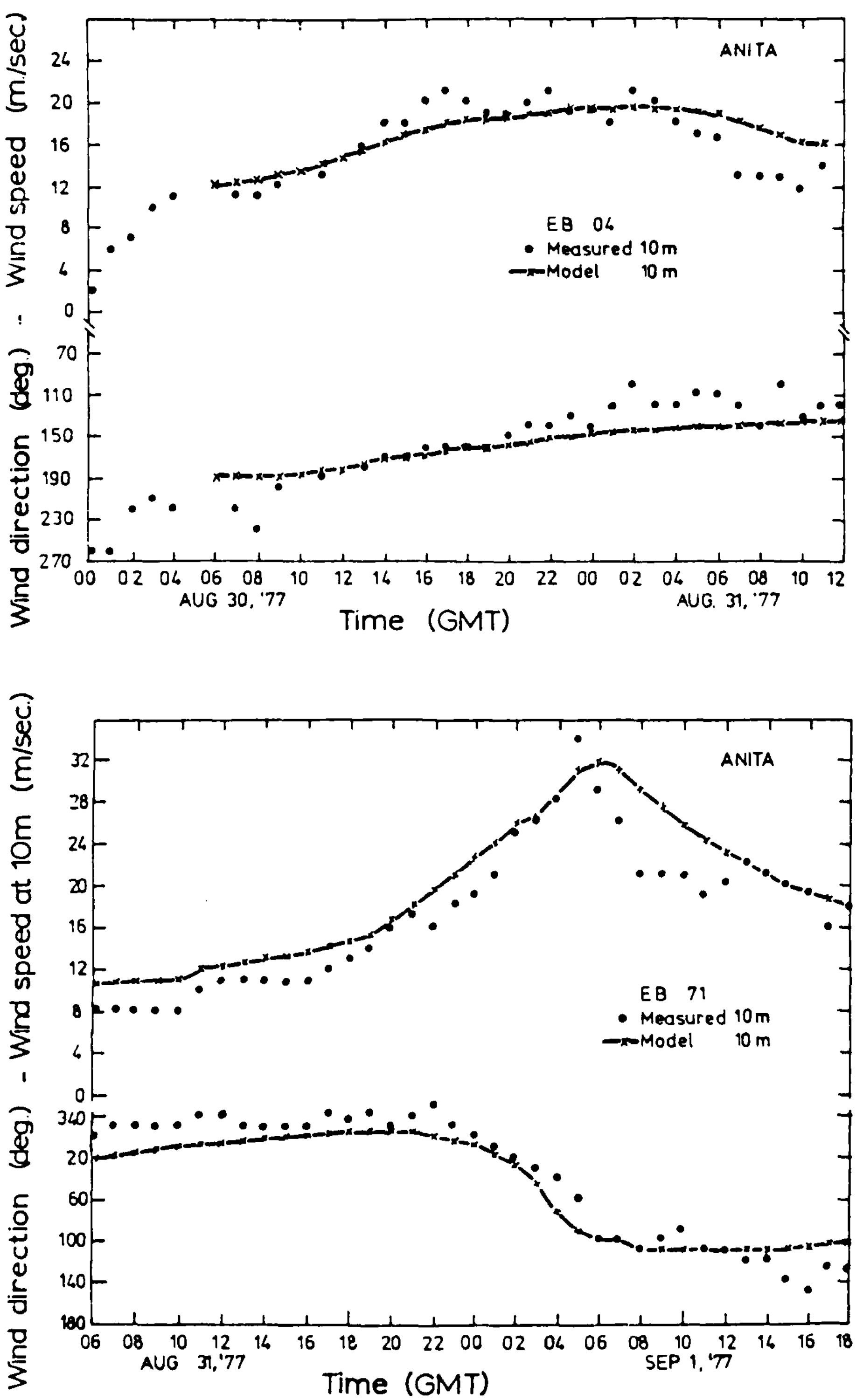



Figure 9. Comparison of measured and modeled wind speed and direction during Hurricane Anita, August-September 1977. Measurements are from ocean data buoys EB04 and EB71 in the northwest Gulf of Mexico and off the central Texas coast respectively

measured. The computer simulation will not allow for small local changes between grid points and cannot reproduce surface features that may vary between grid points. The computer results seem to be quite representative of the actual measured conditions in that products are within ±5 knots of the observed wind. Figure 10 shows a vector plot of an output wind field. The size of the arrow is related to the speed at that point, and the size convention is defined by a set of arrows on the plot. Direction is shown by the orientation of the arrow in polar coordinates. The grid intersections in Figure 10 correspond to the grid shown in Figure 2. Many of the physical interactions in the boundary layer cannot be totally defined by an analytical scheme, and many of the assumptions made about the storm cause slight inaccuracies. Models will continue to be developed that can describe these complexities with an efficient scheme, and future work will attempt to use new formulations that model conditions more realistically.

11. Hurricane winds are generated using two main computer programs: SNAP and HIST. Blending and analysis programs were added to the system after the major calculations were made to provide diagnostic evaluation. SNAP

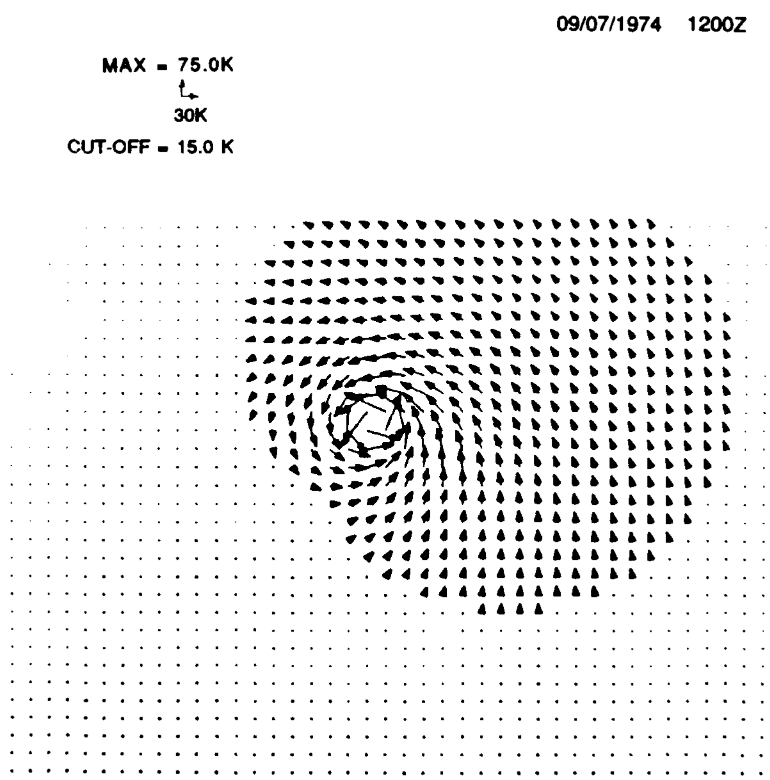



Figure 10. Schematic illustration of winds during Hurricane Carmen. Maximum speed is 75 knots, and no vectors are shown for speeds below 15 knots

produces wind snapshots from preliminary information on the hurricane. A system of nested grids is set up to provide finer resolution along the path of the hurricane. Input to this program includes hurricane parameters at various times during the simulation of the storm. The input data set for hurricane 5910 is given as an example in Figure 11, which shows four separate readings of surface geostrophic wind (SGW), direction of SGW, latitude of the eye, direction of the track, forward speed of the storm, pressure at the eye of the storm, exponential pressure profile scale radius in four quadrants, far-field pressure, and the grid spacing of the innermost nest. Each data set corresponds to a specific time in the storm's development. The PBL equations are solved using these input values for each snapshot. Various constants pertinent to boundary layer calculations are set in the program with the boundary layer height over water normally 500 m. The origin of the coordinate system is at the storm center of the first snapshot. A fine grid is set up as shown in Figure 5. This grid actually represents the first of four quadrants of the storm. This can be thought of as the section of the storm from 0 to 90 deg in polar coordinates. If the storm is considered to be symmetric, this quadrant's information can be used to produce the symmetric cyclonic wind vectors

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       SGW=       10., AN1=      220.  &END
```

Figure 11. Example of data input to the wind program that provides a snapshot of wind conditions

in the other three quadrants. Five nests are used in the SNAP program with grid spacing of 10, 20, 40, 80, and 160 km for each 21 by 21 grid. Ten km was typically used as the finest grid spacing. Some storms that needed a finer mesh in the interior used a grid spacing of 5 km. After the storm solutions are available as a set of snapshots, program HIST does spatial and temporal interpolation to transfer the PBL winds to arbitrary points on an earth-bound coordinate system. Input to this program is shown in Figure 12. A latitude and longitude for each hour of the storm simulation is given in this data file and related to the proper snapshot in the first data set. The final output consists of a wind vector field over the entire grid used in the wave hindcast model.

12. Storm parameters for the above set of computer programs are not readily available. Selection of the input data required examination of the surface pressure charts along with reports of maximum wind speeds to determine a set of representative stages in the storm's evolution. The pressure fields were also analyzed to determine peripheral pressure and steering flow. Storm tracks were analyzed to determine track heading and forward speed at each snapshot position. All available data sources were used to obtain the sea surface temperatures in the vicinity of the storm center. The boundary layer depth is considered to be 500 to 650 m, corresponding to maximum intensity storms. The HIST data require analysis of the storm tracks to determine the track position for each hour of storm simulation and a determination of the direction of the forward motion relative to the snapshot orientation.

## Wave Hindcast Method

13. The WIS used a shallow-water spectral hindcast model (Jensen, Vincent, and Abel 1987) for a 20-year wave hindcast in the Gulf of Mexico. This model uses a discrete matrix consisting of frequency and direction components of the energy at each water point of the grid. It models the sources and sinks in the energy balance equation with several of the functions being represented in a parametric sense. It was modified for this study to account for the rapidly turning winds present in a hurricane. Appendix D provides results compared with actual data for the storms that were used for verification.

14. Input to the wave hindcast model consists of a land-sea grid. A

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  28  40  72  24   2   3  0.1667   0   0
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  29  13  70  36   2   3  0.4167   0   0
  29  24  70   0   2   3  0.5000   0   0
  29  33  69  24   2   3  0.5833   0   0
  29  42  68  48   2   3  0.6667   0   0
  29  51  68  12   2   3  0.7500   0   0
  30   0  67  36   2   3  0.8333   0   0
  30   9  67   0   2   3  0.9167   0   0
  30  18  66  24   3   0  0.0000   0   0
  30  24  65  49   3   4  0.0833   0   0
  30  30  65  11   3   4  0.1667   0   0
  30  36  64  39   3   4  0.2500   0   0
  30  42  64   4   3   4  0.3333   0   0
  30  48  63  29   3   4  0.4167   0   0
  30  54  62  54   3   4  0.5000   0   0
  30  54  62  31   3   4  0.5833   0   0
  30  54  62   8   3   4  0.6667   0   0
  30  54  61  45   3   4  0.7500   0   0
  30  54  61  22   3   4  0.8333   0   0
  30  54  60  59   3   4  0.9167   0   0
  30  54  60  36   4   0  0.0000   0   0
```

Figure 12. Example of data input to the wind program that provides the time-history of wind fields along the track of the storm

section of the grid east of the Florida peninsula was considered land to provide sheltering that the Bahama Islands provide for the eastern Florida coastline. The gulf grid contains only the Gulf of Mexico. The section south of Florida and Cuba was not modeled. The gulf was considered as a closed body of water. The model requires depths for all grid-point intersections since the equations used are dependent on the depth and refraction is simulated. Sixteen direction bands, each consisting of 22.5 deg, were used for computations. The discrete spectrum was composed of 15 equally spaced frequency bands from 0.04 to 0.18 Hz. The region above 0.18 Hz was considered a parametric region. In this region, the spectrum is represented by a Joint North Sea Wave Program (JONSWAP) type spectrum. The five JONSWAP parameters are retained and can be used to reconstruct the shape of the spectrum. The time-step was set at 1,800 sec. Wind input was available every hour and was interpolated to provide winds for every time-step. Model output consists of a spectral matrix and a sea parameter record for each output station for each hour of the simulation. The sea parameter record consists of a significant wave height; period and direction; a height, period, and direction for both the sea and swell components of the spectrum; values for alpha (the Phillips equilibrium constant); and the energy in the parametric region. Wind speed and direction are also saved. The sea parameter information is available in the WIS data base, "Sea-State Engineering Analysis System (SEAS)" (McAneny 1986) for all the Atlantic and gulf hurricanes that have been hindcast. Spectral data have been archived and are available but cannot be accessed using SEAS.

15. Information on the individual storms usually became available when the storm became a full-fledged hurricane. Many times, especially in the Atlantic, the storm had a long life as a tropical storm and had generated wave energy as observed in arrival of swell. In these cases, a "spin-up" period was added to the hindcast. This was less costly than developing a separate approach to modeling the more erratic prehurricane conditions. Many times the hurricane was allowed to remain at the starting point for 12 hr to set up a suitable chaotic sea situation before the storm was moved forward on its track. Several gulf storms with long tropical storm histories were treated to several hours of "spin-up" time.

16. The gulf and Atlantic hurricane hindcasting procedures were essentially the same. The gulf wind fields included the synoptic winds outside the region of influence of the hurricane, which were available from the gulf

20-year hindcast. The Atlantic wind fields did not include the synoptic winds since the hurricane study covered a different region from the Phase II Atlantic 20-year hindcast.

17. Available data for several storms were used to verify the accuracy of the full hindcast procedure. Appendix D provides comparisons of wave height and peak period for a number of storms. Based on these comparisons, it is concluded that the maximum heights predicted in the storms are typically within 10 percent and periods within 15 percent of measured values. The time-history of these parameters during passage of the eye of the storm appear to be equally good. However, at large distances from the storm, agreement should be less accurate because the influence of the hurricane wind field is less and the degree to which the vortex model represents the winds is more variable.

Hindcast products

18. Many displays using the data produced by the hindcast are available, and the data from each storm are also available. The sea parameters discussed previously are available in the SEAS data base at the US Army Engineer Waterways Experiment Station. Tables of hurricane information as shown previously in Tables 1 and 2 are available through the data base. Tables similar to Table 4 for Atlantic storm 7409 (Hurricane Carmen) have been created and are available for all storms through the SEAS data base. These tables describe the maximum wave height in metres and the corresponding period in seconds that occurred at each station during the represented storm. One table is available for each Atlantic or Gulf storm that has been hindcast. Storm names are in a four-digit numerical form as described in the information on Tables 1 and 2. SEAS requires an Atlantic or gulf prefix to access the data.

19. Wave vector plots were routinely done for each storm as a diagnostic tool during the hindcast procedure. Wave vectors describe the height and direction of the waves at each of the computational grid points. The maximum wave height over the entire grid for each date and time is listed on the plot. The sequence of vector plots for Gulf Hurricane Carmen (Figure 13) are shown every 12 hr beginning at noon on 5 September 1974 to midnight on 7 September 1974. Only water computational points are indicated on the wave vector plots. Waves 2 m and below were not plotted. These plots help to show a storm's movement and severity. They show the storm's evolution in terms of waves and may not show the time when the maximum wave height occurred if this time fell between the plotted times.

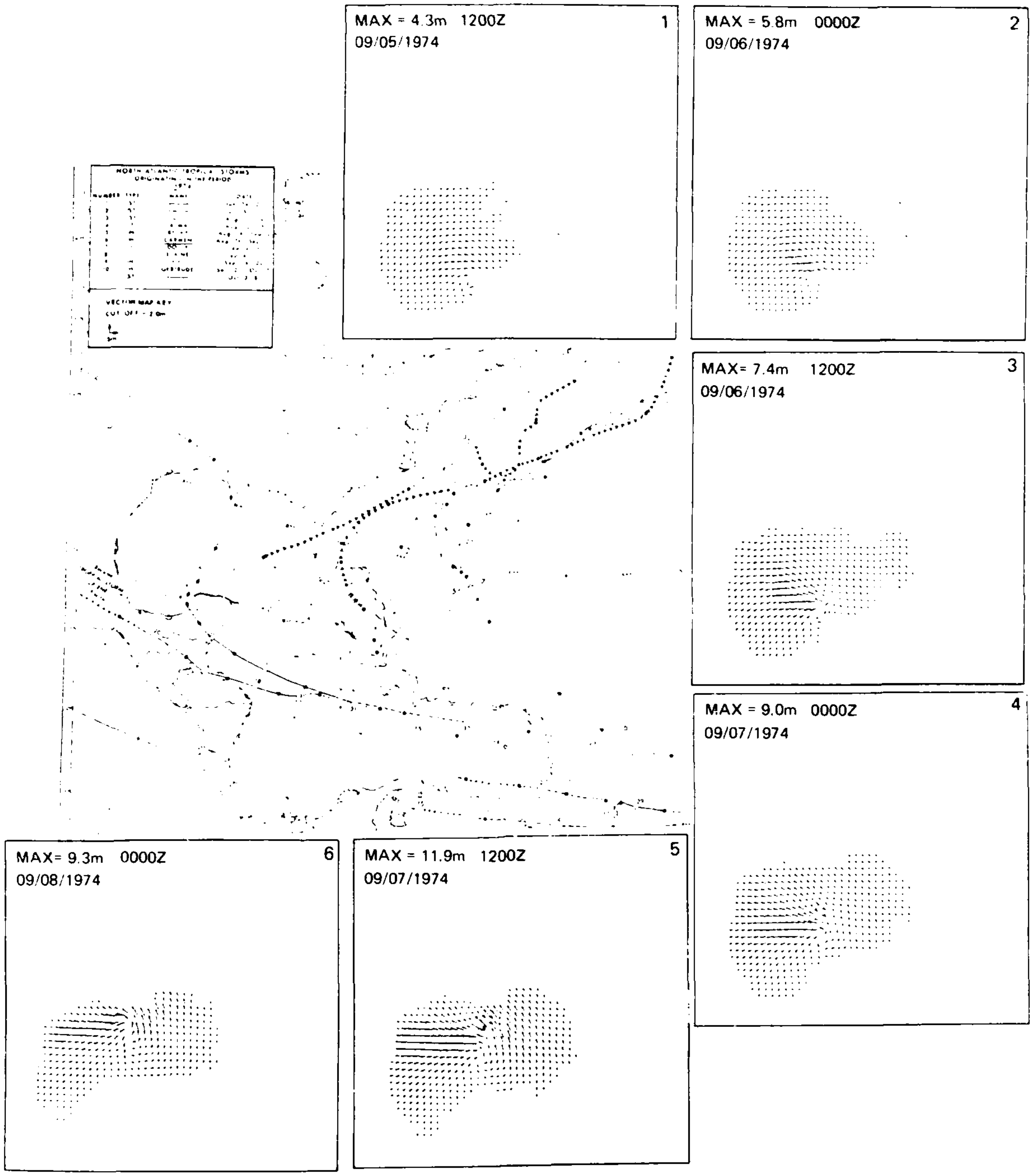



Figure 13. Schematic illustration of wave heights and directions for Hurricane Carmen. Wave heights below 2.0 m are not plotted

20. The maximum wave condition that occurred during the storm was saved. This information was retrieved from an archived file that output the significant wave height and period for all points of the grid for every time-step of the storm simulation. Figure 14 shows a contoured maximum wave height plot for Carmen. This contour plot has been placed on the grid that was used

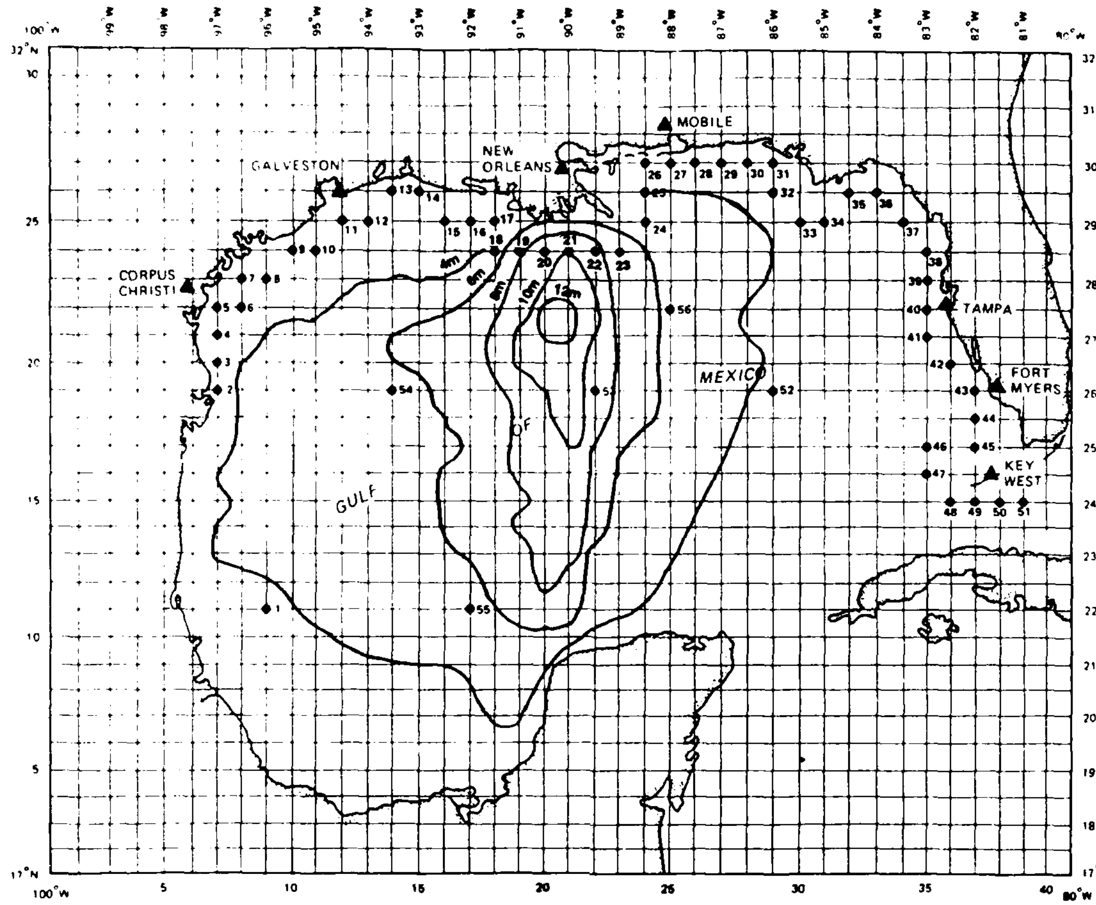



Figure 14. Contours of the maximum wave height present during passage of Hurricane Carmen

for the hindcast, and the output stations are shown. Note that Figure 14 represents maximum conditions for the entire storm at each of the computational points and is not indicative of a storm state at a given hour.

21. The lowest pressure that a hurricane attains and the maximum wave height produced by the storm provide an indication of the severity of the storm. These data are shown in Figure 15. All the storms included in the hindcast have been plotted. Gulf and Atlantic storms are noted separately. One regression line was calculated using the Atlantic storms, and a second regression line was calculated using the gulf data. The lines are so close that it is possible that all the data could have been treated as coming from the same population. These regression lines give an indication of the maximum wave height one could expect if a storm of known pressure was approaching a coastline.

Track analysis

22. A 20-year hindcast gives an idea how vulnerable a section of coast

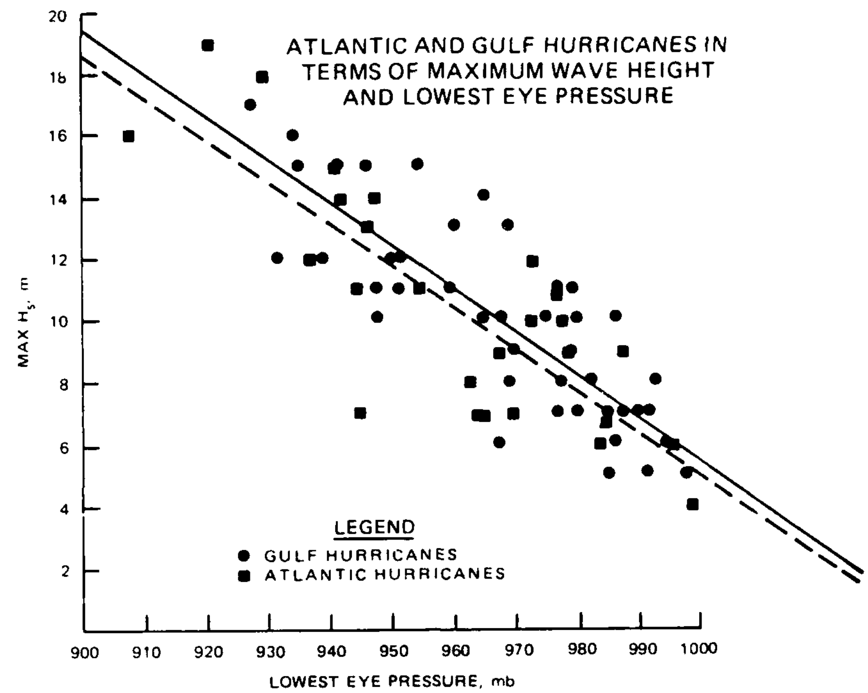



Figure 15. Maximum hindcast wave height versus lowest measured atmospheric pressure for all Gulf of Mexico and Atlantic hurricanes in this study

or open ocean can be by the amount of time a hurricane was actually present in the vicinity. This information is shown in Figure 16. Each grid cell is shaded to correspond to the actual number of hours a hurricane remained in the grid cell. Spin-up time was not included in determination of the number of hours. Only the hurricanes used in the hindcast were included in this figure. This represents a historical analysis of 1956-1975 and does not imply that grid cells devoid of hurricanes are immune from a major storm.

Statistical analysis

23. The 20-year data base of hurricane waves for the Atlantic and gulf provides a data set to analyze using extremal statistical techniques. The WIS Report 15 describes an approach used to create extremal statistics for the regular hindcast of the Atlantic Phase II data. This approach has been used to create extremal statistics for both the Pacific and gulf hindcasts. Storm history or track was not important to the extremal analysis. Only information on the maximum wave height that occurred at each station for each storm was needed. The statistical analysis began by ranking the maximum wave heights produced at each station for each storm. Wave heights under 3 m were discarded since it was assumed that this wave height indicated that this station

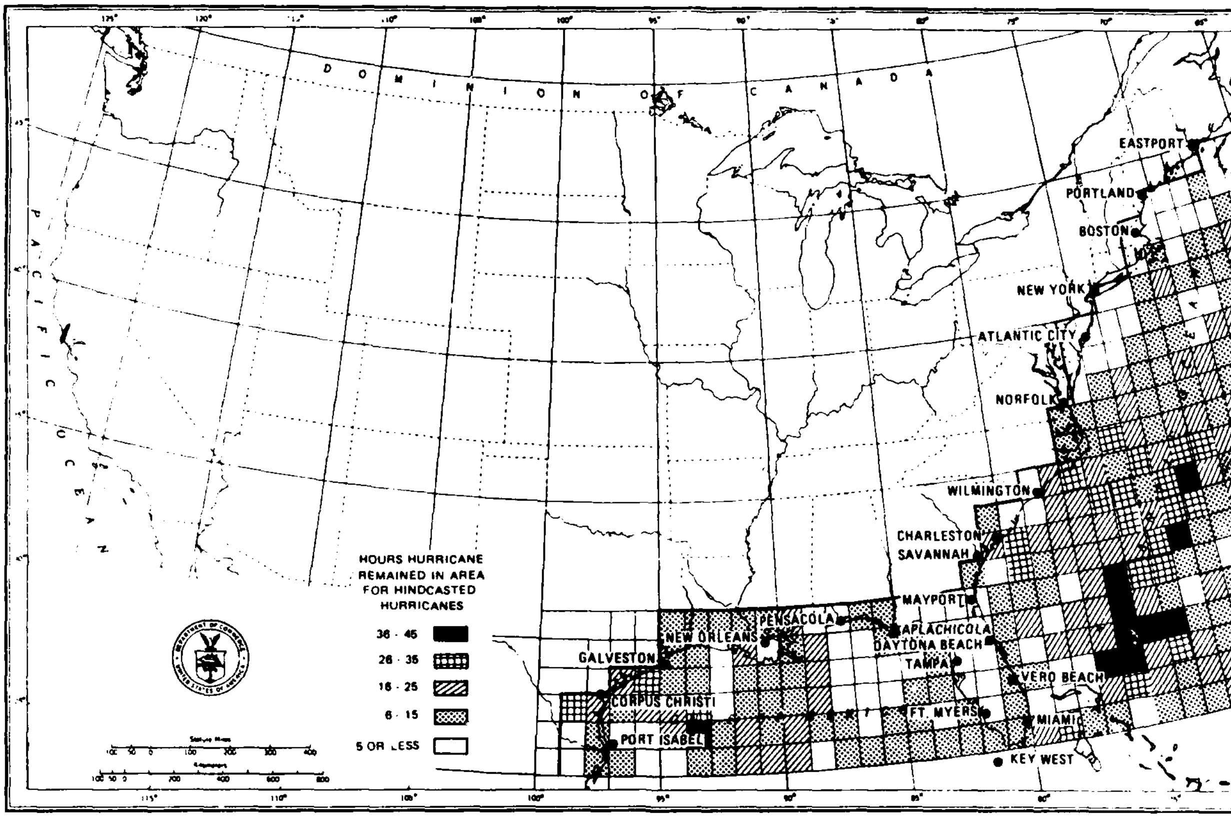



Figure 16. Duration of hurricanes on 1-deg latitude and longitude squares as modeled in this study

was not severely affected. A probability of k/(n + 1) was assigned to each of the ranked waves, where k is the sequential number in the set (1 to n), and k = n is the rank for the highest wave. This probability gives a numerical indication of the probability that this wave with rank equal to k is less than or equal to the wave height with rank equal to k . This probability function was set equal to a negative logarithmic function and analysis continued as discussed in Corson and Tracy (1985). The probability

$$FX(x) = EXP\ [-EXP - (ax + b)] \tag{1}$$

where the x variable is related to the wave height that determined the probability. The equation was evaluated by using the form:

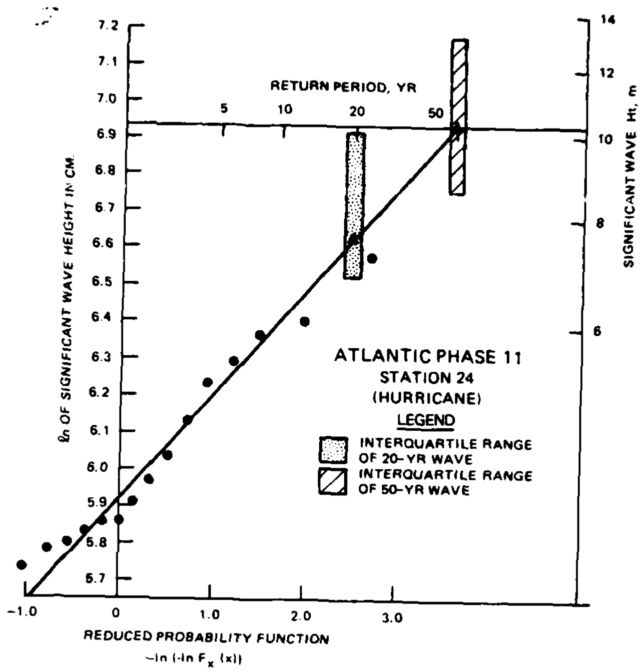
$$-LN\ [-LN\ FX\ (x)] = ax + b \tag{2}$$

Probability was used as the abscissa, and the ordinate was the natural log of the wave height. The extremal waves were analyzed for each station using the method of least squares to determine the linear relationship between the probability and the function of the wave height. This linear relationship can be extrapolated to determine a wave height associated with a higher probability. Assuming that the extreme wave heights make up a sequence of random variables, $x_{max}$ is the maximum of the sequence, and all the random variables have the same distribution function; the probability of the maximum wave of the sequence is equal to [Fx (x)] to the $n^{th}$ power where n is the number of extreme waves at that station. In order to extrapolate to an event beyond the 20-year data base, there should be 2.5 times the number of extreme waves in the 50-year data base. Solving for the probability fractile for the median 50-year wave height,

$$(0.5)^{(1/2.5\,n)} = FX(x) \tag{3}$$

The median value of 0.5 has replaced the probability of the maximum wave of the sequence (n is the number of extreme waves in the 20-year hindcast at the station being considered). Using the linear relationship between the probability and the wave height function, it is possible to pick a wave height to represent the median 50-year wave. Using the same development, a wave height can be associated with the 0.25 and the 0.75 fractiles to give a range of wave heights around the median. Fifty percent of all the 50-year extreme waves should fall within this range. The 20-, 10-, and 5-year waves and their respective interquartile ranges are developed using this same approach. Details of the statistical analysis can be found in Corson and Tracy (1985), and Borgman and Resio (1977). The 20-year data base allows extrapolation to an extremal wave statistic that gives an indication of what the expected 50-year wave might be. An interquartile range of wave heights is also given to show the range of this extremal wave. The 20-, 10-, and 5-year extremal waves and their respective interquartile ranges are given in Appendix A for the Atlantic waves and in Appendix B for the gulf waves. Wave heights were limited to 0.6 times the depth at that station, and when a wave extreme occurred that was larger than this limit, the limiting value was used and is indicated by (*) in the tables. Representative plots for stations in the Atlantic and the gulf are shown in Figures 17 and 18. These plots display the actual data that were used in the analysis. Linear regression was used to

Figure 17. Example plot of significant wave height versus return period for Atlantic Station 24



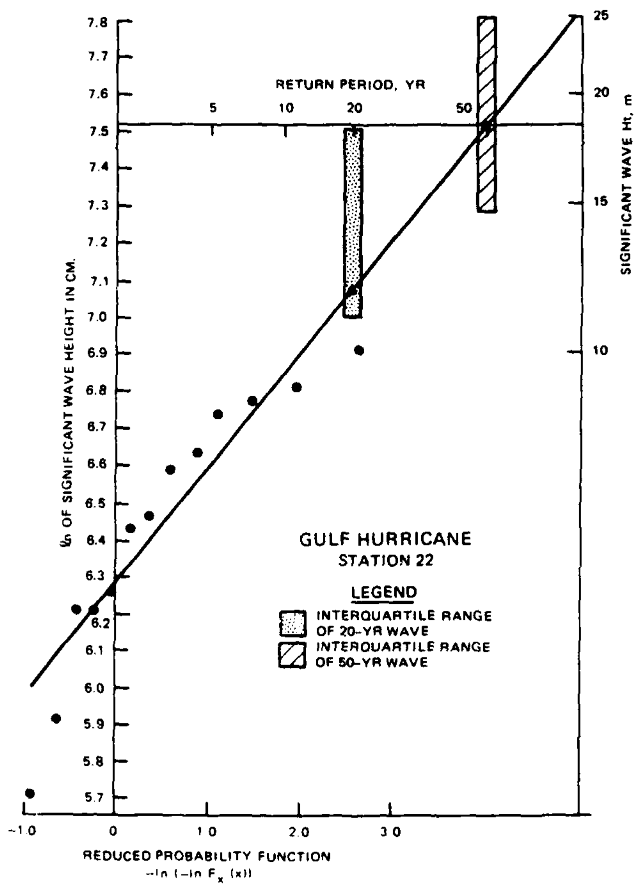




Figure 18. Example plot of significant wave height versus return period for Gulf Station 22

plot the straight line through the data. Interquartile ranges are shown using shading to indicate the range of each of the extreme waves. Stations that did not include enough waves over 3 m for analysis were not included in the extremal analysis. These stations usually represent areas where hurricane conditions are rare and hurricane extremal statistics do not make up the design wave for the area. Figure 19 contains a histogram of the extremal waves for the Atlantic stations. Figure 20 contains a similar histogram for the gulf stations.

Interpretation of results

24. The hindcast wave values and their extrapolation to extremes should be used with the following understanding of possible limitations:

a. The simulations were made on an approximately half-degree grid that is sufficient to define the broad details of the storm characteristics along the coast. Hence, the data should be used as an indication of the approximate order of magnitude of the storm for preliminary planning purposes.

b. The grid representation is not fine enough to resolve any details of the bathymetry or peculiarities of some sites (near capes for example). However, the data may be used to study sites using finer resolution grids. This is particularly important for land-falling storms. The increased resolution will account for effects of bathymetry on wave propagation and better resolve the regions of peak winds and waves.

c. The computations were made at a mean-low-water depth. Hurricanes almost always have surges associated with them that significantly alter the water levels nearshore. Nearshore calculations of the storm-surge levels for the individual storm should be made along with any further wave calculations nearshore. As an approximation, the wave conditions calculated here may be considered valid for the mean-low-water depth plus surge (that is if the water depth on which the calculations were made was 10 m and the storm surge was 2 m, the results may be interpreted at what would normally be the 8-m depth). This assumption is not valid if there is any significant curvature of topography or presence of a shoal or if the slope is very flat.

## Summary

25. This report describes the procedures for production of hurricane wave information and statistics for the Atlantic and gulf over the 20-year hindcast period. Both the wind and wave models represent state-of-the-art methods to hindcast winds and waves. The extremal statistics that were calculated from this data base represent the design wave statistics for the

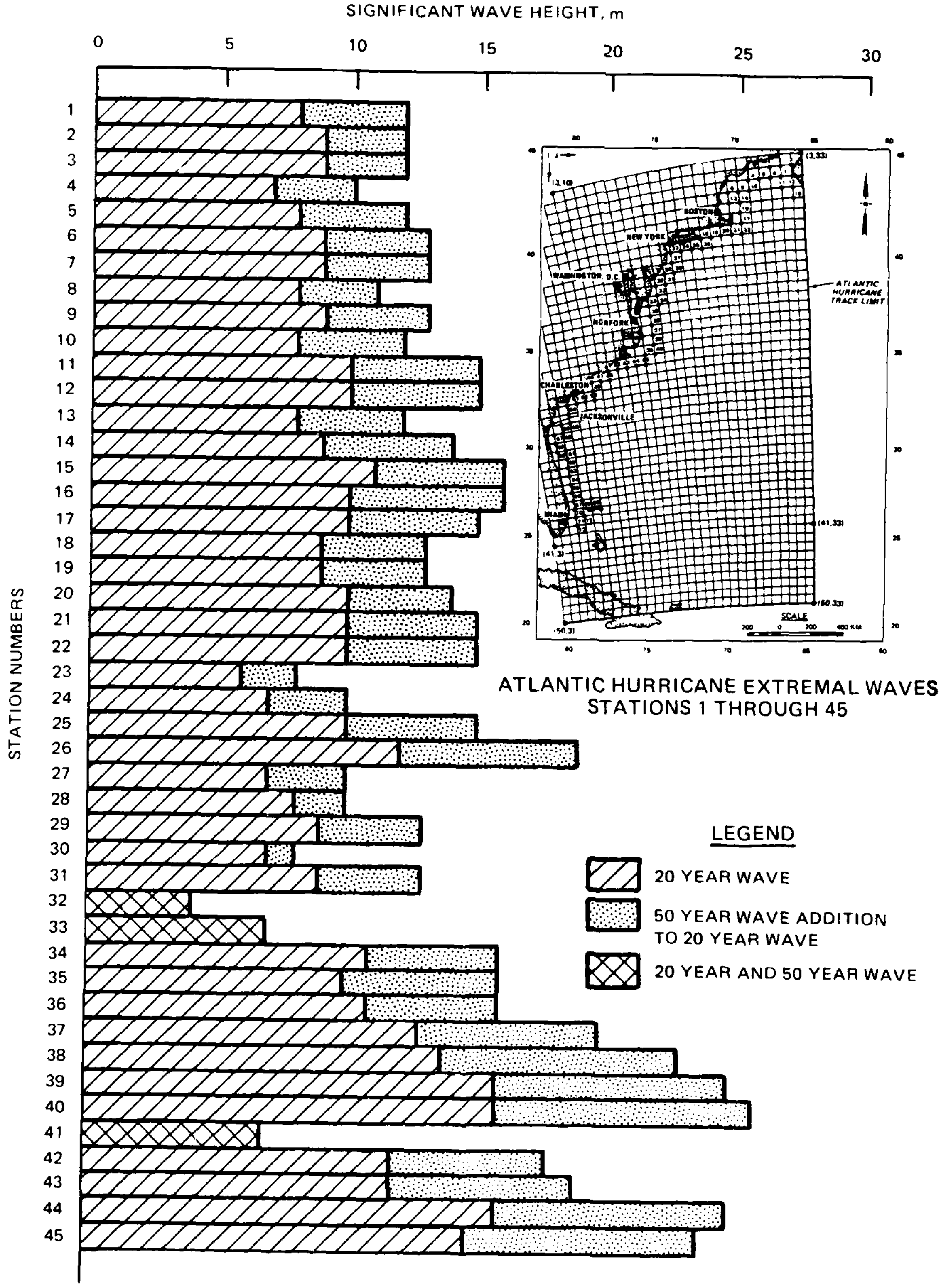



Figure 19. The 20- and 50-year significant wave heights for all Atlantic stations (Continued)

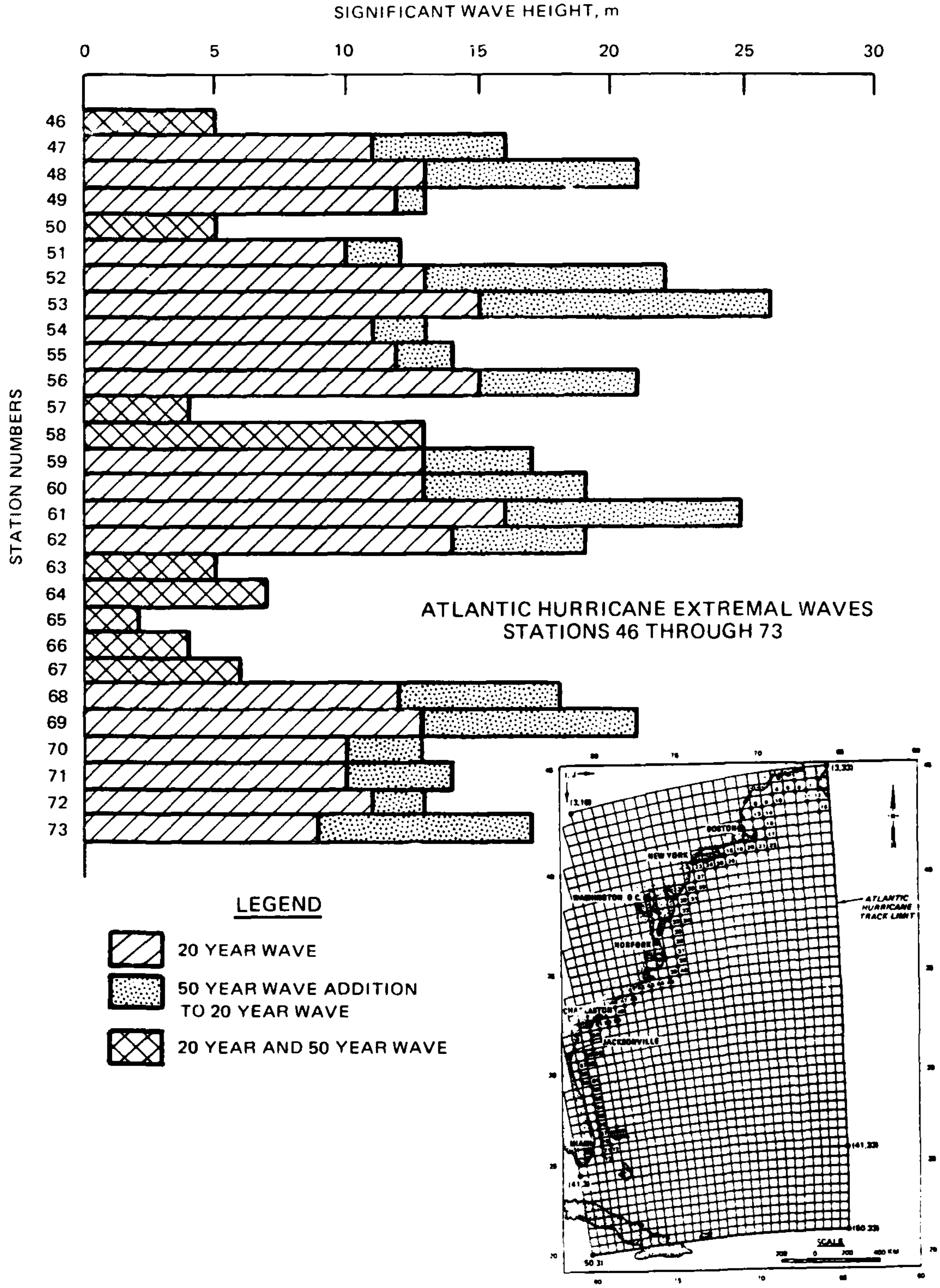



Figure 19. (Concluded)

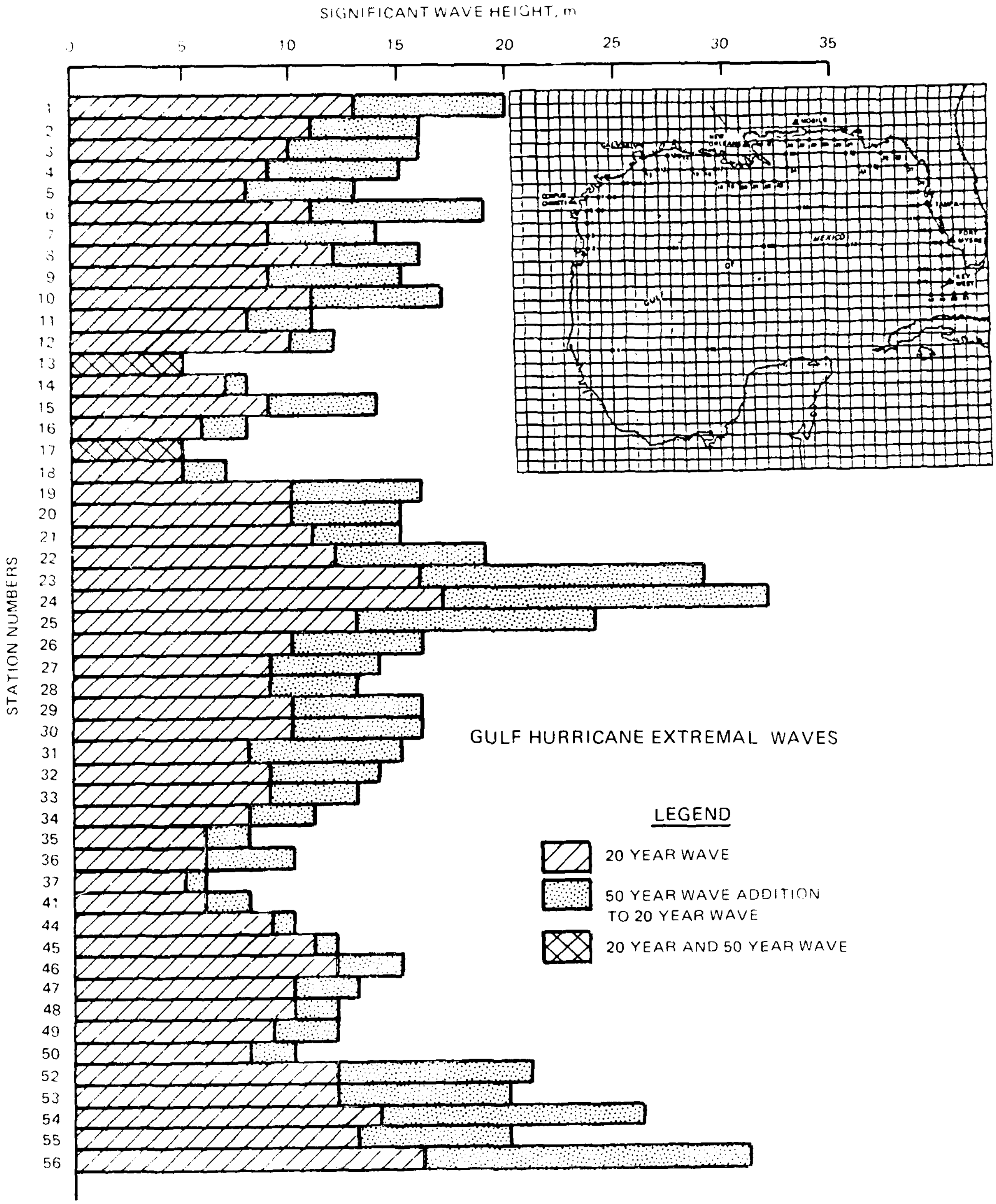



Figure 20. The 20- and 50-year wave heights for all gulf stations

Atlantic and gulf stations. This hindcast procedure and the data extracted from it provide a data base for the engineer who faces coastal design problems.

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Table 1

Hurricane Information File--Atlantic Phase II*

| Storm Number | Storm Name | Beginning Date | Total Hours | Central Pressure | Largest HS, m | Unaffected Stations | Name |
|---|---|---|---|---|---|---|---|
| 1 | 5608 | 56081312 | 121 | 951 | 12 | 73 | Betsy |
| 2 | 5808 | 58082412 | 133 | 935 | 15 | 0 | Daisy |
| 3 | 5809 | 58092312 | 145 | 934 | 16 | 0 | Helene |
| 4 | 5810 | 58100612 | 109 | 968 | 10 | 0 | Janice |
| 5 | 5907 | 59070612 | 73 | 991 | 5 | 1-35,59,60,63-73 | Cindy |
| 6 | 5909 | 59092212 | 181 | 950 | 12 | 0 | Gracie |
| 7 | 5929 | 59092900 | 145 | 959 | 11 | 0 | Hannah |
| 8 | 5910 | 59101806 | 49 | 988 | 7 | 0 | Judith |
| 9 | 6008 | 60081712 | 79 | 982 | 8 | 0 | Cleo |
| 10 | 6009 | 60090900 | 103 | 932 | 12 | 0 | Donna |
| 11 | 6109 | 61091612 | 241 | 927 | 17 | 0 | Esther |
| 12 | 6110 | 61100400 | 133 | 948 | 11 | 60,65,69,71-73 | Frances |
| 13 | 6208 | 62082700 | 85 | 986 | 6 | 59-60,65-67,70-71 | Alma |
| 14 | 6210 | 62100312 | 109 | 965 | 14 | 0 | Daisy |
| 15 | 6220 | 62101512 | 157 | 960 | 13 | 0 | Ella |
| 16 | 6308 | 63080712 | 73 | 969 | 8 | 8,50,57,59-67,70-71,73 | Arlene |
| 17 | 6310 | 63101906 | 253 | 948 | 10 | 0 | Ginny |
| 18 | 6408 | 64082600 | 217 | 967 | 6 | 4-5,8,13,23-24,27-32 | Cleo |
| 19 | 6409 | 64090500 | 145 | 942 | 15 | 0 | Dora |
| 20 | 6429 | 64090712 | 157 | 970 | 9 | 0 | Ethel |
| 21 | 6439 | 64091612 | 187 | 951 | 11 | 0 | Gladys |
| 22 | 6410 | 64101412 | 61 | 980 | 7 | 0 | Isbell |
| 23 | 6509 | 65090206 | 157 | 946 | 15 | 0 | Betsy |
| 24 | 6606 | 66061000 | 109 | 993 | 8 | 0 | Alma |
| 25 | 6607 | 66071918 | 49 | 997 | 5 | 1-17 | Celia |

(Continued)

* This file contains basic information about the 43 hurricanes included in the 1956-1975 Atlantic hurricane hindcasts. The previous Atlantic Phase II WIS grid was not used for the Atlantic hurricanes; a larger grid using the same spacing and same output stations was used (see Figure 1). Stations 1 through 73 are the same locations as referenced throughout Sea-State Engineering Analysis System (SEAS) for Atlantic Phase II. The first column contains the SEAS storm number of the hurricane. The second column contains the four-digit numeric "name" of the storm. The third column contains the beginning date of the storm; the year, month, day, and hour are each indicated by two digits. Time is referenced to Greenwich Mean Time. The fourth column indicates how many hours were included in the hurricane hindcast. The fifth column gives the lowest central pressure in millibars for the storm. The sixth column shows the highest significant wave height (in metres) that occurred over the entire grid during the storm. Column seven indicates those stations which were not affected by the storm, e.g., stations whose maximum wave heights during the selected storm were 1 m or less. The last column lists the hurricanes by name, as identified by the NWS.

Table 1 (Concluded)

| Storm Number | Storm Name | Beginning Date | Total Hours | Central Pressure | Largest HS, m | Unaffected Stations | Name |
|---|---|---|---|---|---|---|---|
| 26 | 6608 | 66082712 | 157 | 954 | 15 | 0 | Faith |
| 27 | 6610 | 66100212 | 61 | 985 | 5 | 0 | Inez |
| 28 | 6709 | 67090912 | 181 | 975 | 10 | 0 | Doria |
| 29 | 6710 | 67102100 | 73 | 994 | 6 | 0 | Heidi |
| 30 | 6806 | 68062012 | 97 | 990 | 7 | 0 | Brenda |
| 31 | 6810 | 68101812 | 73 | 965 | 10 | 0 | Gladys |
| 32 | 6908 | 69081100 | 43 | 992 | 7 | 0 | Blanche |
| 33 | 6909 | 69090800 | 55 | 977 | 7 | 0 | Gerda |
| 34 | 6929 | 69092400 | 49 | 985 | 7 | 0 | T.S. #10 |
| 35 | 6910 | 69101112 | 151 | 978 | 8 | 0 | Kara |
| 36 | 7108 | 71081400 | 73 | 977 | 11 | 46-73 | Beth |
| 37 | 7109 | 71092212 | 217 | 969 | 13 | 0 | Ginger |
| 38 | 7209 | 72090612 | 133 | 997 | 5 | 0 | Dawn |
| 39 | 7307 | 73070212 | 85 | 986 | 10 | 0 | Alice |
| 40 | 7408 | 74082712 | 61 | 979 | 9 | 8,41-44,46-72 | Becky |
| 41 | 7507 | 75072606 | 55 | 980 | 10 | 0 | Blanche |
| 42 | 7509 | 75092600 | 61 | 979 | 11 | 0 | Faye |
| 43 | 7529 | 75092900 | 103 | 939 | 12 | 0 | Gladys |

Table 2

Hurricane Information File--Gulf of Mexico Phase I*

| Storm Number | Storm Name | Beginning Date | Total Hours | Central Pressure | Largest HS, m | Unaffected Stations | Name |
|---|---|---|---|---|---|---|---|
| 1 | 5609 | 56092212 | 73 | 979 | 9 | 0 | Flossy |
| 2 | 5706 | 57062512 | 61 | 946 | 11 | 43-46,48 | Audrey |
| 3 | 5907 | 59072300 | 73 | 984 | 6 | 31-32,38-47 | Debra |
| 4 | 5910 | 59101712 | 31 | 999 | 4 | 0 | Judith |
| 5 | 6009 | 60091400 | 85 | 972 | 12 | 0 | Ethel |
| 6 | 6109 | 61090700 | 133 | 931 | 18 | 0 | Carla |
| 7 | 6309 | 63091612 | 49 | 996 | 6 | 1,39-51,55 | Cindy |
| 8 | 6409 | 64093000 | 115 | 942 | 14 | 0 | Hilda |
| 9 | 6410 | 64101312 | 43 | 964 | 7 | 0 | Isbell |
| 10 | 6509 | 65090800 | 61 | 941 | 15 | 0 | Betsy |
| 11 | 6606 | 66060806 | 49 | 970 | 7 | 8-12,15-17,54 | Alma |
| 12 | 6610 | 66100500 | 139 | 948 | 14 | 0 | Inez |
| 13 | 6709 | 67091700 | 109 | 923 | 19 | 30-31,36-45 | Beulah |
| 14 | 6710 | 67100200 | 61 | 987 | 9 | 31-32,40 | Fern |
| 15 | 6810 | 68101612 | 73 | 965 | 7 | 0 | Gladys |
| 16 | 6908 | 69081600 | 67 | 908 | 16 | 0 | Camille |
| 17 | 6910 | 69101818 | 145 | 973 | 10 | 0 | Laurie |
| 18 | 7008 | 70080112 | 67 | 945 | 7 | 31,35-40,43,47 | Celia |
| 19 | 7009 | 70091018 | 55 | 967 | 9 | 24-44,46-48,50 | Ella |
| 20 | 7109 | 71090712 | 121 | 985 | 7 | 40,43-46 | Fern |
| 21 | 7129 | 71091412 | 55 | 977 | 11 | 0 | Edith |
| 22 | 7206 | 72061700 | 73 | 978 | 10 | 0 | Agnes |
| 23 | 7409 | 74090400 | 121 | 937 | 12 | 0 | Carmen |
| 24 | 7508 | 75082900 | 73 | 963 | 8 | 30-33,35-36,39-51 | Caroline |
| 25 | 7509 | 75092112 | 55 | 955 | 11 | 0 | Eloise |

* This file contains basic information about the 25 hurricanes included in the 1956-1975 Gulf of Mexico hurricane hindcasts. The Gulf Phase I WIS grid was used for the hindcast. Stations 1 through 56 are the same locations as referenced throughout SEAS for the Gulf of Mexico. The first column contains the SEAS storm number of the hurricane. The second column contains the four-digit numeric "name" of the storm. The third column contains the beginning date of the storm; the year, month, day, and hour are each indicated by two digits. Time is referenced to Greenwich Mean Time. The fourth column indicates how many hours were included in the hurricane hindcast. The fifth column gives the lowest central pressure in millibars for the storm. The sixth column shows the highest significant wave height (in metres) that occurred over the entire grid during the storm. Column seven indicates those stations which were not affected by the storm, e.g., stations whose maximum wave heights during the selected storm were 1 m or less. The last column lists the hurricanes by name, as identified by the NWS.

Table 3

Top Hurricane Damage Estimates (through 1975)

| Storm, year | Estimate, Billion Dollars |
|---|---|
| Agnes - 1972 | $3.1 |
| Camille - 1969 | 1.4 |
| Betsy - 1965 | 1.4 |
| *Diane - 1955 | 0.8 |
| *Carol - 1954 | 0.4 |
| Celia - 1970 | 0.4 |
| Donna - 1960 | 0.4 |

*Not included in hindcast

Table 4

Hurricane 7409

| Station | Max Wave Ht m | Period of Max Wave, sec | Station | Max Wave Ht m | Period of Max Wave, sec |
|---|---|---|---|---|---|
| 1 | 3.7 | 10.0 | 29 | 4.0 | 10.0 |
| 2 | 4.1 | 12.5 | 30 | 3.5 | 10.0 |
| 3 | 3.6 | 12.5 | 31 | 2.7 | 10.0 |
| 4 | 3.4 | 12.5 | 32 | 3.2 | 10.0 |
| 5 | 3.5 | 14.3 | 33 | 3.2 | 9.1 |
| 6 | 3.7 | 12.5 | 34 | 2.7 | 8.3 |
| 7 | 3.1 | 12.5 | 35 | 2.5 | 7.7 |
| 8 | 3.3 | 14.3 | 36 | 2.0 | 9.1 |
| 9 | 3.0 | 12.5 | 37 | 1.8 | 9.1 |
| 10 | 3.5 | 12.5 | 38 | 1.5 | 5.9 |
| 11 | 2.9 | 12.5 | 39 | 1.4 | 6.2 |
| 12 | 3.1 | 12.5 | 40 | 1.3 | 5.9 |
| 13 | 2.3 | 6.2 | 41 | 1.5 | 6.2 |
| 14 | 2.8 | 6.7 | 42 | 1.7 | 6.7 |
| 15 | 4.1 | 7.7 | 43 | 1.2 | 4.7 |
| 16 | 4.6 | 8.3 | 44 | 1.3 | 4.8 |
| 17 | 7.4 | 9.1 | 45 | 1.2 | 5.9 |
| 18 | 4.7 | 8.3 | 46 | 1.7 | 6.2 |
| 19 | 8.1 | 10.0 | 47 | 1.8 | 6.7 |
| 20 | 10.0 | 10.0 | 48 | 1.6 | 6.2 |
| 21 | 10.7 | 12.5 | 49 | 1.6 | 5.9 |
| 22 | 8.7 | 12.5 | 50 | 1.7 | 5.9 |
| 23 | 7.5 | 12.5 | 51 | 1.6 | 5.7 |
| 24 | 6.3 | 11.1 | 52 | 3.4 | 9.1 |
| 25 | 5.5 | 11.1 | 53 | 8.3 | 11.1 |
| 26 | 4.8 | 12.5 | 54 | 5.8 | 12.5 |
| 27 | 4.5 | 11.1 | 55 | 4.3 | 11.1 |
| 28 | 4.3 | 11.1 | 56 | 5.7 | 11.1 |

## Appendix A: Atlantic Hurricane Extremal Statistics

ATLANTIC PHASE 2 STATION 1 (44.24N, 67.71W)
HURRICANE WAVE ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 11.6 | 14.5 | 9.7 |
| 20 | 8.3 | 11.4 | 7.7 |
| 10 | 6.9 | 9.6 | 6.4 |
| 5 | 5.7 | 8.0 | 5.4 |

ATLANTIC PHASE 2 STATION 2 (44.28N, 67.02W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.2 | 15.3 | 10.2 |
| 20 | 8.7 | 12.1 | 8.1 |
| 10 | 7.3 | 10.1 | 6.8 |
| 5 | 6.0 | 8.5 | 5.7 |

ATLANTIC PHASE 2 STATION 3 (44.32N, 66.32W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.1 | 15.2 | 10.1 |
| 20 | 8.6 | 12.0 | 8.0 |
| 10 | 7.1 | 10.0 | 6.7 |
| 5 | 5.9 | 8.4 | 5.6 |

ATLANTIC PHASE 2 STATION 4 (43.64N, 69.02W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 9.8 | 10.2* | 8.1 |
| 20 | 6.8 | 9.7 | 6.3 |
| 10 | 5.5 | 8.0 | 5.2 |
| 5 | 4.5 | 6.6 | 4.3 |

* Waveheight limited to 0.6 times water depth.

ATLANTIC PHASE 2 STATION 5 (43.69N, 68.33W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.1 | 15.6 | 9.9 |
| 20 | 8.3 | 12.0 | 7.6 |
| 10 | 6.7 | 9.8 | 6.3 |
| 5 | 5.4 | 8.1 | 5.1 |

ATLANTIC PHASE 2 STATION 6 (43.74N, 67.65W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.4 | 17.1 | 11.0 |
| 20 | 9.3 | 13.2 | 8.5 |
| 10 | 7.6 | 10.9 | 7.0 |
| 5 | 6.2 | 9.0 | 5.8 |

ATLANTIC PHASE 2 STATION 7 (43.79N, 66.96W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.4 | 17.1 | 11.1 |
| 20 | 9.4 | 13.3 | 8.6 |
| 10 | 7.7 | 11.0 | 7.1 |
| 5 | 6.3 | 9.1 | 5.9 |

ATLANTIC PHASE 2 STATION 8 (43.03N, 70.31W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 11.3 | 14.6 | 9.2 |
| 20 | 7.5 | 11.1 | 7.0 |
| 10 | 6.0 | 9.1 | 5.7 |
| 5 | 4.8 | 7.4 | 4.7 |

ATLANTIC PHASE 2 STATION 9 (43.09N, 69.63W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.3 | 17.3 | 10.8 |
| 20 | 8.9 | 13.1 | 8.2 |
| 10 | 7.1 | 10.6 | 6.6 |
| 5 | 5.7 | 8.6 | 5.4 |

ATLANTIC PHASE 2 STATION 10 (43.15N, 68.95W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.2 | 15.7 | 10.1 |
| 20 | 8.4 | 12.1 | 7.8 |
| 10 | 6.9 | 10.0 | 6.4 |
| 5 | 5.5 | 8.2 | 5.3 |

ATLANTIC PHASE 2 STATION 11 (43.29N, 66.90W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.5 | 18.5 | 11.9 |
| 20 | 10.1 | 14.3 | 9.3 |
| 10 | 8.3 | 11.8 | 7.6 |
| 5 | 6.7 | 9.8 | 6.3 |

ATLANTIC PHASE 2 STATION 12 (43.33N, 66.21W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.2 | 19.8 | 12.3 |
| 20 | 10.3 | 15.0 | 9.4 |
| 10 | 8.3 | 12.2 | 7.6 |
| 5 | 6.6 | 9.9 | 6.2 |

ATLANTIC PHASE 2 STATION 13 (42.54N, 70.23W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 11.7 | 15.1 | 9.6 |
| 20 | 7.9 | 11.6 | 7.4 |
| 10 | 6.4 | 9.5 | 6.0 |
| 5 | 5.1 | 7.8 | 5.0 |

ATLANTIC PHASE 2 STATION 14 (42.60N, 69.55W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.0 | 18.2 | 11.3 |
| 20 | 9.4 | 13.8 | 8.6 |
| 10 | 7.5 | 11.2 | 7.0 |
| 5 | 6.0 | 9.1 | 5.6 |

ATLANTIC PHASE 2 STATION 15 (42.83N, 66.16W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.5 | 20.0 | 12.7 |
| 20 | 10.6 | 15.3 | 9.7 |
| 10 | 8.6 | 12.5 | 7.9 |
| 5 | 6.9 | 10.2 | 6.5 |

ATLANTIC PHASE 2 STATION 16 (42.11N, 69.48W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.6 | 20.6 | 12.5 |
| 20 | 10.3 | 15.4 | 9.4 |
| 10 | 8.2 | 12.4 | 7.6 |
| 5 | 6.5 | 10.0 | 6.1 |

ATLANTIC PHASE 2 STATION 17 (41.61N, 69.40W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.2 | 20.2 | 12.2 |
| 20 | 10.1 | 15.1 | 9.1 |
| 10 | 8.0 | 12.1 | 7.3 |
| 5 | 6.3 | 9.7 | 5.9 |

ATLANTIC PHASE 2 STATION 18 (40.88N, 71.96W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.1 | 13.2* | 10.4 |
| 20 | 9.0 | 13.0 | 7.7 |
| 10 | 7.1 | 10.3 | 6.1 |
| 5 | 5.5 | 8.2 | 4.8 |

ATLANTIC PHASE 2 STATION 19 (40.94N, 71.30W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.9 | 16.7 | 10.5 |
| 20 | 8.7 | 12.7 | 8.0 |
| 10 | 7.0 | 10.4 | 6.5 |
| 5 | 5.6 | 8.4 | 5.3 |

ATLANTIC PHASE 2 STATION 20 (41.01N, 70.65W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.1 | 18.5 | 11.5 |
| 20 | 9.5 | 14.0 | 8.7 |
| 10 | 7.7 | 11.3 | 7.0 |
| 5 | 6.1 | 9.2 | 5.7 |

ATLANTIC PHASE 2 STATION 21 (41.06N, 69.99W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.2 | 19.9 | 12.4 |
| 20 | 10.3 | 15.1 | 9.4 |
| 10 | 8.3 | 12.2 | 7.6 |
| 5 | 6.6 | 9.9 | 6.2 |

ATLANTIC PHASE 2 STATION 22 (41.12N, 69.33W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.0 | 19.3 | 12.3 |
| 20 | 10.4 | 14.9 | 9.5 |
| 10 | 8.5 | 12.2 | 7.8 |
| 5 | 6.9 | 10.0 | 6.4 |

ATLANTIC PHASE 2 STATION 23 (40.17N, 73.82W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 8.1 | 10.0 | 6.9 |
| 20 | 6.3 | 8.1 | 5.6 |
| 10 | 5.3 | 6.9 | 4.8 |
| 5 | 4.4 | 5.9 | 4.1 |

ATLANTIC PHASE 2 STATION 24 (40.24N, 73.17W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 10.4 | 13.1 | 8.7 |
| 20 | 7.4 | 10.3 | 6.9 |
| 10 | 6.1 | 8.6 | 5.8 |
| 5 | 5.0 | 7.2 | 4.8 |

ATLANTIC PHASE 2 STATION 25 (40.32N, 72.52W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.0 | 20.1 | 11.9 |
| 20 | 9.7 | 14.8 | 8.8 |
| 10 | 7.6 | 11.7 | 7.0 |
| 5 | 6.0 | 9.3 | 5.5 |

ATLANTIC PHASE 2 STATION 26 (40.39N, 71.87W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 18.5 | 25.7 | 14.3 |
| 20 | 11.5 | 18.3 | 10.2 |
| 10 | 8.8 | 14.1 | 7.9 |
| 5 | 6.7 | 10.9 | 6.1 |

ATLANTIC PHASE 2 STATION 27 (39.68N, 73.72W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 10.1 | 12.6* | 8.5 |
| 20 | 7.4 | 10.1 | 6.7 |
| 10 | 6.1 | 8.4 | 5.6 |
| 5 | 5.0 | 7.0 | 4.7 |

ATLANTIC PHASE 2 STATION 28 (39.12N, 74.26W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 9.9 | 10.8* | 8.3 |
| 20 | 7.5 | 9.8 | 6.6 |
| 10 | 6.3 | 8.3 | 5.6 |
| 5 | 5.2 | 6.9 | 4.7 |

ATLANTIC PHASE 2 STATION 29 (39.20N, 73.62W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.1 | 17.2 | 10.6 |
| 20 | 8.8 | 13.0 | 8.0 |
| 10 | 7.1 | 10.5 | 6.5 |
| 5 | 5.6 | 8.5 | 5.3 |

ATLANTIC PHASE 2 STATION 30 (38.55N, 74.79W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 8.1 | 9.0* | 7.1 |
| 20 | 6.7 | 8.0 | 6.0 |
| 10 | 5.9 | 7.1 | 5.3 |
| 5 | 5.1 | 6.2 | 4.7 |

ATLANTIC PHASE 2 STATION 31 (38.63N, 74.16W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.9 | 16.7 | 10.5 |
| 20 | 9.4 | 12.8 | 8.0 |
| 10 | 7.6 | 10.4 | 6.5 |
| 5 | 6.1 | 8.5 | 5.3 |

ATLANTIC PHASE 2 STATION 32 (38.07N, 74.69W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 4.2* | 4.2* | 4.2* |
| 20 | 4.2* | 4.2* | 4.2* |
| 10 | 4.2* | 4.2* | 4.2* |
| 5 | 4.2* | 4.2* | 4.2* |

ATLANTIC PHASE 2 STATION 33 (37.51N, 75.21W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 6.6* | 6.6* | 6.6* |
| 20 | 6.6* | 6.6* | 6.6* |
| 10 | 6.5 | 6.6* | 5.8 |
| 5 | 5.5 | 6.6* | 5.0 |

ATLANTIC PHASE 2 STATION 34 (37.59N, 74.59W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.9 | 21.0 | 12.8 |
| 20 | 10.5 | 15.7 | 9.6 |
| 10 | 8.4 | 12.6 | 7.7 |
| 5 | 6.6 | 10.1 | 6.2 |

ATLANTIC PHASE 2 STATION 35 (37.03N, 75.11W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.6 | 20.6 | 12.5 |
| 20 | 10.3 | 15.4 | 9.3 |
| 10 | 8.2 | 12.4 | 7.5 |
| 5 | 6.5 | 9.9 | 6.0 |

ATLANTIC PHASE 2 STATION 36 (36.54N, 75.02W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 16.0 | 18.6* | 12.9 |
| 20 | 10.8 | 15.8 | 9.8 |
| 10 | 8.7 | 12.8 | 7.9 |
| 5 | 6.9 | 10.4 | 6.4 |

ATLANTIC PHASE 2 STATION 37 (36.06N, 74.92W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 19.5 | 26.1 | 15.4 |
| 20 | 12.6 | 19.2 | 11.4 |
| 10 | 9.9 | 15.2 | 9.0 |
| 5 | 7.8 | 12.1 | 7.1 |

ATLANTIC PHASE 2 STATION 38 (35.58N, 74.83W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 23.0 | 31.8 | 17.9 |
| 20 | 14.4 | 22.7 | 12.8 |
| 10 | 11.1 | 17.6 | 9.9 |
| 5 | 8.5 | 13.7 | 7.7 |

ATLANTIC PHASE 2 STATION 39 (35.02N, 75.34W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 25.3 | 35.0 | 19.6 |
| 20 | 15.8 | 25.0 | 14.0 |
| 10 | 12.1 | 19.4 | 10.9 |
| 5 | 9.3 | 15.0 | 8.4 |

ATLANTIC PHASE 2 STATION 40 (35.09N, 74.74W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 26.3 | 36.4 | 20.3 |
| 20 | 16.3 | 25.9 | 14.4 |
| 10 | 12.5 | 20.0 | 11.2 |
| 5 | 9.6 | 15.5 | 8.6 |

ATLANTIC PHASE 2 STATION 41 (34.12N, 77.64W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 6.6* | 6.6* | 6.6* |
| 20 | 6.6* | 6.6* | 6.6* |
| 10 | 6.6* | 6.6* | 6.2 |
| 5 | 5.9 | 6.6* | 5.4 |

ATLANTIC PHASE 2 STATION 42 (34.29N, 77.04W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 18.1 | 18.6* | 14.2 |
| 20 | 11.5 | 17.8 | 10.3 |
| 10 | 8.9 | 14.0 | 8.1 |
| 5 | 6.9 | 11.0 | 6.3 |

ATLANTIC PHASE 2 STATION 43 (34.38N, 76.45W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 19.2 | 24.0* | 15.2 |
| 20 | 12.3 | 19.0 | 11.1 |
| 10 | 9.6 | 15.0 | 8.7 |
| 5 | 7.5 | 11.8 | 6.9 |

ATLANTIC PHASE 2 STATION 44 (34.46N, 75.85W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 24.9 | 34.2 | 19.4 |
| 20 | 15.6 | 24.6 | 13.9 |
| 10 | 12.1 | 19.1 | 10.8 |
| 5 | 9.3 | 14.9 | 8.4 |

ATLANTIC PHASE 2 STATION 45 (34.54N, 75.25W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 23.6 | 31.9 | 18.7 |
| 20 | 15.2 | 23.4 | 13.7 |
| 10 | 12.0 | 18.4 | 10.8 |
| 5 | 9.3 | 14.6 | 8.5 |

ATLANTIC PHASE 2 STATION 46 (33.55N, 78.72W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 5.4* | 5.4* | 5.4* |
| 20 | 5.4* | 5.4* | 5.4* |
| 10 | 5.4* | 5.4* | 5.3 |
| 5 | 5.1 | 5.4* | 4.6 |

ATLANTIC PHASE 2 STATION 47 (33.64N, 78.13W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.6* | 15.6* | 13.0 |
| 20 | 11.4 | 15.6* | 9.5 |
| 10 | 8.9 | 12.8 | 7.5 |
| 5 | 6.9 | 10.1 | 5.9 |

ATLANTIC PHASE 2 STATION 48 (33.73N, 77.54W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 21.1 | 29.3 | 16.3 |
| 20 | 13.0 | 20.8 | 11.6 |
| 10 | 10.0 | 16.1 | 9.0 |
| 5 | 7.6 | 12.4 | 6.9 |

ATLANTIC PHASE 2 STATION 49 (33.08N, 78.62W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.2* | 13.2* | 13.2* |
| 20 | 12.6 | 13.2* | 9.8 |
| 10 | 9.7 | 13.2* | 7.6 |
| 5 | 7.4 | 10.5 | 5.9 |

ATLANTIC PHASE 2 STATION 50 (32.33N, 80.26W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 5.4* | 5.4* | 5.4* |
| 20 | 5.4* | 5.4* | 5.4* |
| 10 | 5.4* | 5.4* | 5.3 |
| 5 | 5.4 | 5.4* | 4.6 |

ATLANTIC PHASE 2 STATION 51 (32.42N, 79.68W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.4 | 12.6* | 10.2 |
| 20 | 9.5 | 12.2 | 7.9 |
| 10 | 7.8 | 10.1 | 6.5 |
| 5 | 6.4 | 8.3 | 5.4 |

ATLANTIC PHASE 2 STATION 52 (32.51N, 79.10W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 21.5 | 29.6 | 16.7 |
| 20 | 13.3 | 21.2 | 11.9 |
| 10 | 10.2 | 16.4 | 9.3 |
| 5 | 7.8 | 12.8 | 7.2 |

ATLANTIC PHASE 2 STATION 53 (32.60N, 78.51W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 26.2 | 37.5 | 19.7 |
| 20 | 15.4 | 25.8 | 13.5 |
| 10 | 11.5 | 19.4 | 10.2 |
| 5 | 8.5 | 14.6 | 7.7 |

ATLANTIC PHASE 2 STATION 54 (31.86N, 80.15W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.2* | 13.2* | 12.4 |
| 20 | 11.4 | 13.2* | 9.2 |
| 10 | 9.0 | 12.3 | 7.3 |
| 5 | 7.0 | 9.8 | 5.8 |

ATLANTIC PHASE 2 STATION 55 (31.29N, 80.62W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.4* | 14.4* | 13.3 |
| 20 | 12.1 | 14.4* | 9.4 |
| 10 | 9.2 | 13.1 | 7.2 |
| 5 | 6.9 | 10.1 | 5.6 |

ATLANTIC PHASE 2 STATION 56 (31.39N, 80.01W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 21.1 | 22.2* | 16.1 |
| 20 | 14.6 | 20.8 | 11.3 |
| 10 | 11.0 | 15.9 | 8.6 |
| 5 | 8.3 | 12.1 | 6.6 |

ATLANTIC PHASE 2 STATION 57 (30.73N, 81.08W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 4.2* | 4.2* | 4.2* |
| 20 | 4.2* | 4.2* | 4.2* |
| 10 | 4.2* | 4.2* | 4.2* |
| 5 | 4.2* | 4.2* | 4.2* |

ATLANTIC PHASE 2 STATION 58 (30.82N, 80.51W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.2* | 13.2* | 13.2* |
| 20 | 13.0 | 13.2* | 10.1 |
| 10 | 9.9 | 13.2* | 7.7 |
| 5 | 7.5 | 10.8 | 6.0 |

ATLANTIC PHASE 2 STATION 59 (30.26N, 80.98W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 16.8* | 16.8* | 14.2 |
| 20 | 12.7 | 16.8* | 9.8 |
| 10 | 9.5 | 13.9 | 7.4 |
| 5 | 7.0 | 10.6 | 5.6 |

ATLANTIC PHASE 2 STATION 60 (29.79N, 80.88W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 18.5 | 18.6* | 14.4 |
| 20 | 13.2 | 18.3 | 10.4 |
| 10 | 10.2 | 14.2 | 8.1 |
| 5 | 7.8 | 11.1 | 6.3 |

ATLANTIC PHASE 2 STATION 61 (29.89N, 80.31W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 25.4 | 27.6* | 19.2 |
| 20 | 15.6 | 25.0 | 13.2 |
| 10 | 11.7 | 18.9 | 10.0 |
| 5 | 8.6 | 14.3 | 7.5 |

ATLANTIC PHASE 2 STATION 62 (29.42N, 80.21W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 18.6* | 18.6* | 15.0 |
| 20 | 13.5 | 18.6* | 10.3 |
| 10 | 10.0 | 14.7 | 7.7 |
| 5 | 7.4 | 11.1 | 5.8 |

ATLANTIC PHASE 2 STATION 63 (28.95N, 80.11W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 5.4* | 5.4* | 5.4* |
| 20 | 5.4* | 5.4* | 5.4* |
| 10 | 5.4* | 5.4* | 5.3 |
| 5 | 5.1 | 5.4* | 4.4 |

ATLANTIC PHASE 2 STATION 64 (28.48N, 80.02W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 7.2* | 7.2* | 7.2* |
| 20 | 7.2* | 7.2* | 7.2 |
| 10 | 7.1 | 7.2* | 6.0 |
| 5 | 5.9 | 7.2* | 5.0 |

ATLANTIC PHASE 2 STATION 65 (28.01N, 79.93W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 2.4* | 2.4* | 2.4* |
| 20 | 2.4* | 2.4* | 2.4* |
| 10 | 2.4* | 2.4* | 2.4* |
| 5 | 2.4* | 2.4* | 2.4* |

ATLANTIC PHASE 2 STATION 66 (27.54N, 79.84W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 4.2* | 4.2* | 4.2* |
| 20 | 4.2* | 4.2* | 4.2* |
| 10 | 4.2* | 4.2* | 4.2* |
| 5 | 4.2* | 4.2* | 4.1 |

ATLANTIC PHASE 2 STATION 67 (27.07N, 79.75W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 6.0* | 6.0* | 6.0* |
| 20 | 6.0* | 6.0* | 6.0* |
| 10 | 6.0* | 6.0* | 5.1 |
| 5 | 5.1 | 6.0* | 4.3 |

ATLANTIC PHASE 2 STATION 68 (27.15N, 79.20W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 18.2 | 26.2 | 13.6 |
| 20 | 12.1 | 17.9 | 9.3 |
| 10 | 8.9 | 13.4 | 7.0 |
| 5 | 6.5 | 10.0 | 5.2 |

ATLANTIC PHASE 2 STATION 69 (27.23N, 78.64W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 21.1 | 31.6 | 15.3 |
| 20 | 12.8 | 20.7 | 10.1 |
| 10 | 9.1 | 15.1 | 7.3 |
| 5 | 6.3 | 11.0 | 5.3 |

ATLANTIC PHASE 2 STATION 70 (26.60N, 79.67W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.3 | 17.7 | 10.7 |
| 20 | 9.7 | 13.2 | 7.9 |
| 10 | 7.7 | 10.5 | 6.3 |
| 5 | 6.0 | 8.4 | 5.1 |

ATLANTIC PHASE 2 STATION 71 (26.13N, 79.58W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.2 | 19.0 | 11.2 |
| 20 | 10.2 | 14.0 | 8.3 |
| 10 | 7.9 | 11.1 | 6.6 |
| 5 | 6.1 | 8.8 | 5.2 |

ATLANTIC PHASE 2 STATION 72 (26.20N, 79.03W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.1 | 18.6 | 9.9 |
| 20 | 10.7 | 12.9 | 6.9 |
| 10 | 8.0 | 9.8 | 5.2 |
| 5 | 5.9 | 7.4 | 4.0 |

ATLANTIC PHASE 2 STATION 73 (25.66N, 79.50W)
HURRICANE WAVES ONLY

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 17.4 | 25.7 | 12.7 |
| 20 | 13.7 | 17.1 | 8.5 |
| 10 | 9.9 | 12.5 | 6.2 |
| 5 | 7.1 | 9.2 | 4.6 |

## Appendix B: Gulf of Mexico Hurricane Extremal Statistics

GULF STATION 1 (22.0 N, 96.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 19.7 | 28.7 | 14.6 |
| 20 | 12.6 | 19.3 | 9.8 |
| 10 | 9.2 | 14.4 | 7.3 |
| 5 | 6.7 | 10.7 | 5.4 |

GULF STATION 2 (26.0 N, 97.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.6* | 15.6* | 13.5 |
| 20 | 10.7 | 15.6* | 9.5 |
| 10 | 8.1 | 13.4 | 7.2 |
| 5 | 6.0 | 10.2 | 5.5 |

GULF STATION 3 (26.5 N, 97.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 16.0 | 21.0* | 12.3 |
| 20 | 9.9 | 15.8 | 8.7 |
| 10 | 7.5 | 12.2 | 6.7 |
| 5 | 5.6 | 9.4 | 5.2 |

GULF STATION 4 (27.0 N, 97.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.6 | 20.2 | 11.3 |
| 20 | 9.1 | 14.4 | 8.1 |
| 10 | 6.9 | 11.2 | 6.3 |
| 5 | 5.2 | 8.6 | 4.8 |

* Waveheight limited to 0.6 times water depth.

GULF STATION 5 (27.5 N, 97.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.7 | 15.6* | 10.1 |
| 20 | 8.3 | 12.5 | 7.5 |
| 10 | 6.5 | 10.0 | 6.0 |
| 5 | 5.0 | 8.0 | 4.7 |

GULF STATION 6 (27.5 N, 96.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 18.9 | 27.3 | 14.2 |
| 20 | 11.0 | 18.7 | 9.7 |
| 10 | 8.1 | 14.0 | 7.2 |
| 5 | 5.8 | 10.5 | 5.4 |

GULF STATION 7 (28.0 N, 96.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.4 | 15.6* | 11.1 |
| 20 | 8.9 | 14.2 | 7.8 |
| 10 | 6.7 | 10.9 | 6.0 |
| 5 | 4.9 | 8.4 | 4.6 |

GULF STATION 8 (28.0 N, 96.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 20.8 | 26.4* | 15.2 |
| 20 | 11.8 | 20.5 | 10.1 |
| 10 | 8.5 | 15.0 | 7.4 |
| 5 | 5.9 | 11.0 | 5.4 |

GULF STATION 9 (28.5 N, 95.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.7 | 15.6* | 11.3 |
| 20 | 9.1 | 14.5 | 8.0 |
| 10 | 6.9 | 11.1 | 6.1 |
| 5 | 5.1 | 8.6 | 4.7 |

GULF STATION 10 ( 28.5 N, 95.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 17.2 | 19.8* | 13.2 |
| 20 | 10.7 | 16.9 | 9.4 |
| 10 | 8.1 | 13.1 | 7.2 |
| 5 | 6.0 | 10.1 | 5.6 |

GULF STATION 11 ( 29.0 N, 94.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 10.8* | 10.8* | 9.2 |
| 20 | 8.2 | 10.8* | 7.2 |
| 10 | 6.8 | 9.1 | 6.0 |
| 5 | 5.5 | 7.6 | 5.0 |

GULF STATION 12 ( 29.0 N, 94.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.0* | 12.0* | 12.0 |
| 20 | 9.7 | 12.0* | 8.6 |
| 10 | 7.4 | 11.8 | 6.7 |
| 5 | 5.5 | 9.2 | 5.2 |

GULF STATION 13 ( 29.5 N, 93.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 5.4* | 5.4* | 5.4* |
| 20 | 5.4* | 5.4* | 5.4* |
| 10 | 5.2 | 5.4* | 4.7 |
| 5 | 4.1 | 5.4* | 3.9 |

GULF STATION 14 (29.5 N, 93.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 7.8* | 7.8* | 7.8* |
| 20 | 6.9 | 7.8* | 5.9 |
| 10 | 5.2 | 7.8* | 4.6 |
| 5 | 3.8 | 6.3 | 3.6 |

GULF STATION 15 ( 29.0 N, 92.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.5 | 14.4* | 10.6 |
| 20 | 8.6 | 13.3 | 7.7 |
| 10 | 6.7 | 10.5 | 6.0 |
| 5 | 5.0 | 8.2 | 4.7 |

GULF STATION 16 (29.0 N, 92.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 8.4 | 9.6* | 7.3 |
| 20 | 6.4 | 8.3 | 6.1 |
| 10 | 5.6 | 7.3 | 5.3 |
| 5 | 4.7 | 6.3 | 4.6 |

GULF STATION 17 (29.0 N, 91.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 5.4* | 5.4* | 5.4* |
| 20 | 5.4* | 5.4* | 5.4* |
| 10 | 5.4* | 5.4* | 5.4* |
| 5 | 5.4* | 5.4* | 5.4* |

GULF STATION 18 (28.5 N, 91.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 6.5 | 7.3 | 5.9 |
| 20 | 5.3 | 6.4 | 5.1 |
| 10 | 4.7 | 5.8 | 4.7 |
| 5 | 4.2 | 5.3 | 4.2 |

GULF STATION 19 (28.5 N, 91.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.5 | 19.8* | 12.4 |
| 20 | 10.0 | 15.3 | 9.2 |
| 10 | 7.9 | 12.3 | 7.4 |
| 5 | 6.1 | 9.8 | 5.9 |

GULF STATION 20 (28.5 N, 90.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.5 | 18.6 | 11.8 |
| 20 | 9.8 | 14.3 | 9.1 |
| 10 | 7.9 | 11.7 | 7.4 |
| 5 | 6.3 | 9.6 | 6.1 |

GULF STATION 21 (28.5 N, 90.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.4 | 19.6 | 12.7 |
| 20 | 10.5 | 15.2 | 9.8 |
| 10 | 8.6 | 12.5 | 8.1 |
| 5 | 6.9 | 10.3 | 6.7 |

GULF STATION 22 (28.5 N, 89.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 18.5 | 24.6 | 14.8 |
| 20 | 11.9 | 18.3 | 11.0 |
| 10 | 9.4 | 14.6 | 8.7 |
| 5 | 7.3 | 11.6 | 7.0 |

GULF STATION 23 (28.5 N, 89.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 29.1 | 42.3 | 21.6 |
| 20 | 16.4 | 28.6 | 14.6 |
| 10 | 12.0 | 21.3 | 10.8 |
| 5 | 8.6 | 15.8 | 8.1 |

GULF STATION 24 (29.0 N, 88.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 32.0 | 48.1 | 23.2 |
| 20 | 17.1 | 31.4 | 15.1 |
| 10 | 12.2 | 22.8 | 11.0 |
| 5 | 8.5 | 16.5 | 7.9 |

GULF STATION 25 (29.5 N, 88.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 23.5 | 30.6* | 17.7 |
| 20 | 13.4 | 23.2 | 12.1 |
| 10 | 9.8 | 17.4 | 9.1 |
| 5 | 7.1 | 13.0 | 6.8 |

GULF STATION 26 (30.0 N, 88.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.6* | 15.6* | 12.4 |
| 20 | 9.8 | 15.6 | 9.0 |
| 10 | 7.5 | 12.2 | 7.0 |
| 5 | 5.7 | 9.6 | 5.5 |

GULF STATION 27 (30.0 N, 88.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.1 | 15.6* | 11.3 |
| 20 | 9.1 | 13.9 | 8.4 |
| 10 | 7.2 | 11.2 | 6.7 |
| 5 | 5.6 | 8.9 | 5.4 |

GULF STATION 28 (30.0 N, 87.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.3 | 14.4* | 10.7 |
| 20 | 8.8 | 13.1 | 8.1 |
| 10 | 7.0 | 10.6 | 6.6 |
| 5 | 5.5 | 8.6 | 5.3 |

GULF STATION 29 (30.0 N, 87.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.7 | 21.5 | 12.3 |
| 20 | 9.7 | 15.5 | 8.9 |
| 10 | 7.4 | 12.1 | 6.9 |
| 5 | 5.6 | 9.5 | 5.4 |

GULF STATION 30 (30.0 N, 86.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 16.1 | 22.5 | 12.3 |
| 20 | 9.5 | 15.9 | 8.7 |
| 10 | 7.1 | 12.2 | 6.7 |
| 5 | 5.3 | 9.3 | 5.1 |

GULF STATION 31 (30.0 N, 86.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.7 | 18.6* | 10.9 |
| 20 | 7.8 | 14.5 | 7.3 |
| 10 | 5.5 | 10.7 | 5.4 |
| 5 | 3.7 | 7.9 | 4.0 |

GULF STATION 32 (29.5 N, 86.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 14.3 | 19.5 | 11.2 |
| 20 | 8.8 | 14.1 | 8.1 |
| 10 | 6.7 | 11.0 | 6.3 |
| 5 | 5.1 | 8.6 | 4.9 |

GULF STATION 33 (29.0 N, 85.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 13.1 | 17.3 | 10.6 |
| 20 | 8.6 | 13.0 | 8.0 |
| 10 | 6.9 | 10.5 | 6.4 |
| 5 | 5.4 | 8.5 | 5.2 |

GULF STATION 34 (29.0 N, 85.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 10.5 | 12.7 | 9.0 |
| 20 | 7.7 | 10.4 | 7.3 |
| 10 | 6.5 | 8.9 | 6.2 |
| 5 | 5.4 | 7.6 | 5.3 |

GULF STATION 35 (29.5 N, 84.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 7.6 | 8.8 | 6.8 |
| 20 | 6.0 | 7.6 | 5.8 |
| 10 | 5.3 | 6.8 | 5.2 |
| 5 | 4.6 | 6.0 | 4.6 |

GULF STATION 36 (29.5 N, 84.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 9.3 | 10.8* | 7.6 |
| 20 | 5.7 | 9.4 | 5.6 |
| 10 | 4.3 | 7.5 | 4.5 |
| 5 | 3.0 | 6.0 | 3.6 |

GULF STATION 37 (29.0 N, 83.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 6.2 | 7.4 | 5.4 |
| 20 | 4.6 | 6.2 | 4.5 |
| 10 | 3.9 | 5.3 | 3.9 |
| 5 | 3.2 | 4.6 | 3.4 |

GULF STATION 41 (27.0 N, 83.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 7.9 | 9.4 | 7.0 |
| 20 | 6.1 | 7.9 | 5.9 |
| 10 | 5.3 | 6.9 | 5.2 |
| 5 | 4.4 | 6.1 | 4.5 |

GULF STATION 44 (25.5 N, 82.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 9.6* | 9.6* | 8.3 |
| 20 | 8.9 | 9.6* | 6.1 |
| 10 | 6.9 | 8.2 | 4.8 |
| 5 | 5.2 | 6.5 | 3.7 |

GULF STATION 45 (25.0 N, 82.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.0* | 12.0* | 9.9 |
| 20 | 10.7 | 12.0* | 6.9 |
| 10 | 8.0 | 9.8 | 5.2 |
| 5 | 5.8 | 7.4 | 4.0 |

GULF STATION 46 (25.0 N, 83.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 15.1 | 21.0 | 11.6 |
| 20 | 11.5 | 14.8 | 8.2 |
| 10 | 8.7 | 11.4 | 6.3 |
| 5 | 6.4 | 8.8 | 4.8 |

GULF STATION 47 (24.5 N, 83.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.8 | 16.2* | 10.1 |
| 20 | 9.8 | 12.6 | 7.3 |
| 10 | 7.7 | 9.9 | 5.8 |
| 5 | 5.9 | 7.8 | 4.6 |

GULF STATION 48 (24.0 N, 82.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.4 | 16.8 | 9.8 |
| 20 | 9.6 | 12.3 | 7.2 |
| 10 | 7.5 | 9.7 | 5.7 |
| 5 | 5.7 | 7.6 | 4.5 |

GULF STATION 49 (24.0 N, 82.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 12.1 | 16.9 | 9.4 |
| 20 | 9.4 | 12.0 | 6.6 |
| 10 | 7.1 | 9.2 | 5.1 |
| 5 | 5.3 | 7.1 | 3.9 |

GULF STATION 50 (24.0 N, 81.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 9.9 | 13.3 | 7.8 |
| 20 | 8.4 | 9.8 | 5.8 |
| 10 | 6.5 | 7.8 | 4.6 |
| 5 | 5.0 | 6.1 | 3.6 |

GULF STATION 52 (26.0 N, 86.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 20.7 | 29.8 | 15.5 |
| 20 | 11.8 | 20.3 | 10.5 |
| 10 | 8.7 | 15.2 | 7.9 |
| 5 | 6.3 | 11.4 | 5.9 |

GULF STATION 53 (26.0 N, 89.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 20.1 | 27.7 | 15.6 |
| 20 | 12.3 | 19.8 | 11.1 |
| 10 | 9.5 | 15.3 | 8.6 |
| 5 | 7.2 | 11.9 | 6.7 |

GULF STATION 54 (26.0 N, 93.5 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 26.1 | 38.9 | 19.1 |
| 20 | 14.4 | 25.7 | 12.6 |
| 10 | 10.4 | 18.8 | 9.2 |
| 5 | 7.4 | 13.7 | 6.7 |

GULF STATION 55 (22.0 N, 92.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 20.4 | 30.2 | 15.0 |
| 20 | 12.6 | 20.1 | 9.9 |
| 10 | 9.1 | 14.7 | 7.3 |
| 5 | 6.4 | 10.8 | 5.3 |

GULF STATION 56 (27.5 N, 88.0 W)

| RETURN PERIOD (YRS) | HS(M) | UPPER LIMIT HS(M) ASSOCIATED WITH .75 FRACTILE | LOWER LIMIT HS(M) ASSOCIATED WITH .25 FRACTILE |
|---|---|---|---|
| 50 | 30.5 | 46.1 | 22.1 |
| 20 | 16.4 | 30.0 | 14.4 |
| 10 | 11.6 | 21.7 | 10.4 |
| 5 | 8.1 | 15.7 | 7.5 |

## Appendix C: Station Locations and Depths

| Station, No. | Latitude/Longitude | Water Depth, m |
|---|---|---|
| | Atlantic Phase II Hurricane Stations | |
| 1 | 44.24N/67.71W | 82.0 |
| 2 | 44.28N/67.02W | 110.0 |
| 3 | 44.32N/66.32W | 117.0 |
| 4 | 43.64N/69.02W | 17.0 |
| 5 | 43.69N/68.33W | 220.0 |
| 6 | 43.74N/67.65W | 92.0 |
| 7 | 43.79N/66.96W | 55.0 |
| 8 | 43.03N/70.31W | 92.0 |
| 9 | 43.09N/69.63W | 110.0 |
| 10 | 43.15N/68.95W | 128.0 |
| 11 | 43.29N/66.90W | 137.0 |
| 12 | 43.33N/66.21W | 60.0 |
| 13 | 42.54N/70.23W | 128.0 |
| 14 | 42.60N/69.55W | 73.0 |
| 15 | 42.83N/66.16W | 92.0 |
| 16 | 42.11N/69.48W | 220.0 |
| 17 | 41.61N/69.40W | 37.0 |
| 18 | 40.88N/71.96W | 22.0 |
| 19 | 40.94N/71.30W | 37.0 |
| 20 | 41.01N/70.65W | 53.0 |
| 21 | 41.06N/69.99W | 55.0 |
| 22 | 41.12N/69.33W | 73.0 |
| 23 | 40.17N/73.82W | 19.0 |
| 24 | 40.24N/73.17W | 51.0 |
| 25 | 40.32N/72.52W | 73.0 |
| 26 | 40.39N/71.87W | 112.0 |
| 27 | 39.68N/73.72W | 21.0 |
| 28 | 39.12N/74.26W | 18.0 |
| 29 | 39.20N/73.62W | 33.0 |
| 30 | 38.55N/74.79W | 15.0 |
| 31 | 38.63N/74.16W | 31.0 |
| 32 | 38.07N/74.69W | 7.0 |
| 33 | 37.51N/75.21W | 11.0 |
| 34 | 37.59N/74.59W | 55.0 |
| 35 | 37.03N/75.11W | 37.0 |
| 36 | 36.54N/75.02W | 31.0 |
| 37 | 36.06N/74.92W | 46.0 |
| 38 | 35.58N/74.83W | 55.0 |
| 39 | 35.02N/75.34W | 999.0 |
| 40 | 35.09N/74.74W | 999.0 |
| 41 | 34.12N/77.64W | 11.0 |
| 42 | 34.29N/77.04W | 31.0 |
| 43 | 34.38N/76.45W | 40.0 |
| 44 | 34.46N/75.85W | 999.0 |
| 45 | 34.54N/75.25W | 999.0 |

(Continued)

| Station, No. | Latitude/Longtitude | Water Depth, m |
|---|---|---|
| **Atlantic Phase II Hurricane Stations (Concluded)** | | |
| 46 | 33.55N/78.72W | 9.0 |
| 47 | 33.64N/78.13W | 26.0 |
| 48 | 33.73N/77.54W | 68.0 |
| 49 | 33.08N/78.62W | 22.0 |
| 50 | 32.33N/80.26W | 9.0 |
| 51 | 32.42N/79.68W | 21.0 |
| 52 | 32.51N/79.10W | 55.0 |
| 53 | 32.60N/78.51W | 419.0 |
| 54 | 31.86N/80.15W | 22.0 |
| 55 | 31.29N/80.62W | 24.0 |
| 56 | 31.39N/80.01W | 37.0 |
| 57 | 30.73N/81.08W | 7.0 |
| 58 | 30.82N/80.51W | 22.0 |
| 59 | 30.26N/80.98W | 28.0 |
| 60 | 29.79N/80.88W | 31.0 |
| 61 | 29.89N/80.31W | 46.0 |
| 62 | 29.42N/80.21W | 31.0 |
| 63 | 28.95N/80.11W | 9.0 |
| 64 | 28.48N/80.02W | 12.0 |
| 65 | 28.01N/79.93W | 4.0 |
| 66 | 27.54N/79.84W | 7.0 |
| 67 | 27.07N/79.75W | 10.0 |
| 68 | 27.15N/79.20W | 424.0 |
| 69 | 27.23N/78.64W | 458.0 |
| 70 | 26.60N/79.67W | 439.0 |
| 71 | 26.13N/79.58W | 100.0 |
| 72 | 26.20N/79.03W | 494.0 |
| 73 | 25.66N/79.50W | 970.0 |
| **Gulf of Mexico Stations** | | |
| 1 | 22.00N/96.00W | 2,762.0 |
| 2 | 26.00N/97.00W | 26.0 |
| 3 | 26.50N/97.00W | 35.0 |
| 4 | 27.00N/97.00W | 40.0 |
| 5 | 27.50N/97.00W | 26.0 |
| 6 | 27.50N/96.50W | 73.0 |
| 7 | 28.00N/96.50W | 26.0 |
| 8 | 28.00N/96.00W | 44.0 |
| 9 | 28.50N/95.50W | 26.0 |
| 10 | 28.50N/95.00W | 33.0 |
| 11 | 29.00N/94.50W | 18.0 |
| 12 | 29.00N/94.00W | 20.0 |
| 13 | 29.50N/93.50W | 9.00 |
| 14 | 29.50N/93.00W | 13.0 |
| 15 | 29.00N/92.50W | 24.0 |
| 16 | 29.00N/92.00W | 16.0 |
| 17 | 29.00N/91.50W | 9.0 |

(Continued)

| Station, No. | Latitude/Longtitude | Water Depth, m |
|---|---|---|
| Gulf of Mexico Stations (Concluded) | | |
| 18 | 28.50N/91.50W | 46.0 |
| 19 | 28.50N/91.00W | 33.0 |
| 20 | 28.50N/90.50W | 38.0 |
| 21 | 28.50N/90.00W | 91.0 |
| 22 | 28.50N/89.50W | 457.0 |
| 23 | 28.50N/89.00W | 860.0 |
| 24 | 29.00N/88.50W | 622.0 |
| 25 | 29.50N/88.50W | 51.0 |
| 26 | 30.00N/88.50W | 26.0 |
| 27 | 30.00N/88.00W | 26.0 |
| 28 | 30.00N/87.50W | 24.0 |
| 29 | 30.00N/87.00W | 71.0 |
| 30 | 30.00N/86.50W | 57.0 |
| 31 | 30.00N/86.00W | 31.0 |
| 32 | 29.50N/86.00W | 59.0 |
| 33 | 29.00N/85.50W | 68.0 |
| 34 | 29.00N/85.00W | 40.0 |
| 35 | 29.50N/84.50W | 24.0 |
| 36 | 29.50N/84.00W | 18.0 |
| 37 | 29.00N/83.50W | 15.0 |
| 38 | 28.50N/83.00W | 7.0 |
| 39 | 28.00N/83.00W | 11.0 |
| 40 | 27.50N/83.00W | 16.0 |
| 41 | 27.00N/83.00W | 33.0 |
| 42 | 26.50N/82.50W | 20.0 |
| 43 | 26.00N/82.00W | 13.0 |
| 44 | 25.50N/82.00W | 16.0 |
| 45 | 25.00N/82.00W | 20.0 |
| 46 | 25.00N/83.00W | 48.0 |
| 47 | 24.50N/83.00W | 27.0 |
| 48 | 24.00N/82.50W | 869.0 |
| 49 | 24.00N/82.00W | 988.0 |
| 50 | 24.00N/81.50W | 1,024.0 |
| 51 | 24.00N/81.00W | 1,061.0 |
| 52 | 26.00N/86.00W | 3,237.0 |
| 53 | 26.00N/89.50W | 3,200.0 |
| 54 | 26.00N/93.50W | 2,377.0 |
| 55 | 22.00N/92.00W | 79.0 |
| 56 | 27.50N/88.00W | 2,615.0 |

## Appendix D: Wave Model Verification

1. The shallow-water spectral hindcast model used in the hurricane simulation is a variation on a model originally developed by Resio (1982)* and subsequently modified. The model is described in Hughes and Jensen (1986) and in Jensen, Vincent, and Abel (1987). Examples of where it has been applied are Hubertz, Abel, and Jensen (1988) and Jensen, Vincent, and Abel (1987). The model contains the following source terms: wind input, nonlinear transfer, wave dissipation, bottom friction, percolation, and shallow-water breaking. The model includes refraction and shoaling. The model is termed pseudo-discrete in that the directional spectrum is represented explicitly in the model as a matrix of values. However, the source term balance for the actively growing wind sea is handled parametrically. For deepwater fetch-limited conditions, the model will produce the Joint North Sea Wave Program (JONSWAP) wave-growth curves and spectral shape. At full development, it will produce the Pierson-Moskowitz spectrum (Pierson and Moskowitz 1964). For finite depth conditions with a flat bottom, it will produce the TMA spectrum (Bouws et al. 1985, 1987) for a wind sea. It must be understood, however, that the spectral shape, in both frequency and direction space, is not constrained to a particular form. The model will produce directionally sheared and multiple peak spectra. The model is not constrained to have a particular directional spread; indeed, the directional spreads can be very narrow or quite broad depending upon the nature of the wind field and the presence of swell.

2. Since there is little scientific concensus on the physics to be incorporated into a hurricane model, a significant effort was made to verify the model for hurricane wave conditions. The principal adjustable coefficients in the model were set to make the model reproduce the growth rate curves in the Sea Wave Modeling Project (SWAMP) (SWAMP Group 1985) (Figure D1) and spectral shapes of the JONSWAP/TMA/Pierson-Moskowitz type. The wind model was run, the results input to the wave model and the results compared with wave observations. Hurricanes simulated included Camille, Frederic, Carmen, Edith, Gloria, Belle, and tropical storm Delia. Wave observations from depths of 100 m or more to as little as 6.5 m were used for comparison. Figure D2

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* See References at the end of the main text.

indicates the comparison of the maximum predicted and observed significant wave heights, and Figure D3 indicates the corresponding periods. Typically, the maximum values occurred within an hour of the measured values. For the maximum conditions, the differences were within about 10 percent for height and 15 percent for period. Given the broadness of some of the wave spectra, the wider difference in period may simply be due to the statistical uncertainties in the spectral values. Hurricane Camille is the best-documented extreme hurricane to strike the United States. The Ocean Data Gathering Program (ODGP) collected data from three oil platforms that experienced significant wave heights from 7 to almost 14 m. The site at 29° N, 88.75° W was very close and to the right of eye passage. The other stations were to the left of eye passage. Simulations of the storm (Figure D4) show that the model matches the general pattern of wave height, growth, and maximum recorded conditions. The cross bars in Figure D4 indicate the range of wave heights reported by different analysis of the same gage data. For the 29° N, 88° W site, the hindcasts run slightly higher than the observations, but it should be noted that the gage broke and it is not clear what the actual maximum was. Figure D5 provides examples of observed and simulated frequency spectra.

3. Hurricane Carmen was a severe hurricane that struck the south coast of Louisiana. The hindcasts replicated the general trend of the storm at gage sites east and west of eye passage, with the exception that the model at the site nearest eye passage underpredicted waves after the eye of the storm had passed onto land. The hindcast wind field at the site had a distinct decrease in wind velocities associated with the decay of the eye over land, and the model reacted accordingly. The wind instrument at the platform did not work so there is no information on whether the winds actually decreased. As the storm passes over land, it may well be possible that the portion remaining over water may not decay as rapidly as the region near the eye. This should be an area for future research. A comparison of the directional spectrum reported by Forristall, Ward, and Cardone (1980) is given in Figure D6.

4. Hurricane Frederic crossed the coast near Mobile Bay. Hindcasts (Figure D7) of the storm indicate that points surrounding the gage site bracket both the height and wave direction curves at the gage. Plots of hindcast data are made only up to the point that the gage malfunctioned.

5. Hurricane Belle was a moderately strong hurricane on the Atlantic coast. Plots of the wave height history (Figure D8) and frequency spectra,

(Figure D9) indicate that the model represented the general pattern of the storm.

6. Hurricane Gloria was the strongest storm passing close to the US Atlantic coastline in the 1980's. Simulations of the storm were made, Hubertz, Abel, and Jensen (1988) and Jensen, Vincent, and Abel (1987) including a higher resolution nearshore grid. The wave height histories at 18-m depth (Figure D10) were computed with the time dependent model, the 6-m depth time-histories of height and direction. Figures D11 and D12 were made with a steady-state transformation of the hindcast data. The general magnitude of the storm wave heights were well predicted. Wave direction was within 10 deg. The hindcasts slightly lagged the storm observations, and there was a slight tendency for overprediction after the eye passed. Since this represents a case where a substantial portion of the storm was overland, but not the eye region, it may be indicative of an inability to correctly specify the hurricane wind field in cases where the storm has a significant interaction with land.

7. Hurricane Edith moved northeastward along the Texas coast and crossed land in southwest Louisiana. Figure D13 provides a comparison of the hindcast and observed waves at gage sites nearest eye crossing. Comparison of predicted and observed winds indicates that the winds were underpredicted at the peak of the storm, which may account for the 1-m underprediction by the model.

8. The conclusion reached was that the model reproduced the general magnitude and characteristics of the storms observed without site-specific tuning. Although in individual cases improvements in the verifications can be obtained by tuning the wind or slightly altering the track of the storm, within the known variability of these parameters, it was decided to accept the verifications as a sufficient indication of the quality of the model, recognizing that in many historical storms sufficient information would not be available to allow more specific tuning.

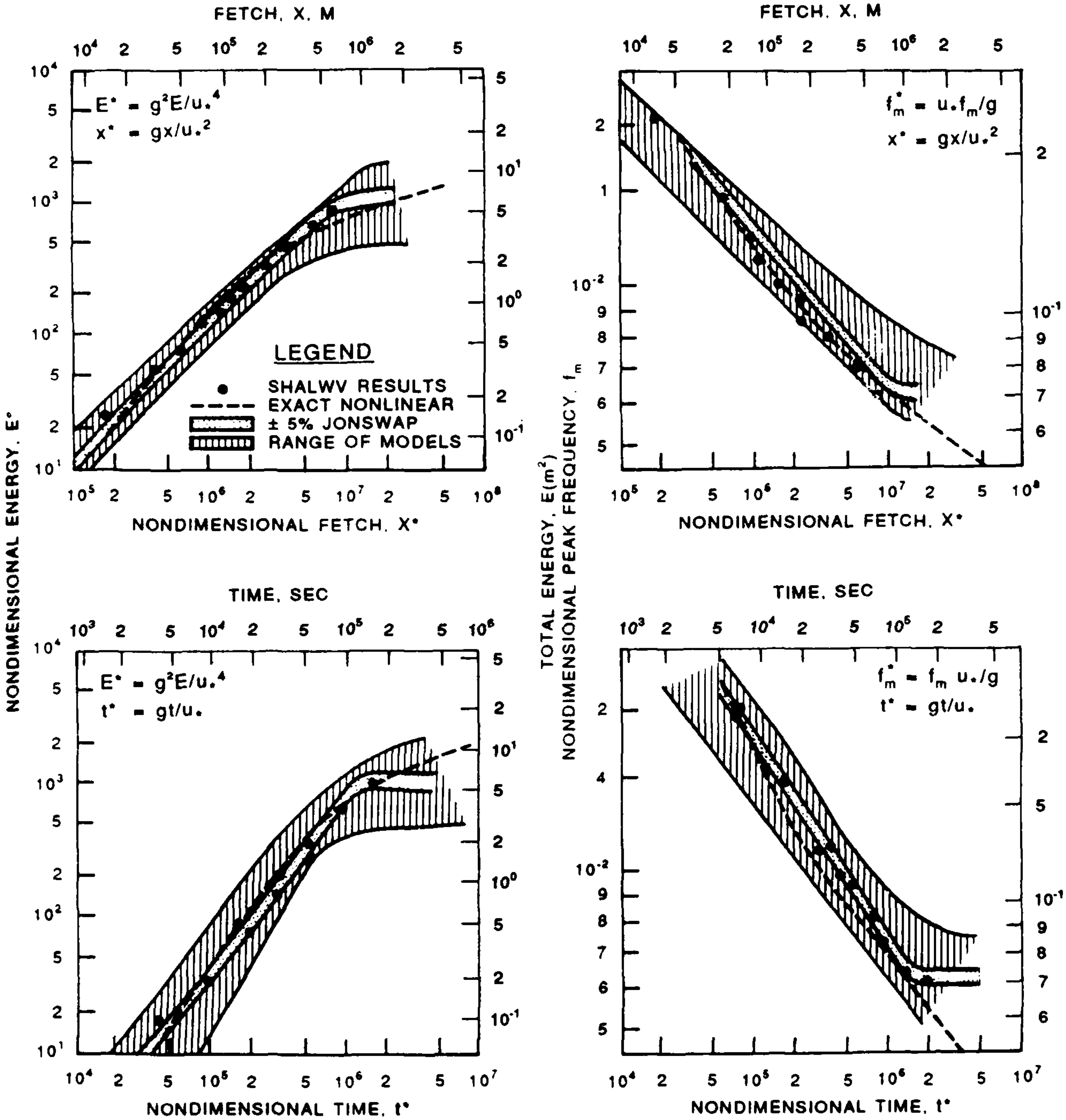



Figure D1. Nondimensional wave growth versus nondimensional fetch and time for different models

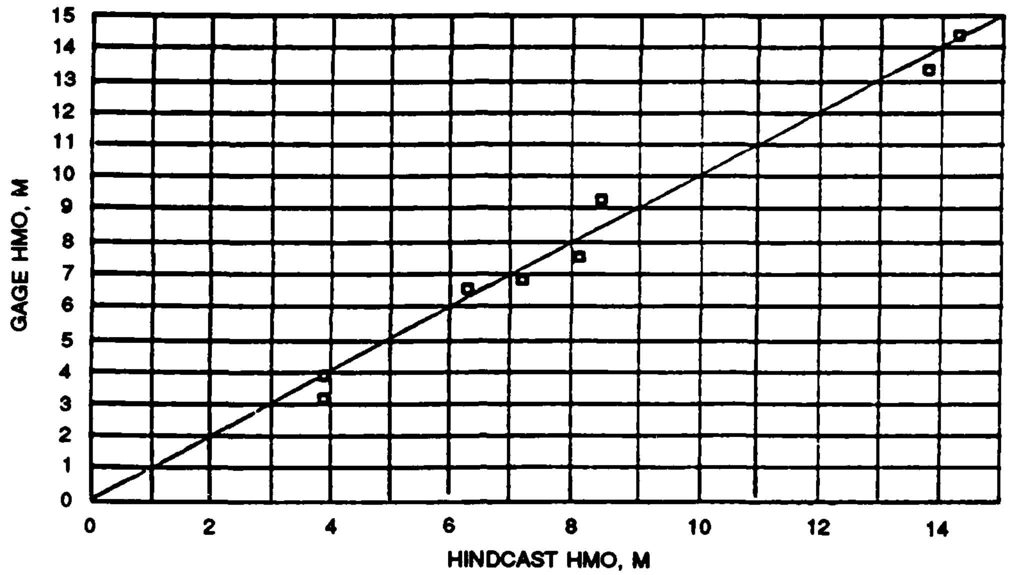



Figure D2. Hindcast wave height versus measured wave height for the tropical storms discussed in Jensen, Vincent, and Abel (1987)

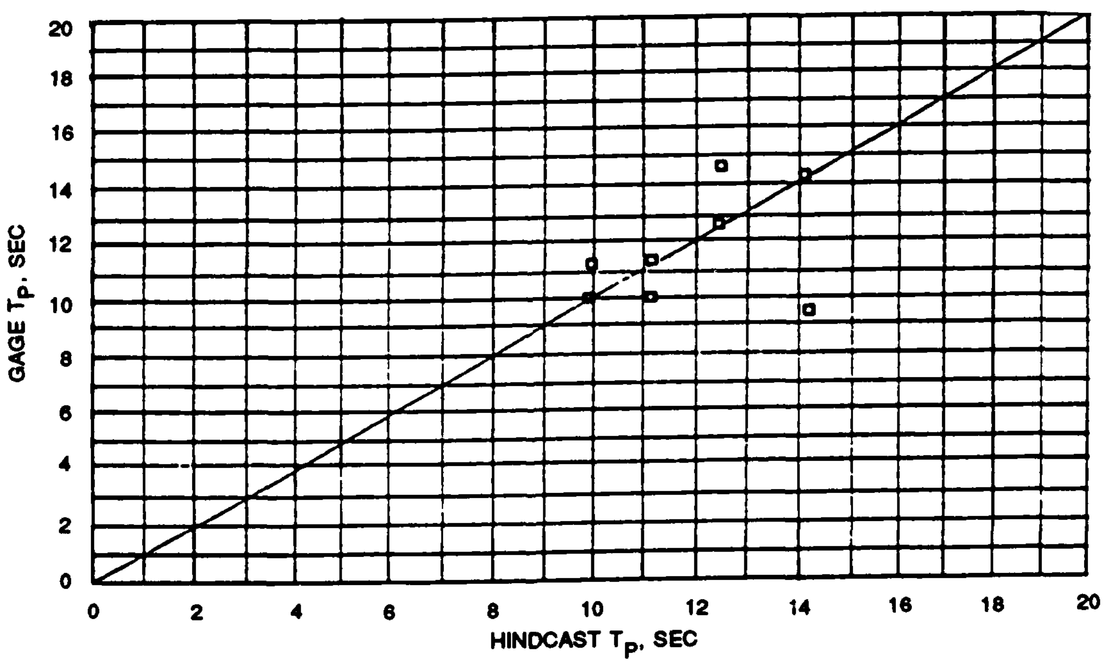



Figure D3. Hindcast wave period versus measured wave period for the tropical storms discussed in Jensen, Vincent, and Abel (1987)

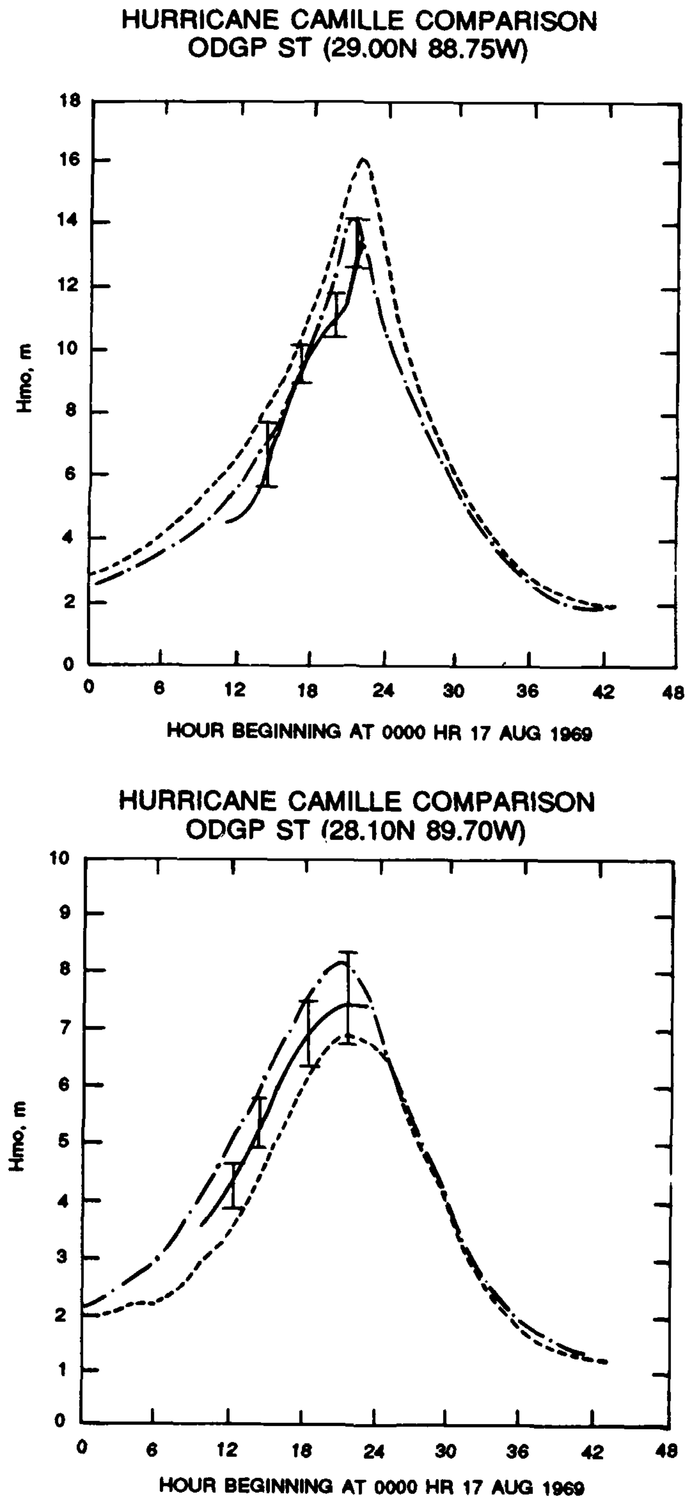



Figure D4. Comparison of measured (solid lines) and modeled (broken lines) wave height during Hurricane Camille at two different sites

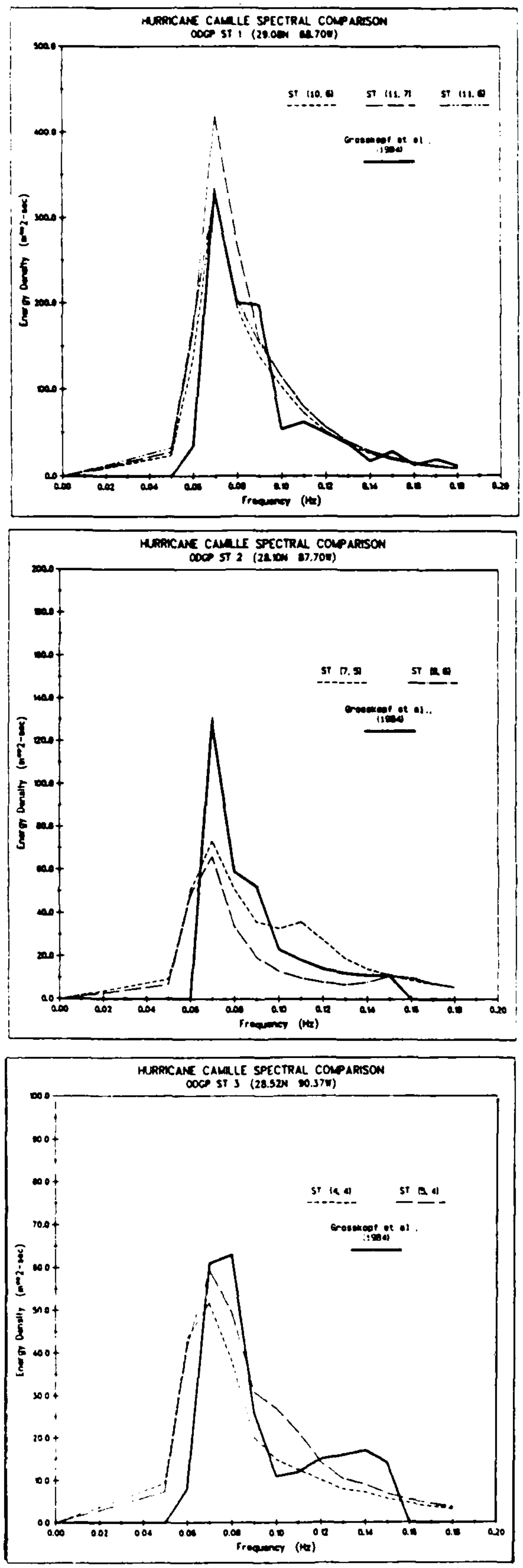



Figure D5. Comparison of measured and modeled wave spectra for maximum wave conditions during Hurricane Camille at three different sites

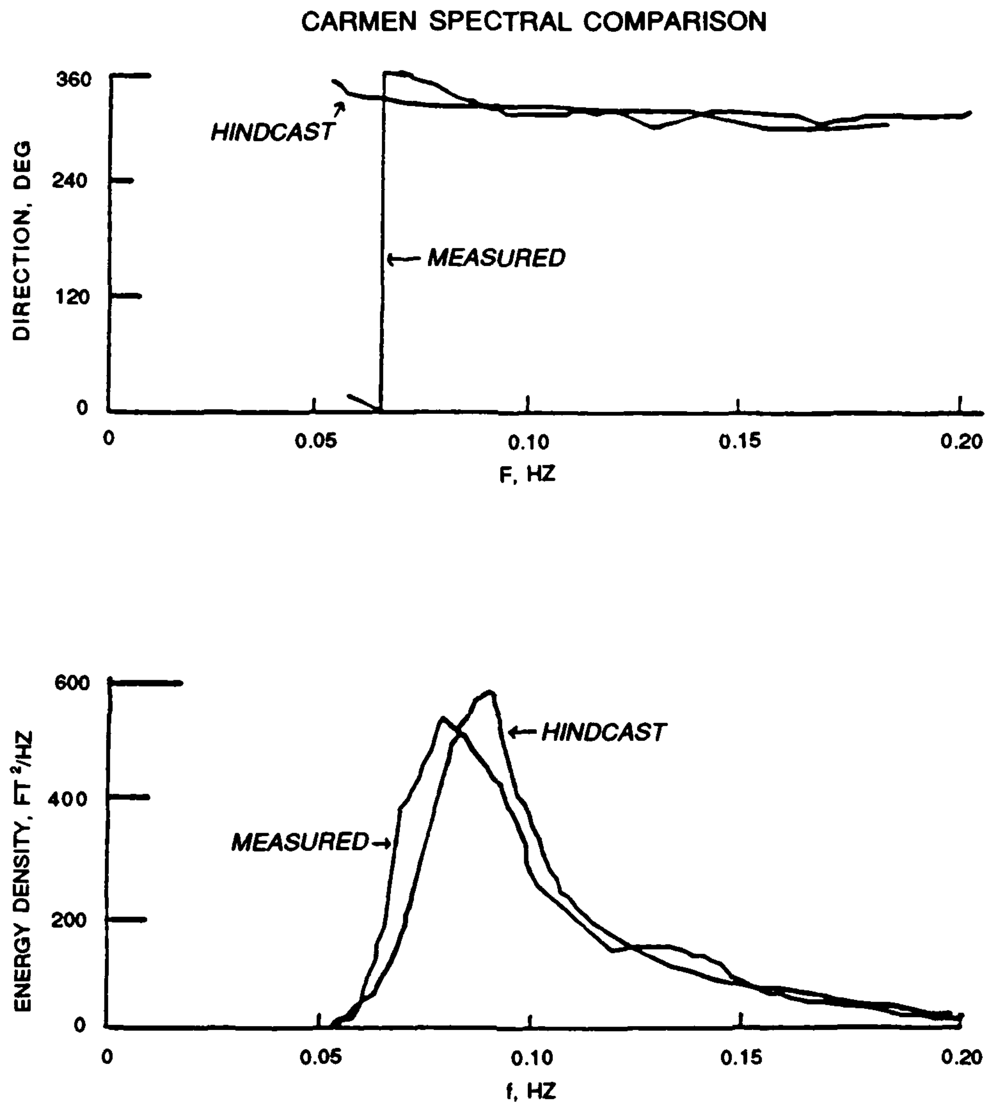
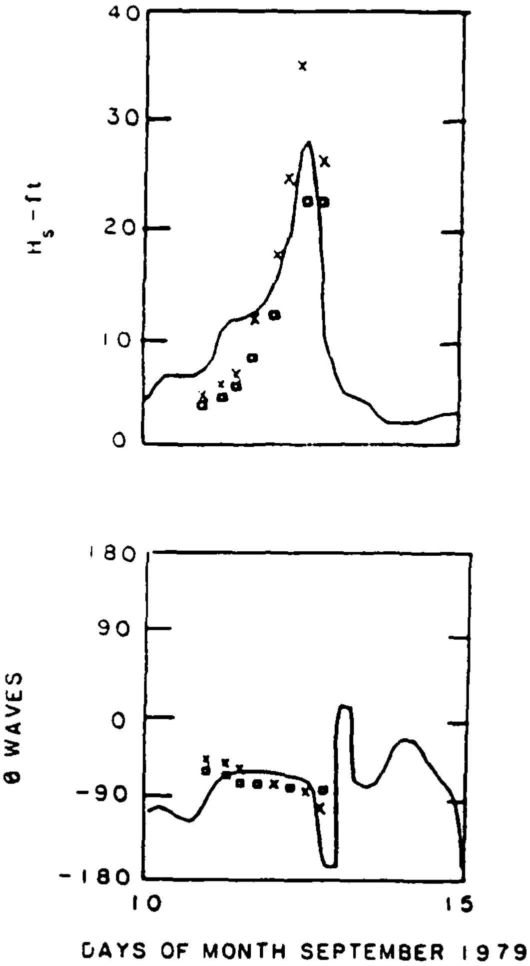



Figure D6. Comparison of measured and modeled wave spectra and direction for Hurricane Carmen




WAVE STAFF TAGLINE
BROKEN
9/12/79 to 9/23/79

LEGEND

x AT 28.5°N, 88.5°W

□ AT 29.0°N, 89.0°W

—— HURRICANE FREDERIC

COGNAC LOCATED AT
28°47' 27" N,
89°3' 22" W

Figure D7. Comparison of measured and modeled wave height and direction during Hurricane Frederic

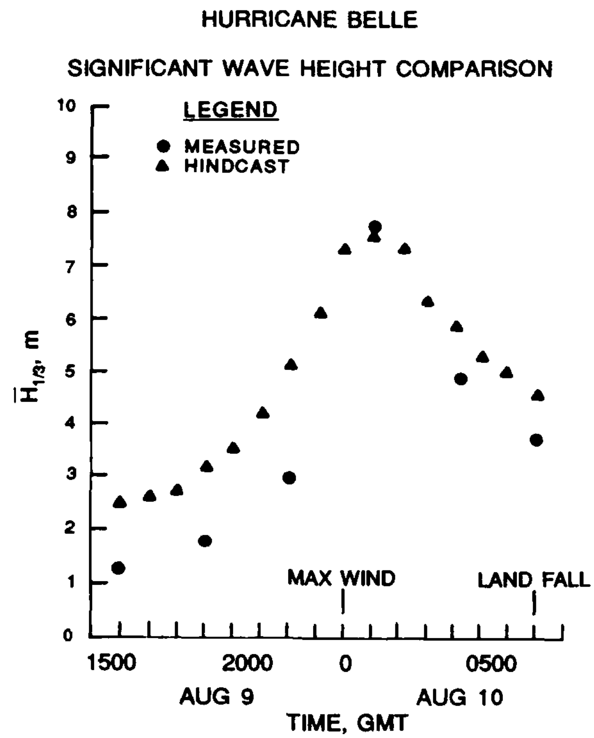



Figure D8. Comparison of measured and modeled wave height during Hurricane Belle at ocean data buoy EB 41 off the coast of New Jersey

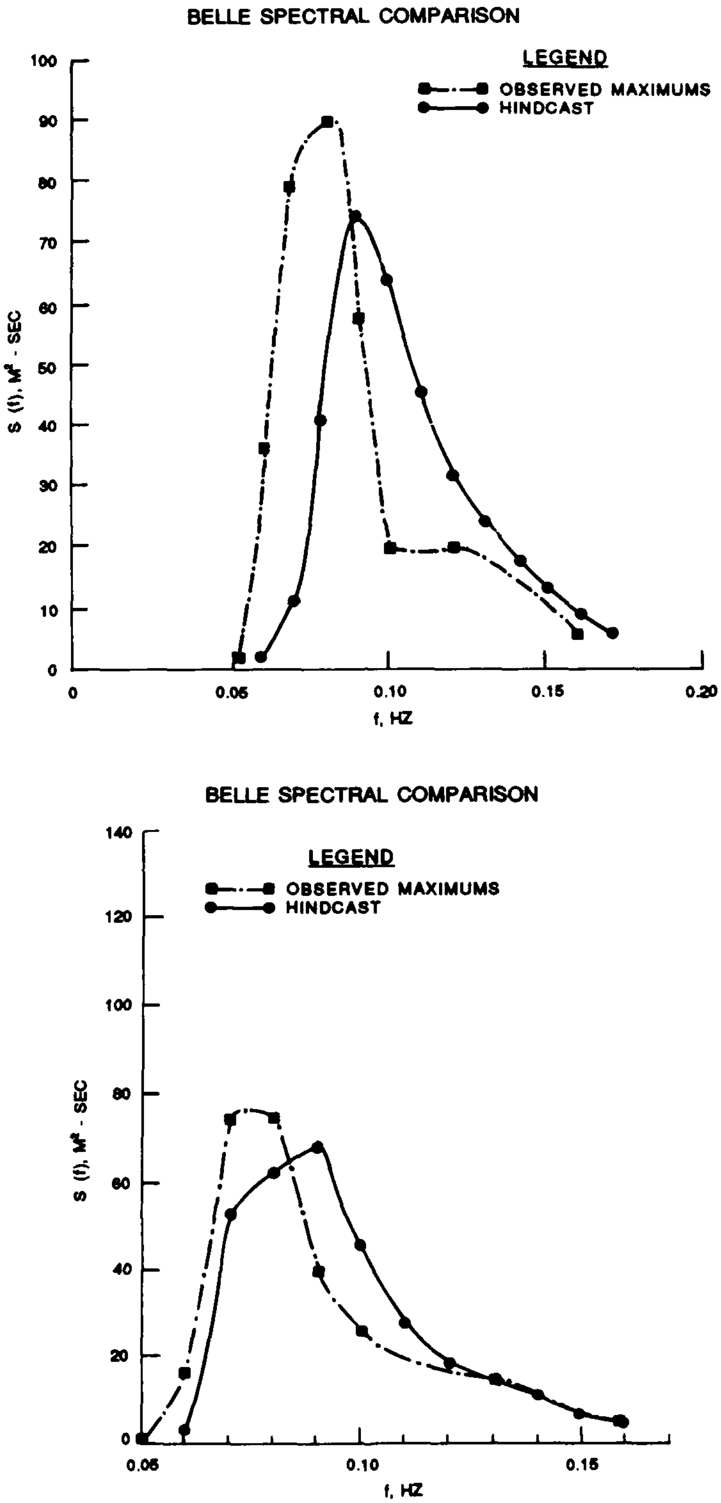



Figure D9. Comparison of measured and modeled wave spectra for Hurricane Belle at ocean data buoy EB 41 off the coast of New Jersey and ocean data buoy EB 15 off the coast of South Carolina

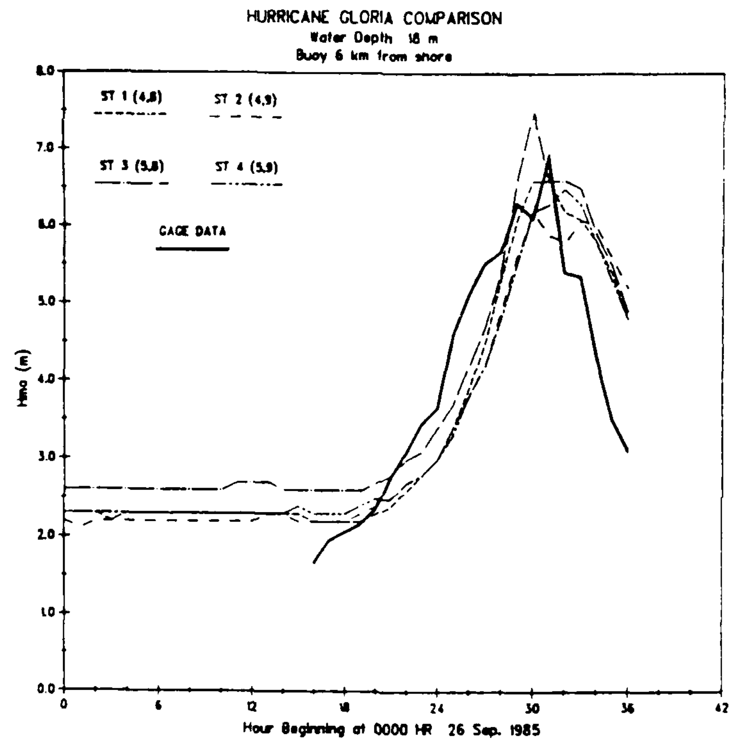



Figure D10. Comparison of measured and modeled wave height during Hurricane Gloria offshore of North Carolina

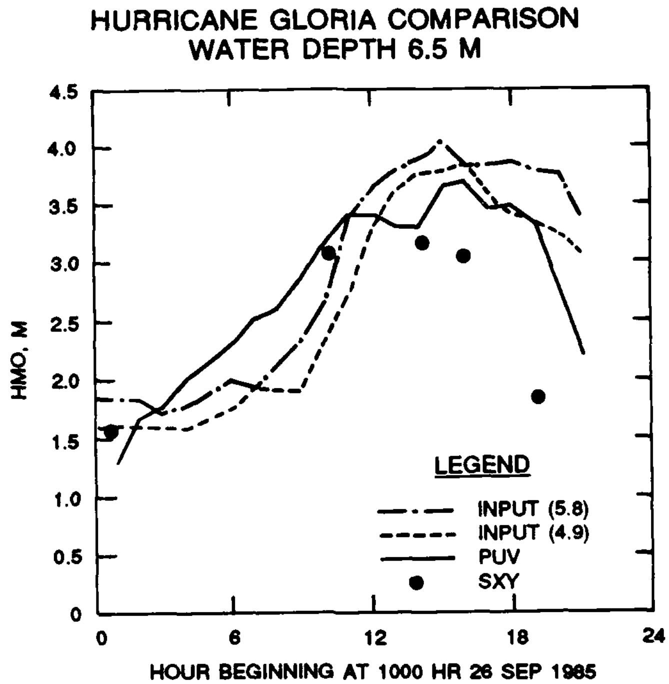



Figure D11. Comparison of measured and modeled wave height during Hurricane Gloria at Duck, North Carolina

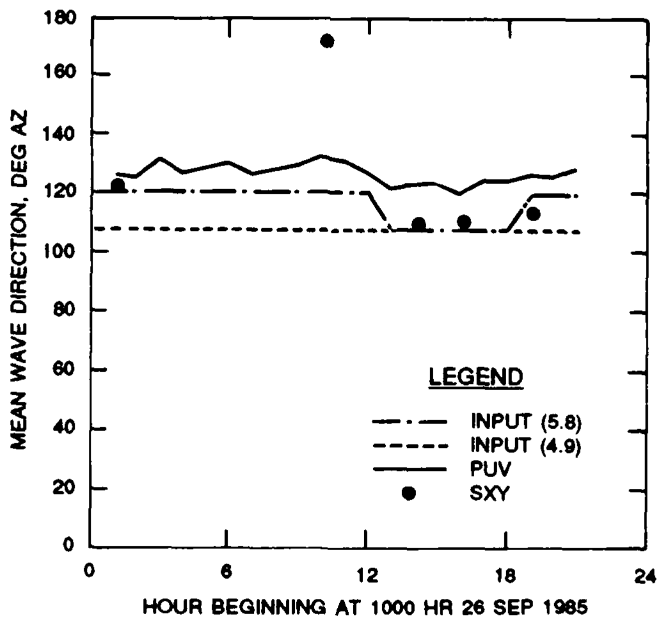
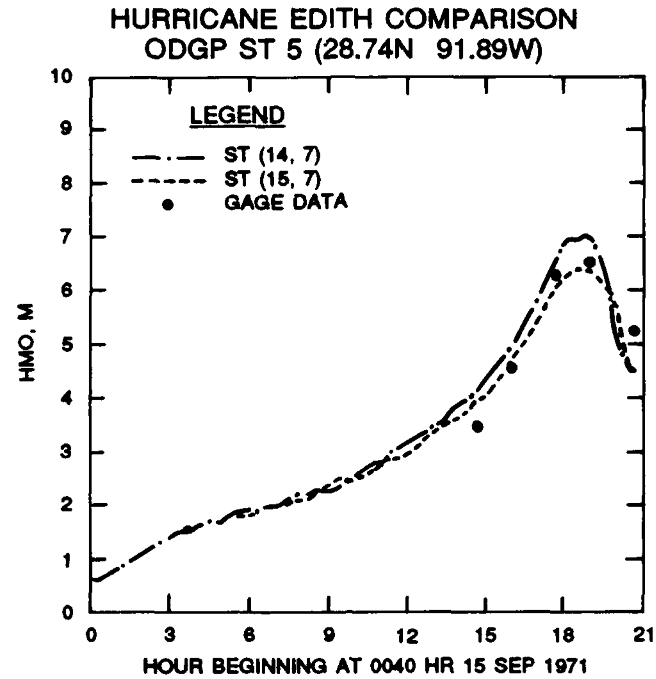



Figure D12. Comparison of measured and modeled wave direction during Hurricane Gloria at Duck, North Carolina



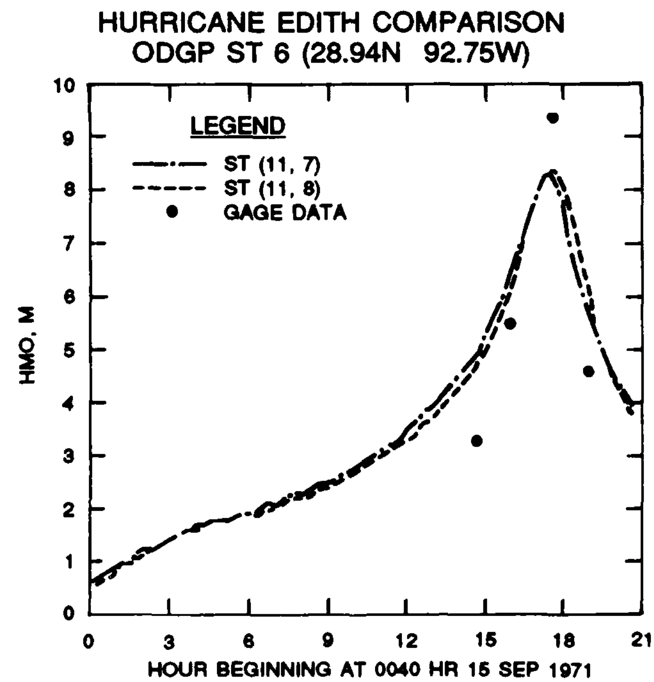




Figure D13. Comparison of wave height during Hurricane Edith at two sites in the Gulf of Mexico

# SUPPLEMENTARY

# INFORMATION

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
3909 HALLS FERRY ROAD
VICKSBURG, MISSISSIPPI 39180-6199

REPLY TO
ATTENTION OF

ERRATA



**Errata Sheet**

**For**

**WIS Report 19**

The attached table of wave heights at various return periods for locations along the Atlantic and Gulf of Mexico coastlines is provided as an addendum to Appendices A and B of:

Abel, C. E., B. A. Tracy, C. L. Vincent, and R. E. Jensen. 1989. "Hurricane Hindcast Methodology and Wave Statistics for Atlantic and Gulf Hurricanes from 1956-1975," USAE Waterways Experiment Station, 3909 Halls Ferry Rd., Vicksburg, MS 39180-6199.

The values in the attached table were calculated using the latest Coastal Engineering Research Center (CERC) procedure which is the Extremal Significant Wave Height Analysis module in the Automated Coastal Engineering System (ACES) package. This module is available in version 1.05 of the ACES package which can be obtained from:

US Army Engineer Waterways Experiment Station
ATTN: CEWES-IM-MI-S
3909 Halls Ferry Road
Vicksburg, MS 39180-6199
(601-634-2571)

It is believed that this procedure gives more realistic values, especially at some locations where the previous procedure gave very large values.

Note that the section on Statistical Analysis in WIS Report 19 and results in Figures 19 and 20 are not consistent with the new procedure for calculating confidence intervals as described on pages 1-3-4,5 of the ACES Technical Reference Manual Version 1.05.

Wave Information Studies (WIS) - Addendum to WIS Report 19:
"Hurricane Hindcast Methodology and Wave Statistics for Atlantic and Gulf Hurricanes from 1956 - 1975"
Return Period Significant Wave Heights (m) for WIS Stations Using Fisher-Tippett Type 1 Distribution

**Atlantic**

| Return Period (years): Station | 5 | 10 | 20 | 50 |
|---|---|---|---|---|
| 1 | 5.6 | 6.5 | 7.3 | 8.4 |
| 2 | 6.0 | 6.8 | 7.7 | 8.7 |
| 3 | 5.9 | 7.0 | 8.0 | 9.3 |
| 4 | 4.5 | 5.4 | 6.3 | 7.4 |
| 5 | 5.5 | 6.5 | 7.5 | 8.9 |
| 6 | 6.2 | 7.2 | 8.1 | 9.4 |
| 7 | 6.3 | 7.3 | 8.2 | 9.5 |
| 8 | 4.8 | 5.9 | 7.0 | 8.4 |
| 9 | 5.7 | 6.8 | 7.9 | 9.3 |
| 10 | 5.6 | 6.6 | 7.7 | 9.0 |
| 11 | 6.7 | 7.7 | 8.7 | 10.1 |
| 12 | 6.6 | 7.7 | 8.7 | 10.1 |
| 13 | 5.1 | 6.2 | 7.2 | 8.6 |
| 14 | 6.0 | 7.1 | 8.2 | 9.7 |
| 15 | 6.9 | 8.0 | 9.0 | 10.4 |
| 16 | 6.5 | 7.7 | 8.8 | 10.2 |
| 17 | 6.3 | 7.3 | 8.3 | 9.6 |
| 18 | 5.1 | 6.3 | 7.6 | 9.1 |
| 19 | 5.7 | 6.8 | 7.9 | 9.3 |
| 20 | 6.1 | 7.2 | 8.2 | 9.5 |
| 21 | 6.6 | 7.6 | 8.7 | 10.0 |
| 22 | 6.7 | 7.8 | 8.8 | 10.2 |
| 23 | 4.1 | 4.9 | 5.7 | 6.7 |
| 24 | 5.0 | 5.9 | 6.8 | 7.9 |
| 25 | 6.0 | 7.0 | 8.0 | 9.3 |
| 26 | 6.7 | 7.9 | 9.0 | 10.5 |
| 27 | 4.8 | 5.7 | 6.6 | 7.7 |
| 28 | 4.8 | 5.6 | 6.4 | 7.5 |
| 29 | 5.6 | 6.6 | 7.5 | 8.7 |
| 30 | 4.7 | 5.3 | 5.8 | 6.5 |
| 31 | 5.6 | 6.6 | 7.6 | 8.9 |
| 32 | (4.2) | (4.2) | (4.2) | (4.2) |
| 33 | 5.1 | 5.8 | 6.5 | (6.6) |
| 34 | 6.5 | 7.7 | 8.8 | 10.2 |
| 35 | 6.4 | 7.5 | 8.5 | 9.9 |
| 36 | 6.8 | 7.9 | 9.0 | 10.4 |
| 37 | 7.6 | 9.0 | 10.3 | 11.9 |
| 38 | 8.3 | 9.8 | 11.3 | 13.2 |
| 39 | 9.2 | 10.9 | 12.5 | 14.8 |
| 40 | 9.3 | 11.0 | 12.7 | 14.9 |
| 41 | 5.5 | 6.3 | (6.6) | (6.6) |
| 42 | 7.0 | 8.2 | 9.5 | 11.1 |
| 43 | 7.6 | 9.0 | 10.3 | 12.1 |
| 44 | 9.2 | 10.9 | 12.6 | 14.8 |
| 45 | 9.1 | 10.8 | 12.4 | 14.5 |
| 46 | 4.6 | 5.3 | (5.4) | (5.4) |
| 47 | 6.5 | 7.9 | 9.2 | 10.9 |
| 48 | 7.7 | 9.2 | 10.7 | 12.6 |
| 49 | 6.5 | 7.8 | 9.1 | 10.8 |
| 50 | 4.6 | 5.3 | (5.4) | (5.4) |
| 51 | 5.6 | 6.6 | 7.5 | 8.7 |
| 52 | 7.8 | 9.3 | 10.8 | 12.6 |
| 53 | 8.5 | 10.3 | 12.0 | 14.1 |
| 54 | 6.1 | 7.4 | 8.6 | 10.2 |
| 55 | 6.0 | 7.4 | 8.7 | 10.5 |
| 56 | 7.0 | 8.7 | 10.3 | 12.4 |
| 57 | (4.2) | (4.2) | (4.2) | (4.2) |
| 58 | 6.5 | 7.9 | 9.3 | 11.0 |
| 59 | 6.0 | 7.7 | 9.3 | 11.4 |
| 60 | 6.7 | 8.4 | 9.9 | 12.0 |
| 61 | 8.3 | 10.3 | 12.1 | 14.5 |
| 62 | 6.3 | 8.0 | 9.6 | 11.6 |
| 63 | 4.5 | 5.4 | (5.4) | (5.4) |
| 64 | 5.2 | 6.1 | 6.9 | (7.2) |
| 65 | (2.4) | (2.4) | (2.4) | (2.4) |
| 66 | 4.2 | (4.2) | (4.2) | (4.2) |
| 67 | 4.3 | 5.3 | (6.0) | (6.0) |
| 68 | 5.6 | 7.5 | 9.3 | 11.7 |
| 69 | 5.5 | 7.8 | 10.0 | 12.8 |
| 70 | 5.3 | 6.9 | 8.4 | 10.3 |
| 71 | 5.4 | 7.1 | 8.8 | 11.0 |
| 72 | 4.2 | 5.8 | 7.4 | 9.4 |
| 73 | 4.6 | 6.8 | 8.9 | 11.6 |

**Gulf of Mexico**

| Return Period (years): Station | 5 | 10 | 20 | 50 |
|---|---|---|---|---|
| 1 | 6.0 | 8.3 | 11.2 | 13.3 |
| 2 | 5.5 | 7.7 | 10.5 | 12.6 |
| 3 | 5.2 | 7.6 | 10.6 | 12.9 |
| 4 | 5.2 | 7.2 | 9.8 | 11.7 |
| 5 | 5.8 | 6.7 | 7.9 | 8.7 |
| 6 | 6.2 | 8.2 | 10.7 | 12.6 |
| 7 | 4.8 | 6.5 | 8.6 | 10.1 |
| 8 | 4.6 | 8.0 | 12.3 | 15.6 |
| 9 | 3.3 | 6.1 | 9.6 | 12.2 |
| 10 | 5.9 | 7.7 | 10.0 | 11.7 |
| 11 | 5.6 | 6.3 | 7.3 | 8.0 |
| 12 | 6.2 | 7.1 | 8.3 | 9.1 |
| 13 | 4.5 | 5.2 | (5.4) | (5.4) |
| 14 | 4.9 | 5.5 | 6.2 | 6.8 |
| 15 | 6.2 | 7.1 | 8.2 | 9.0 |
| 16 | 5.2 | 5.6 | 6.1 | 6.4 |
| 17 | (5.4) | (5.4) | (5.4) | (5.4) |
| 18 * | - | - | - | - |
| 19 | 5.9 | 7.8 | 10.2 | 12.0 |
| 20 | 6.2 | 7.7 | 9.5 | 10.8 |
| 21 | 6.9 | 8.2 | 9.9 | 11.1 |
| 22 | 7.5 | 8.6 | 10.1 | 11.1 |
| 23 | 8.9 | 11.1 | 13.9 | 16.0 |
| 24 | 8.9 | 11.4 | 14.7 | 17.2 |
| 25 | 7.3 | 9.5 | 12.4 | 14.5 |
| 26 | 6.8 | 7.8 | 9.0 | 9.9 |
| 27 | 6.3 | 7.2 | 8.2 | 9.0 |
| 28 | 6.2 | 7.0 | 8.0 | 8.7 |
| 29 | 6.1 | 7.4 | 9.0 | 10.2 |
| 30 | 5.2 | 7.1 | 9.5 | 11.2 |
| 31 | 7.5 | 7.7 | 8.0 | 8.2 |
| 32 | 5.1 | 6.7 | 8.7 | 10.2 |
| 33 | 5.8 | 6.7 | 7.9 | 8.7 |
| 34 | 5.4 | 6.3 | 7.4 | 8.2 |
| 35 * | - | - | - | - |
| 36 * | - | - | - | - |
| 37 * | - | - | - | - |
| 38 * | - | - | - | - |
| 39 * | - | - | - | - |
| 40 * | - | - | - | - |
| 41 | 4.4 | 5.2 | 6.1 | 6.7 |
| 42 * | - | - | - | - |
| 43 * | - | - | - | - |
| 44 | 3.3 | 4.7 | 6.5 | 7.8 |
| 45 | 4.0 | 5.4 | 7.2 | 8.5 |
| 46 | 4.0 | 6.3 | 9.1 | 11.3 |
| 47 | 3.9 | 5.7 | 7.9 | 9.6 |
| 48 | 7.0 | 7.0 | 7.1 | 7.1 |
| 49 | 4.0 | 5.4 | 7.2 | 8.6 |
| 50 | 4.5 | 5.3 | 6.2 | 6.8 |
| 51 * | - | - | - | - |
| 52 | 6.1 | 8.8 | 12.2 | 14.8 |
| 53 | 7.7 | 8.8 | 10.1 | 11.1 |
| 54 | 7.2 | 10.3 | 14.1 | 17.0 |
| 55 | 6.0 | 8.1 | 10.8 | 12.8 |
| 56 | 8.4 | 11.3 | 15.0 | 17.7 |

* Stations that did not include enough waves over 3 meters were not analyzed.

() Wave height limited to 0.6 times water depth.