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Woods Hole Oceanographic Institution

Wind and Wave Climatology on the New England Shelf May 1987 – August 1988

by

Matthew M. Sharpe and Hans C. Graber

February 1990

Technical Report

Funding was provided by the Office of Naval Research through contract Number N00014-86-K-0715 under the University Research Initiative Program.

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May 1987 – August 1988

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Department of Applied Ocean Physics and Engineering

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

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Abstract

Wave power spectra from four waverider buoys on the New England Shelf and wind velocity records from three of those buoys and a fixed platform were analyzed. The data span the period from May 1987 through August 1988. Time series plots of significant wave height, mean wave period and modal (peak) period and distribution histograms of significant wave height, mean frequency and modal frequency are presented for the two buoys nearest to Martha's Vineyard. Time series plots of wind speed and vector velocity and distribution histograms of speed and direction are plotted for one buoy and the platform. For all stations, monthly and seasonal mean and extreme values of significant wave height, mean and modal wave periods, wind speed and mean weighted and unweighted values of wind direction are provided in tabular form. Five and ten year extreme wave height predictions are also calculated.

1 Overview

1.1 Objectives

This technical report provides time series, histograms and extreme value wave height analyses which detail the changing wind conditions and sea states on the New England Shelf. The products in this document are designed to facilitate both qualitative and quantitative interpretation of the data.

Time series in this report are presented on identical scales to allow side-by-side comparison of different data in the same time period. For example, the vector plot of wind velocity can easily be compared with the the significant wave height time series for the same period. In this way, event durations, maximum values, times of steady conditions or rapid change, and other characteristics of interest may be estimated by inspection or their occurrences noted for detailed investigation.

Histograms are provided to approximate the distributions of values for selected parameters.

The 18 month record of significant wave height is evaluated using extreme value analysis and the resulting five and ten year return period wave heights are tabulated.

1.2 Summary of Graphs and Tables

Graphs and tables in this report are described in detail in Section 3, Data Analysis. Data are presented graphically for Martha's Vineyard Buoy, Buzzards Bay Tower and Buoy 44008, the nearest stations to Martha's Vineyard. Tabular information is presented for all stations. The tables and graphs are listed here.

Wave Data Time Series:

- Significant Wave Height (H_s)
- Mean Wave Period ($\overline{T}$)
- Modal (Peak) Wave Period (T_m)

Wave Data Histograms:

- Significant Wave Height
- Mean Frequency ($\bar{f} = 1/\bar{T}$)
- Modal (Peak) Frequency ($f_m = 1/T_m$)

Wind Data Time Series:

- Wind Speed (U_{10})
- Vector Velocity (U_{10} at angle θ)

Wind Data Histograms:

- Wind Speed

- Wind Direction

Wave Data Tables, Monthly and Seasonal Summaries:

- Significant Wave Height
  Minimum, Mean and Maximum
- Mean Wave Period
  Minimum, Mean and Maximum
- Modal Wave Period
  Minimum, Mean and Maximum

Wind Data Tables, Monthly and Seasonal Summaries:

- Wind Speed
  Minimum, Mean and Maximum
- Mean Direction (weighted by speed)
- Mean Direction (unweighted)

Extreme Value Analysis, by Calendar Month:

- Mean Significant Wave Height
- Expected Five Year Extreme Significant Wave Height
- Expected Ten Year Extreme Significant Wave Height

2 Data Sources

2.1 Buoy and Platform Locations

Wave and wind data were recorded at the following stations:

Station Name	Organization	Data Type
Martha's Vineyard Buoy	WHOI	Wave
Buzzards Bay Tower	NODC	Wind
Buoy 44004	NODC	Wave & Wind
Buoy 44008	NODC	Wave & Wind
Buoy 44011	NODC	Wave & Wind

Station locations are given below and are shown in the charts of Figure 1 and Figure 2.

Station Name	Latitude	Longitude	Depth
Martha's Vineyard Buoy	41° 16′ N	71° 02′ W	42 m
Buzzards Bay Tower	41° 24′ N	71° 00′ W	11 m
Buoy 44004	38° 30′ N	70° 36′ W	3231 m
Buoy 44008	40° 30′ N	69° 30′ W	60 m
Buoy 44011	41° 06′ N	66° 36′ W	93 m

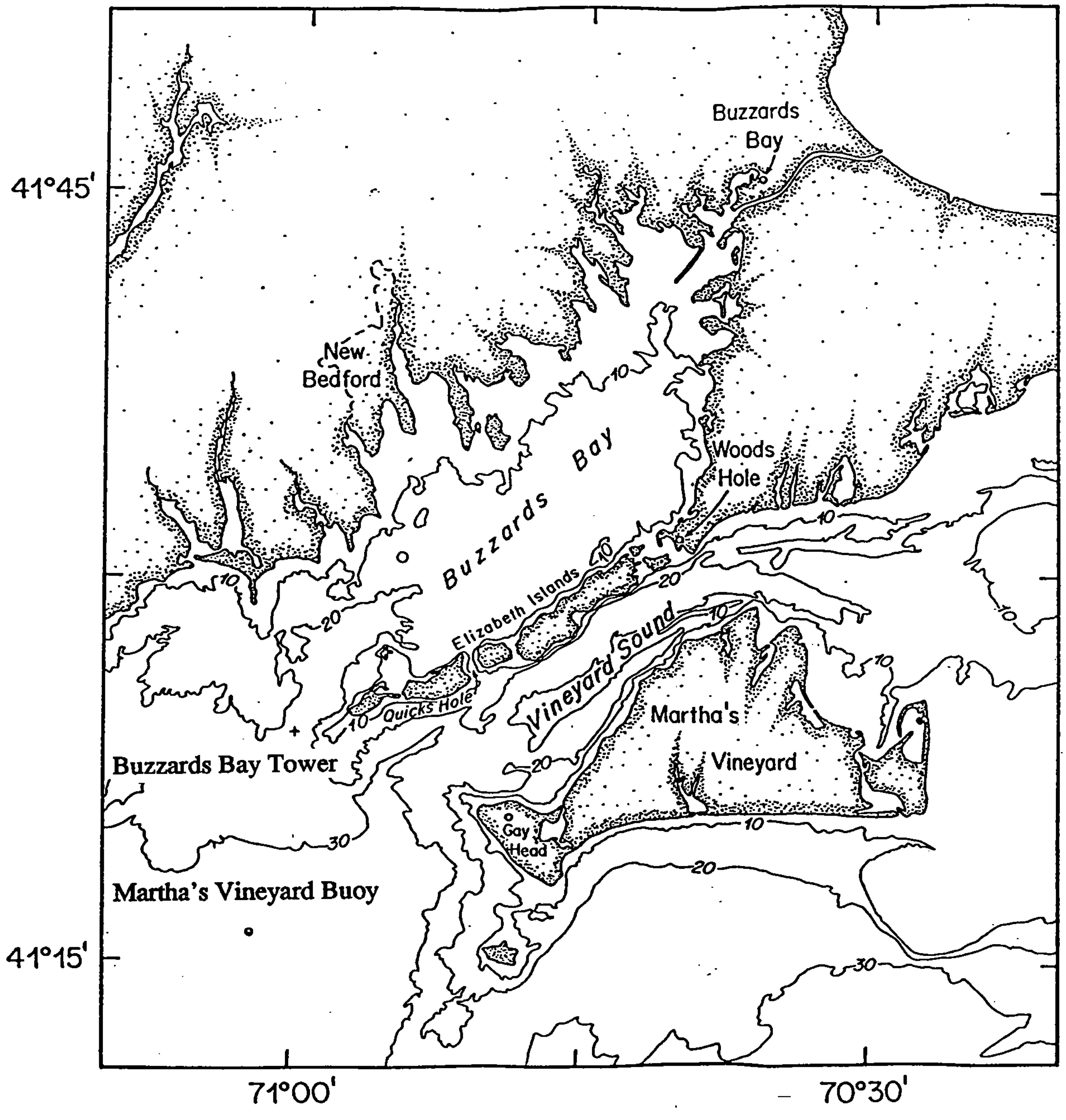

Figure 1: Buoy and Platform Locations Near Buzzards Bay

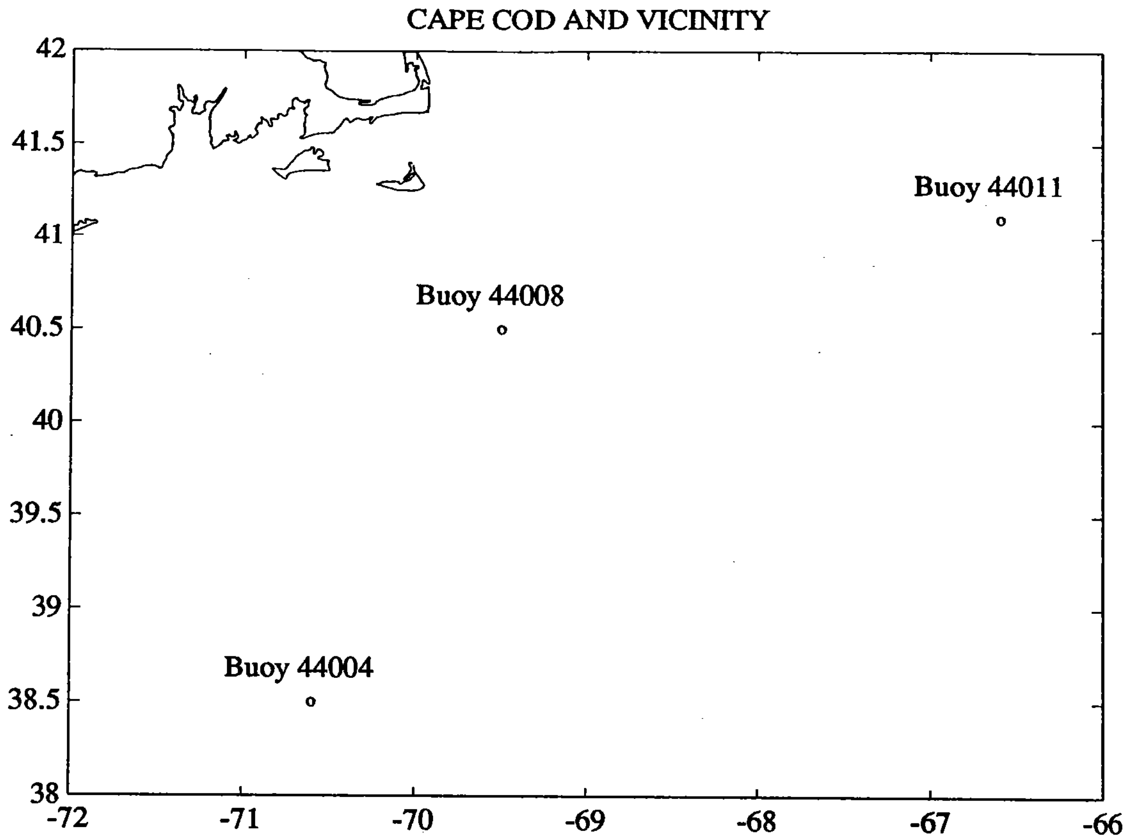

Figure 2: Buoy Locations on the New England Shelf

2.2 Data Formats

2.2.1 NODC Sources

The National Oceanographic Data Center (NODC) waverider buoys sampled sea surface height at a rate of 1.5 Hz during a 20 minute sampling interval. The time series of surface elevations were processed and available as wave energy spectra. Environmental data from the NODC stations were obtained on nine-track tapes in ASCII as Meteorology and Wave Spectrum File 191 format files. See NODC (1986) for a detailed description of the File 191 format and other information about data products available from NODC. These files provided hourly summaries of environmental conditions.

2.2.2 WHOI Sources

The Martha's Vineyard Buoy Telemetry Project was operated by the University Research Initiative Program at WHOI. A general goal of the project is to develop techniques for gathering *in situ* data from the ocean and disseminating them to users in a timely and efficient way. A secondary objective was to test the feasibility of this telemetering technique for long-term surface wave monitoring in coastal waters. The waverider sampled sea surface height at the rate of 2 Hz during sampling intervals of 17 minutes centered on each hour and half hour. The buoy did not have meteorological sensors but was located near the instrumented Buzzards Bay Tower (Figure 2). The Martha's Vineyard Buoy wave data were obtained as summary files and spectrum files. Details of the data acquisition, processing and dissemination are described by Briscoe et al. (1988). The data files contain an environmental summary for each half-hour period.

3 Data Analysis

3.1 Wave Data

3.1.1 Definitions

The n^{th} moment of a continuous spectrum is

$$m_n = \int_0^\infty f^n \, S(f) \, df \tag{1}$$

where $S(f)$ is the spectral density at frequency f and has units of m^2/Hz. For the NODC buoys, using samples of the spectral density at discrete frequencies $S(f_i)$, (1) can be expressed as

$$m_n = \sum_{f_i=f_{min}}^{f_{max}} f_i^n \, S(f_i) \, \Delta f \tag{2}$$

with f_{min}, f_{max} and Δf given in Table 1.

The spectrum files for WHOI's waverider buoy list the spectral energy, E_{f_i}, in each frequency interval, not the energy density, $S(f_i)$. These are related by

$$E_{f_i} = S(f_i) \, \Delta f \tag{3}$$

with $\Delta f = 1/128 \, Hz$ for these records. The spectral energy, E_{f_i}, has units of m^2. For the WHOI buoy, using spectral energy in each frequency interval, (2) can be written as

$$m_n = \sum_{f_i=f_{min}}^{f_{max}} f_i^n \, E_{f_i} \tag{4}$$

Frequency information for the four buoys is listed in Table 1.

Station	f_{min}	f_{max}	Δf	Intervals
Martha's Vineyard	4/128	63/128	1/128	60
Buoy 44004	0.03	0.50	0.01	48
Buoy 44008	0.03	0.40	0.01	38
Buoy 44011	0.03	0.50	0.01	48

Table 1: Low and High Cut-Off Frequencies in Hz for Waverider Buoys.

3.1.2 Data Preparation

Significant wave height, H_s, is derived from the zero'th spectral moment using the following definition:

$$H_s = 4\sqrt{m_0} \tag{5}$$

Significant wave height is conventionally defined to be the average height of the one-third highest waves in a time series. As used here and defined in (5), H_s is also a measure of the total energy of the wave spectrum. These two definitions agree well for narrowband spectra, i.e., for spectra in which most of the energy is concentrated in a narrow range of frequencies, which is typically located around the peaks. Ochi (1982) has explored the agreement of the two definitions for various sea conditions.

Mean wave period, $\bar{T}$, is the reciprocal of the mean wave frequency, $\bar{f}$, and is given by

$$\bar{T} = m_0/m_1 \tag{6}$$

A more correct name for mean frequency, $\bar{f}$, is the centroid frequency of the energy spectrum. See Nath and Yeh (1987) for a discussion of this issue. The mean wave period, $\bar{T}$, as defined in (6), is one measure of the wave period about which energy is concentrated. For the general case of a bimodal or a multi-modal spectrum, $\bar{T}$ may actually fall between spectral peaks in a part of the spectrum with relatively little energy.

The modal (peak) period, T_m, is chosen simply as the frequency corresponding to the largest spectral energy density.

The mean, median, mode, percent above the mode and standard deviation were calculated for the above quantities for each month. In finding the mode for these continuous values, the range of each was divided into appropriately sized bins, and the value of the bin with the most occurrences assigned as the mode.

3.1.3 Presentation

Significant wave height, mean wave period, and modal wave period are plotted as time series of hourly values in bar graph format. Each plot covers one calendar month.

Significant wave height is presented again in monthly histogram format. Each value of significant wave height is assigned to a bin. The distribution of significant wave heights varies with the seasons. To aid in standardizing these histograms, the bins are not based on absolute wave heights but on standard deviation units. Bin zero is centered on the mean and bins are spaced at intervals of 0.2 standard deviation units. Each bar of the histogram represents the percentage of wave heights assigned to that bin.

Modal frequencies, the frequencies corresponding to the peak spectral energy densities, and mean frequencies are also plotted as histograms. Modal frequency is the inverse of modal period:

$$f_m = 1/T_m \tag{7}$$

and mean frequency is the inverse of mean period:

$$\bar{f} = 1/\bar{T} \tag{8}$$

Frequency is used here because the discrete frequencies for which we are given spectral energy densities are equally spaced while their corresponding periods are not. The bins are in units of frequency and the bars again represent the percentage of peak frequencies in each bin.

Summaries of significant wave height, modal wave period and mean wave period are presented in tabular form. The first section of the table for each station shows the minimum value, mean value and maximum value for each quantity during each month. The second part of the table is similar but displays the information over seasons, not months, with the seasons defined as follows:

Spring	March – May
Summer	June – August
Autumn	September – November
Winter	December – February

3.2 Wind Data

3.2.1 Definitions

Wind speed, unless otherwise specified, has been converted from anemometer height to an equivalent ten-meter height assuming neutral stability and is designated U_{10}. Details of this conversion are covered in Section 3.2.2.

Tabulated wind direction is the direction toward which the wind is blowing, expressed in degrees from true north. When plotted, the arrows representing wind direction follow this convention and point downwind.

3.2.2 Data Preparation

The four stations providing wind speed and direction have anemometers at the following heights:

Station	Anemometer Height
Buoy 44004	5.0 m
Buoy 44008	5.0 m
Buoy 44011	5.0 m
Buzzards Bay Tower	43.3 m

The wind speed measured at the instrument height is designated as U_z. The algorithm for conversion to ten-meter reference height, U_{10}, assumes a neutral air column. We can then express U_z in terms of von Karman's constant, κ, the friction velocity, u_*, height in meters, z, and roughness height, z_0,

$$U_z = 1/\kappa \, u_* \ln \frac{z}{z_0} \tag{9}$$

where the friction velocity is related to the ten-meter wind speed through

$$u_* = \sqrt{C_{d10}}\, U_{10} \tag{10}$$

and $\kappa = 0.4$. Empirical values of the drag coefficient C_{d10} are given by Janssen et al. (1987)

$$C_{d10} = \begin{cases} (0.8 + 0.065 U_{10}) \times 10^{-3} & U_{10} \geq 7.5\, m/s \\ 1.2875 \times 10^{-3} & U_{10} < 7.5\, m/s \end{cases} \tag{11}$$

To eliminate the unknown z_0, write one equation for the measured U_z and one for the desired U_{10} in the following form,

$$\begin{aligned} U_z &= 1/\kappa\, u_* \ln z - 1/\kappa\, u_* \ln z_0 & (12) \\ U_{10} &= 1/\kappa\, u_* \ln 10 - 1/\kappa\, u_* \ln z_0 & (13) \end{aligned}$$

and subtract to give,

$$U_z - U_{10} = 1/\kappa\, u_* \ln \frac{z}{10} \tag{14}$$

Substituting (10) for u_* and rearranging gives

$$U_{10} = \frac{U_z}{1/\kappa \sqrt{C_{d10}} \ln \frac{z}{10} + 1} \tag{15}$$

This is non-linear (C_{d10} is a function of U_{10}) and is iterated to solve for U_{10}. Instead of iterating until a convergence criterion is met, a simplified two-step procedure produced errors of less than $0.1\, m/s$ over the full range of wind speeds. The procedure used here is detailed below:

Step 1: Take a first estimate of U_{10} as $U_{43.3} \times 0.83$ or $U_5 \times 1.1$. These coefficients are found to give an acceptable first approximation.

Step 2: Using this value of U_{10}, find C_{d10} using Equation 11.

Step 3: Refine U_{10} using (15) with the new value of C_{d10}.

Step 4: Refine C_{d10} using (11).

Step 5: Find final value of U_{10} using (15).

Wind speed is treated as a scalar for some presentations. In these cases, the mean, mode, median and standard deviation are calculated in the same way as the scalar wave quantities, described in Section 3.1.2.

There are two mean wind directions calculated, an unweighted mean based only upon wind direction, and a mean with directions weighted by the corresponding wind speeds.

The unweighted mean direction is given by

$$\bar{\theta}_{unweighted} = \arctan\{ \frac{\sum_{i=1}^{N} \sin\theta_i}{\sum_{i=1}^{N} \cos\theta_i} \} \tag{16}$$

where θ_i is the wind direction in degrees from true north of the i'th of N measurements.

The weighted mean direction and speed are given by

$$\bar{\theta}_{weighted} = \arctan\{\frac{\sum_{i=1}^{N} U_i \sin\theta_i}{\sum_{i=1}^{N} U_i \cos\theta_i}\} \tag{17}$$

$$\bar{U}_{weighted} = \frac{1}{N}\sqrt{(\sum_{i=1}^{N} U_i \sin\theta_i)^2 + (\sum_{i=1}^{N} U_i \cos\theta_i)^2} \tag{18}$$

where U_i is the wind speed of the i'th measurement.

3.2.3 Presentation

Ten-meter wind speed, U_{10} is plotted as hourly time series in a bar graph format with each plot covering one month. The wind velocity field is plotted as a feather diagram, with vectors originating at four hour intervals along the time axis and pointing in the downwind direction with length equal to U_{10}.

Two histograms are also presented. The first plots the percentage of wind speeds in each bin of width $0.1 m/s$. The other plot is a rose plot or a circular histogram showing the percentage of wind directions in each bin of width 10 degrees. This plot also shows station name and month.

Summaries of wind speed and direction are presented in tabular form. The first section of the table for each station shows the minimum speed, mean speed, maximum speed, mean weighted direction and mean unweighted direction for each month. The second part of the table is similar but displays the information over seasons, not months, with seasons defined as in Section 3.1.3.

4 Wave Height Extreme Value Analysis

4.1 Overview

Estimates of significant wave height five and ten year return values, H_{s5} and H_{s10}, were obtained for each of the four buoys by fitting a Fisher-Tippett Type 1 distribution to the observed distributions of H_s and extrapolating to the required probabilities.

In using extreme value analysis to predict extreme wave heights, it is customary to forecast a 50 or 100 year maximum. The short length of our record, 18 months, precluded forecasting these long return periods but supported the shorter intervals.

4.2 Sampling and Preparation Methods

Extreme value analysis is most easily applied to a series of maximum values taken from fixed time periods of equal length. We used the monthly maxima. The analysis assumes that these data are independent realizations of identically distributed random variables. This requires special preparation because wave heights from different calendar months are not identically distributed. We assume two properties of the distributions:

- Wave heights from different calendar months have different distributions. There is a seasonal trend with a period of one year.
- Wave heights from the same calendar month in different years are from the same distribution.

In order to prepare the data it was necessary to remove the deterministic trend. This was done in two steps. The 18 months of data were reduced to twelve calendar months by combining the data from the same months in different years. The data were then normalized to approximate identical distributions by dividing the maximum significant wave height from each month by the mean of all significant wave heights for that month. While the distribution of significant wave heights is too complicated to normalize by the mean alone, this is a useful first approximation. It is worthwhile to note that Rayleigh distributions may be completely normalized using this technique. A thorough review of extreme value analysis of wave heights is provided by Muir (1986).

4.3 Selection of the Extreme Value Distribution

We selected the Fisher-Tippett Type 1 as the appropriate extreme value distribution. The domain of attraction of an extreme value distribution is the collection of all distributions which have that extreme value distribution as their limiting type. The Fisher-Tippett Type 1 distribution has as its domain of attraction the distributions for which all positive moments exist. This includes the Rayleigh, Weibull, normal and lognormal distributions. Since wave heights are always positive and finite, this distribution is therefore an appropriate choice.

The Fisher-Tippett Type 1 distribution is defined by its cumulative distribution function:

$$P_N = \mathrm{Prob}(H_s < H_{SN}) = \exp\{-\exp[-(H_{SN} - A)/B]\} \tag{19}$$

$$H_{SN} = A + B\{-\ln[-\ln P_N]\} \tag{20}$$

Here, A is a location parameter and B is a scale parameter. H_{SN} is the N year extreme value significant wave height and P_N is the probability associated with the N year return period.

The mean, μ, and variance, σ^2, of this distribution are given by

$$\begin{aligned} \mu &= A + \gamma B && (21)\\ \gamma &= 0.5772\cdots && (22)\\ \sigma^2 &= \pi^2 B^2/6 && (23) \end{aligned}$$

4.4 Fitting the Distribution

The distribution was fit to the data sets using a combination of two methods, the method of moments and maximum likelihood estimation. These and other fitting methods are described in detail by Carter and Challenor (1983).

The method of moments solves for the estimators $\hat{A}$ and $\hat{B}$ by using the sample mean $\bar{x}$ and sample variance from (21) and (23) above. The estimators are:

$$\hat{B} = \frac{\sqrt{6}}{\pi}\sqrt{\frac{\sum[x_i - \bar{x}]^2}{n-1}} \tag{24}$$

$$\hat{A} = \bar{x} - \gamma\hat{B} \tag{25}$$

where $x_i(i = 1, n)$ are the sample values.

Maximum likelihood estimators are obtained by solving the following system of maximum likelihood equations:

$$\sum_{i=1}^{n} \exp\left[-(x_i - \hat{A})/\hat{B}\right] - n = 0 \tag{26}$$

$$\sum_{i=1}^{n} (x_i - \hat{A})\left\{1 - \exp\left[-(x_i - \hat{A})/\hat{B}\right]\right\} - n\hat{B} = 0 \tag{27}$$

The iterative scheme we used combines the methods as follows:

Step 1: Use the method of moments to solve for starting values of the estimators.

Step 2: Solve (26) three times using $\hat{A}$ and the perturbed values $\hat{A} + \Delta$ and $\hat{A} - \Delta$ where Δ is initially assigned the value 0.01. Find the equation with the smallest error and update the value of $\hat{A}$ if necessary.

Step 3: Repeat step 2 using (27) and perturbed values of $\hat{B}$.

Step 4: Repeat steps 2 & 3 until unperturbed values of both estimators give the smallest errors. This procedure changes each parameter with a fixed step size until the errors in (26) and (27) are minimized.

Step 5: Divide Δ by 10.

Step 6: Repeat steps 2 through 5 until until $\Delta < 0.0001$.

4.5 Extrapolating to Predict Maxima

The procedure described above will give the Fisher-Tippett Type 1 distributions of the normalized significant wave heights for each station. The probabilities associated with five and ten year return periods are

$$P_5 = 1 - \frac{1}{5 \times 12} = 0.98333 \tag{28}$$

$$P_{10} = 1 - \frac{1}{10 \times 12} = 0.99167 \tag{29}$$

These probabilities are used in (20) to solve for a five and ten year extreme normalized significant wave height for each buoy. The normalized height is then multiplied by each monthly mean to give a five and ten year extreme wave height for each month for each buoy. These mean, five and ten year expected maxima are listed for each station in Tables 18, 19, 20, and 21.

Information in the extreme value tables should be interpreted as follows. Recall that we removed the seasonal trends to reduce monthly maximum significant wave heights to a common distribution. We then predicted the five and ten year expected maxima for this normalized distribution. The maxima of the normalized distribution may occur during any month and will be associated with actual wave heights which depend on the monthly mean. For example, the extreme five year wave which might happen in March, a stormy month, would be higher than had it happened in August.

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A Time Series Plots and Distribution Histograms

Time series plots and distribution histograms are presented in this appendix in the following sequence:

- Martha's Vineyard Buoy Wave Data
- Buzzards Bay Tower Wind Data
- Buoy 44008 Wave Data
- Buoy 44008 Wind Data

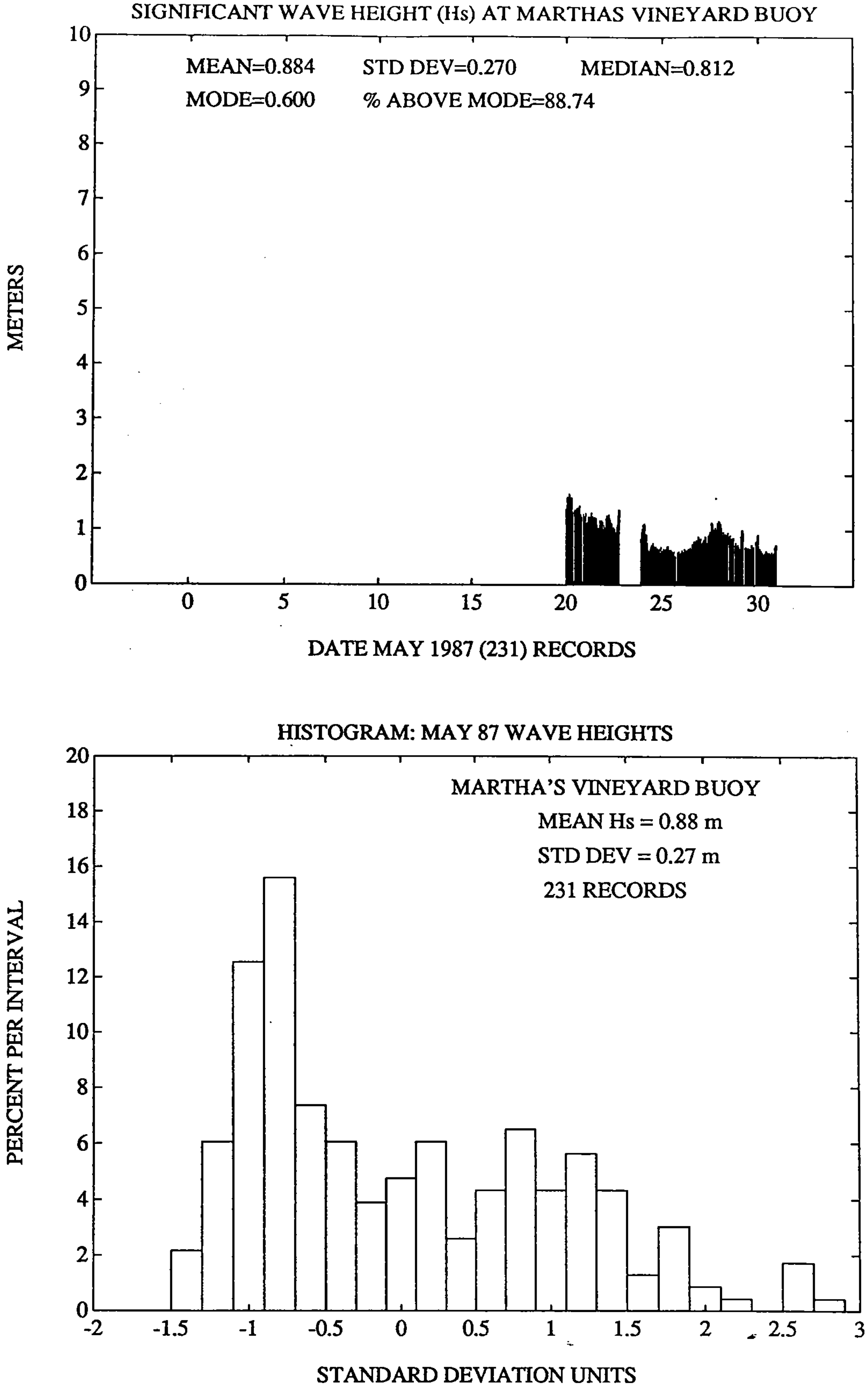
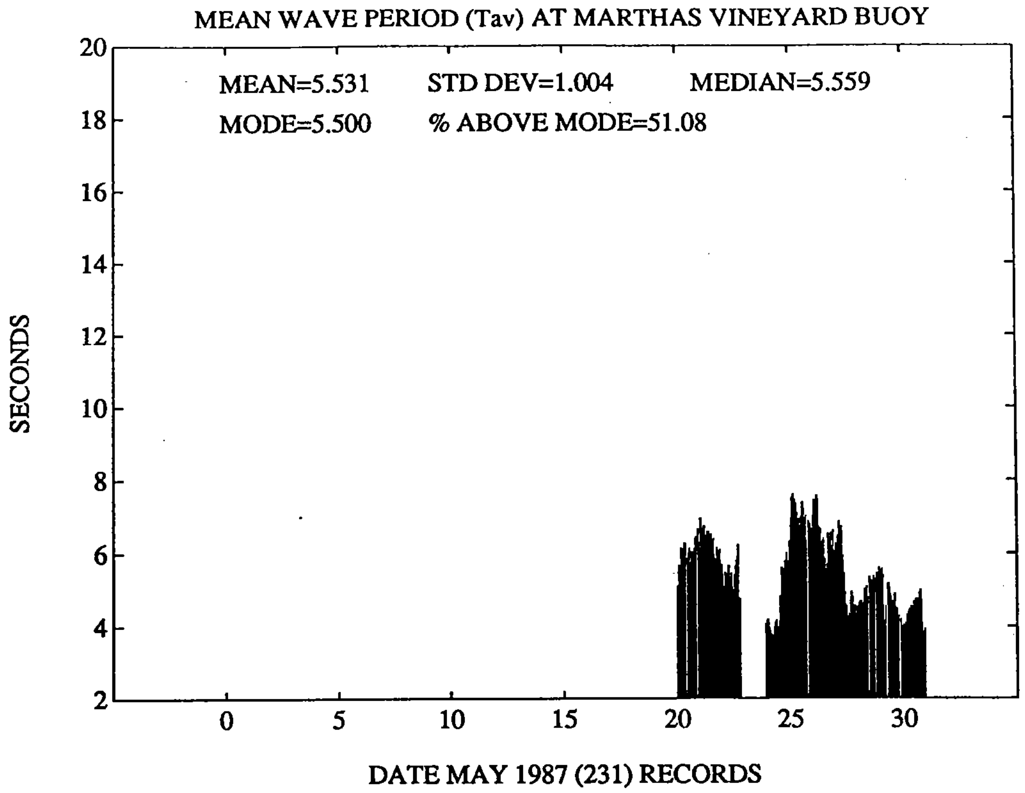


Figure 3: Wave height and period at Martha's Vineyard Buoy, May 1987. (a) Significant wave height time series, and (b) distribution.



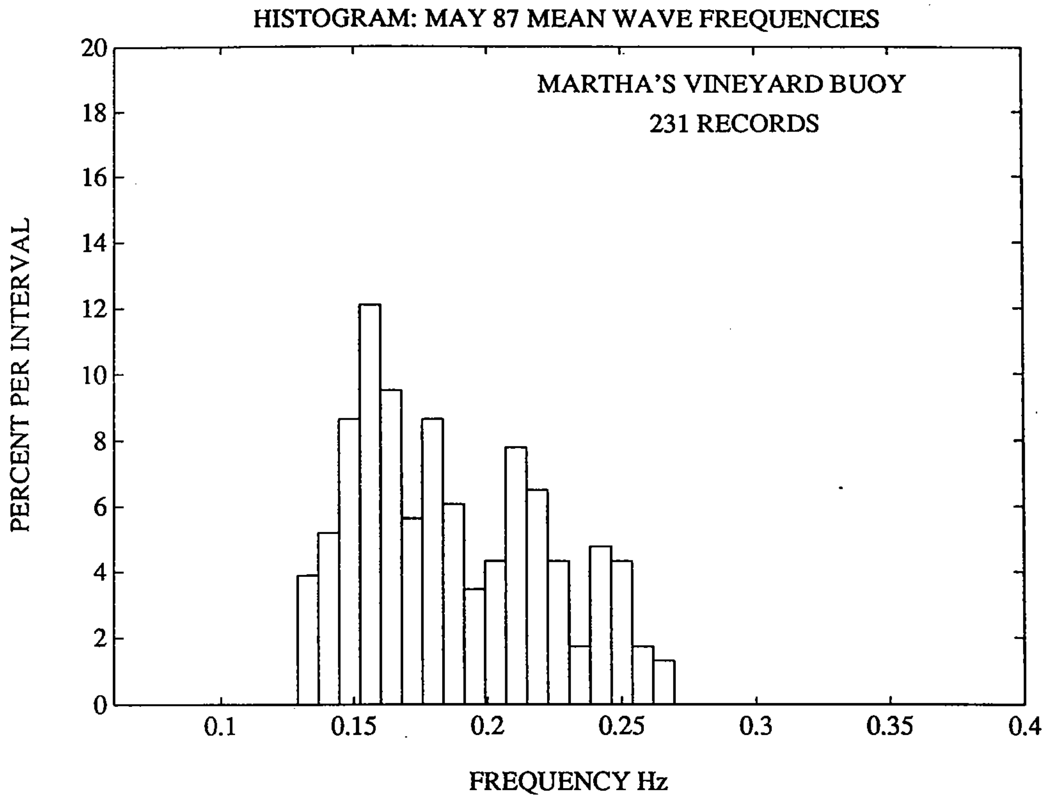
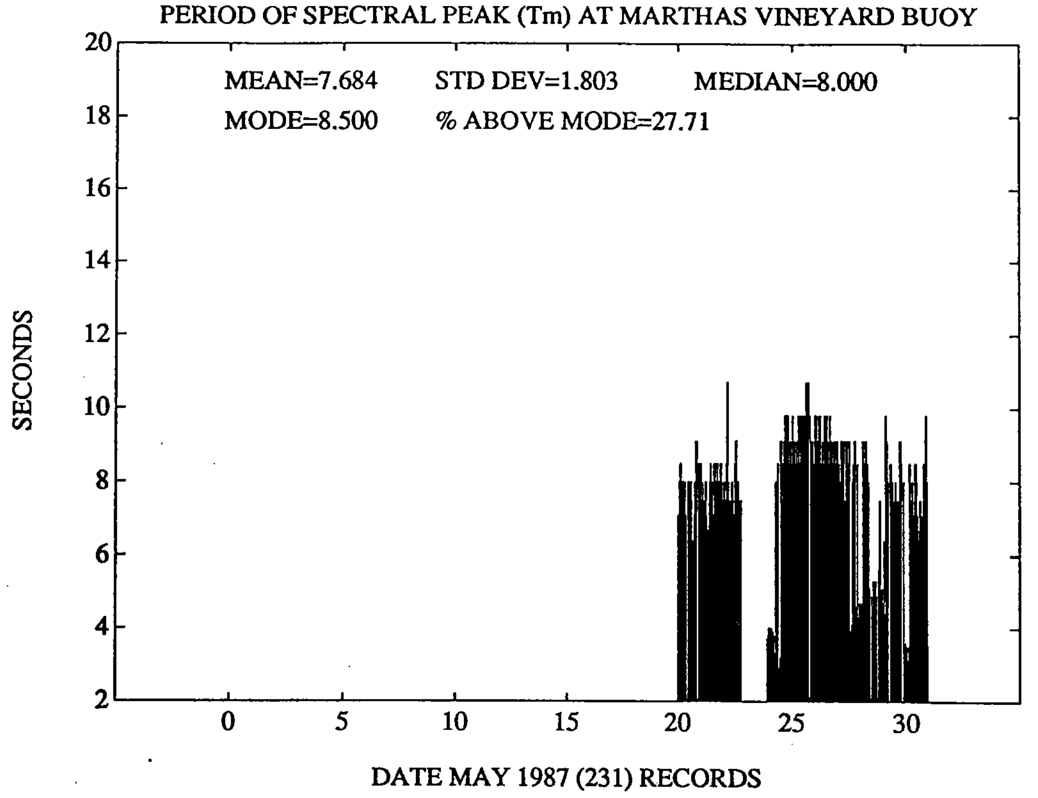


Figure 3: (continued) (c) Mean wave period time series, and (d) mean wave frequency distribution.



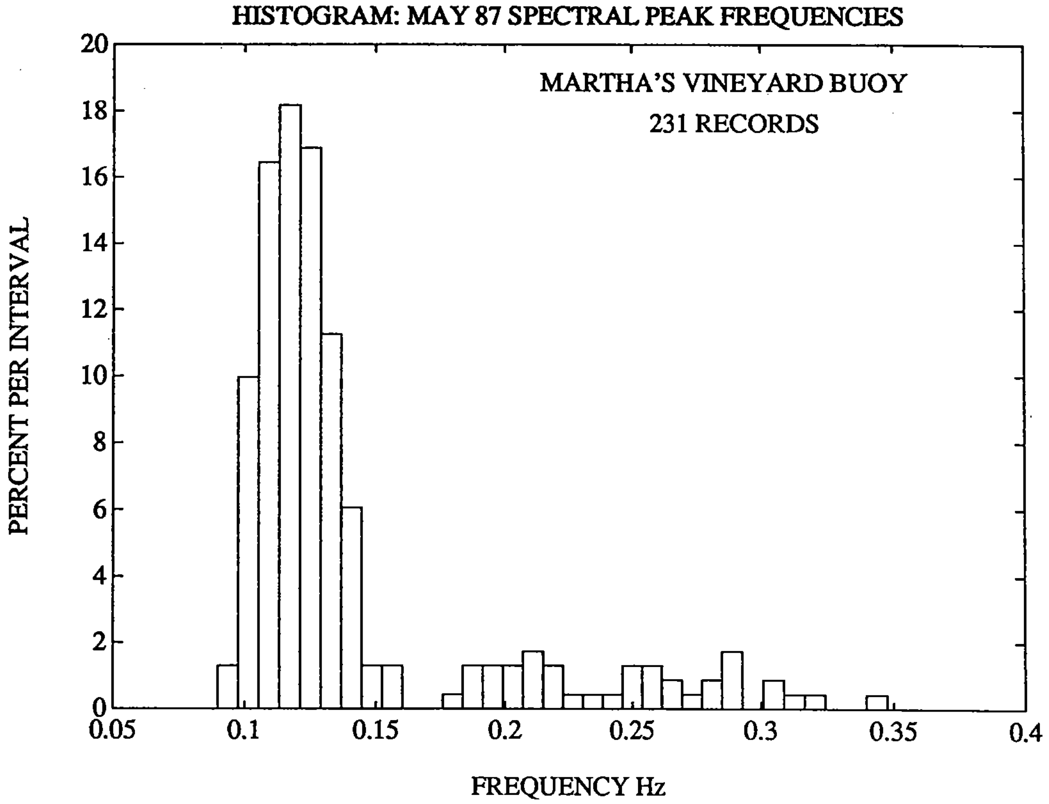


Figure 3: (continued) (e) Spectral peak period time series, and (f) spectral peak frequency distribution.