Comparative Analysis of Winter Storm Episodes and Significant Wave Events: Newport, Oregon 1982-1990

by

N. Daniela Assail

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Abstract

Data on ocean wave height and energy have been gathered via microseismometer at Hatfield Marine Science Center in Newport, Oregon since 1971. Data on wave characteristics at Newport for the winter seasons (November through March) from 1982 to 1990 were analyzed to ascertain any relationships with winter storm events. Newport storm data was compiled in 1991 for winter periods 1981 through 1990. In this study, that storm data is compared to wave data to quantify the spatial and temporal relationships of storms and storm waves occurring at Newport during the winters from 1982 to 1990. Statistical analysis of the two data sets provides evidence to reject the hypothesis that significantly energetic storm waves should precede significant storm events, but does not provide evidence to reject the hypothesis that significantly high waves should precede significant storm events. In general, the significant waves occurred between 28 and 34 hours after the storms had moved onshore. Thus the conclusion was that the wave energy and storm data sets do not correlate, but the correlation between the wave height and storm data sets is questionable. Other important factors for further analysis into climate-wave relations are suggested. In addition, a discourse on basic wind generated wave theory as well as discussion on the use of the microseismometer as a data gathering tool are included.

Introduction

For over one hundred years, sailors aboard ships have observed and reported the characteristics of waves at sea. Millions of observations have accumulated, some of which have been valuable and useable resources to scientists (Changery and Quayle 1987:259). Today, the fact that winds at sea generate ocean waves is well accepted, but questions concerning the exact mechanism of energy transfer still remain. In 1925, geophysicist H. Jeffreys first proposed a theory of how energy is transferred from wind to water (Jelley 1989:148). Since then, much work has been done not only on relating wind and water, but also on the interrelationship of wind driven waves, wave heights, and subsequent coastal erosion. This study will address the relationship between climatic storm events and significant ocean wave events at one station, Newport, Oregon as a step toward better understanding the wave climates of the central Oregon coast.

Jeffrey's theory was developed for waves of a single wavelength, i.e., a monochromatic wave. In the ocean, however, waves of many different wavelengths are seen to exist concurrently, and not only move through and among each other, but also frequently travel in different directions (Ibid.). Figure 1 shows the spectrum of waves covering the full range of periods. This range extends over five decades, from ripples (~1 sec) to the long tidal periods: the semidiurnal (SD, 12 hours), the diurnal (D, 24 hours), and the quarterdiurnal (Q, 6 hours) (Ibid.). The inset in the Figure 1 refers to the development of storms and will be discussed shortly.

Wind generates waves of varying sizes depending on its intensity. Ripples will grow into swells as wind speed increases. Such waves span a range of periods between approximately two and twenty seconds (Ibid.:149). In general, the appearance and "roughness" of the sea, known as "sea state" or just "sea", depend on three factors: the wind strength, or speed; the duration, or time the wind has been blowing; and the fetch, the distance over the water that it has been blowing.

Duration of the storm is important because the longer the winds blow, the more energy they are able to transfer to the waves. Fetch works similarly, in that

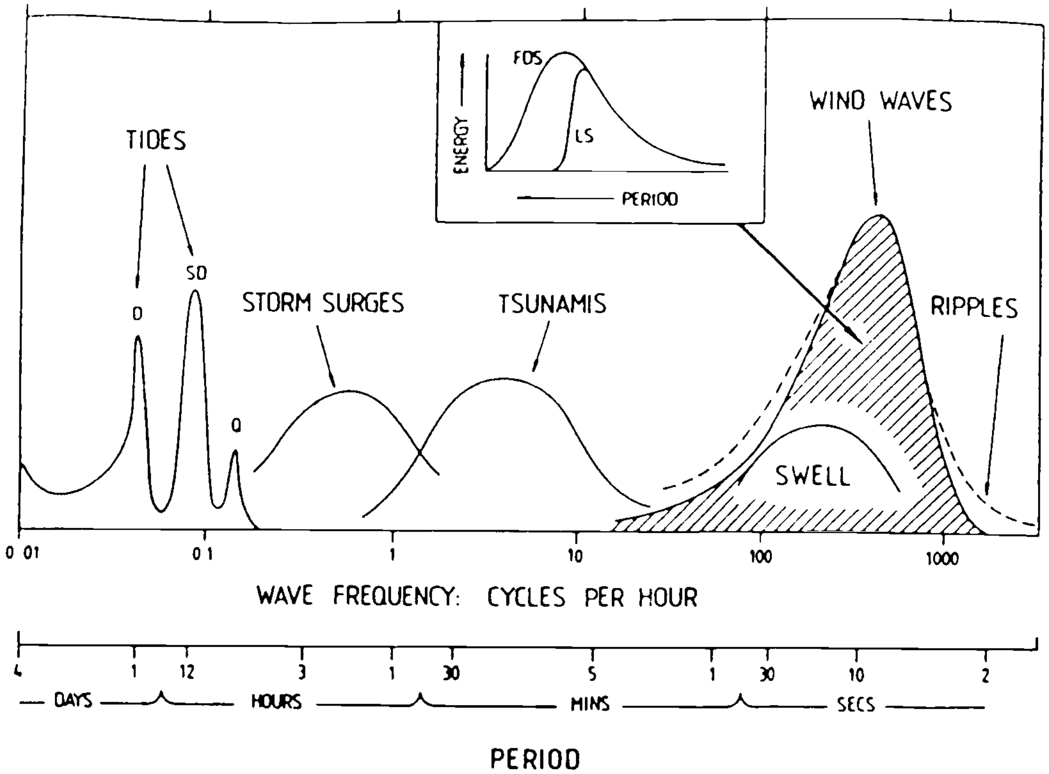

Figure 1.
The full spectrum of waves on water, from ripples to tides (Jelley 1989).

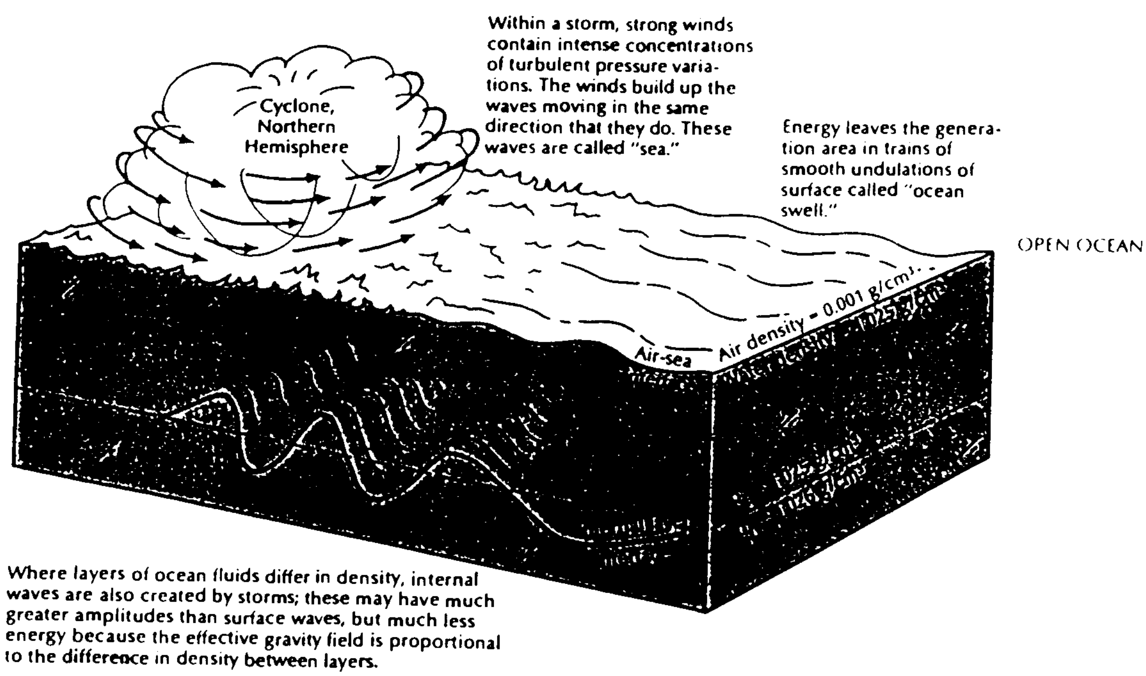

Figure 2.
Waves move energy (Neshyba 1987)

the area of the storm governs the length of time the winds are able to act directly on the waves (Komar 1992:6). Fetch is particularly important because it controls the maximum height a wave can reach at any particular spot (Smith 1970:368). As the waves are forming, they move across the ocean's surface and can pass beyond the area of the storm. At this point, they no longer acquire energy from the winds but continue to travel (Komar 1992:6). Depending on their wavelength, waves may travel at a different rate than the storm.

The term "limited sea" describes the water during the early stages of a storm, and the energy spectrum looks roughly like LS (Fig. 1 inset). As the storm develops further, the energy increases and a larger portion appears in longer waves, or swell (described below). The water is then described as a "fully developed sea" (FDS, Fig. 1 inset). The energy distributions shown in Figure 1 are smooth curves, but in reality their structures are continuously changing. Even so, in a rough sea, an observer often notices waves of some dominant wavelength and height, then referred to as "significant waves" (Ibid.).

The rate at which waves travel in deep water is directly related to their wavelength. A generally accepted theory is that smaller, shorter wavelength waves grow faster than larger, longer wavelength waves. The smaller waves reach their critical height sooner, and break. As they do so, their momentum is added to that of the larger waves upon whose slopes they are riding (Smith 1970:365). Thus longer waves continue to grow as additional short waves are forming (Ibid.). Under the continuing influence of the wind, the longer waves begin to travel outward from the storm and eventually overtake the smaller waves (Fig. 2). While the larger waves retain their energy for a considerable time, the smaller ones travel slowly and lose energy more quickly. The larger waves are called swell (Ibid.:368), and reach shore first (Jelley 1989:151).

When waves approach shore, they "feel" the bottom, slow down, and change shape. Because velocity is directly proportional to depth, as deep water waves become shallow water waves their velocity decreases. Likewise, velocity and wavelength (l) are directly proportional and wavelength decreases as well. Therefore, the ratio between height and wavelength, the wave steepness (H/l), changes and the waves steepen. These changes are not matched by a change in period, however, which remains the same.

This steepening of waves is what creates breakers. When the steepness ratio begins to exceed 1:7, i.e., when the height of the wave grows to one-seventh its length, wind waves break (Neshyba 1987:313). The longshore transport of sediments depends on both the energy and direction of these breaking waves (Komar 1976:204). After the waves break, the water travels back out to sea, usually at an angle to its initial direction. The refracted wave retains its wave motion and encounters other waves travelling towards the shore. As the incoming and outgoing waves meet, a standing wave is created. This fact is the heart of the Longuet-Higgins theory which, as is discussed in a later section, is the basis for the use of the microseismometer as a data gathering tool.

Another well accepted fact is that water waves can propagate great distances over the ocean. The wavelength of an ocean wave can be several hundred meters (Breeding 1986:406). Breakers on a beach may have carried energy transferred from winds thousands of miles off shore before dissipating along a coastline (Changery and Quayle 1987:259). Thus a storm does not have to be in the immediate coastal zone to deliver waves to a particular area (Komar 1992:6). In fact since the days before radio, swells have been considered to be precursors of storms (Jelley 1989:151).

In the winter, storms tracking into the Pacific Northwest originate in southern latitudes. These storms travel northward bringing warm, mild air into the region. Waves generated from these storms may affect the Oregon coast, but the coast receives waves from storms all over the Pacific Ocean. Even storms in the southern hemisphere near Antarctica can create waves that affect Oregon (Komar 1992:6). Our largest waves, however, are derived from winter storm systems travelling south from the north Pacific and the Gulf of Alaska (Ibid.). This is an important fact because this study looks at the relationship between storms and storm waves at Newport. From this information, it would seem that the significant storms that make landfall at Newport originate from systems to the south, but the significant storm waves experienced at Newport originate from systems to the north. Although the null hypothesis tested in this study is that the two data sets, climate storm events and significant storm wave events at Newport, do in fact correlate, the facts discussed above suggest that the results should provide evidence for rejection of the null hypothesis.

Study Site

Newport is located on the central Oregon coast, just north of Yaquina Bay (Fig. 3). Like most coastal areas, Newport, and coastal Oregon as a whole, is experiencing developmental pressures. Housing structures are being built immediately behind the beach, within dune areas, and atop cliffs overlooking the ocean. Not surprisingly, problems associated with beach erosion and cliff landsliding are increasing (Ibid.:4).

Scientists have frequently warned developers about the inherent instability and erosional hazards of coastal zones, but construction has continued anyway. Increased knowledge of how ocean waves and currents shape beaches and attack

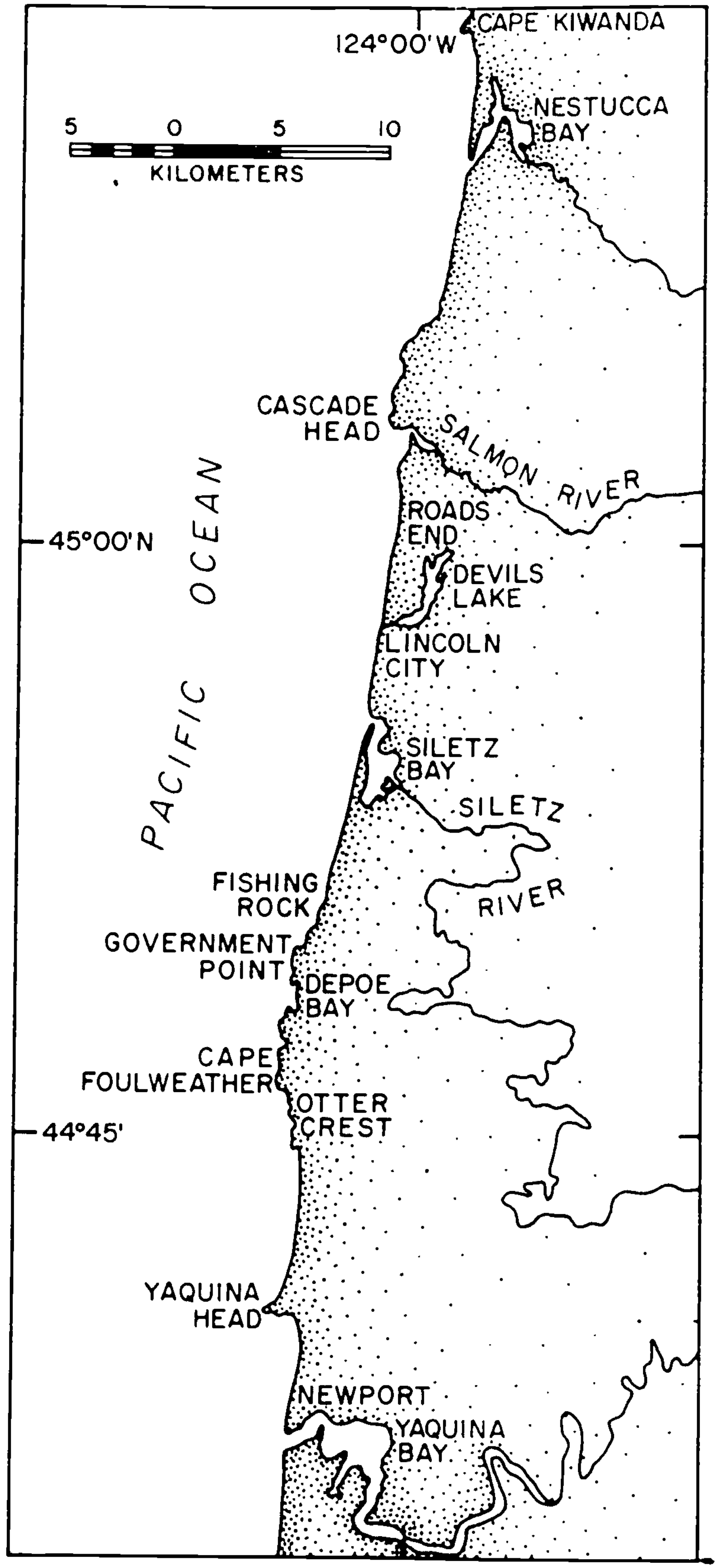

Figure 3.
Map of the central Oregon coast from Cape Kiwanda to Yaquina Bay (McKinney 1976)

coastal properties may help prevent such problems before they occur. Thus more studies examining the relationships of climatic storm events, severe ocean waves, and erosion may aid in the selection of appropriate areas for development.

Purpose of Study

This analysis of wave height and energy data from Newport was conducted to be included in a comprehensive study of shoreline erosion in the Pacific Northwest. The basic questions to be answered were: "Is there a correlation between significant climatic winter storm events and significant winter wave heights recorded at Newport?", and if so, "What is the timing of these events in relation to one another?" Answers to these questions will add to the growing inventory of information about the relation of climatic forcing to erosional processes.

Data Acquisition

Data on wave height and energy were derived from a record of microseismic disturbances generated by waves travelling to shore. The oscillations produced by the microseisms were directly recorded by a wavemeter onto a strip chart (Fig.4). The oscillations are a series of sinusoidal curves measured at six hour intervals for ten minutes at a time. Thus the record consists of a curve that travels back and forth about a zero line. The data on wave energy (discussed more fully in Data Transformation) is deduced using the number of times the curve crosses the zero line, i.e., the number of zero crossings. The wave heights are determined using a template placed over the strip chart itself.

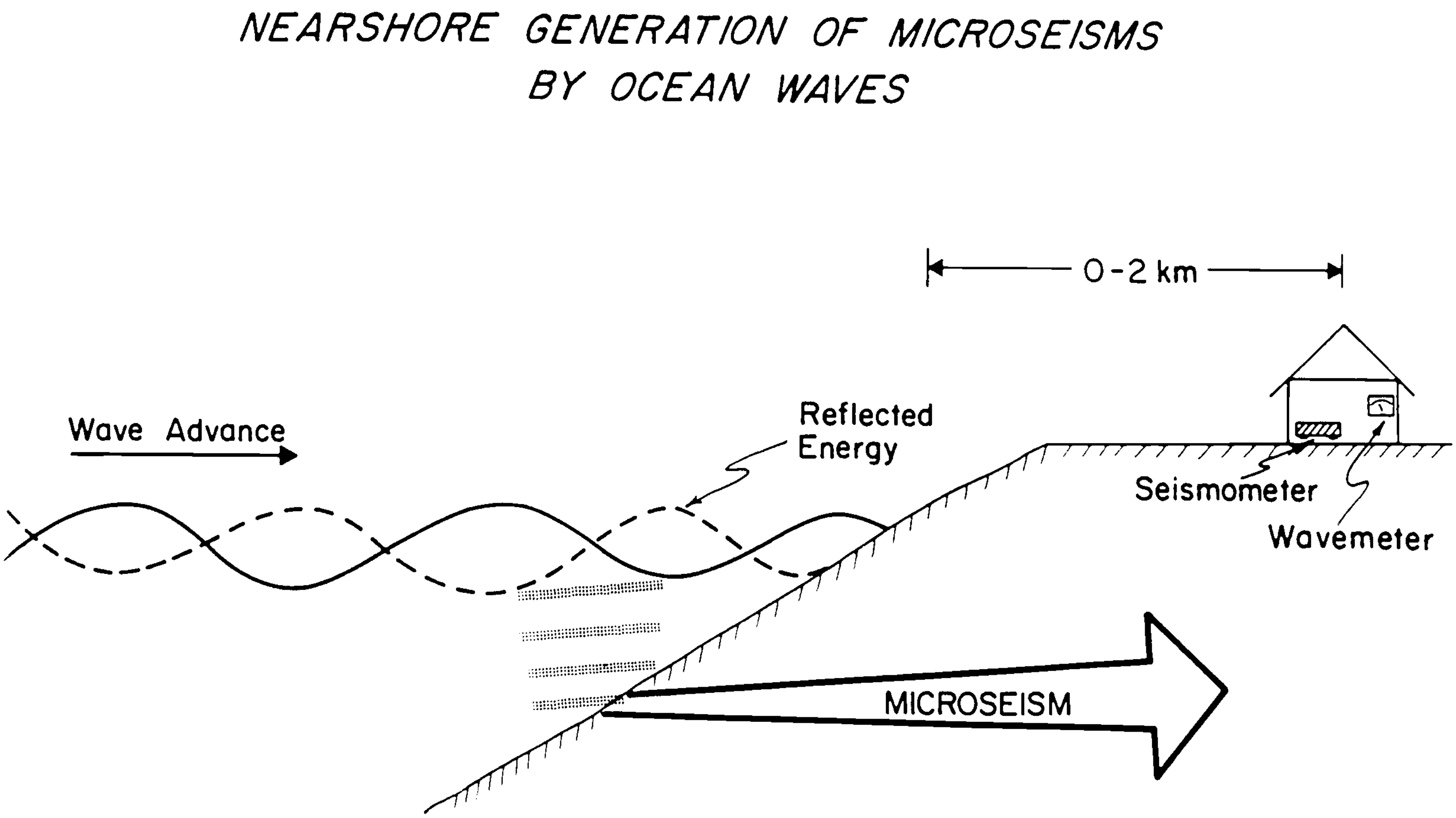

Figure 4.
(Creech 1981)

Theory Behind the Seismometer

A better understanding of how the wave data was acquired comes with knowledge of how the microseismometer works. Since at least 1905, it has been suspected that seismic activity measured in coastal areas was in some way related to meteorological factors. The activity measured was microseismic, i.e., small vibrations with periods between 4 and 10 seconds and amplitudes up to 20 microns (Darbyshire 1962: 700). In 1930, S.K. Banerji noticed that the microseisms measured in India were often associated with monsoon activity in Indian seas, but were always recorded before the swell arrived at the coast. He concluded that the activity was caused by waves at sea and not by those on the coast. In some way the sea wave energy was being transmitted to the sea bottom to create microseisms. Banerji himself, however, could not provide an acceptable explanation (Ibid.:701).

During the next 20 years much research was conducted to help explain this relationship. A correlation was found between the amplitude and period of sea waves and the amplitude and period of microseisms. Around 1950, M. Longuet-Higgins gave a physical explanation for the relationship. Simply put, he stated that waves coming on shore meet with those being reflected away from the shore, and a standing wave is formed. The total volume of water is the same in all stages of the wave cycle, but in stages one and three (see Fig. 5), some water is raised above the mean water level. There is an increase in the height of the center of gravity and thus there must be extra pressure exerted on the sea bottom to counteract this. The increase in pressure occurs twice per cycle (Ibid.). This explained the observation that the period of the sea waves was related to twice the microseism period. Furthermore, Darbyshire (p. 701) states

> If one considers a train of such stationary waves, it is clear that, at

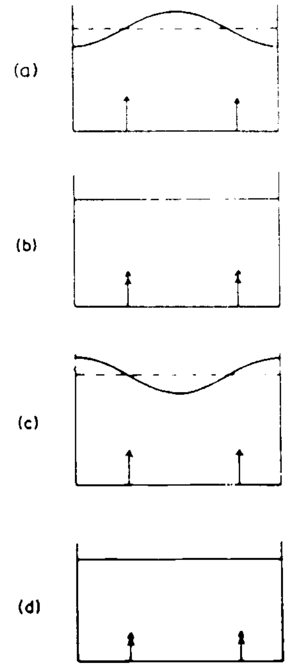

Figure 5.
Diagram showing various stages in a stationary wave cycle (Darbyshire 1962).

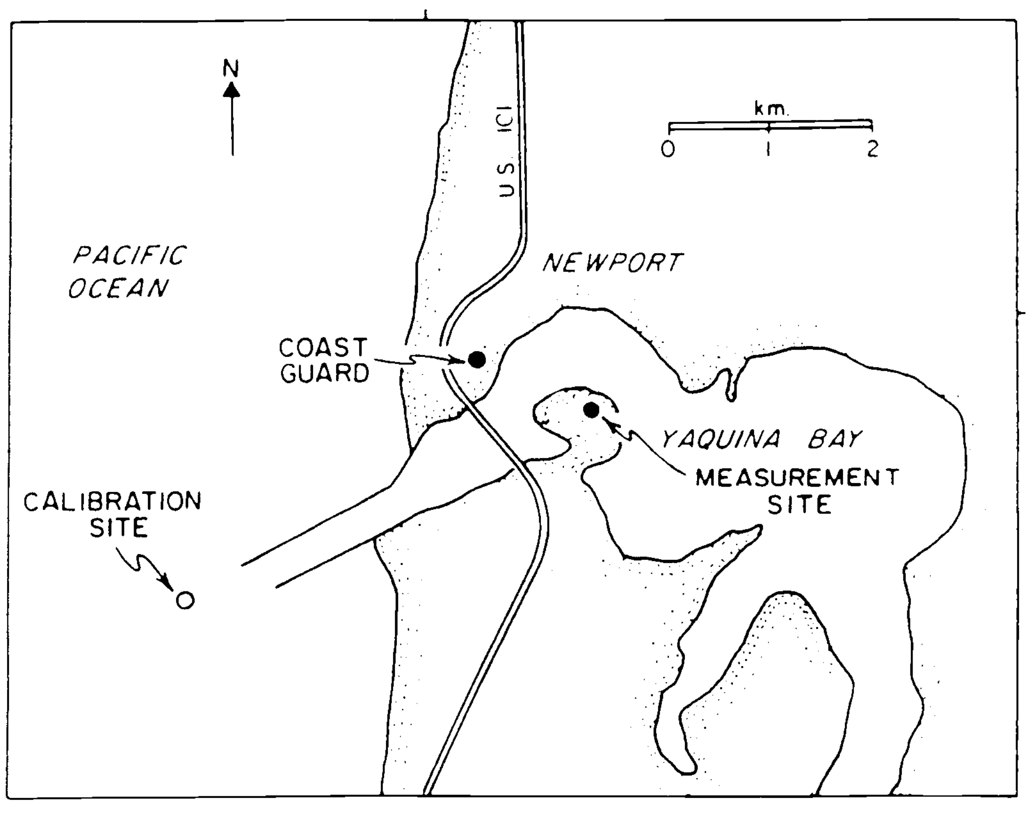

Figure 6.
Logistics of microseismometer set up (Creech 1981).

stage 1 for instance, the centre of gravity of all the waves is lifted up and the waves reinforce each other and the extra pressure can persist over a distance as long as the microseism wavelength.

Further work was conducted, and Longuet-Higgins found good agreement between his theory and observations. His work showed, as Banerji had found,that the increase in microseism activity preceded the related swell and that microseisms could be used as storm warnings. In addition, because the microseism period is half the sea wave period in storm areas, the wind speed in the storm area can be determined (Ibid.:704). Since this work, other researchers have confirmed these findings.

Microseismometer at Newport

Using Longuet-Higgins' theory that pressure waves can be detected some distance from their source, a microseismometer was set up at Hatfield Marine Science Center in Newport, Oregon in May 1971 (Figs.4 and 6). The system was placed two kilometers from shore, and went into operation in November 1971.

The system was calibrated by comparing seismometer recordings to direct observations of wave heights and periods causing the microseisms. From this information, an empirical equation was derived that related ocean wave heights to amplitudes of oscillation of the seismometer recording. Scatter diagrams of the seismometer predicted wave heights versus visually observed heights and pressure sensor wave heights showed good agreement (Komar et. al. 1976: 104).

Direct measurements of wave period confirmed Longuet-Higgins' theory that the period of seism oscillation is half the period of the waves. By 1976, researchers at the Newport station were convinced that Longuet-Higgins' theory matched their observations. Other tests at different locations showed that seismometer installations combined with simple electronics could produce useful estimates of nearshore wave height and period (Zopf, et. al. 1976:19).

Notice should be taken, however, that the readings taken from the strip charts represent averages over a 10 minute period, and are not measurements from individual waves. In addition, the waves recorded are the average of the highest one third of the waves. Thus the significant wave data reported in this study represent averages of an even smaller percentage of the highest waves. Other important idiosyncrasies of the system are as follows: 1) the seismometer detects earthquakes, but periods last longer than 10 minutes and trained observers should be able to pick out such anomalous readings; 2) readings will be high if incoming waves encounter a strong offshore wind; and 3) period readings are not accurate for wave heights less than about 5 feet, but depending on anticipated use of the data, this might not be operationally significant (Ibid.:23).

Data Transformation

As discussed above, the seismometer senses the vertical velocity of ground motion, and the resulting oscillating trace is recorded on a strip chart. An overlay template is then used to relate strip chart readings to wave heights in feet. It was assumed that the larger waves in a recording sequence approximated $H_{1/10}$, the average height of the highest 10% of the waves in a record. This value is then reduced by 20% according to a formula proposed by Longuet-Higgins (1952). This calculation yields Hs (significant wave height), the average of the highest 33% of the waves, for that record. ($Hs = .8\ H_{1/10}$.) Four significant wave heights and periods are determined and calculated each day at six hour intervals (Creech 1981:2).

The ocean wave period is calculated by multiplying the seismic period by two (Komar et. al. 1976:104). The parameter "Nz", number of zero crossings, is a unitless measure of wave energy derived from the following equation:

$Nz = 600\ sec/2T$ where Nz = number of zero upcrossings

600 sec = duration of record

T = ocean wave period in seconds

The denominator is multiplied by two to compensate for the fact that only the zero up-crossings (being distinct from the down-crossings) are counted.

Use of Wave Height Measurements

Houmb and Vik, two researchers working out of the Technical University of Norway in Trondheim, have done extensive study on duration of storms. Their work on the duration of sea states was performed using significant wave heights as the sole parameter for their analysis. Smith (1988:4) felt that this implied that the significant (or zero moment) wave height is the most appropriate measure of extreme event intensities for applications of duration statistics. He proceeded to test out other parameters that might be better representatives of the overall intensity or extreme nature of a storm. Statistical comparisons were conducted using peak period (T), wavelength (L), wave steepness (H/gT^2), and wave severity (H^2L).

He found that H, peak zero moment wave height, was consistently the most significant parameter. To him, this confirmed that an extreme event identification and duration definition procedure using this parameter was best. In addition, he did not find a strong correlation of duration with any of the alternate intensity parameters. Thus, he stated, "...for practical purposes, extreme event duration may be taken as independent of the peak intensity of the extreme event" (p. 13).

In conclusion, he said

> The conventional parameter for long term wave statistics, the zero moment wave height, appears to be the most practical and reliable indicator of the intensity of wave conditions. The percentage of exceedence of waves above a threshold is roughly 30% of the average number of extreme events per year, regardless of the absolute intensity of the wave climate.... The investigation does not rigorously prove statistical independence, but the assumption of independence of duration from peak intensity is proposed as an expedient measure. This assumption greatly simplifies prediction of durations of wave conditions above a critical threshold.
>
> (p. 14-15)

Although many researchers have used significant wave height alone to simplify calculations, others have expressed concern over the fact that other factors have received less attention. In particular, M.A. Srokosz (1988:385) stated "The problem of predicting extreme wave height has been extensively studied, whereas the question of the period associated with extreme waves has receive less attention, despite its importance...". Thus for simplicity, use of a height parameter alone in assessing erosional potential may be sufficient. Wave period, however, should not be entirely overlooked.

Analysis of Data

Data on the characteristics of Oregon coast winter storm events were compiled by Geography student Hongyun Zhang in 1991. The data were composed of wind direction, wind speed, and precipitation for three stations: Astoria, Newport, and Cape Blanco, and were manipulated to show daily, monthly, and yearly storm distribution during winter periods between 1981 to 1990 (Zhang 1991:7). In the study, statistical analysis was conducted to define significant storms. Thus "significant" events were defined as those with "a statistical ranking greater than one standard deviation above the 'average' events for the study period" (Ibid.:13).

Because this study compared Zhang's climatic data for Newport with Newport wave data, the same criteria were used to define significant events; i.e., significant wave events were those occurring on days with values of height and/or energy that equalled or exceeded one standard deviation above the mean values. The days with significant wave events were studied in comparison with the climatic data. Then statistical tests were performed to correlate the timing of the climatic and storm wave data, and will be described below.

Because the wave readings were taken four times a day at six hour intervals, while the climatic data were compiled once daily, the wave data were averaged to produce one daily reading each for height and Nz (number of zero upcrossings), an energy parameter. These daily readings were then averaged again to get average values for the entire data set. As described above, significant wave height and energy thresholds were set at one standard deviation above the average values. Therefore a "significant" height or energy value is one that is at or above the mean height or energy value (for the entire data set) plus one standard deviation. Many waves had values above this significance "boundary" of mean+1SD, and will be discussed later.

In numerous instances, waves with a significant height value did not have a significant energy value and vice versa. According to the equation $Nz=600/2T$ outlined above, this would make sense because the energy parameter is not dependent on height. Furthermore, as mentioned in the section

Microseismometer at Newport, the waves recorded by the equipment at Newport are the average of the highest one third of the waves. Thus the significant wave events discussed in this study represent averages of a smaller percentage of the highest waves, and may even be considered extreme.

Although researchers frequently use a height parameter alone in calculations, both height and energy data were examined in this study. Plots of the entire data set month by month can be found in Appendices 2 (height data) and 3 (energy data). Note that the boundary of significance (i.e., average overall height + 1 SD and average overall Nz + 1 SD) are plotted as thick, horizontal lines for easy reference (e.g., Fig. 7) . Larger gaps (2+ bars in width) represent times where no data were available or recorded. Once criteria for significance were set, the significant waves occurring during each winter period were noted.

Zhang's work primarily quantified significance thresholds for determining timing and duration of storm events at Newport. This data was input, for use in this study, using a dummy variable, 0, for periods in between storms, and the variable 1 for the storms themselves (see also Appendix 1). Thus duration of calms and duration of storms were analyzed directly with the four daily wave readings.

Both the wave and climatic data sets comprise stationary stochastic time series. Many examples of time series occur in the physical sciences, especially in meteorology, marine science, and geophysics (Chatfield 1989:2). A time series is simply a collection of measurements ordered in time. A stationary time series is one where the data do not exhibit a systematic change in mean or variance (Ibid.:10). Stochasticity refers to the fact that the processes examined in this study, i.e., ocean waves and climatic storms making landfall, involve a random element in their structure (Ibid.:27). This is true of

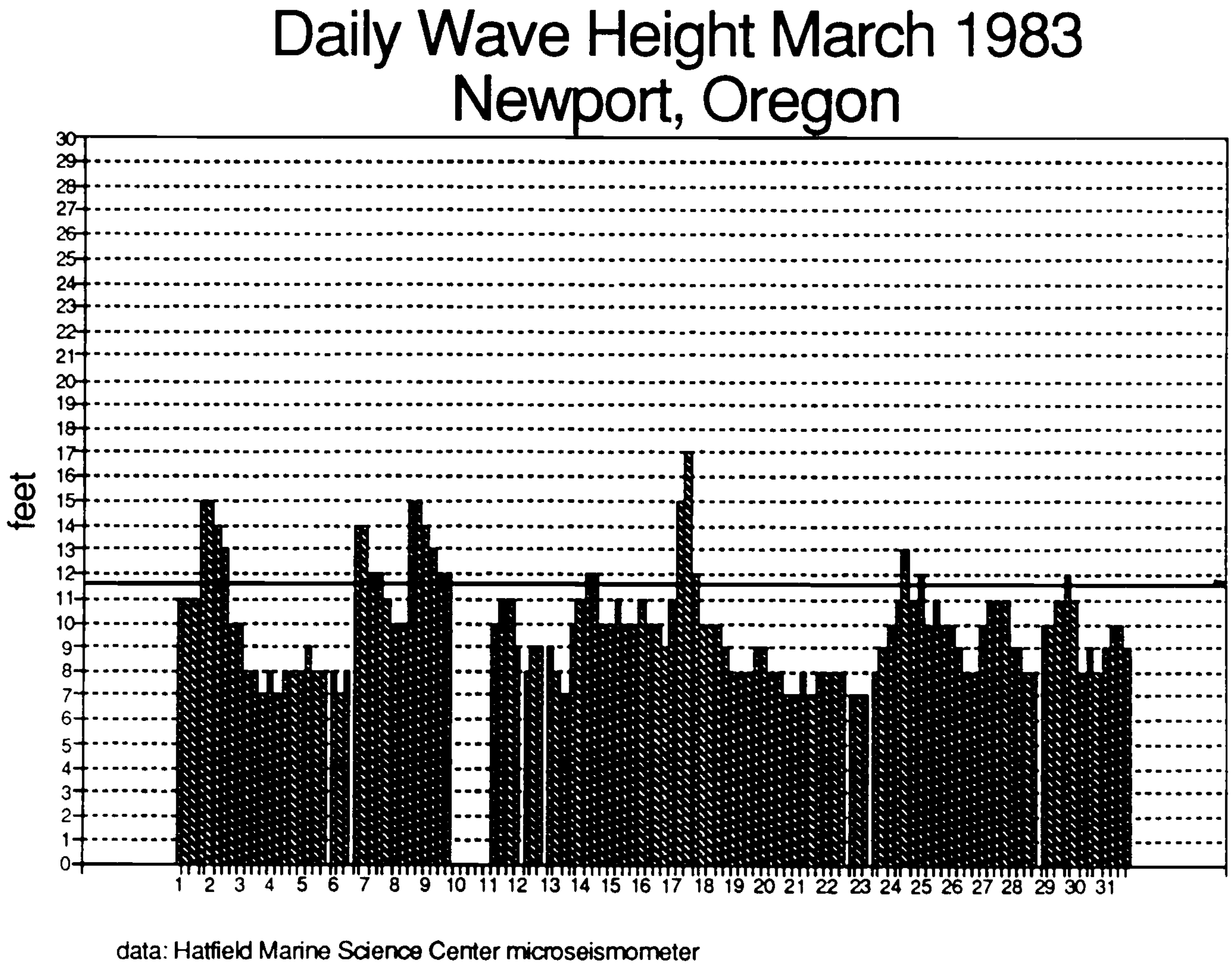

Figure 7.
Data on height for March 1983. Note thick, horizontal line that represents the "boundary of significance"; for height the boundary = 11.6 ft.

most physical processes in the real world (Ibid.). In addition, the measurements involved in this study are not independent observations. This is an important consideration for any statistical analysis in ensuring that an appropriate tool is utilized.

Statistical time series analysis accounts for the fact that successive observations are usually not independent. Thus the order of the observations is of particular importance (Ibid.:5). Chatfield (p.5) describes the technique in more detail:

> When successive observations are dependent, future values may be predicted from past observations. If a time series can be predicted exactly, it is said to be **deterministic** [sic]. But most time series are **stochastic** [sic] in that the future is only partly determined by past values, so that exact predictions are impossible and must be replaced by the idea that future values have a probability distribution which is conditioned by a knowledge of past values.

The time series tool employed in this study was autocorrelation. Autocorrelation helps to describe the evolution of a process through time (Ibid.:7), and is an important tool for assessing the properties of a stationary stochastic process (Ibid.:30). Through sample correlation coefficients that are derived from the data, this technique examines the correlation between dependent measurements and aims to create a mathematical model that approximates the real process, i.e. interdependent storms and waves making landfall. The coefficients measure the correlation between observations at different distances apart, and usually provide insight into the probability model that generated the data (Ibid.:18-19). In this study, the object of the time series analysis was to define a mathematical model (i.e., an equation) that describes the random interaction of ocean waves and storms over time. The null hypothesis tested was that the two data sets did indeed correlate. Additional linear regression analysis was performed to quantify this correlation in the context of this study.

With the help of Dr. Fred Ramsey (Oregon State University Statistics Department) the two data sets were submitted to a time series analysis to account for serial correlation. Again, the objective of such an analysis is to develop a mathematical model that accurately describes the stochastic process. A more detailed account of the steps taken and results obtained is in Appendix 1. The analysis will be described briefly here.

After the climatic, or storm, data was input using a dummy variable, an initial simple linear regression was performed. This was done to obtain estimated mean wave height and wave energy for storm versus non-storm events. The storm and wave data sets were manipulated to mimic a time lapse between them; that is, the two data sets were lagged with respect to one another. A wide range of lag times were used, where one lag equalled 6 hours (the time between successive wave measurements), to find the timing at which the difference in the storm and non-storm means was at a maximum. Positive values represented time periods after storms made landfall, and negative values represented those prior to landfall.

The lag at which the difference in means was a maximum was recorded for each winter season. Figure 8 shows the results for the 1982-1983 season. Note that the maxima occur during positive lag times, i.e. after storm landfall. This was true for all years except for wave energy during the 1985-1986 season (see Appendix 4 and Fig. 11). A complete set of graphs for the results by year and by individual lag periods are in Appendices 4 and 5.

The lag times at which the maximum difference in means occurred were averaged over the eight years (1982-1990) to provide one lag for wave energy and one lag for wave height. Thus an actual lag time, in hours, was found at which

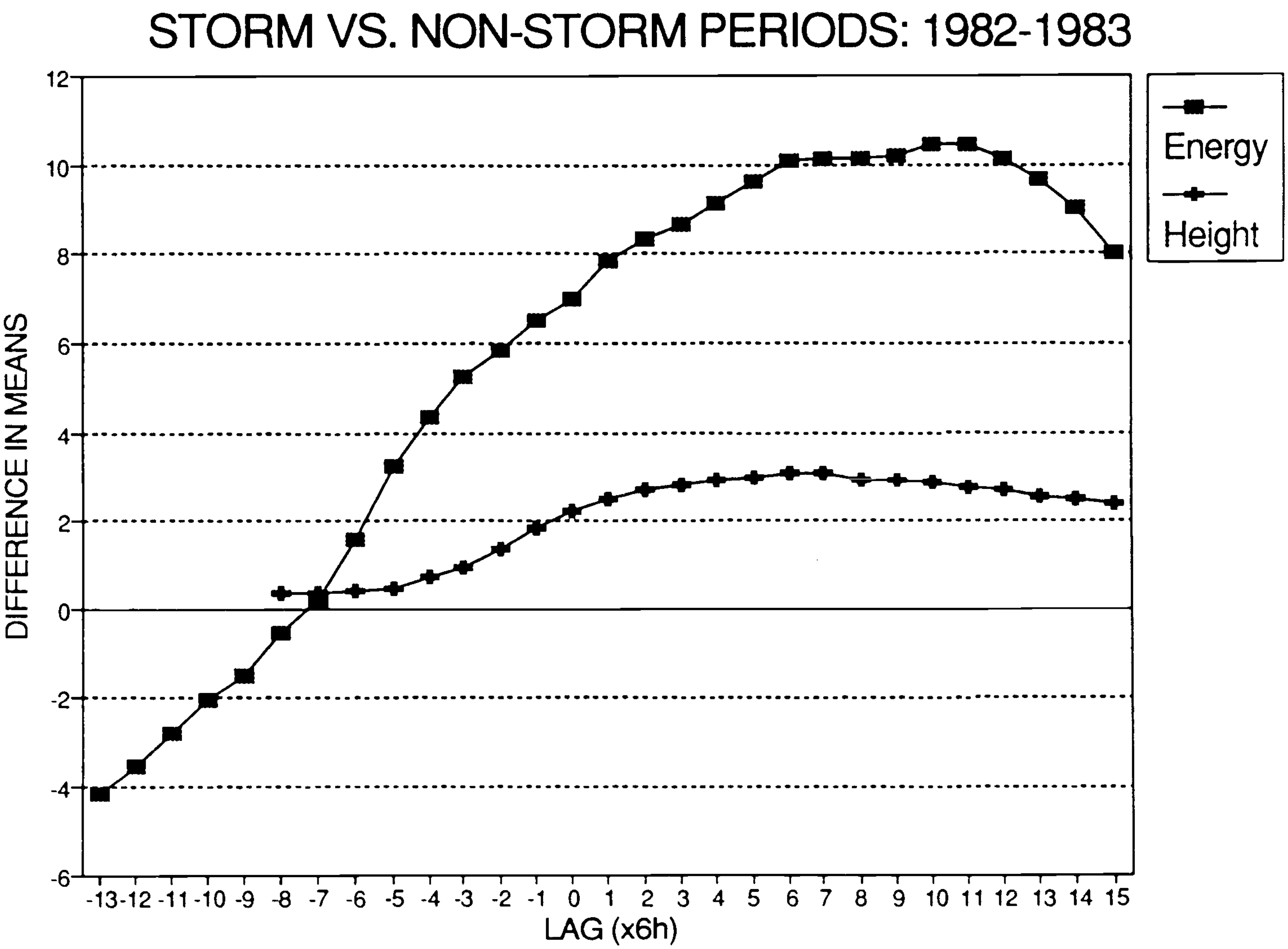

Figure 8.
Difference in mean height and energy values between storm and non-storm events, 1982-1983. Note that the differences reach a maximum during positive lags. Positive lags represent times after storms made landfall; negative lags represent times before storms made landfall. The expected result was for the lags to peak in the negative range.

waves during non-storms (calms) and storms showed the largest difference in energy and height values. These lag times were submitted to a second simple linear regression, and residual values were added to the data set as new variables. By using the residuals, any trends in the data resulting from a systematic change in mean that would hinder the time series analysis were removed.

The residuals were submitted to time series analysis using the partial autocorrelation function. At this point, correlation coefficients for the mathematical model describing the stochastic process were obtained. Using these coefficients, equations were derived with which to transform the original energy and height data (see Appendix 1). Because the autocorrelation function describes the internal structure of the data, the data transformed by the correlation coefficients describe the internal pattern of the serial correlation between the wave and storm observations.

The last step was another simple linear regression performed on the transformed data. This step quantified the estimated mean wave height and energy during storm and non-storm events at the lag times where the differences were at a maximum. In addition, a measure of statistical significance was obtained by calculating a t-statistic and p-value from the regressed data. The results are reported below.

Results

The average values for height (in feet) and energy (which is unitless because it is based on the number of zero upcrossings) for the entire data set were 9.7 feet (SD=1.9 feet) and 81.2 (SD=5.3) respectively. Thus the boundaries of significance were 11.6 feet and 86.5. Again these values are represented as thick horizontal lines in Appendices 2 and 3. The results year to year are shown in Table 1. At least 57.3% of the days surveyed had waves meeting or exceeding one of both of these values (see Table 2). The qualifier "at least" is placed in front of the percentage because the data set had many recording gaps; some of which interrupted long periods of significant waves.

Season	average energy	modal energy	average height	modal height
82/83	79.05	83	9.98 ft.	8
83/84	76.74	81	8.11 ft.	7
84/85	84.32	84	6.64 ft.	7
85/86	77.72	83	10.2 ft.	10
86/87	85.12	86	12.7 ft.	10
87/88	76.88	84	11.2 ft.	10
88/89	78.45	88	10.0 ft.	8
89/90	91.63	86	8.75 ft.	8

Table 1.

Season	#days w/sign. energy	#days w/sign. height	%days* with either	%days** w/sign. storms
82/83	41	36	49.0	51.2
83/84	26	20	28.3	23.0
84/85	46	9	34.4	15.7
85/86	48	55	60.9	24.8
86/87	65	83	74.8	19.8
87/88	65	71	69.1	13.1
88/89	79	62	70.2	32.2
89/90	84	27	71.5	24.8

*based on November through March
**based on December through March

Table 2.

Interestingly, the winter of 1982-1983, which Zhang found to be the most stormy winter in her data set with significant storms, had only 49.0% of its days with significant waves at or above one of the parameters; a relatively low percentage. The season with the lowest percentage was 1983-1984 with 28.3% and the season with the highest percentage was 1986-1987 with 74.8% (Table 2). Again, these percentages are minimum values because of data contingencies.

Another important consideration is that the wave data were obtained from November to March, but the climate data were compiled from December to March only. The percentages shown in Table 2 take this consideration into account. Note that many more significant waves were recorded than significant storms.

Although the criterion for determining significance was an energy and/or height value one standard deviation above the mean, many waves had values that were much larger. Every winter season examined in this study had at least one energy or height value that exceeded four standard deviations. Table 3 shows the breakdown of significant waves by standard deviation. The total number of days with significantly energetic or high waves is shown in the row labeled total for each season. This information is shown in Table 1 as well. The # columns represent the number of waves with energy or height values falling one, two, three,..., or eleven standard deviations above the mean. The % columns are the number of waves in each standard deviation class divided by the total number of significant waves. Energy and height are kept separate throughout the chart. Total percentages did not always add to 100 because of rounding.

The graphs in Appendices 2 and 3 are useful for yearly comparisons, and show the unusually high values of Nz for 1989-1990 (e.g., see Fig. 9). This season had exceptionally high values of energy without many significantly high waves. Table 3 illustrates this as well. The graphs also show that winter 1986-1987 was by far the most active year for significant waves (see also Table 2 and Fig. 10). Eighty three days registered wave heights above 11.6 feet (mean+2 SD), most of them being above 14 feet (mean+3 SD). Table 3 shows the breakdown; 57.8% of the

Season	SD	#(Energy)	%(Energy)	#(Height)	%(Height)
82/83	1	8	19.5	6	16.7
	2	17	41.5	14	38.9
	3	10	24.4	8	22.2
	4	6	14.6	2	5.6
	5	--	------	4	11.1
	6	--	------	1	2.7
	7	--	------	--	------
	8	--	------	1	2.7
total		41	100.0	36	99.9
83/84	1	9	34.6	4	20.0
	2	10	38.5	10	50.0
	3	6	23.1	2	10.0
	4	1	3.8	4	20.0
total		26	100.0	20	100.0
84/85	1	14	30.4	4	44.4
	2	17	37.0	2	22.2
	3	7	15.2	1	11.1
	4	5	10.9	1	11.1
	5	1	2.2	1	11.1
	6	2	4.3	--	------
total		46	100.0	9	99.9
85/86	1	21	43.8	15	27.3
	2	11	22.9	13	23.6
	3	12	25.0	12	21.8
	4	4	8.3	13	23.6
	5	--	------	2	3.6
total		48	100.0	55	99.9
86/87	1	25	38.5	16	19.3
	2	21	32.3	19	22.9
	3	13	20.0	23	27.7
	4	5	7.7	15	18.1
	5	1	1.5	9	10.8
	6	--	------	1	1.2
total		65	100.0	83	100.0
87/88	1	25	38.5	15	21.1
	2	20	30.8	22	31.0
	3	15	23.1	12	16.9
	4	5	7.7	7	9.9
	5	--	------	15	21.1
total		65	100.1	71	100.0

Table 3.

Season	SD	#(Energy)	%(Energy)	#(Height)	%(Height)
88/89	1	18	22.8	13	21.0
	2	35	44.3	19	30.6
	3	16	20.3	20	32.3
	4	7	8.9	6	9.7
	5	3	3.8	4	6.5
total		79	100.1	62	100.1
89/90	1	16	19.0	8	29.6
	2	18	21.4	9	33.3
	3	17	20.2	7	25.9
	4	5	6.0	3	11.1
	5	--	------	--	------
	6	5	6.0	--	------
	7	10	11.9	--	------
	8	4	4.8	--	------
	9	4	4.8	--	------
	10	4	4.8	--	------
	11	1	1.2	--	------
total		84	100.1	27	99.9

Table 3 (con't).
Seasonal breakdown of significant waves by standard deviation. For energy, 1 SD=5.30; for height 1 SD=1.87

significantly high waves were three or more standard deviations above the average.

In the context of this study, such anomalies are difficult to interpret, but underscore the importance of broadening wave analysis to include period as well as height. Factors such as sea level (e.g., Komar and McKinney 1977; Peterson, Jackson, et. al. 1990), El Nino-Southern Oscillation (e.g., Niebauer 1988; Komar 1992), and positioning of the Aleutian low (e.g., Peterson, Jackson, et. al. 1990; Komar 1992; Niebauer 1988) have been discussed by numerous authors, and may play a role in determining the wave climate off the coast of Oregon.

As stated in the introductory literature review, swells travel faster than the winds (and thus the storms) that generate them, arriving on shore first. Given that the microseismometer records the movement of swells, the expected result

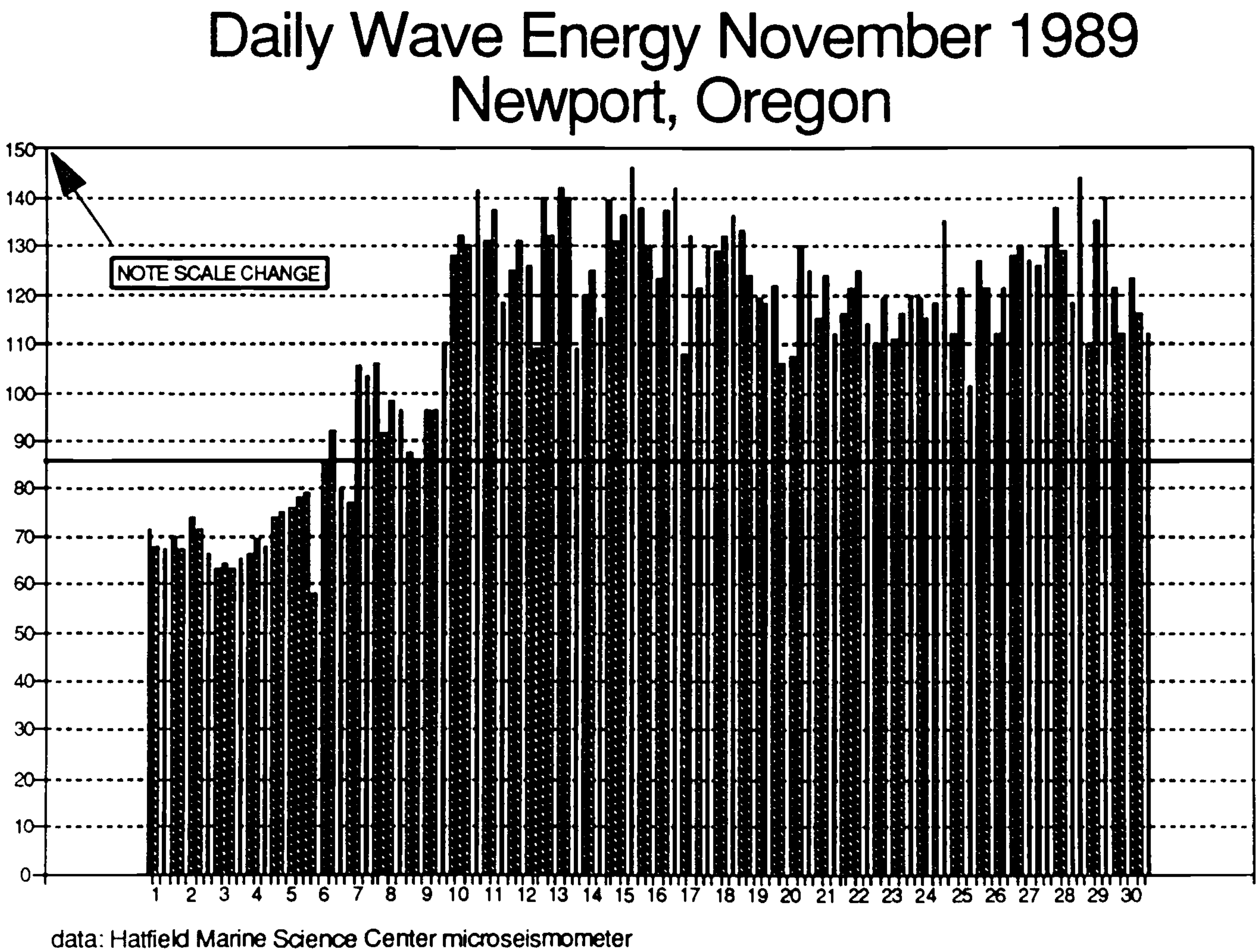

Figure 9.
Data on energy for November 1989. Note scale change indicative of exceptionally high values.

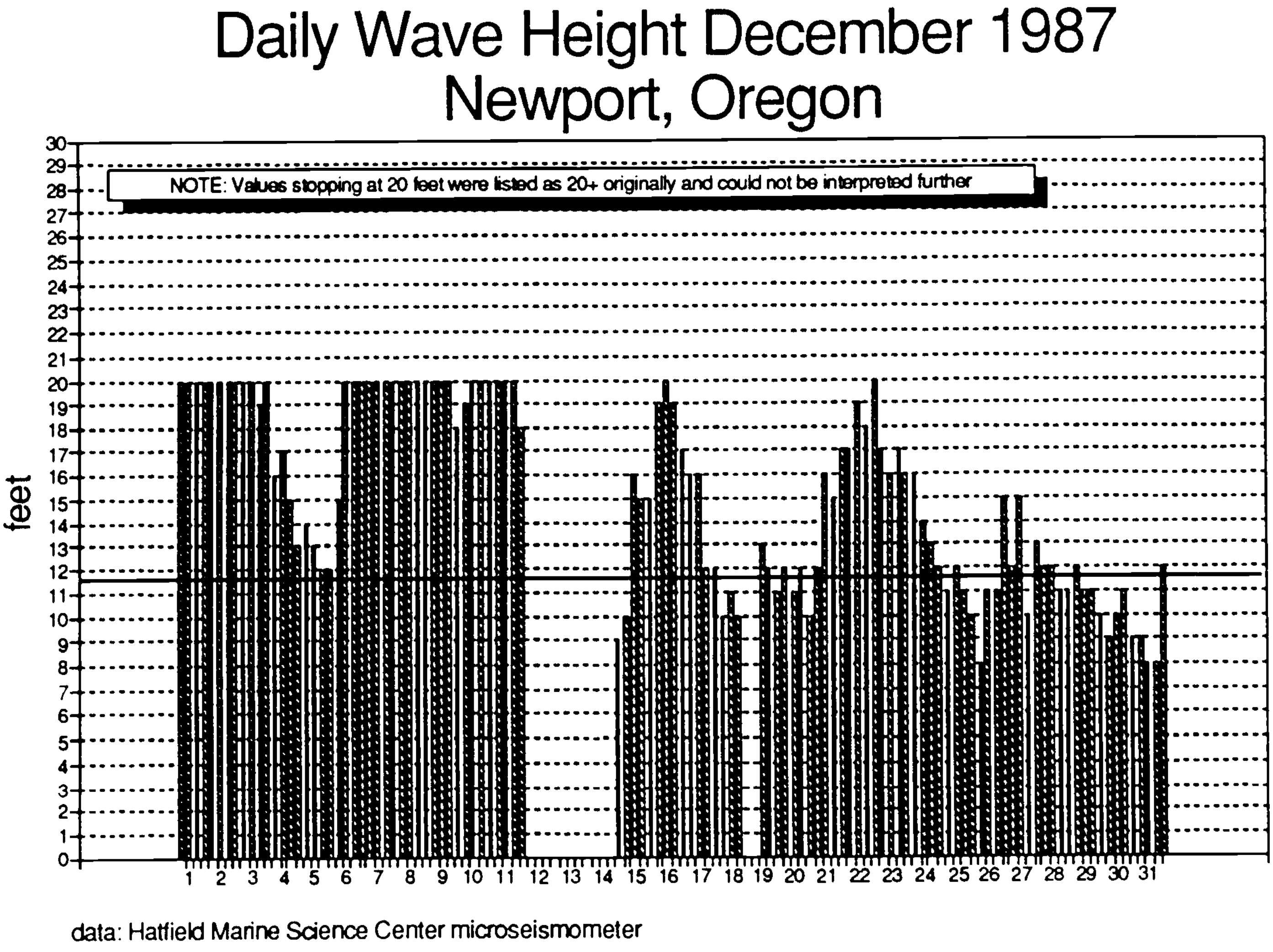

Figure 10.
Data on height for December 1987. Note the numerous days with values exceeding the boundary of significance.

was for the most significant waves to arrive Newport sometime before the storms arrived. Preliminary regression statistics, however, yielded values indicating that the most significant waves arrived up to seventy-two hours *after* the storms made landfall.

In the statistical analysis height and energy were evaluated separately. Significantly high waves were found, on average, to arrive at Newport twenty-eight hours after the storms. No winter season of record had an average lag time for height that preceded the storm episodes (see Appendix 4). Waves with significantly high energy values had an average lag time of thirty-four hours after storm episodes. During the winter of 1985-1986, however, significant waves generally preceded storm episodes; on average thirty hours prior to storms (Fig. 11). Table 4 outlines these results; positive values represent time periods following storms, negative values represent time periods preceding storms.

The serial correlation analysis was utilized to quantify the the increases in height and energy for the average lag periods derived above. Because each lag period represented six hour blocks of time, the average values used were not 34 h and 28 h, but 6 and 5; i.e., 34 h/6=5.7 which rounds to 6 and 28 h/6=4.7 which rounds to 5.

Time series analysis showed that 6 lag periods (36 h) after the storms, there was an average increase in Nz of 5 units. In other words, the significant waves occurring 36 h after the storms had an average of 5 more zero upcrossings than at all other times. This figure was highly significant, $t=8.81$ ($p<<.0005$) (see Appendix 1 for an explanation of t-statistics and p-values). The energy results were not significant for all seasons individually, but six out of the eight seasons had increases in Nz that were significant. In the other two seasons, the reason for lack of significance may have been that the lag time was very different from the average value of 6.

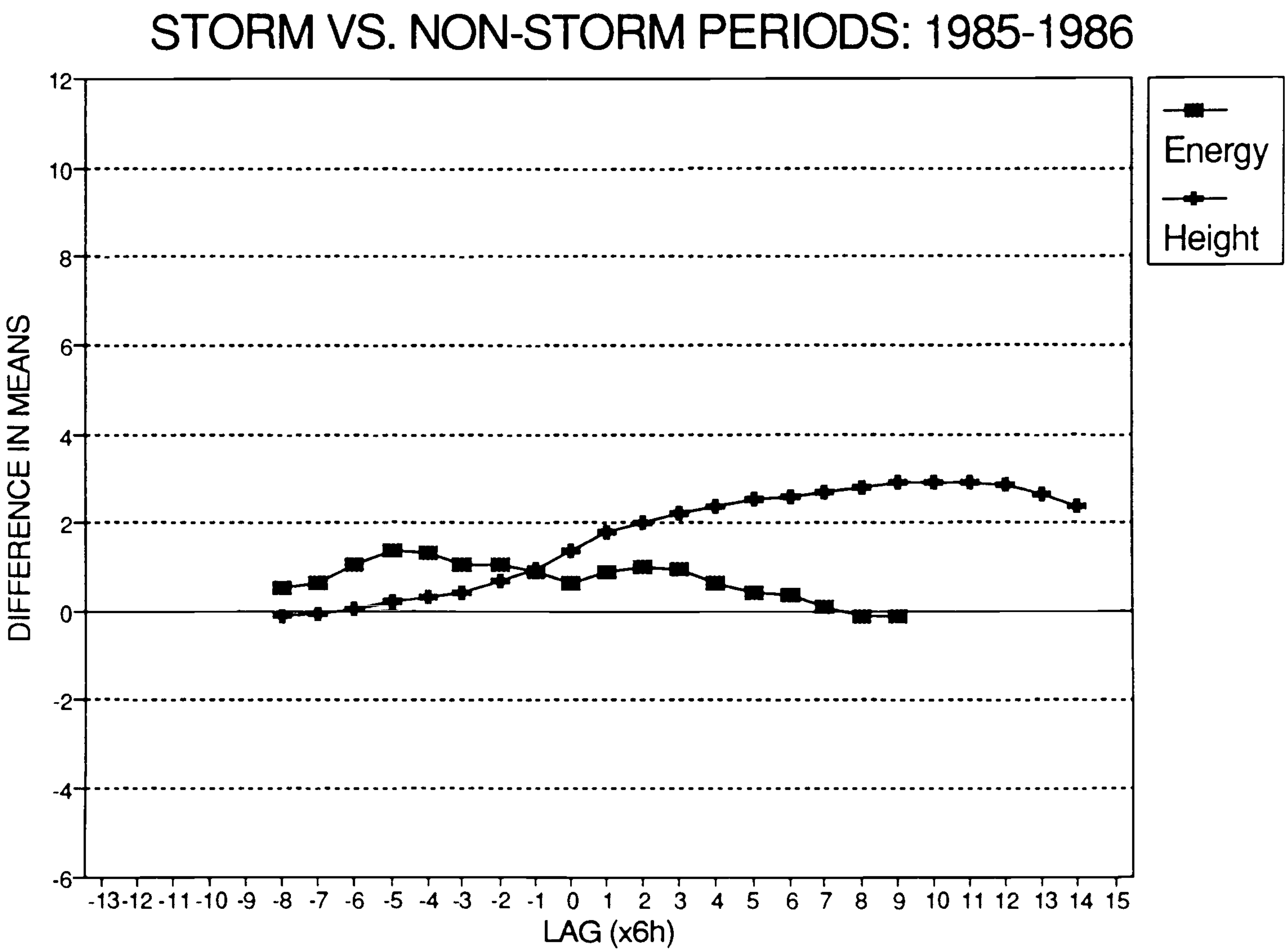

Figure 11.
Difference in mean height and energy values between storm and non-storm events, 1985-1986. Note that the difference for energy reaches a maximum during negative lags. This is an exception: in all other years both energy and height differences reached maxima during positive lags. The expected result was for the lags to peak in the negative range.

Season	average* energy lag time	average* height lag time
82/83	+66 h	+42 h
83/84	+30 h	+33 h
84/85	+18 h	+42 h
85/86	-30 h	+54 h
86/87	+18 h	+6 h
87/88	+72 h	+18 h
88/89	+42 h	+18 h
89/90	+54 h	+6 h
average	+34 h	+28 h

* + values indicate hours after storm landfall
- values indicate hours before storm landfall

Table 4.

The results for the height time series, however, were less definitive. The average increase in height was 0.19 feet (t=10.6, p≅.1). Thus 5 lag periods, or thirty hours, after storms hit, the waves were .19 feet higher on average than at all other times. Not enough evidence was provided for a rejection of the null hypothesis. In addition, the results were not statistically significant for all seasons individually.

Conclusions

Because the wave data used in this study represent information on significant waves, i.e., the highest and strongest third of all waves washed onto shore, this data is considered to represent swells. The results of the statistical analyses provide reason to question the initial assumption that swells reach shore prior to the winds that generate them. Given that the microseismometer was designed to record swells, it appears that the wave data do not correlate with the storm data. The results of the t-statistics and p-values provide evidence that the null hypothesis that the wave energy and storm data sets correlate should be rejected. The correlation between the wave height and storm data sets, however, requires further investigation.

The relatively mild winter temperatures experienced by the Pacific Northwest is largely a product of the seasonal southwesterly winds. These winds usher warm frontal storms off the ocean and onto the coast. The active Pacific seas are also a product of seasonal winds, but it is unclear which winds generate the most extreme waves. Some claim that the most severe waves originate from the north, and are brought onto the Oregon coast by northerly winds. This study, while not encompassing enough information to definitively support this theory, certainly does not refute it.

The questions addressed in this study were quite specific, and basically ignore a whole host of other important factors. A key piece of data that is missing in this study is wave direction. This could help identify the location of the storms that actually generated these waves. In addition, considerations that have been addressed by numerous authors, such as ENSO, the effects of sea level, and the positioning of the Aleutian low pressure cell, are well worth looking into in the future.

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Appendix 1.

Outline of Statistical Analysis

1. Data Entry

- data transformed from strip charts was entered in the following manner:

date	time	energy	height	storm*
Nov 1	0	w	ww	0
	6	x	xx	0
	12	y	yy	0
	18	z	zz	0
Nov 2	0	a	aa	1
	6	b	bb	1
	12	c	cc	1
	18	d	dd	1
				etc....

*entered prior to statistical analysis as a dummy variable where 0=no storm and 1=storm

2. Data Examined by Partial Autocorrelation

The first step is to examine the data descriptively, i.e., graphically, to identify trends. The data was checked for normality. Energy and height were plotted against time (lag periods) using partial autocorrelation.

Results:

- data showed normal distribution with few outliers
- data showed constant variance
- no initial data transformation required

3. Initial Simple Linear Regression

An initial simple linear regression was performed to obtain estimated mean wave height and estimated mean wave energy for storm versus non-storm events. Use of a dummy variable to represents storms and "non-storms" simplified the process, which is described below.

Steps:

- regression of storm on height and of storm on energy performed individually by winter season according to the following equation:

$Y = B_0 + B_1X$ where $X = 0$ or 1, for no storm or storm, respectively

- so when $X = 0$, $Y = B_0$
- and when $X = 1$, $Y = B_0 + B_1$
- thus the mean difference between storm and no storm periods = B_1

For each season, over eight winter seasons (1982-1990), a wide range of lag times was used in the regression to determine the coefficient B_1. A lag is simply an expression of time. In this case 1 lag = 6 hours, the time between successive measurements. By doing this, the dependence of future measurements on past measurements can be examined. Later, during the time series analysis, autocorrelation is used to actually measure the correlation between a measurement at time t [X(t)] and a measurement at time t + lag period [X(t+t)]. Again, the lag period is six hours, or a multiple thereof, because it represents the time between measurements.

Steps:
- for each season, the lag time at which B_1 was at a maximum for energy and height was determined (see also Appendices 4 and 5)
- positive lags represented time after the storms made landfall; negative lags represented times before storms made landfall (see also Table 4, text p. 31)
- the eight lag times (one for each winter season) were averaged to produce one value for energy and one value for height at which B_1 was a maximum

Results:
- the mean difference between energy values during storm and non-storm periods peaked 36 hours, or 6 lags, after storms made landfall
- the mean difference between height values during storm and non-storm periods peaked 30 hours, or 5 lags, after storms made landfall

4. Simple Linear Regression

Once two lag times were obtained for height and energy, another regression was performed with the data shifted to reflect the appropriate lags. In other words the energy and storm data were regressed with a shift of 36 hours between them, and the height and storm data were regressed with a shift of 30 hours between them. The residuals from these two regressions were saved and used in further calculations. In this way energy and height were isolated from the storm component.

Steps:
- regression of 6 lag storm on energy and 5 lag storm on height
- saved residuals
- residuals became new variables: HRESIDS (for height) and ERESIDS (for energy)

Results:
- isolated energy and height components
- storm component removed from analysis

5. Time Series Investigation

Because the measurements are not independent, multiple regression was not an appropriate analytical tool. Autocorrelation, however, takes dependence into account, and is appropriate for data collected from a stochastic process (see text p.19). It is similar to multiple regression, but the dependent variable is regressed on past measurements, not on independent variables; thus the prefix "auto" (Chatfield 1989:35). The following steps were performed to develop the mathematical model of the data. It is an autoregressive model of order 2 for regression residuals:

$$\text{Energy}_t = B_0 + B_1(6 \text{ lag storm})t + e_t$$

where: $e_t = \alpha_1 e_{t-1} + \alpha_2 e_{t-2} + \zeta_t$ = energy regression residuals

α_1 and α_2 = correlation coefficients

ζ_t = random component term

A similar model is developed for height using 5 lag storm and height regression residuals. Note the similarity to the regression equation described in section 3 of this appendix.

Steps:

- residuals for each winter season plotted using the partial autocorrelation function
- values at the first and second lags recorded and averaged over the eight winter seasons; energy and height calculated separately
- averages used to derive the correlation coefficients that are part of the mathematical model describing the data:

Φ_1 = value at 1 lag = $\alpha_1/(1-\alpha_2)$ height and energy each have an α_1 and α_2

Φ_2 = value at 2 lag = α_2

- data transformed using α_1 and α_2 (different values for height and energy):

TENERGY = energy - [α_1* (1 lag energy)] - [α_2* (2 lag energy)]

TSTORME = (6 lag storm) - [α_1* (7 lag storm)] - [α_2* (8 lag storm)]

THEIGHT = height - [α_1* (1 lag height)] - [α_2* (2 lag height)]

TSTORMH = (5 lag storm) - [α_1* (6 lag storm)] - [α_2* (7 lag storm)]

Results:

- for energy: $\Phi_1 = .6312$

  $\Phi_2 = \alpha_2 = .1470$

  $\alpha_1 = .5384$

- for height: $\Phi_1 = .7769$

  $\Phi_2 = \alpha_2 = .1186$

  $\alpha_1 = .8815$

6. Simple Linear Regression

Transformed data was submitted to regression in order to quantify the estimated difference in means between storm and non-storm events.

Steps:

- regressed TENERGY on TSTORME
- regressed THEIGHT on TSTORMH
- recorded B_1 and standard error
- averaged B_1 and standard error over the eight winter seasons

Results:

- on average, waves making landfall during storm events had 4.8 more units of energy (zero upcrossings) than waves making landfall during non-storm events, se = 0.55
- on average, waves making landfall during storm events were 0.19 feet higher than waves making landfall during non-storm events, se = 0.19 ft.

7. Calculated t-statistics and p-values

A t-statistic is a measure of how extreme a particular data point is. A large t-stat has a corresponding low p-value, while a small t-stat has a corresponding high p-value. A p-value represents the probability of other data points being greater than the data point at hand. Low p-values provide significant evidence for rejection of the null hypothesis (H_0); high p-values provide significant evidence for not rejecting H_0. At p-values of 0.01 and below, H_0 is generally rejected.

Steps:

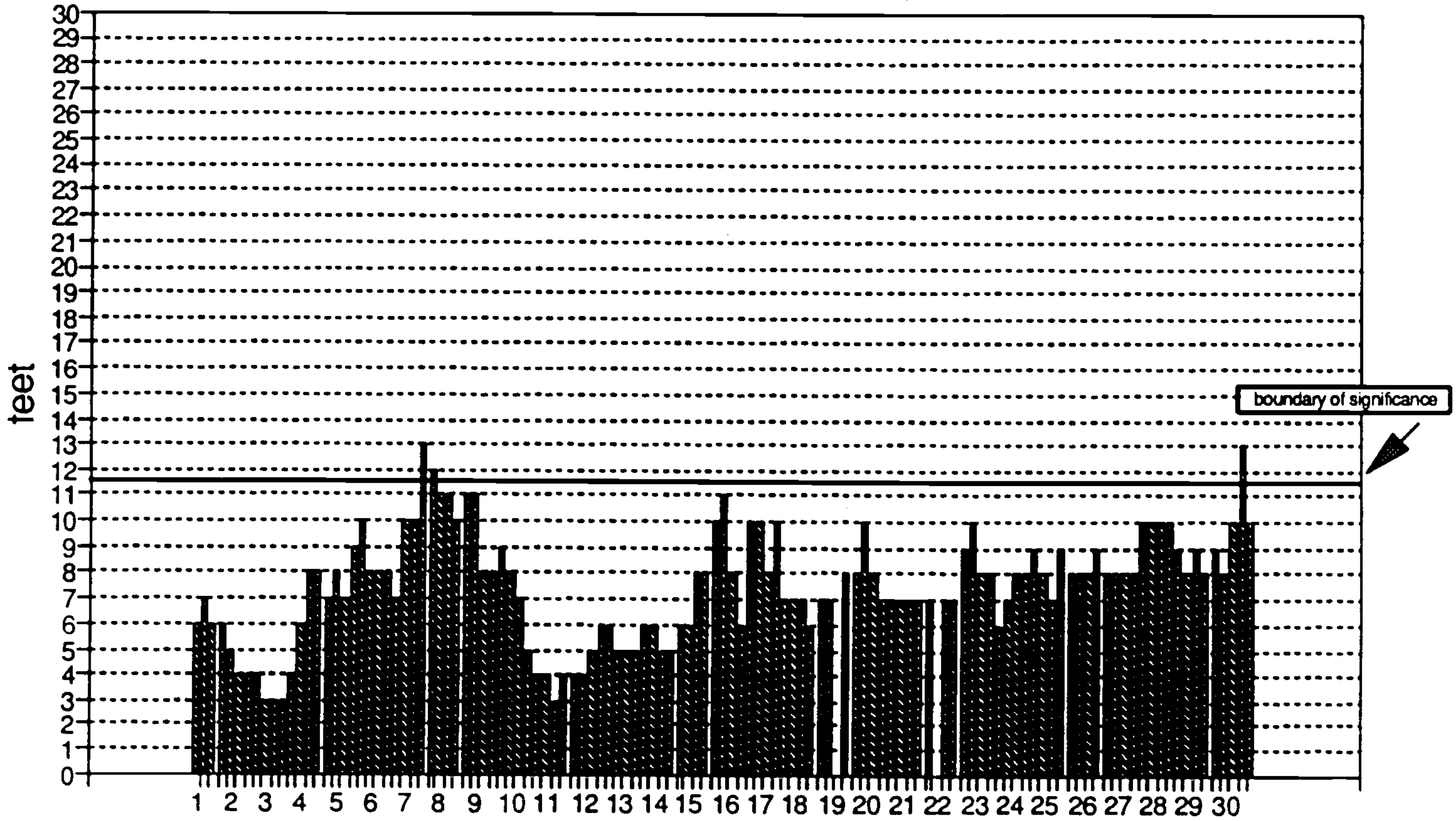
- t-stat = B_1(avg)/se
- p-value derived from t-distribution table (*Statistical Data Analysis Course Notes* 1991: Appx. 2)

Results:

- for energy, $t = 8.81$ and $p << 0.0005$; therefore, reject H_0
- for height, $t = 0.989$ and $0.1 < p < 0.15$; therefore, do not reject H_0

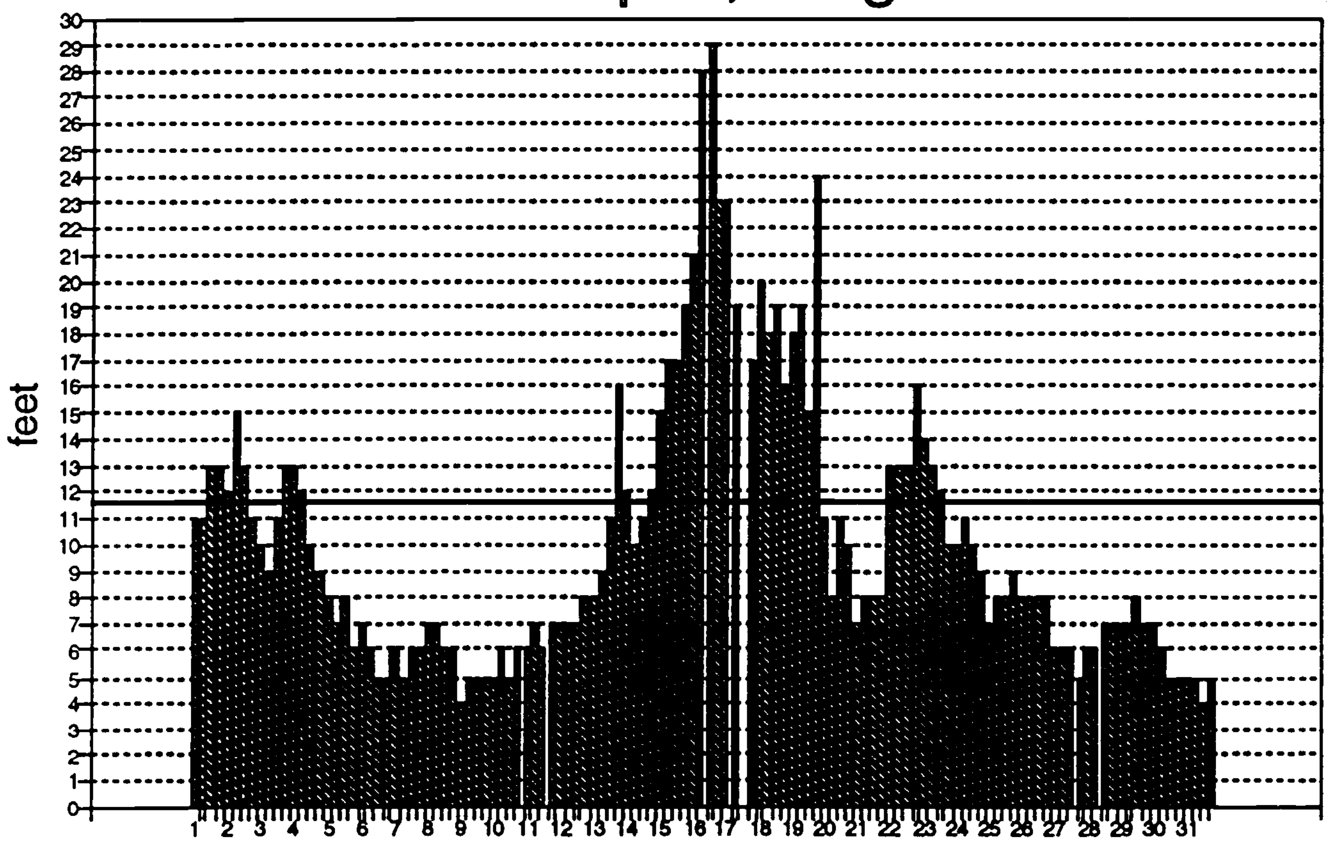
Appendix 2.
Data on Height

Daily Wave Height November 1982
Newport, Oregon



data: Hatfield Marine Science Center microseismometer

Daily Wave Height December 1982
Newport, Oregon



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Daily Wave Height January 1983
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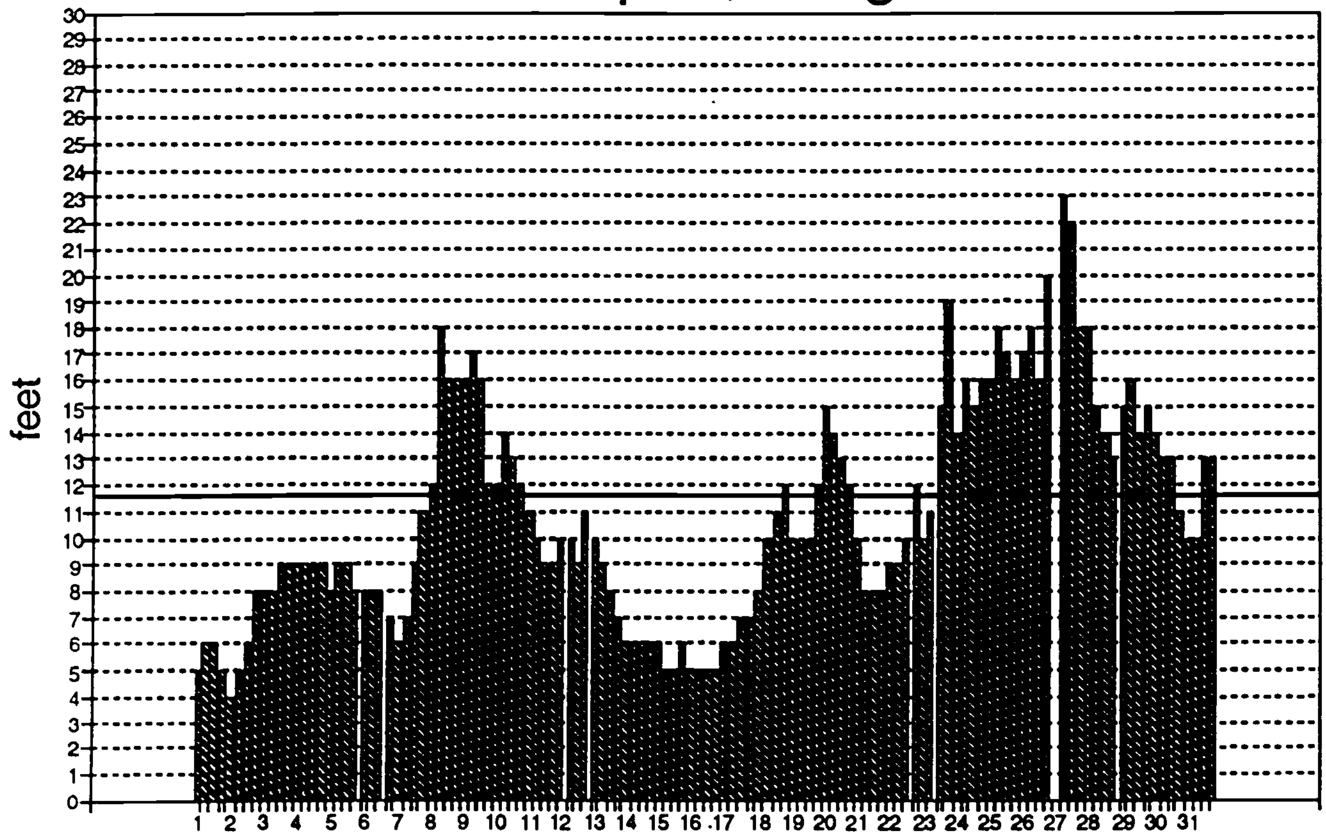

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Daily Wave Height February 1983
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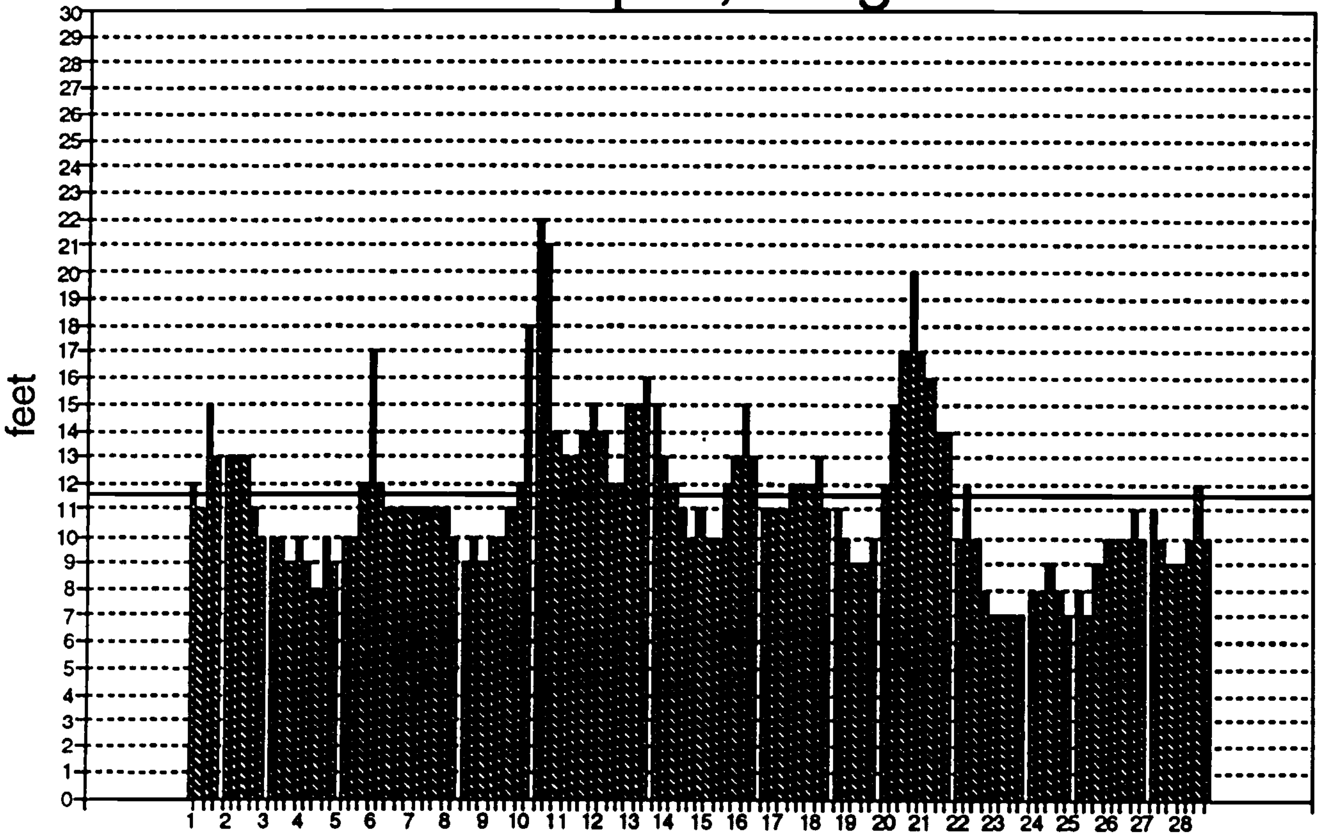

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Daily Wave Height March 1983
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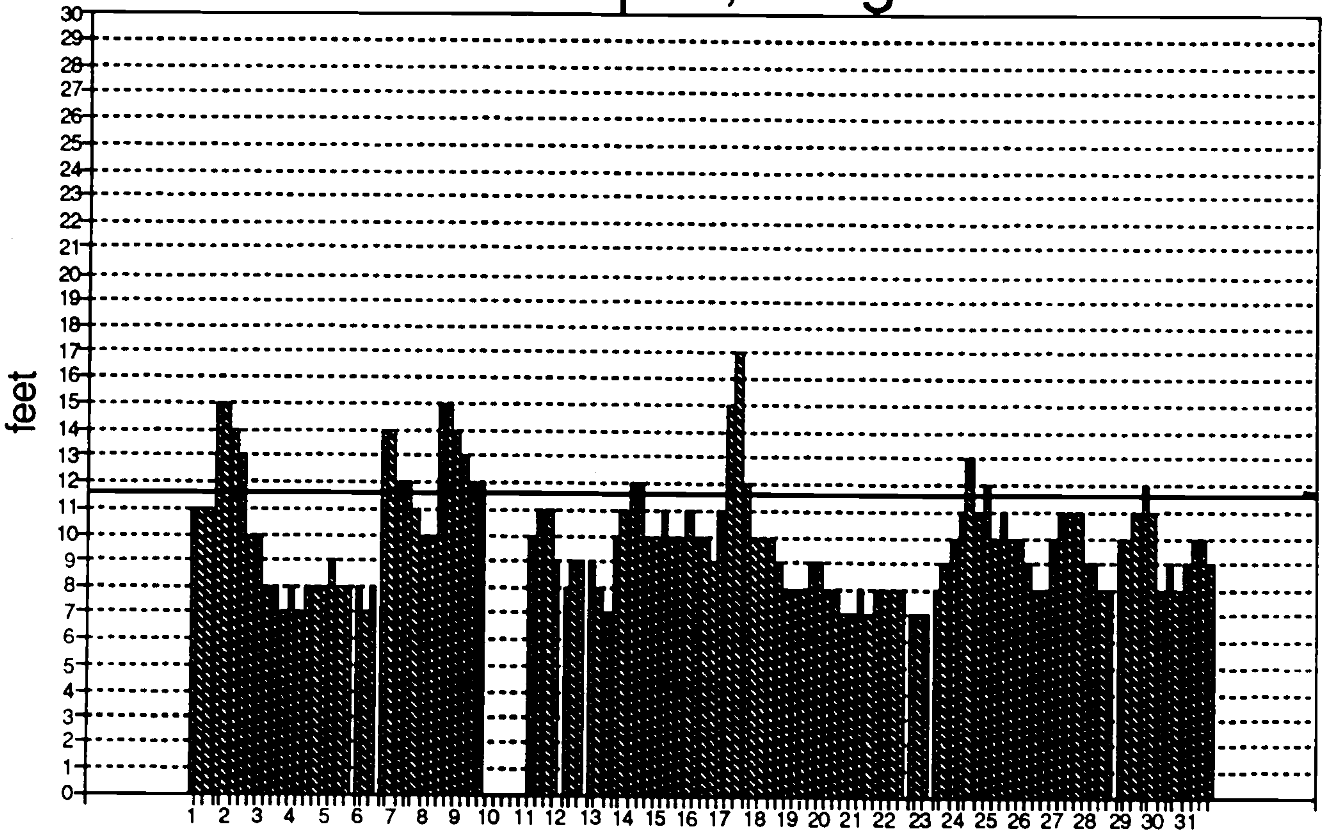

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Daily Winter Wave Height November 1983
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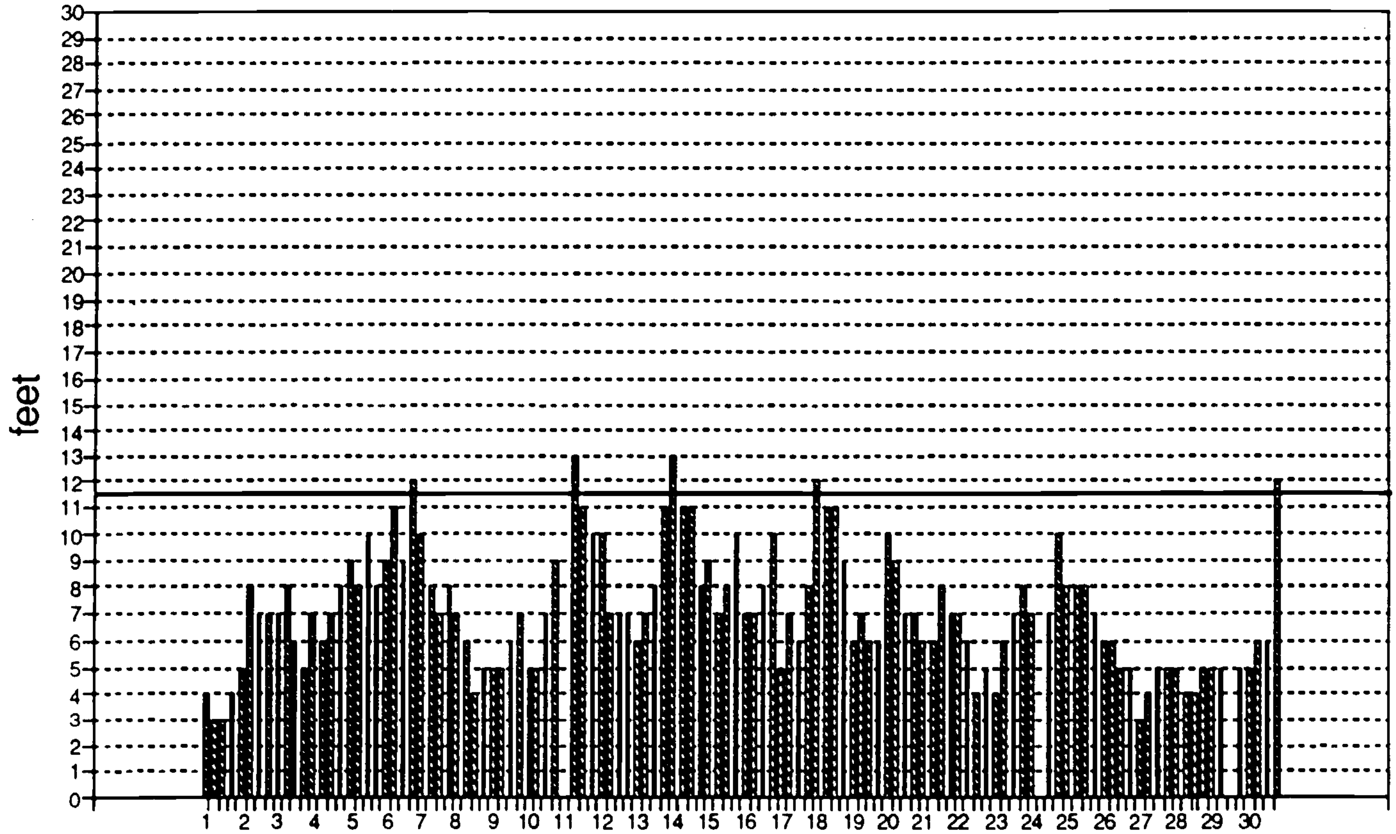

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Daily Winter Wave Height December 1983
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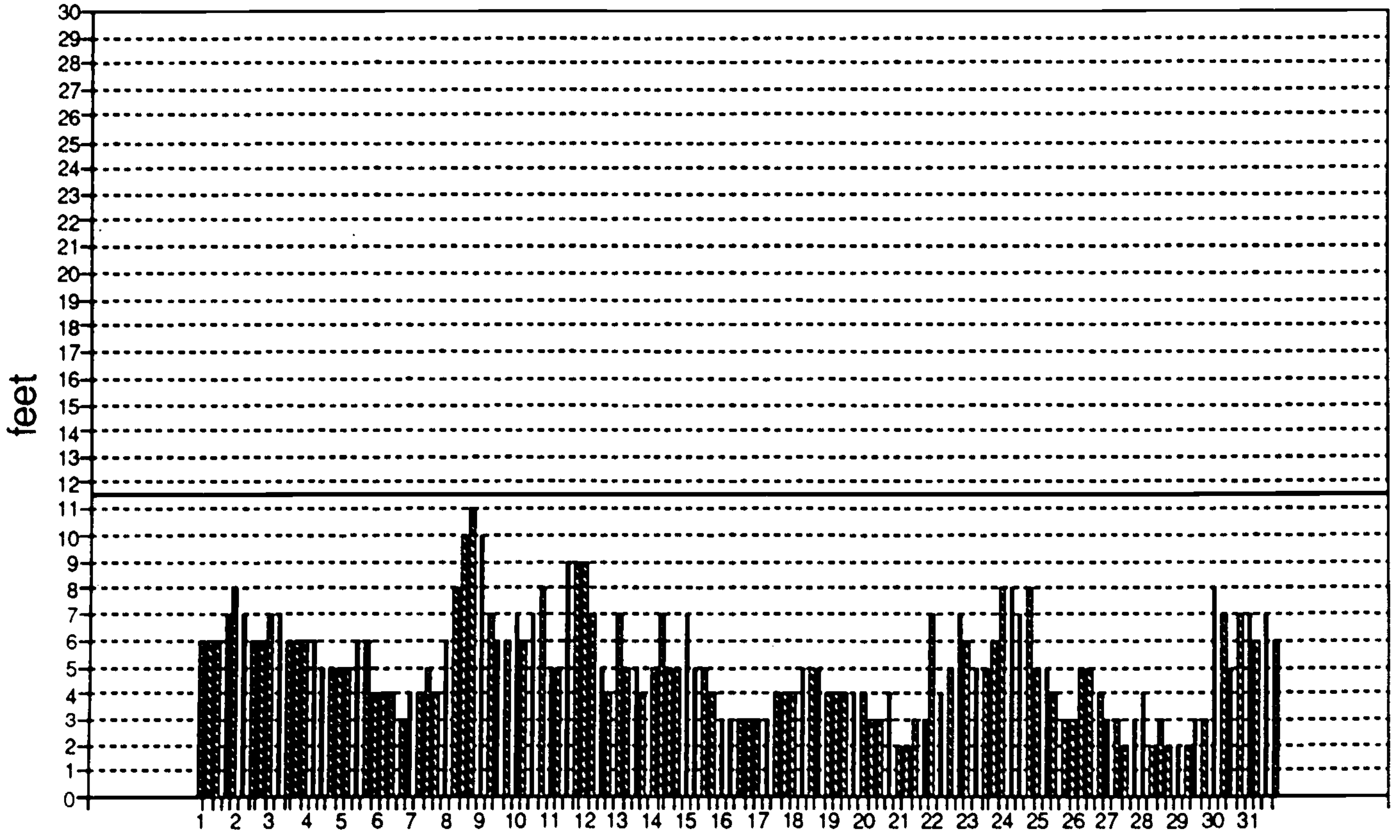

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Daily Winter Wave Height January 1984
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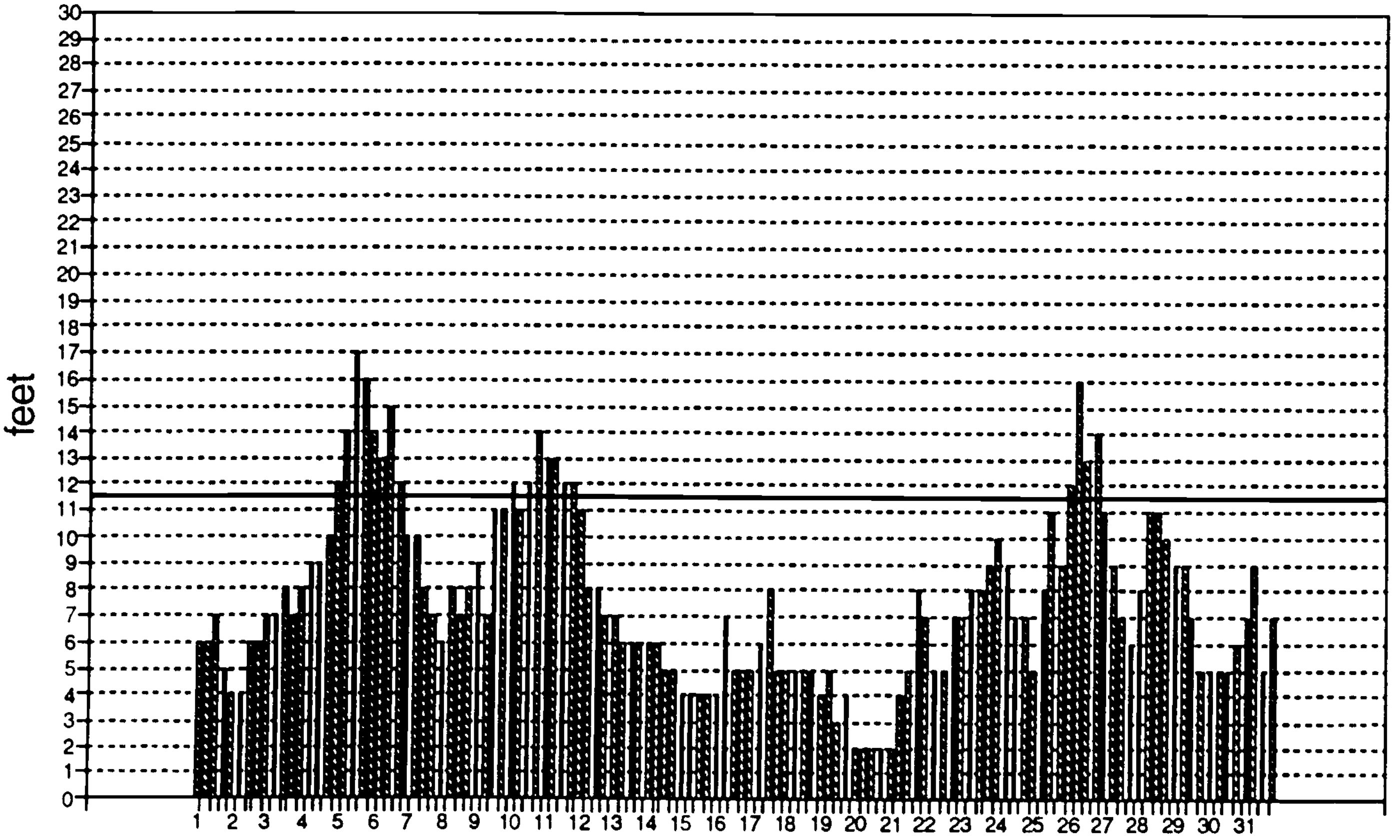

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Daily Winter Wave Height February 1984
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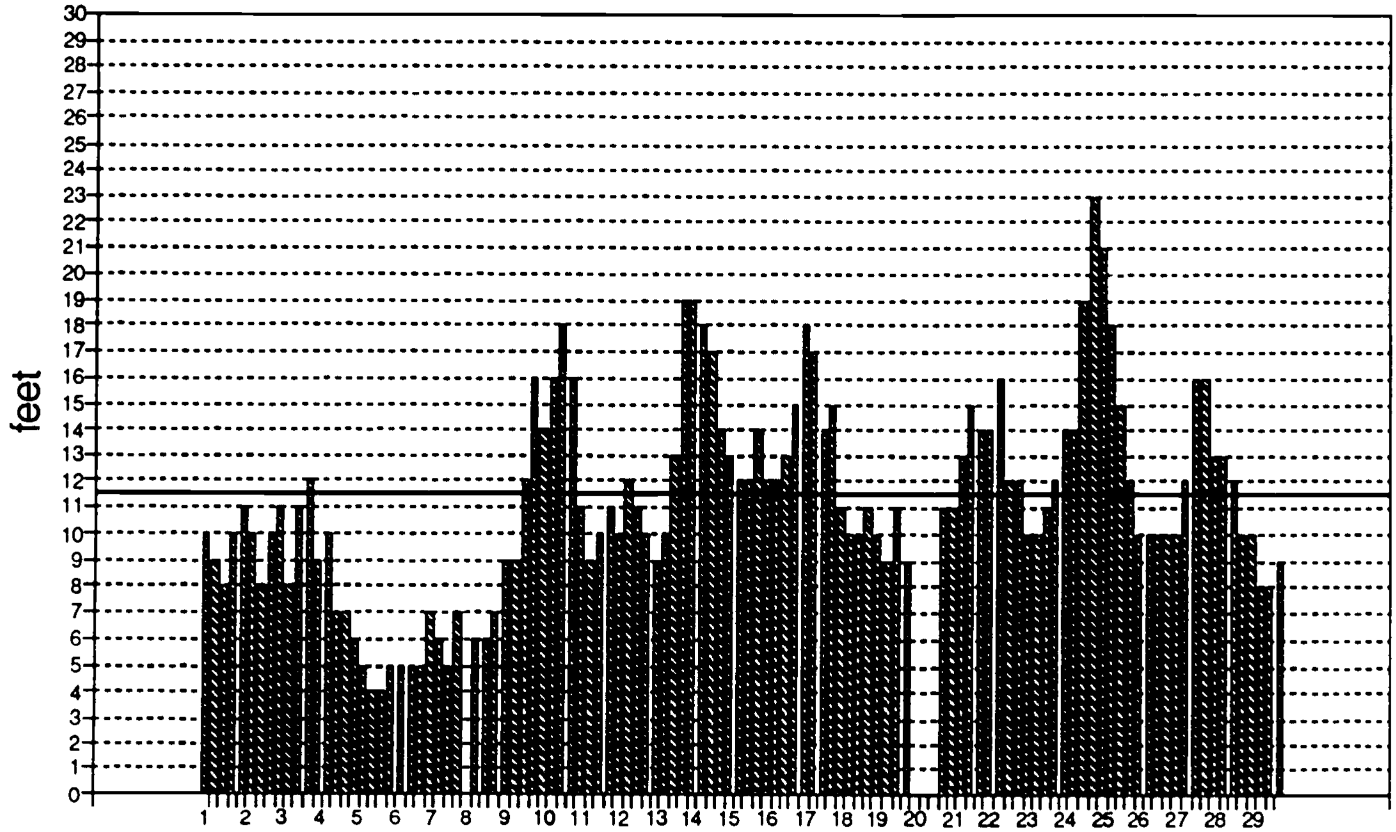

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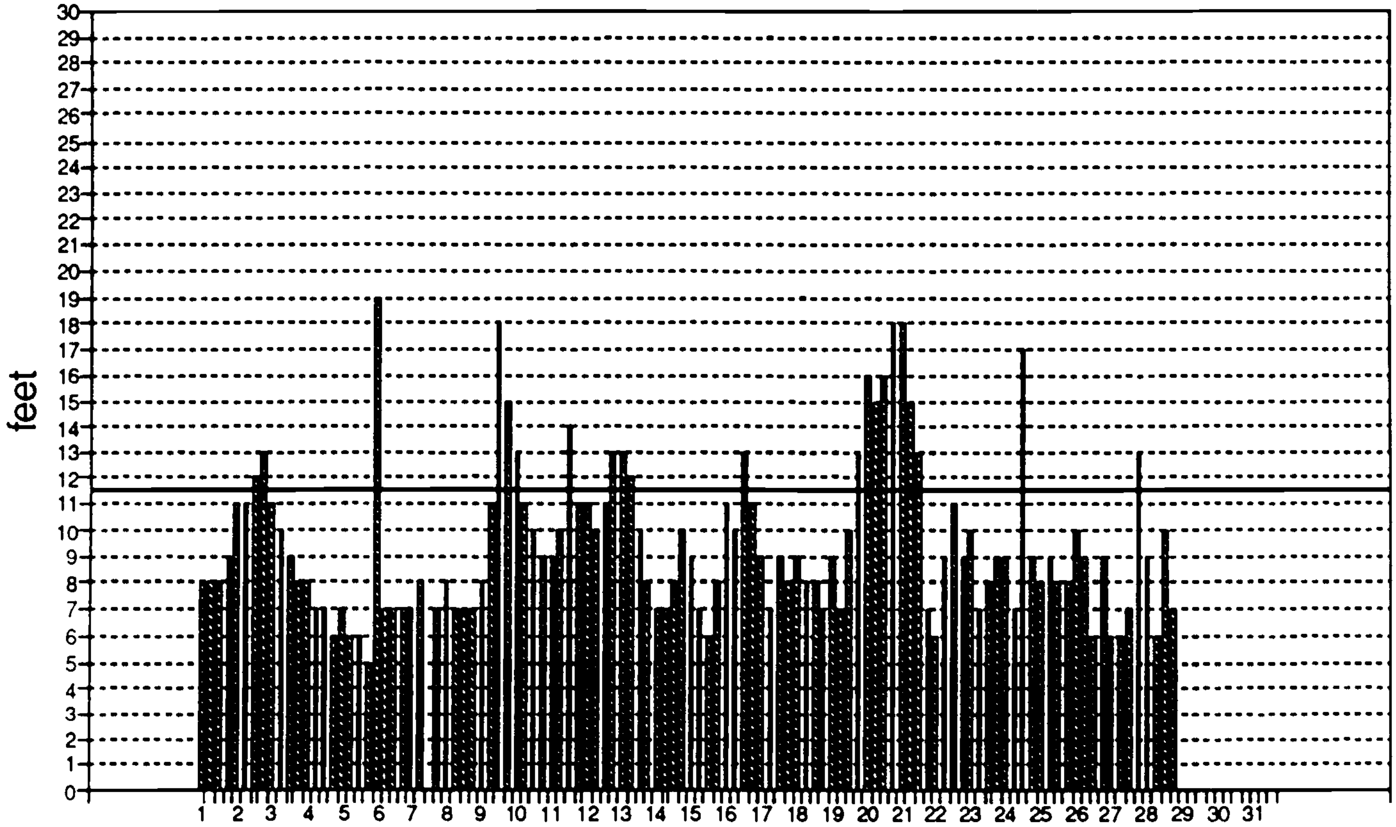

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Daily Wave Height November 1984
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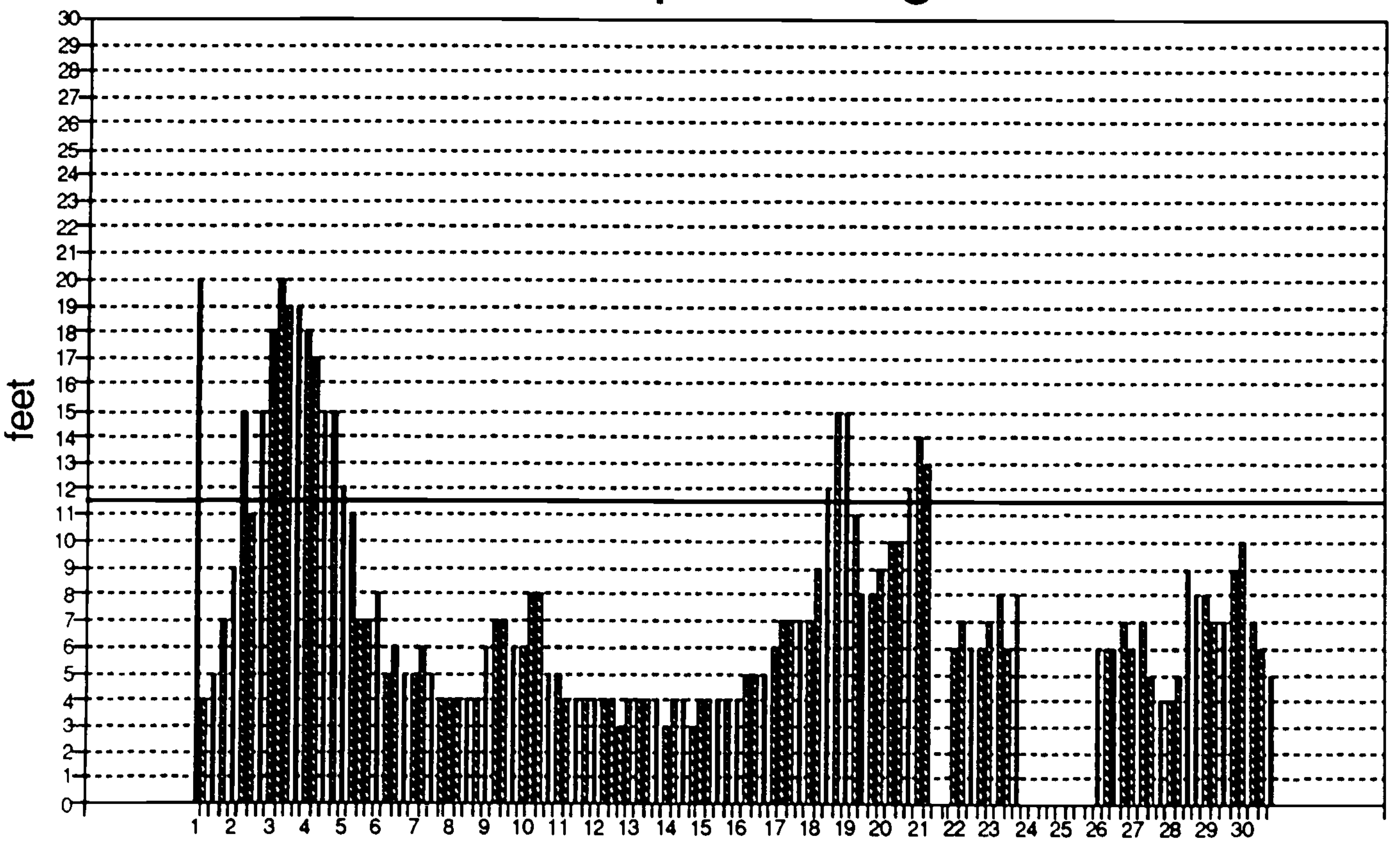

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Daily Wave Height December 1984
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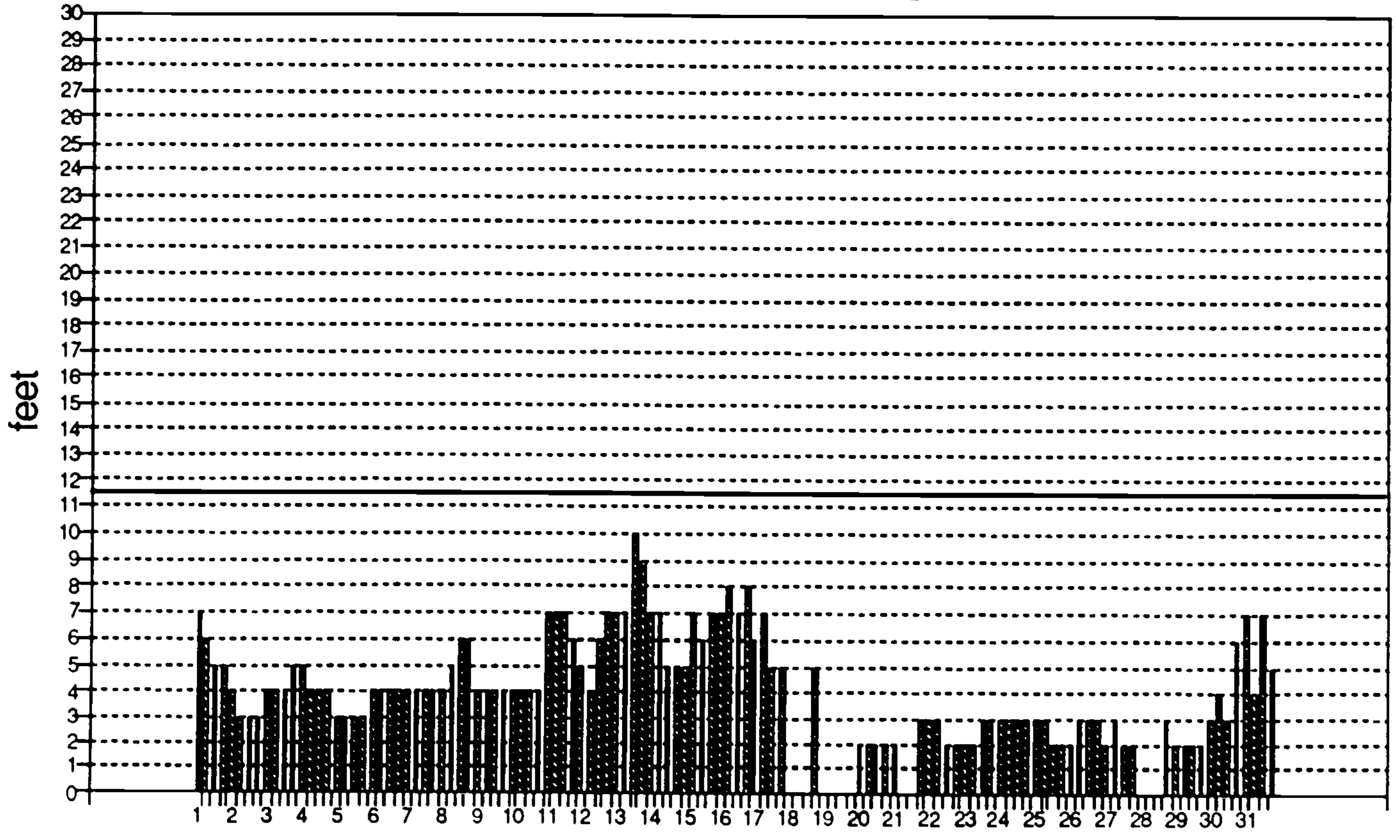

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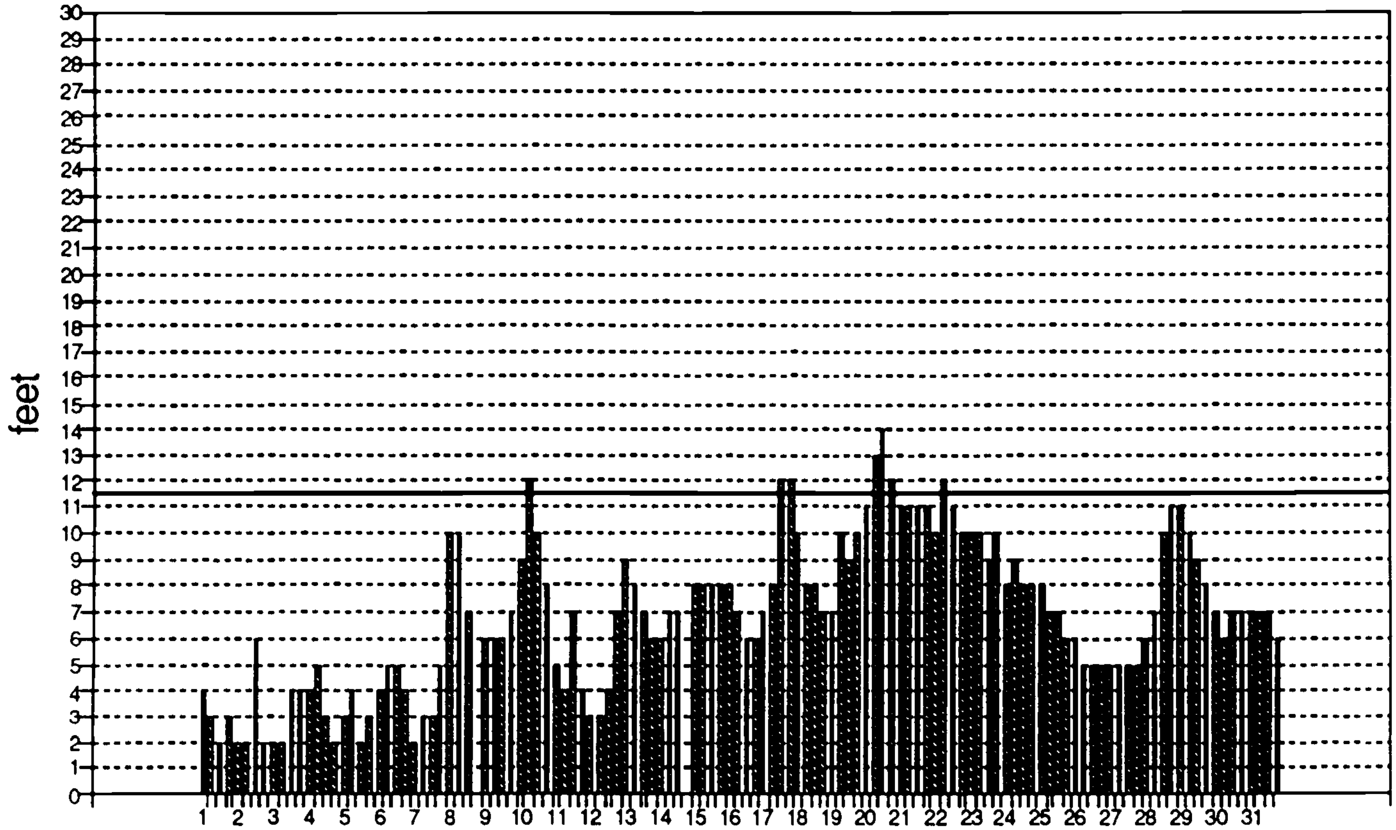
Daily Wave Height January 1985
Newport, Oregon



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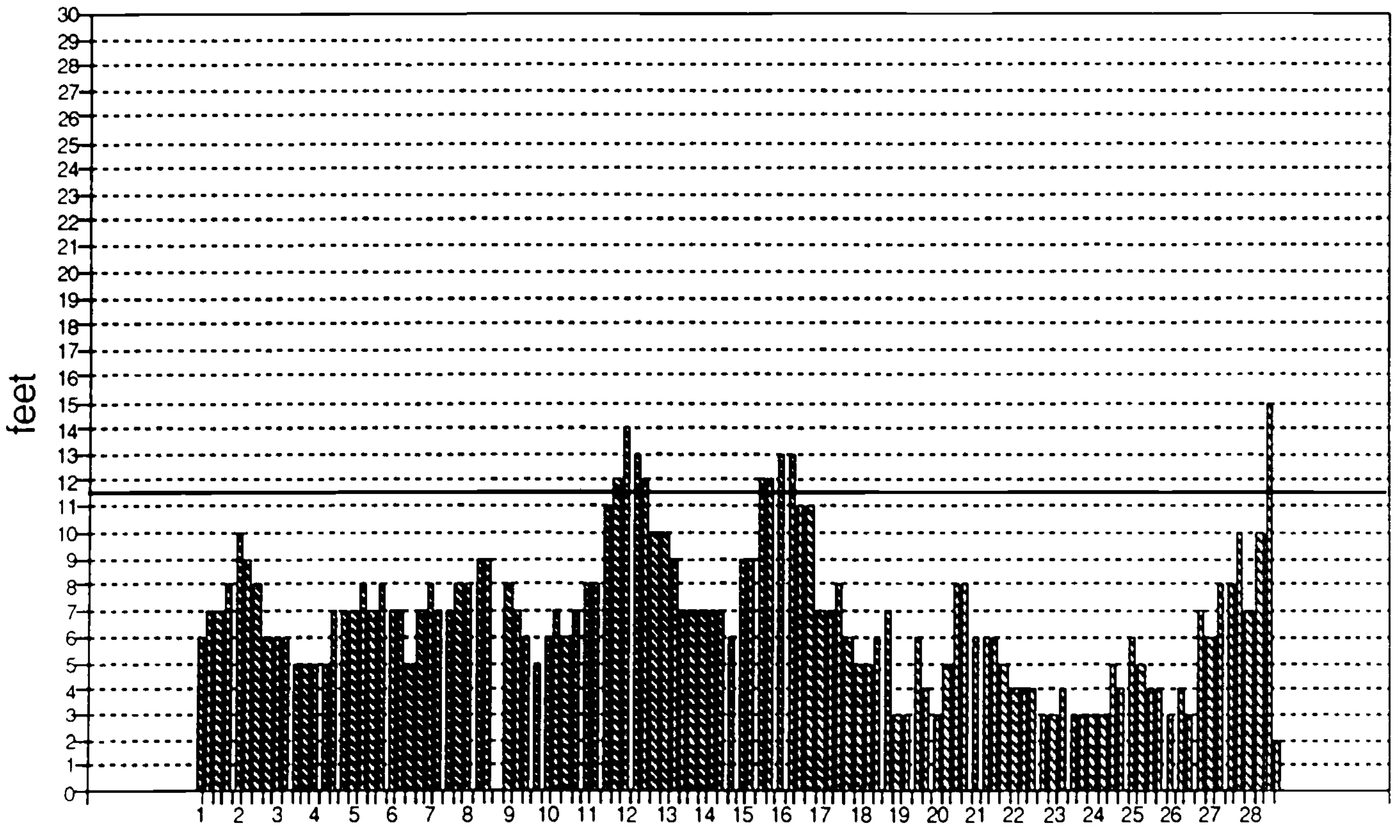
Daily Wave Height February 1985
Newport, Oregon



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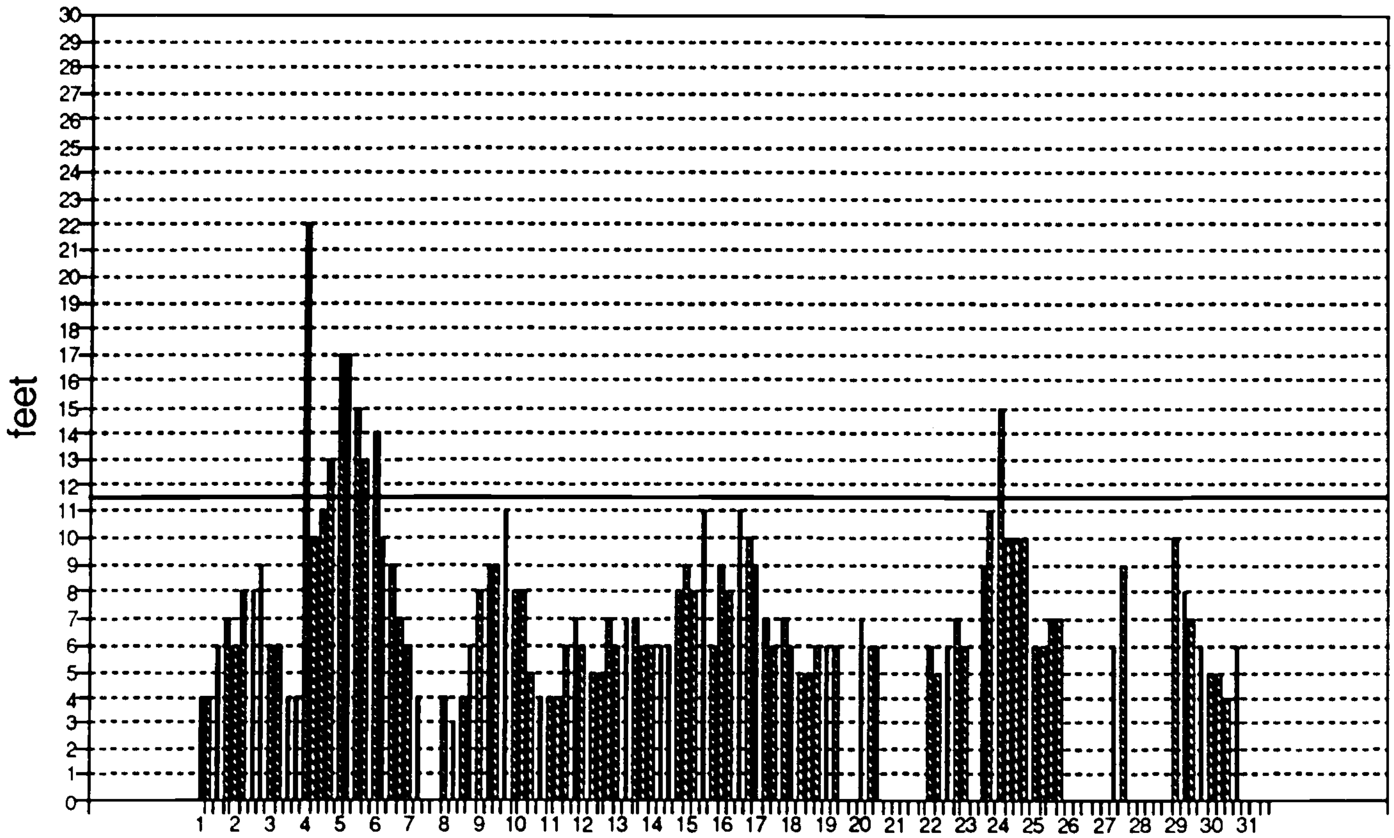
Daily Wave Height March 1985
Newport, Oregon



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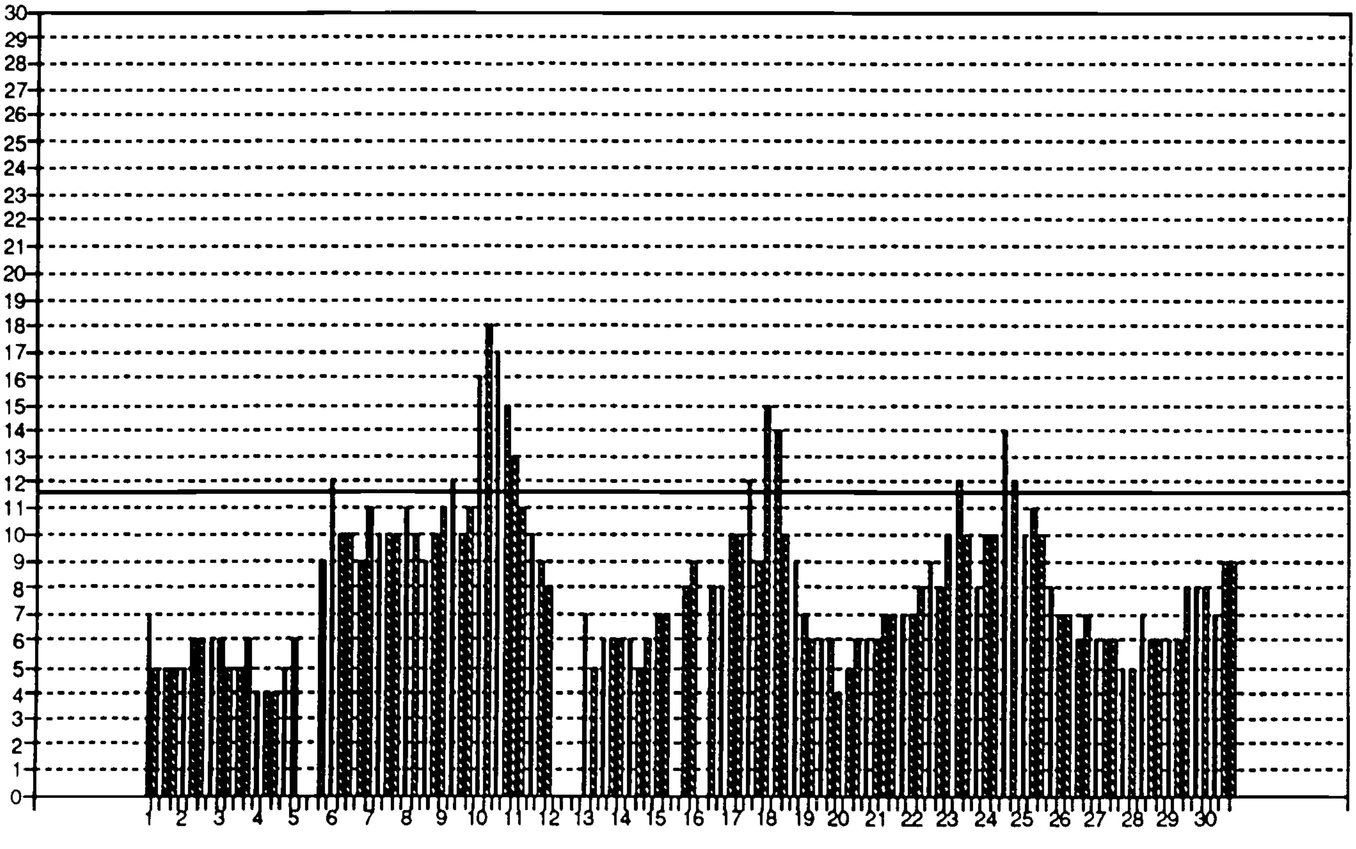
Daily Wave Height November 1985
Newport, Oregon



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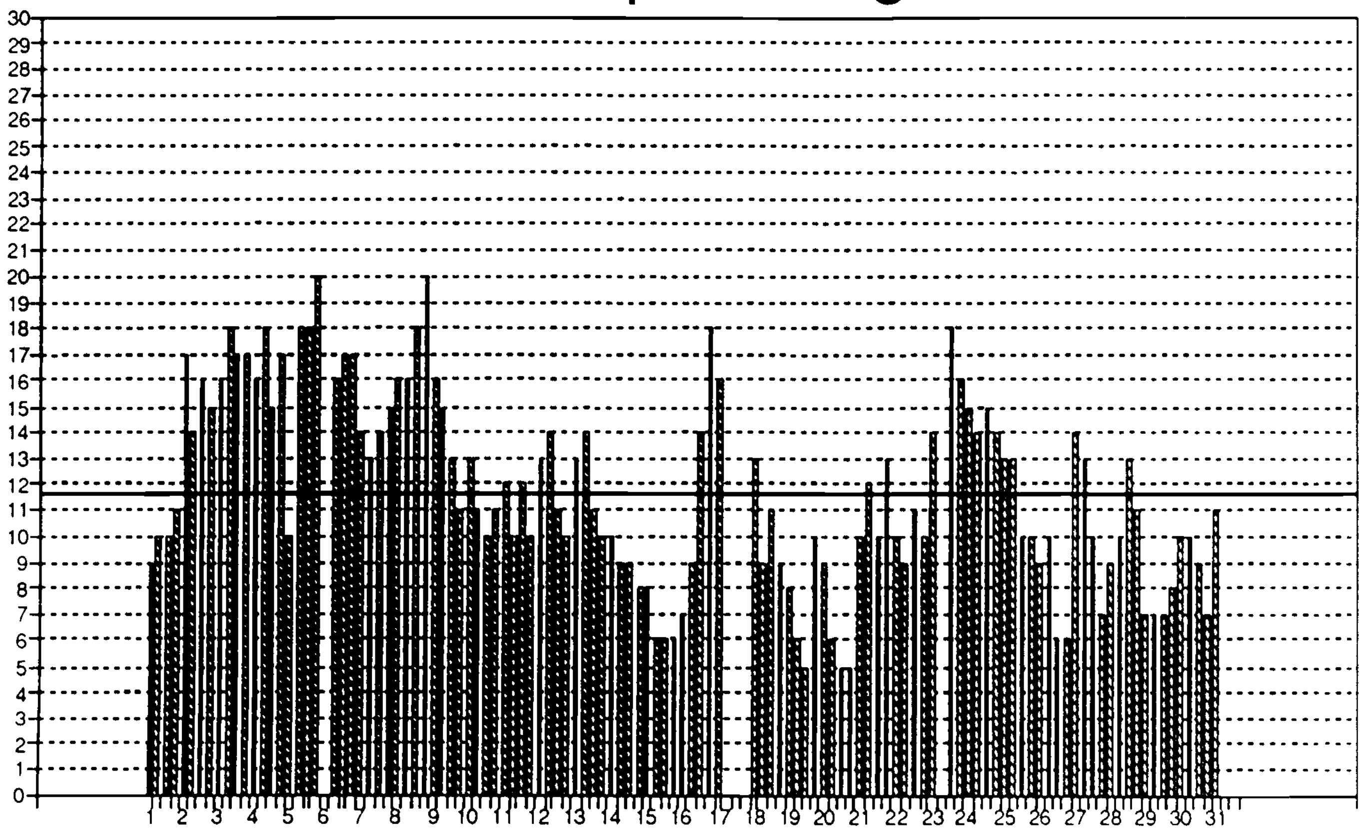
Daily Wave Height December 1985
Newport, Oregon



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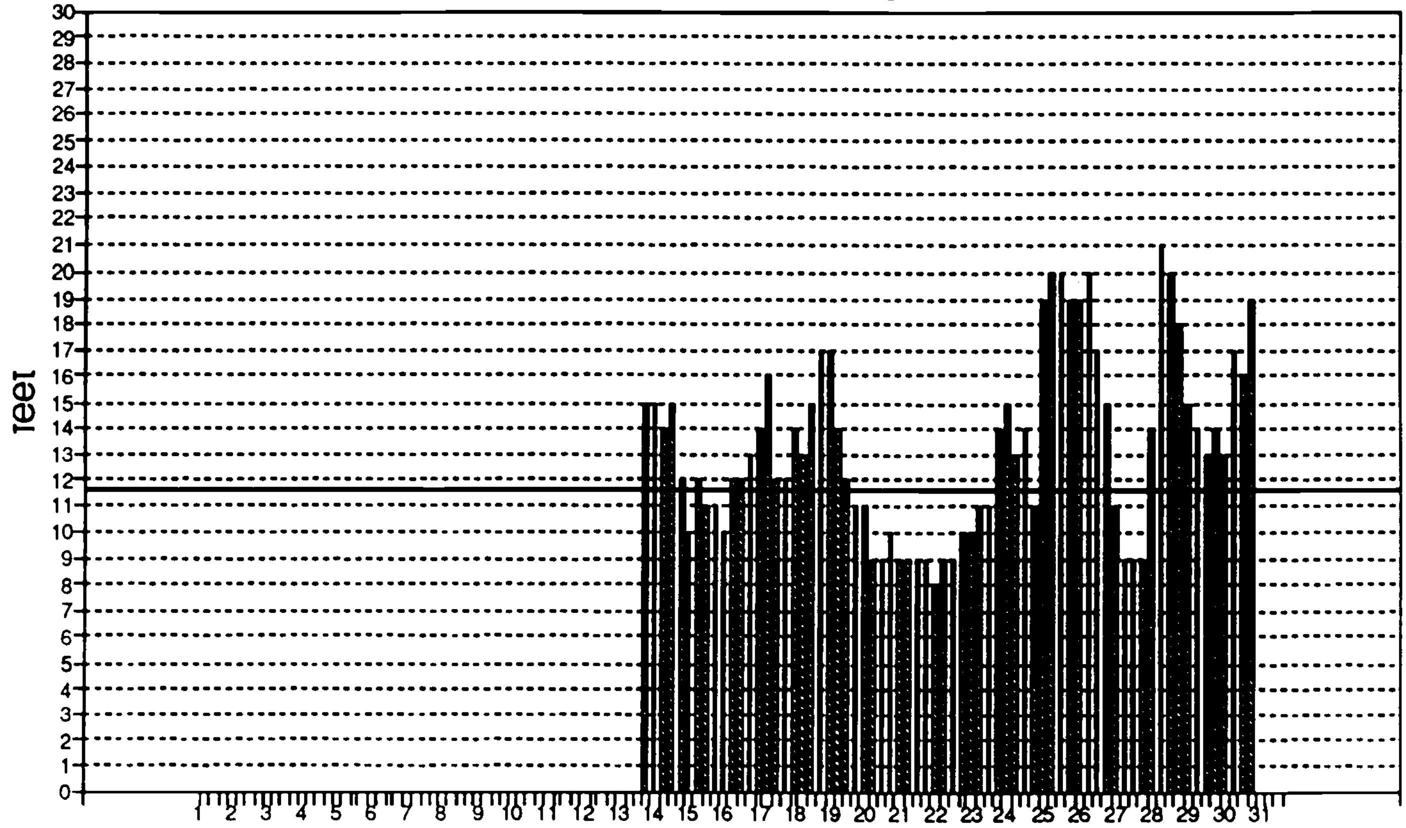
Daily Wave Height January 1986
Newport, Oregon



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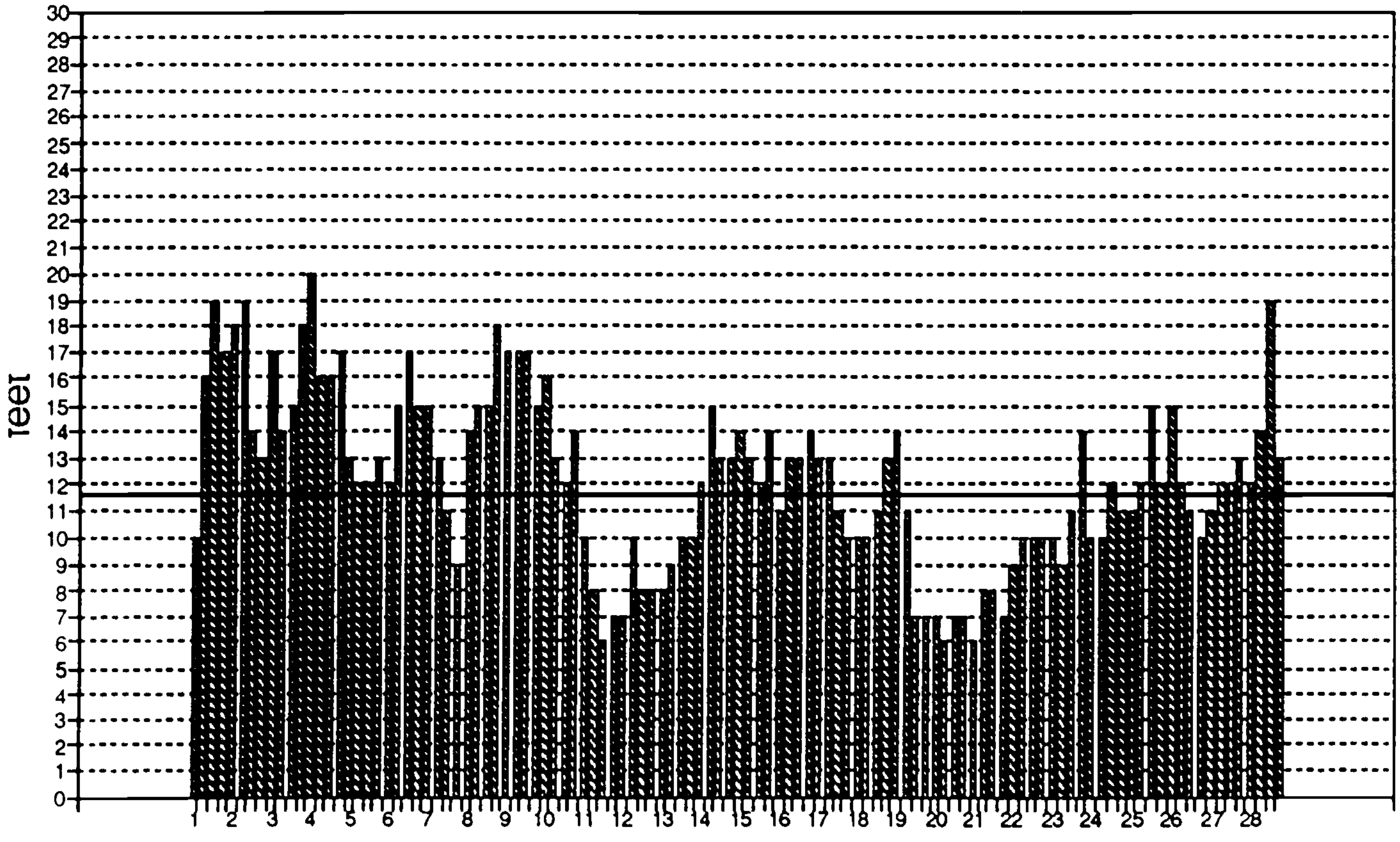
Daily Wave Height February 1986
Newport, Oregon



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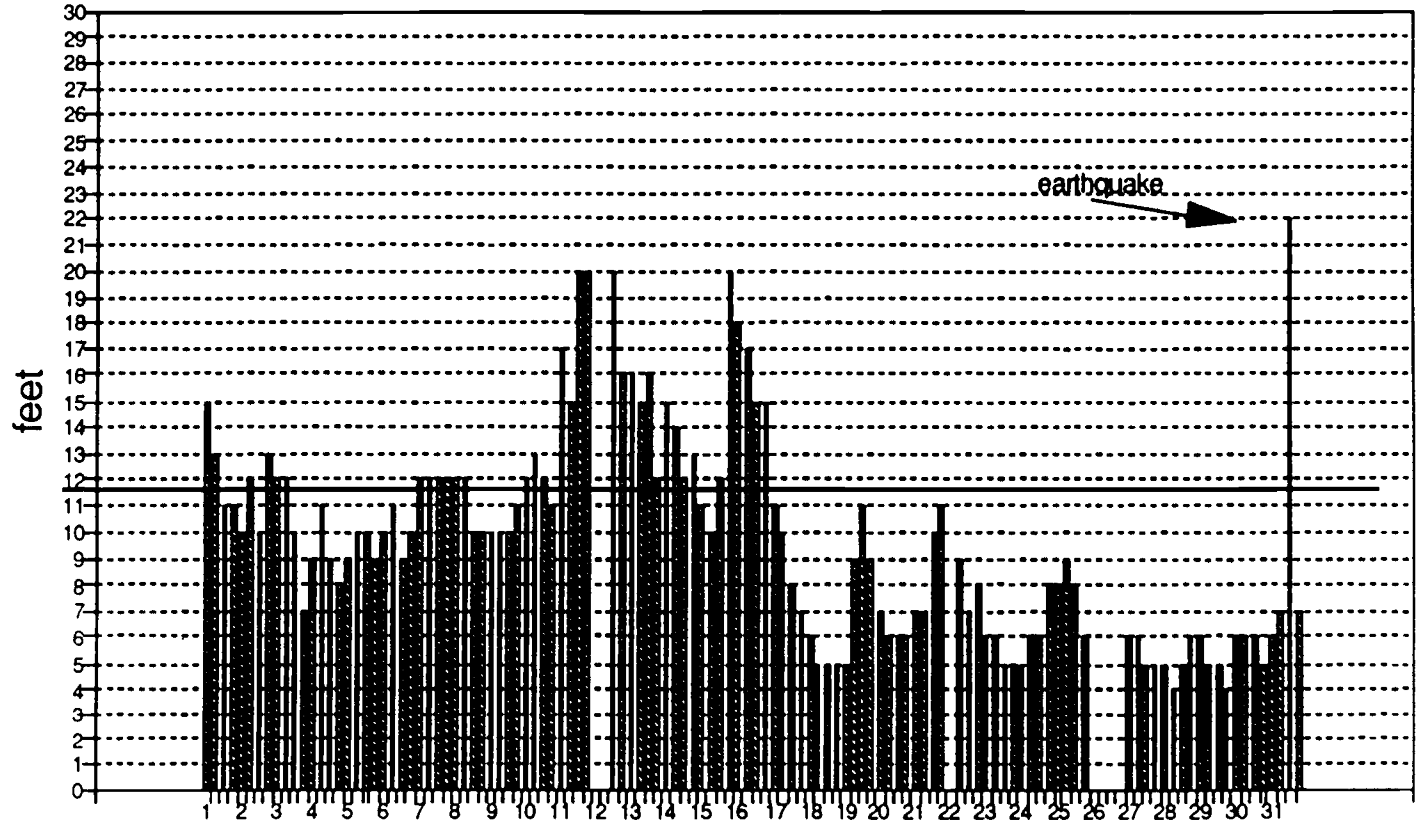
Daily Wave Height March 1986
Newport, Oregon



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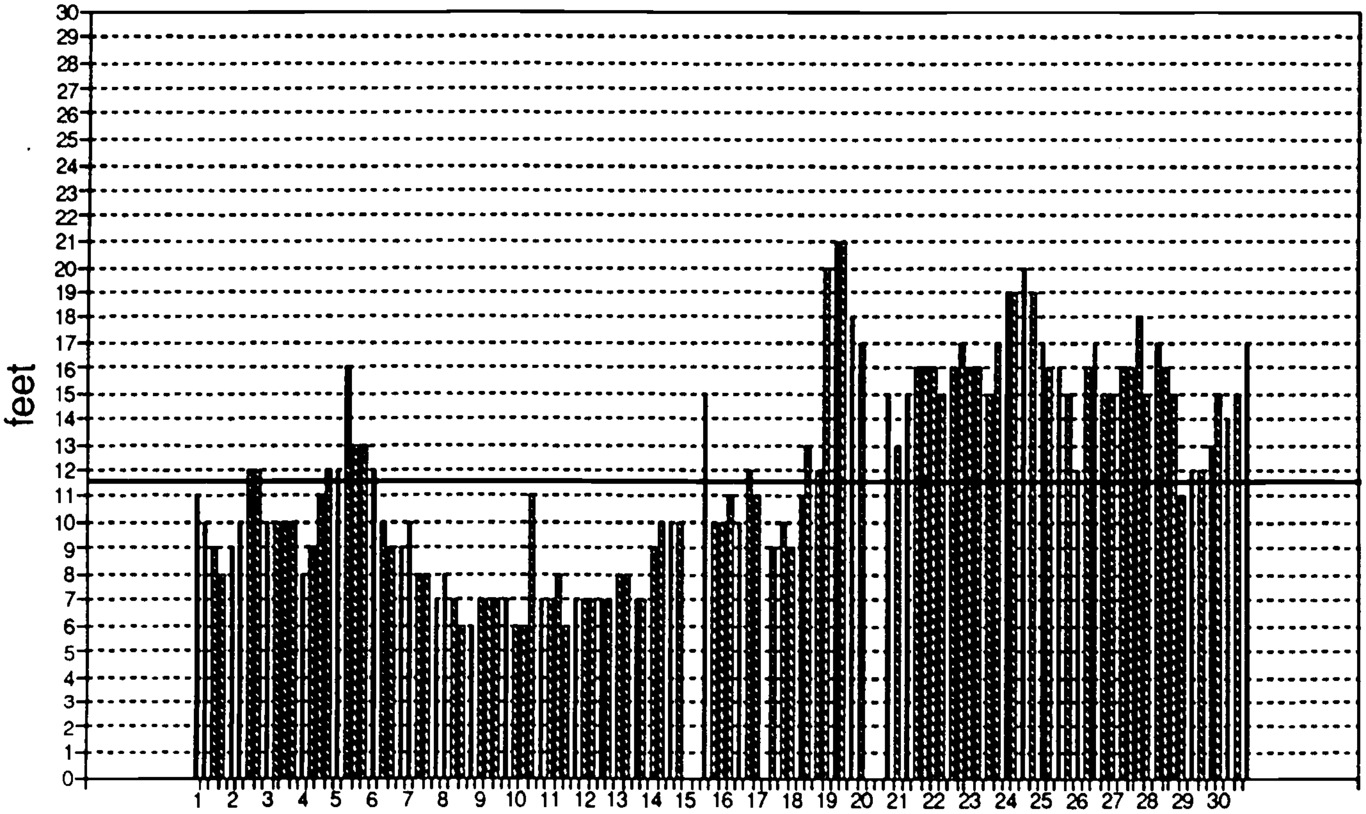
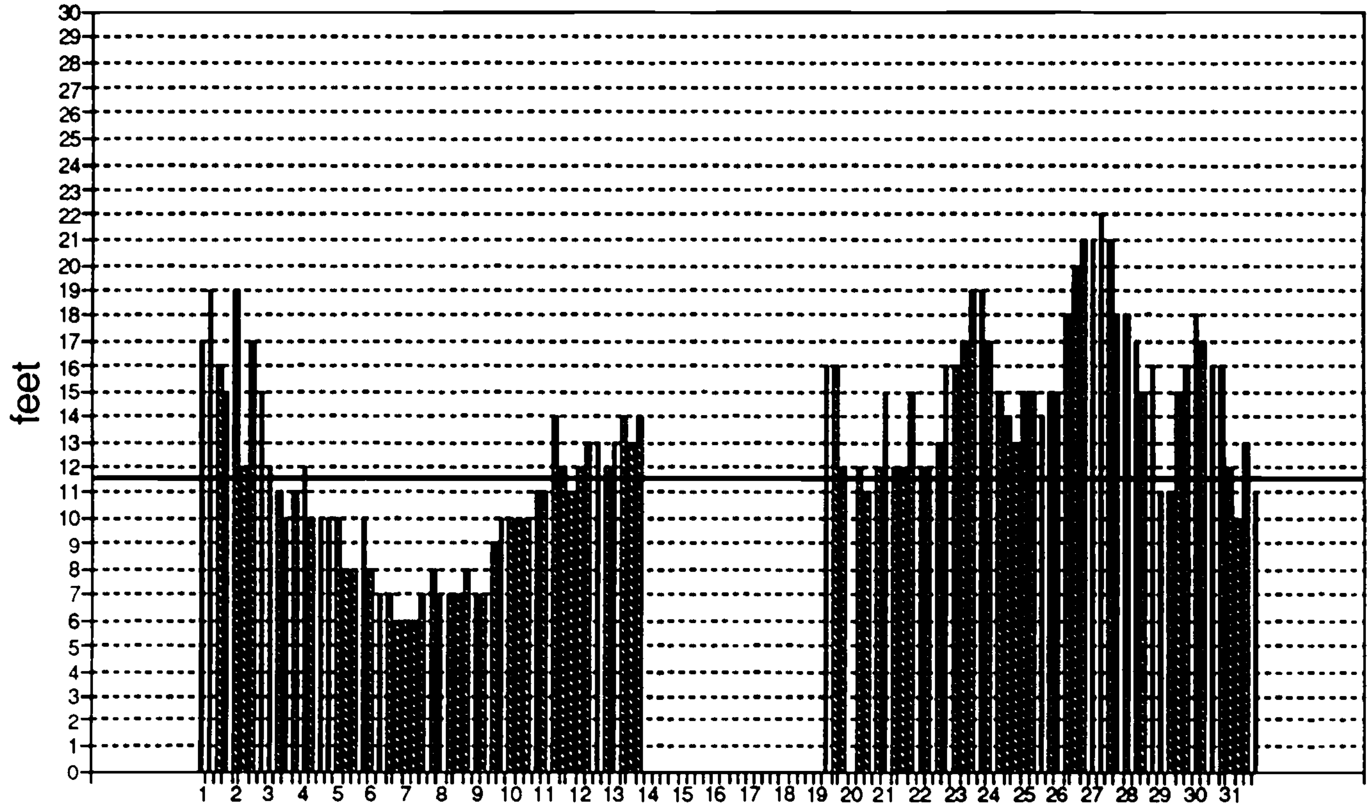
Daily Wave Height November 1986
Newport, Oregon



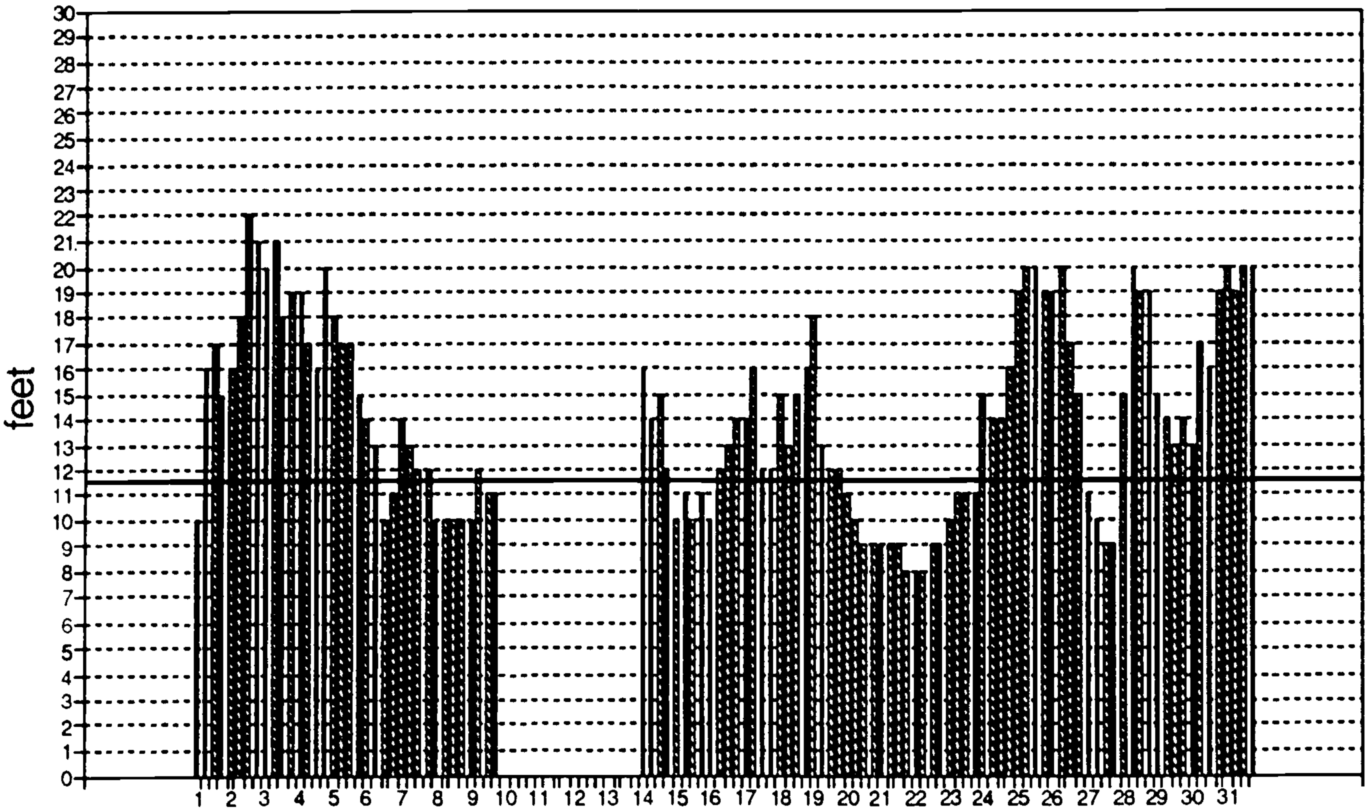
data: Hatfield Marine Science Center microseismometer

Daily Wave Height December 1986
Newport, Oregon



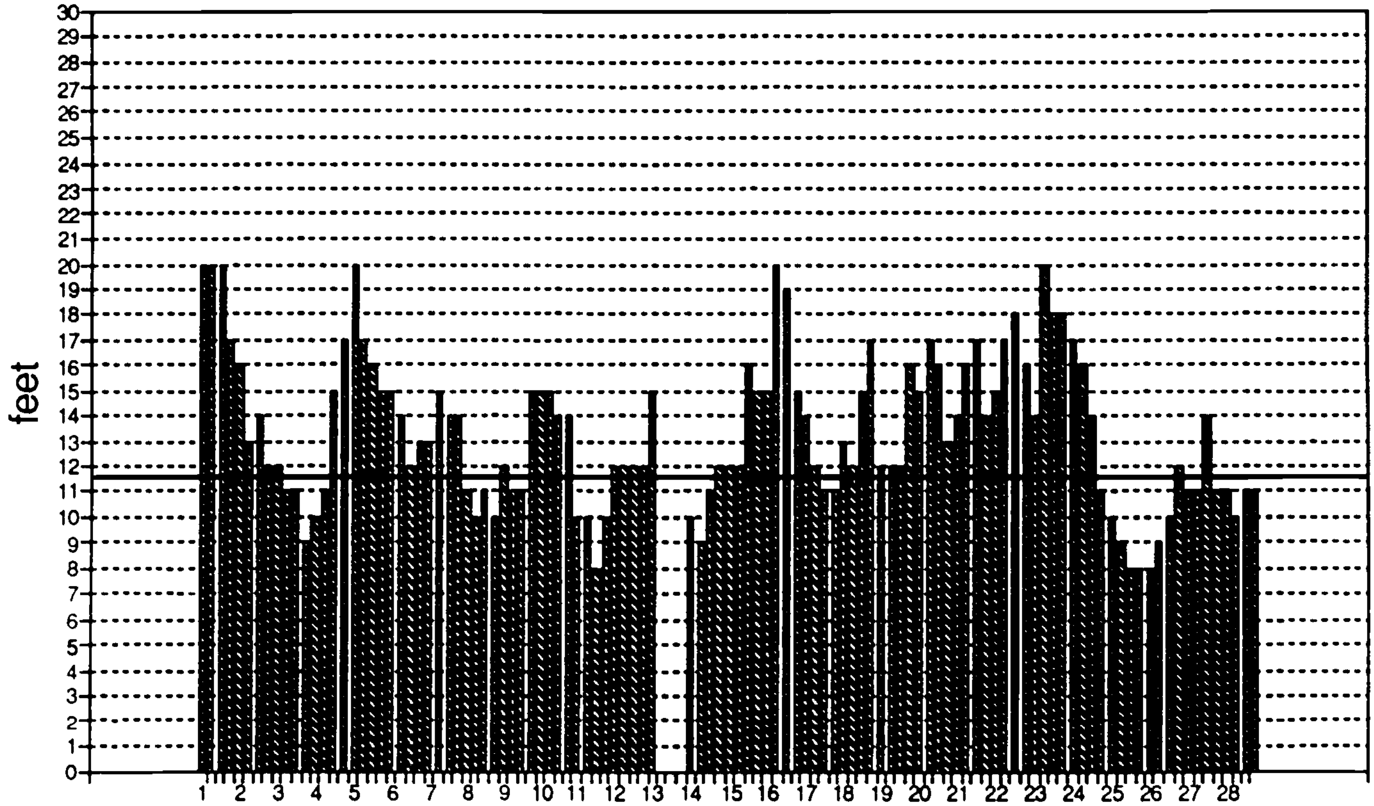
data: Hatfield Marine Science Center microseismometer

Daily Wave Height January 1987
Newport, Oregon



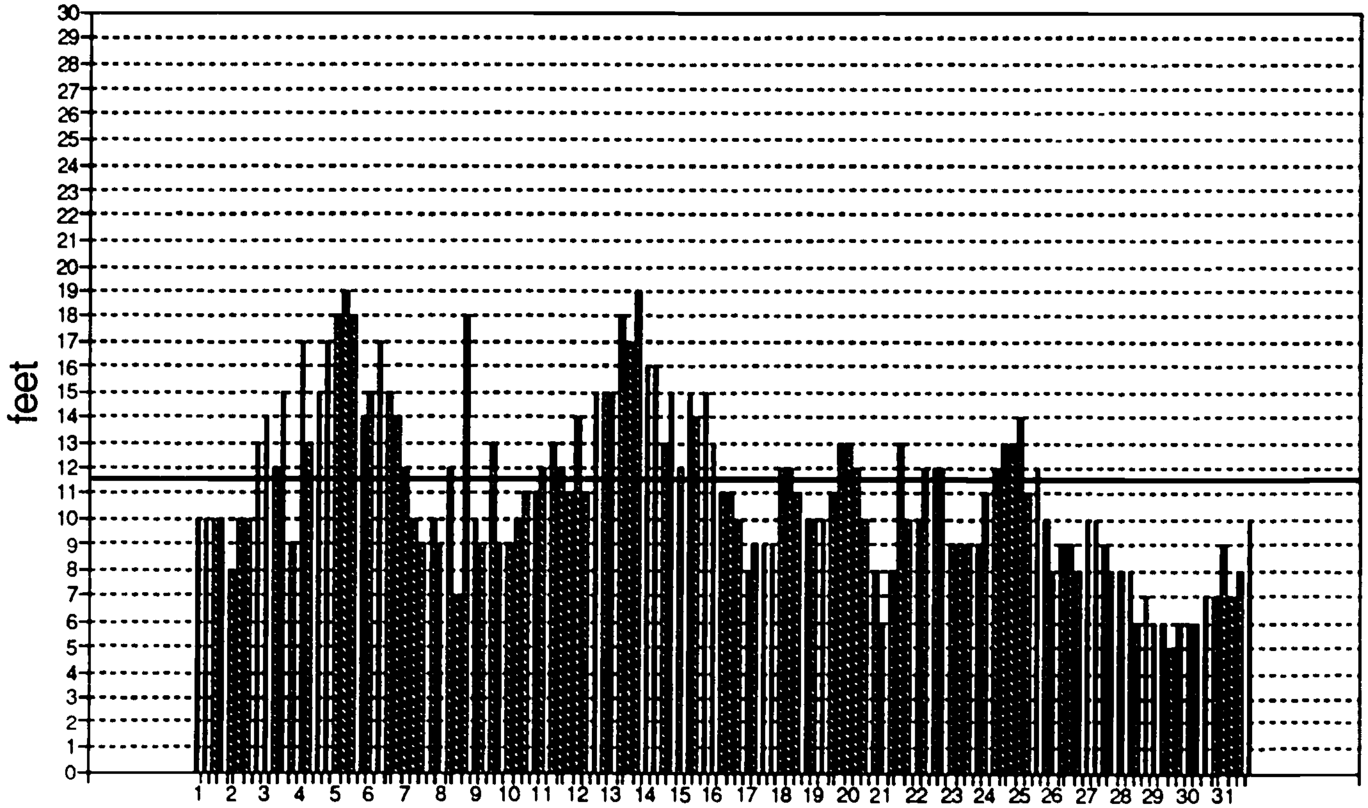
data: Hatfield Marine Science Center microseismometer

Daily Wave Height February 1987
Newport, Oregon



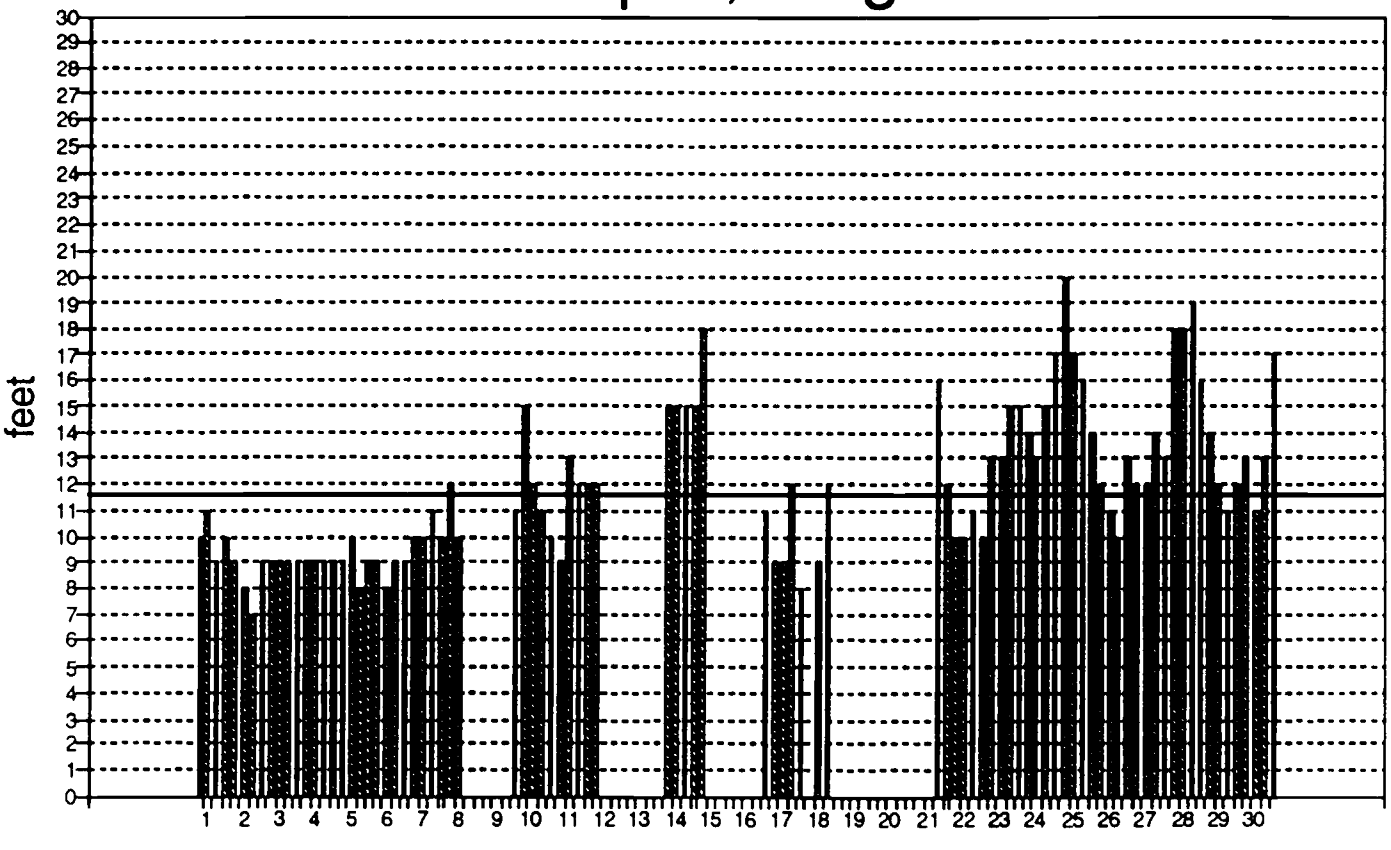
data: Hatfield Marine Science Center microseismometer

Daily Wave Height March 1987
Newport, Oregon



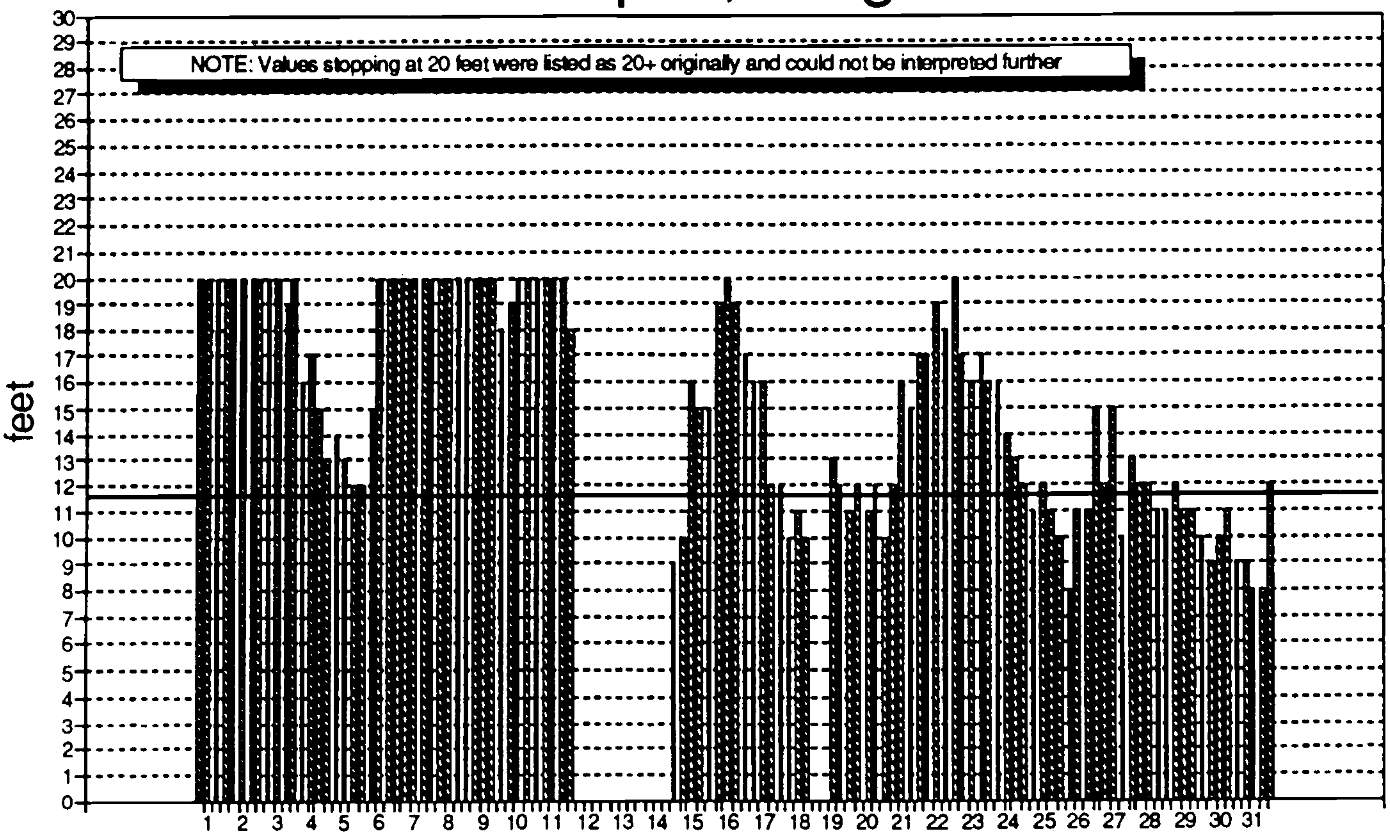
data: Hatfield Marine Science Center microseismometer

Daily Wave Height November 1987
Newport, Oregon



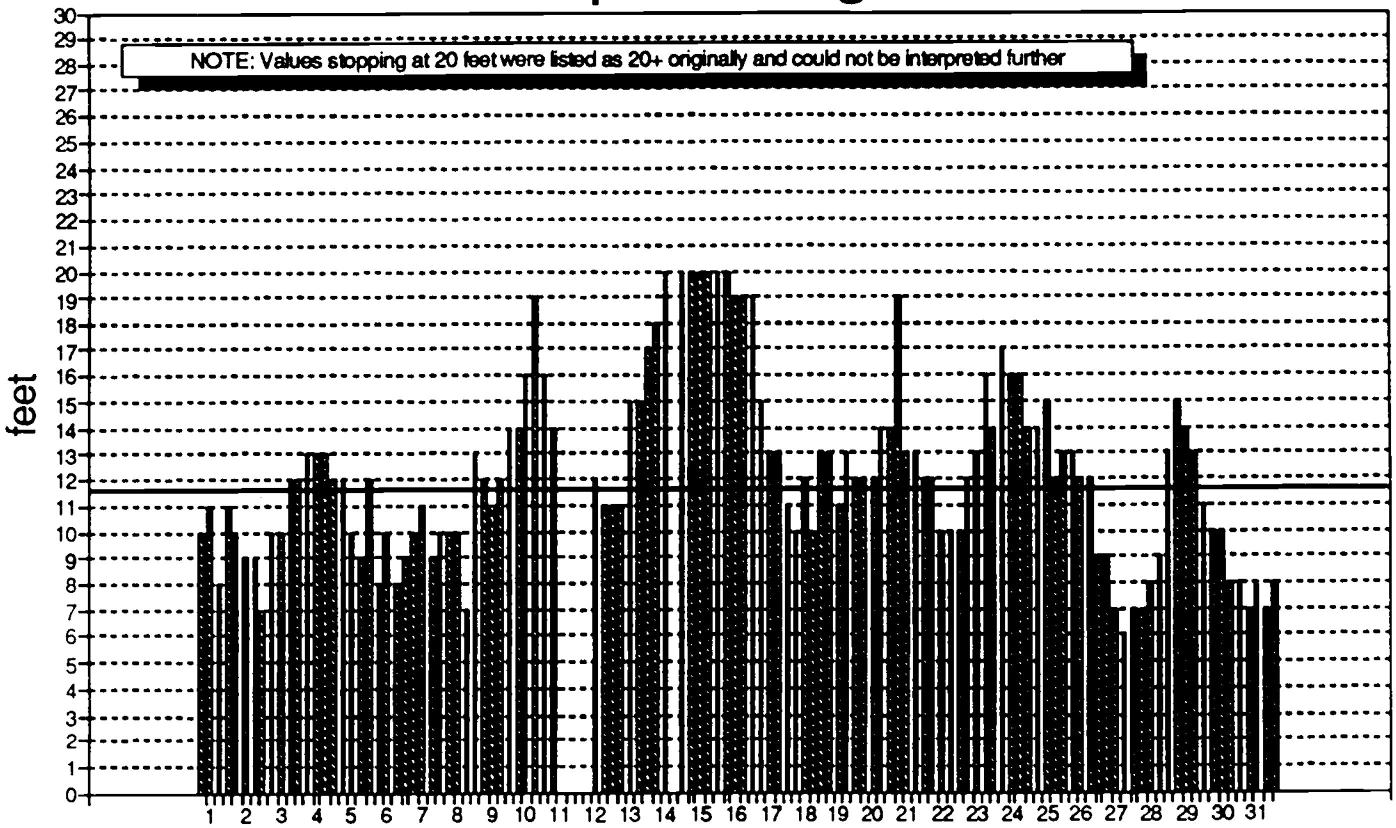
data: Hatfield Marine Science Center microseismometer

Daily Wave Height December 1987
Newport, Oregon



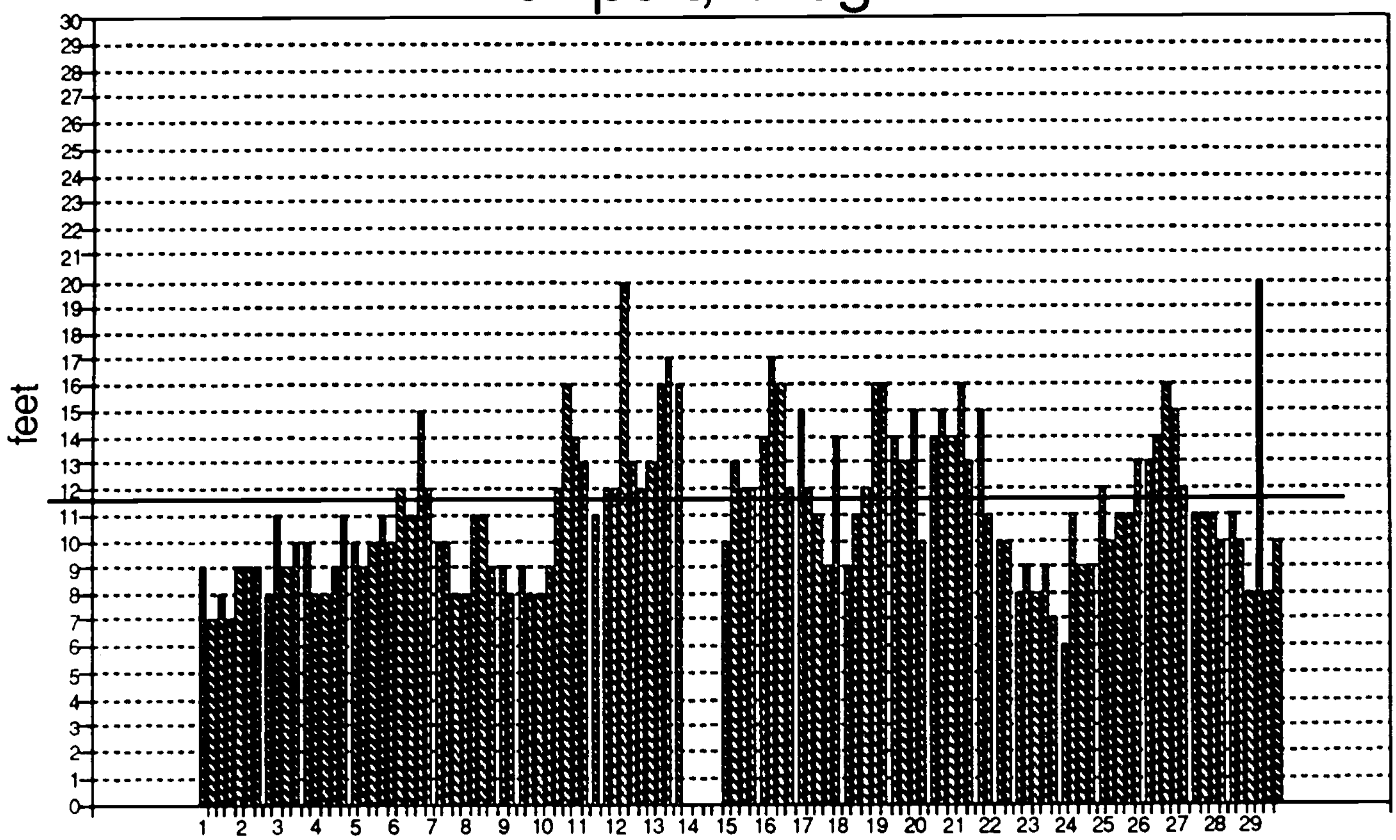
data: Hatfield Marine Science Center microseismometer

Daily Wave Height January 1988
Newport, Oregon



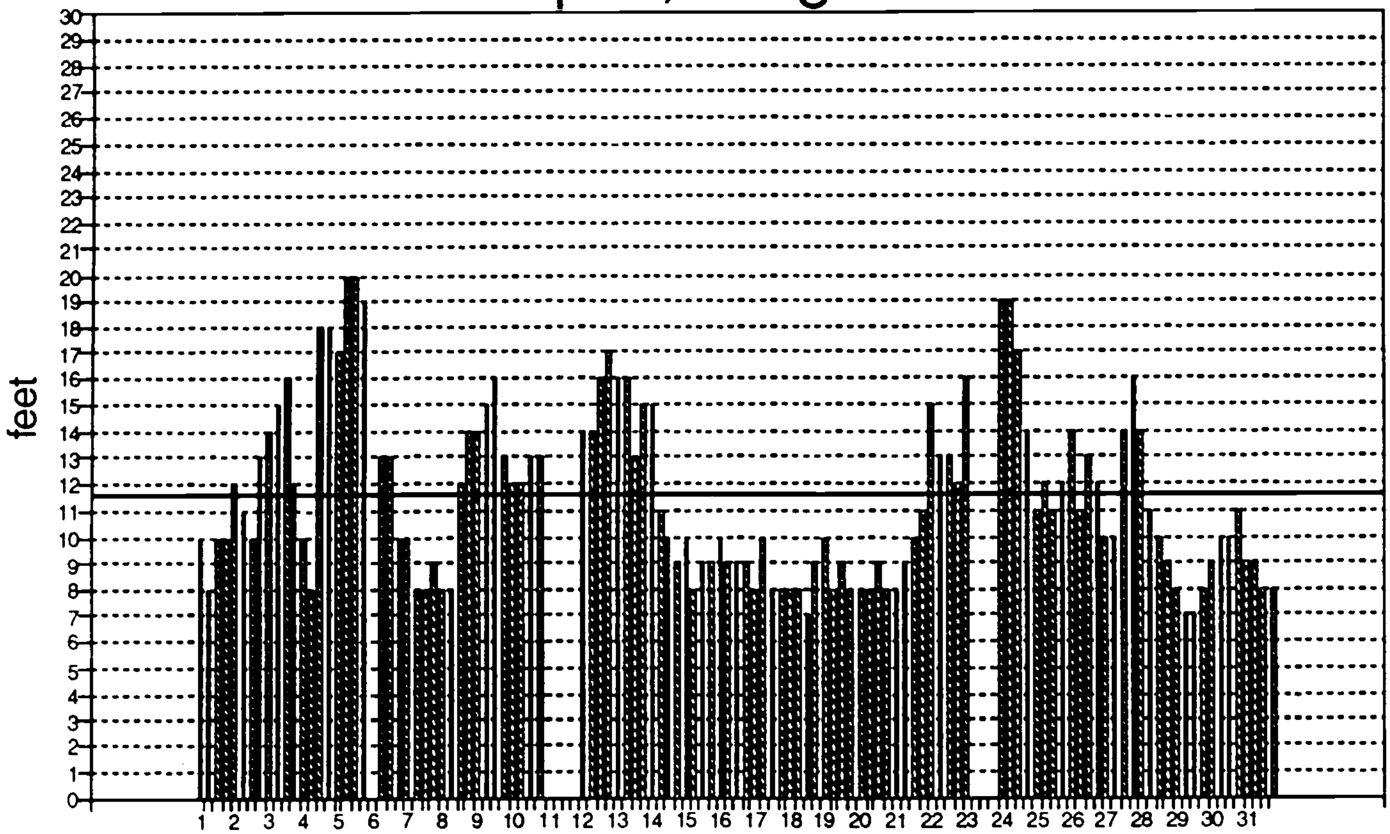
data: Hatfield Marine Science Center microseismometer

Daily Wave Height February 1988
Newport, Oregon



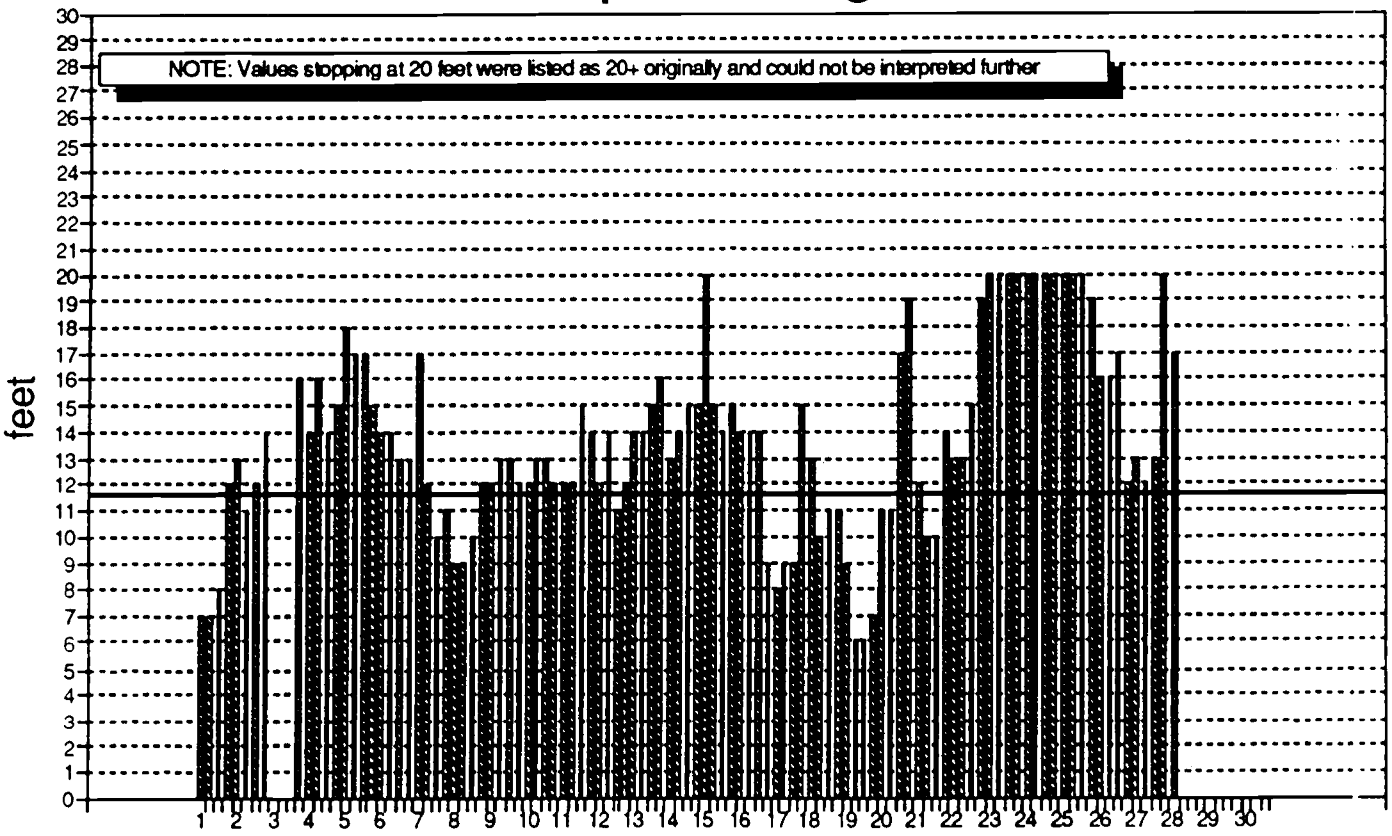
data: Hatfield Marine Science Center microseismometer

Daily Wave Height March 1988
Newport, Oregon



data: Hatfield Marine Science Center microseismometer

Daily Wave Height November 1988
Newport, Oregon



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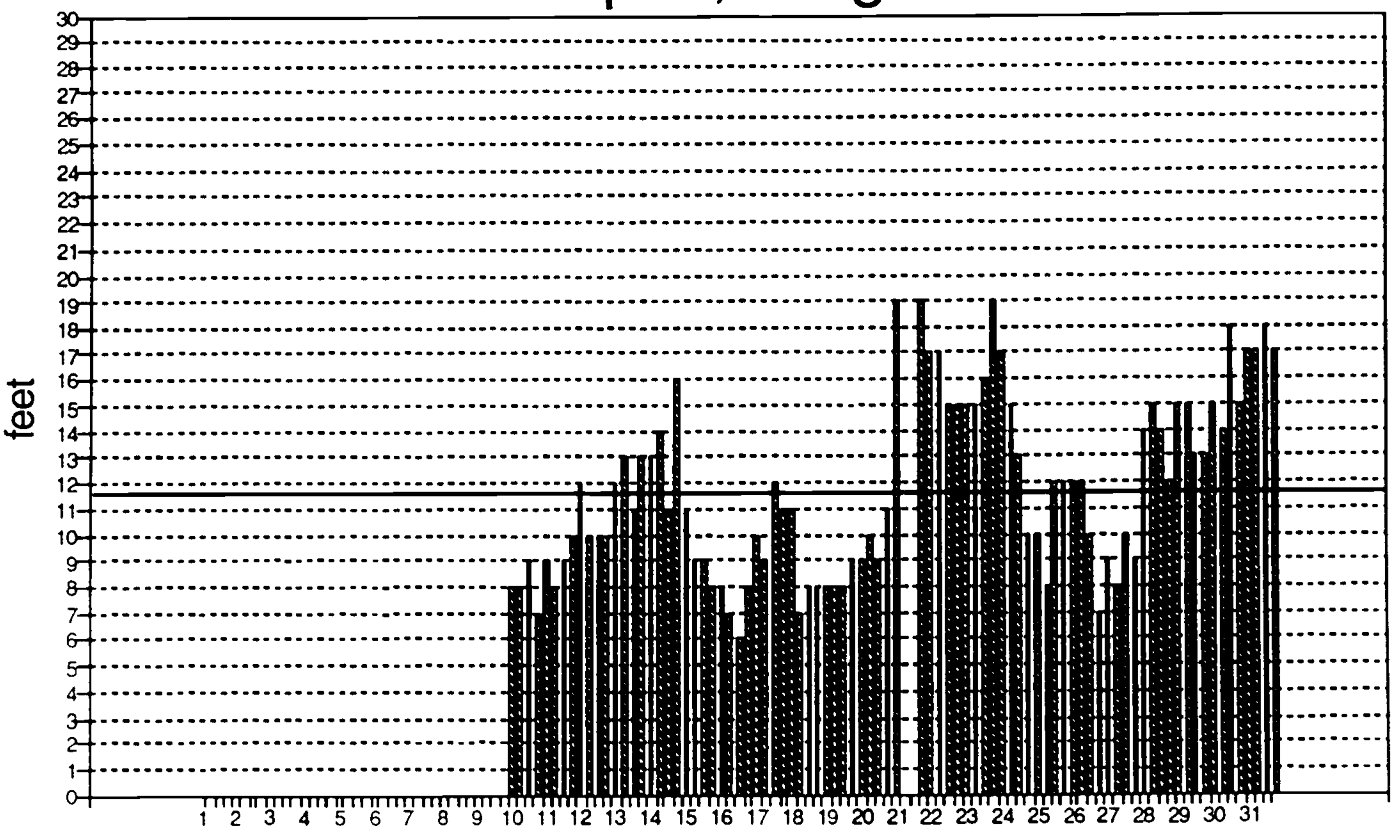
Daily Wave Height December 1988
Newport, Oregon



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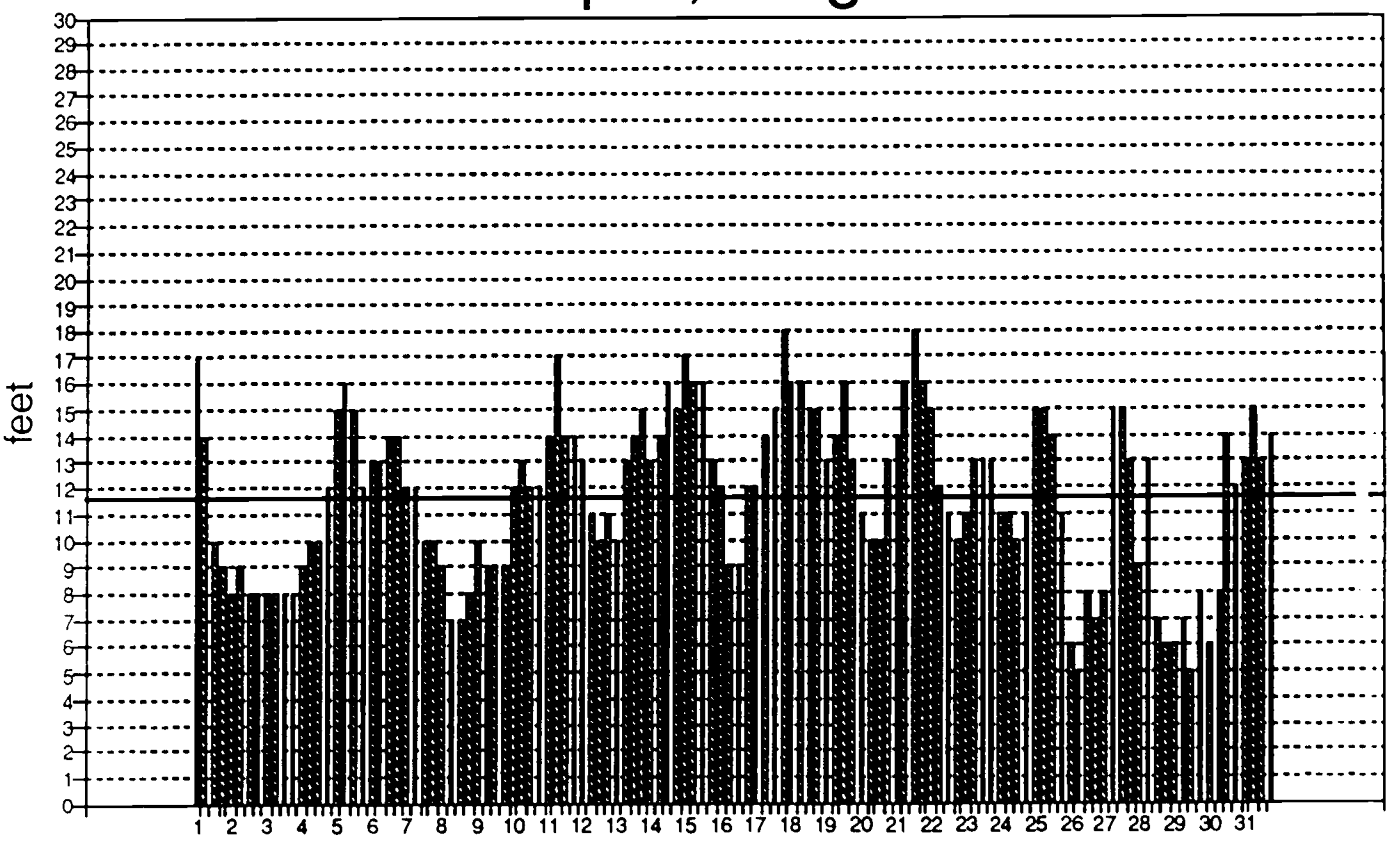
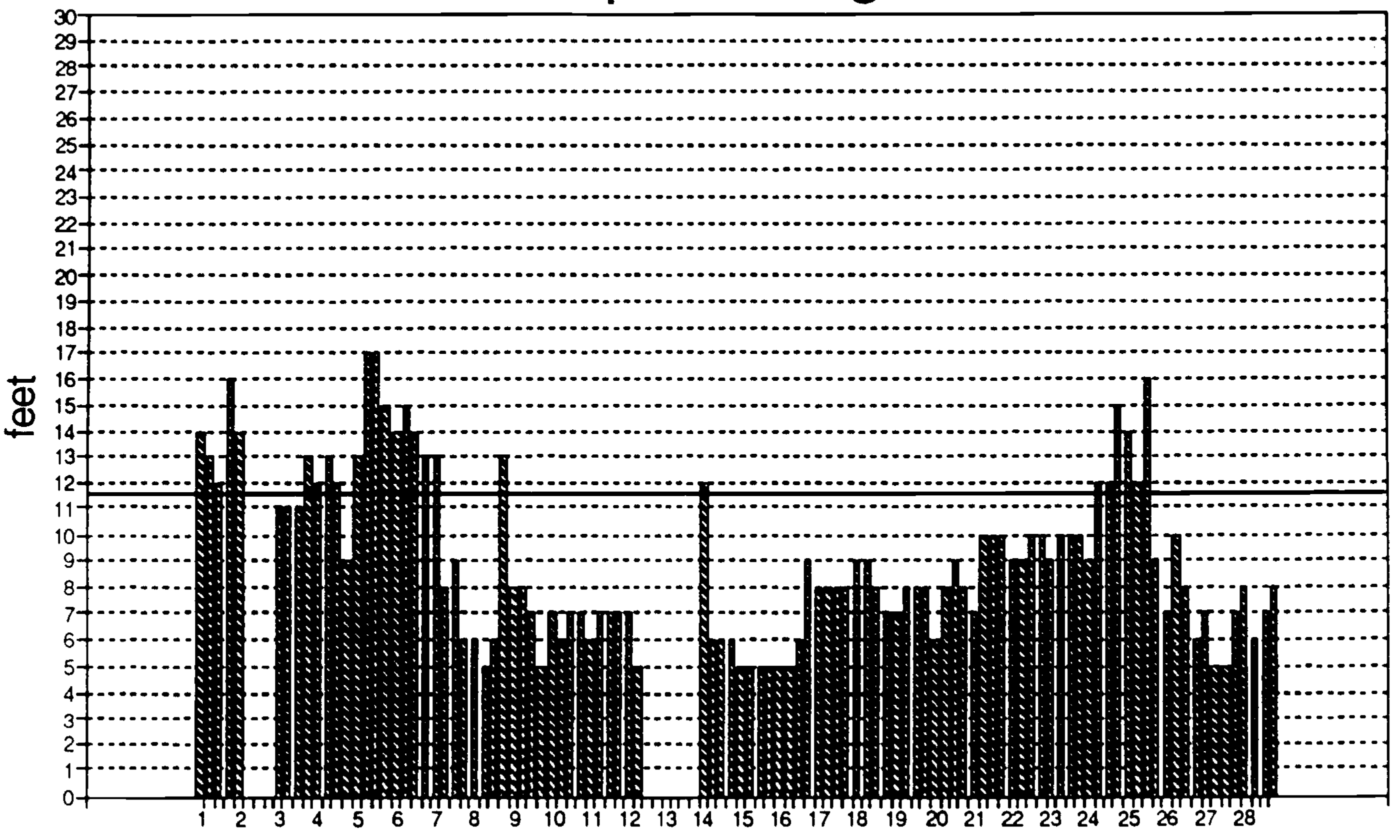
Daily Wave Height January 1989
Newport, Oregon



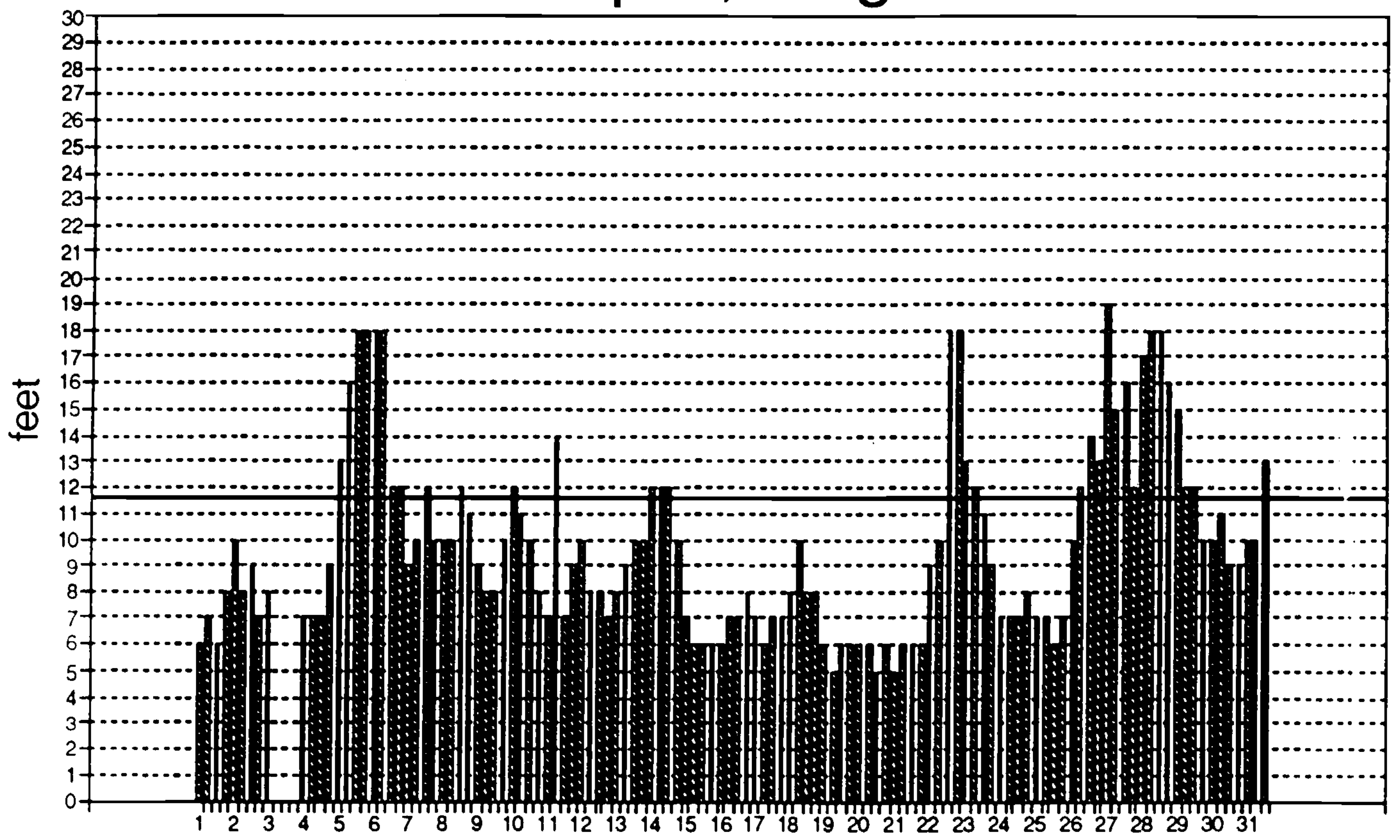
data: Hatfield Marine Science Center microseismometer

Daily Wave Height February 1989
Newport, Oregon



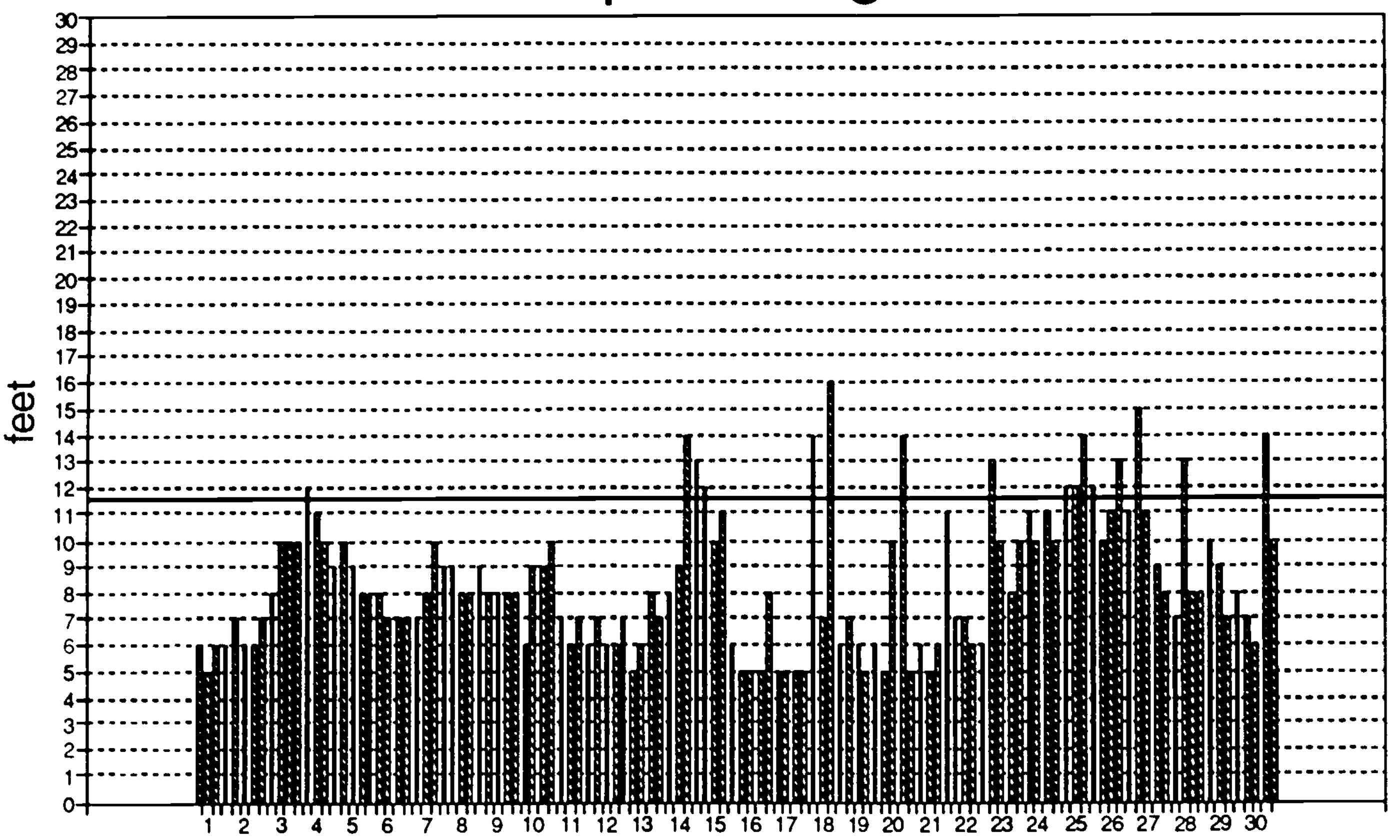
data: Hatfield Marine Science Center microseismometer

Daily Wave Height March 1989
Newport, Oregon



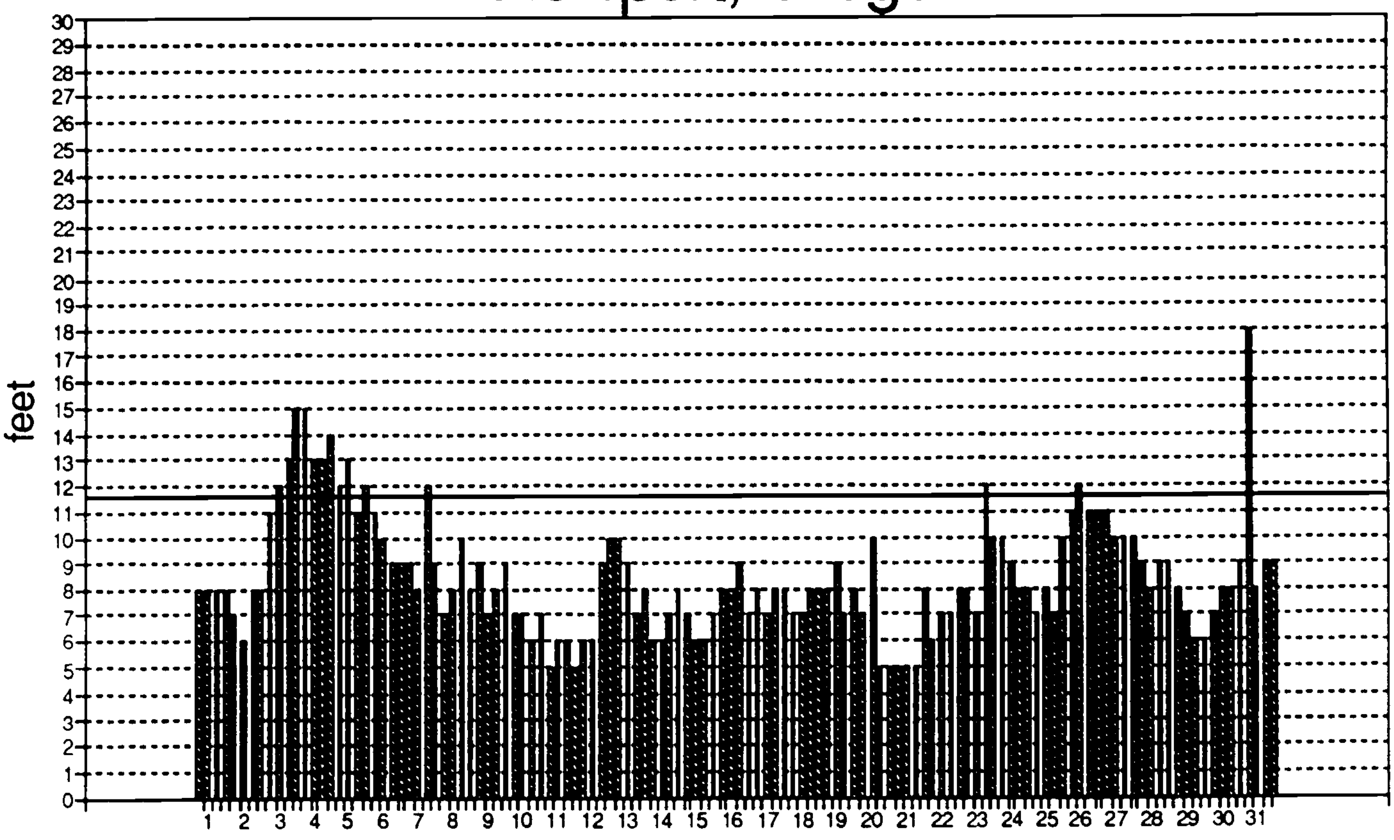
data: Hatfield Marine Science Center microseismometer

Daily Wave Height November 1989
Newport, Oregon



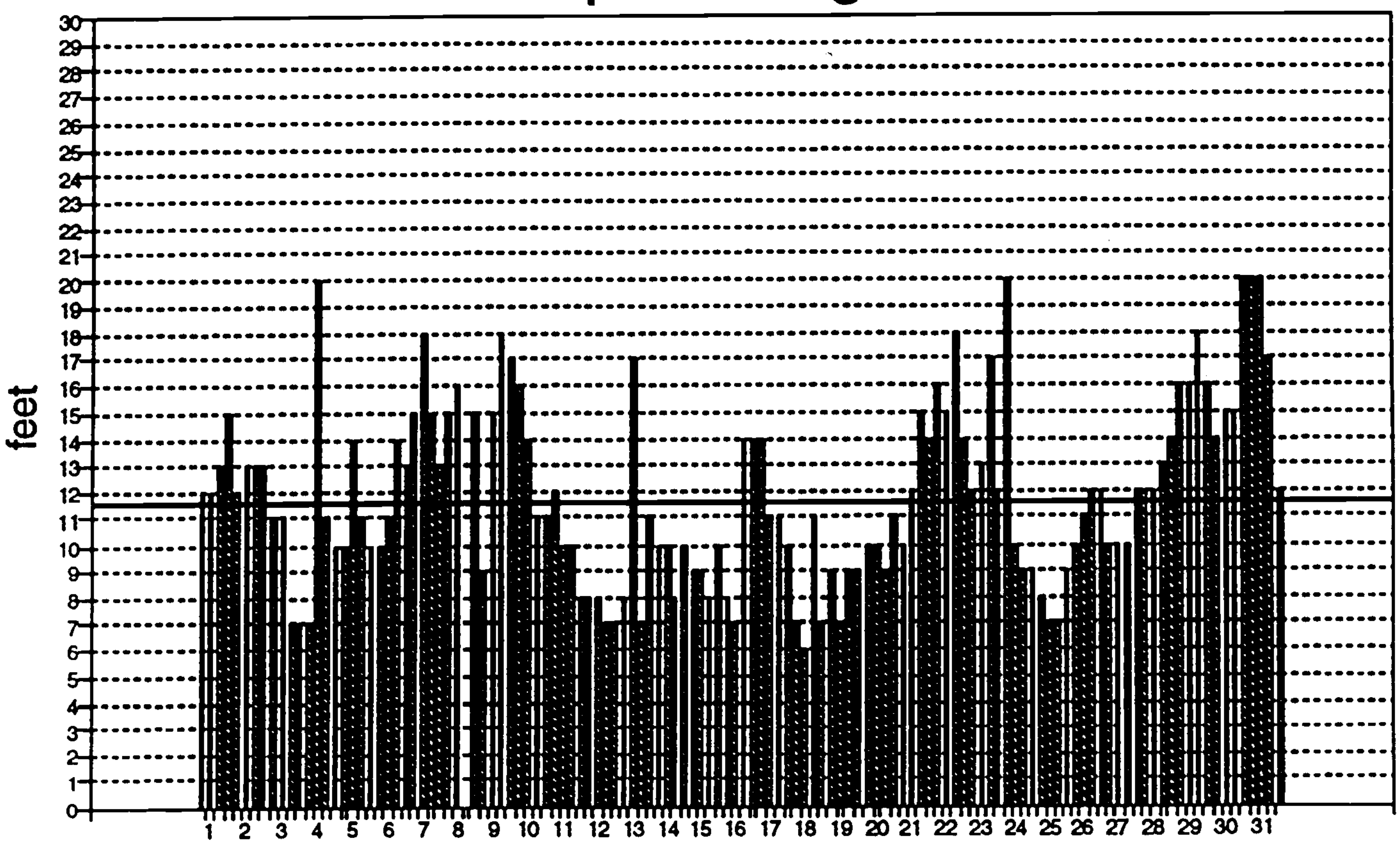
data: Hatfield Marine Science Center microseismometer

Daily Wave Height December 1989
Newport, Oregon



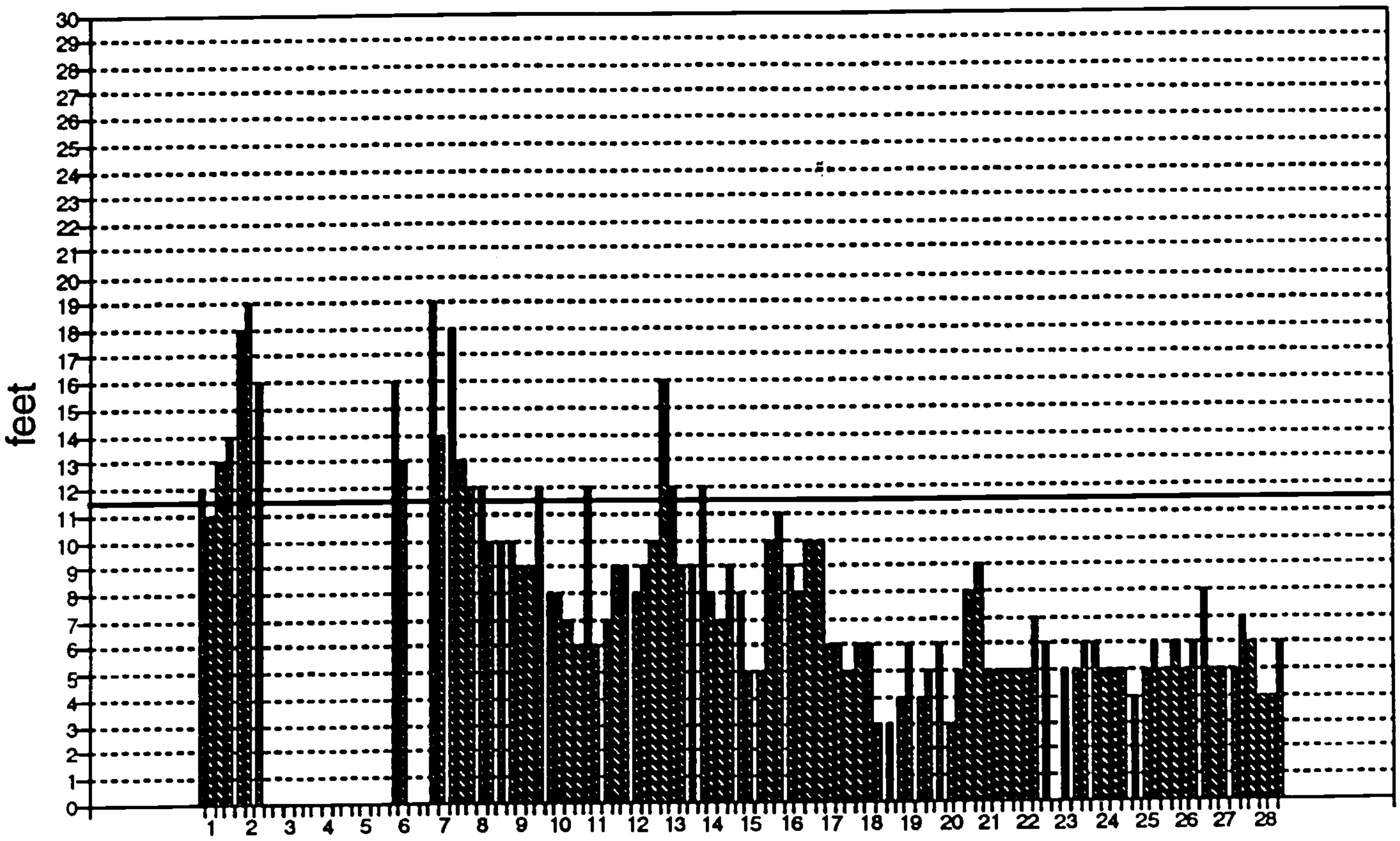
data: Hatfield Marine Science Center microseismometer

Daily Wave Height January 1990
Newport, Oregon



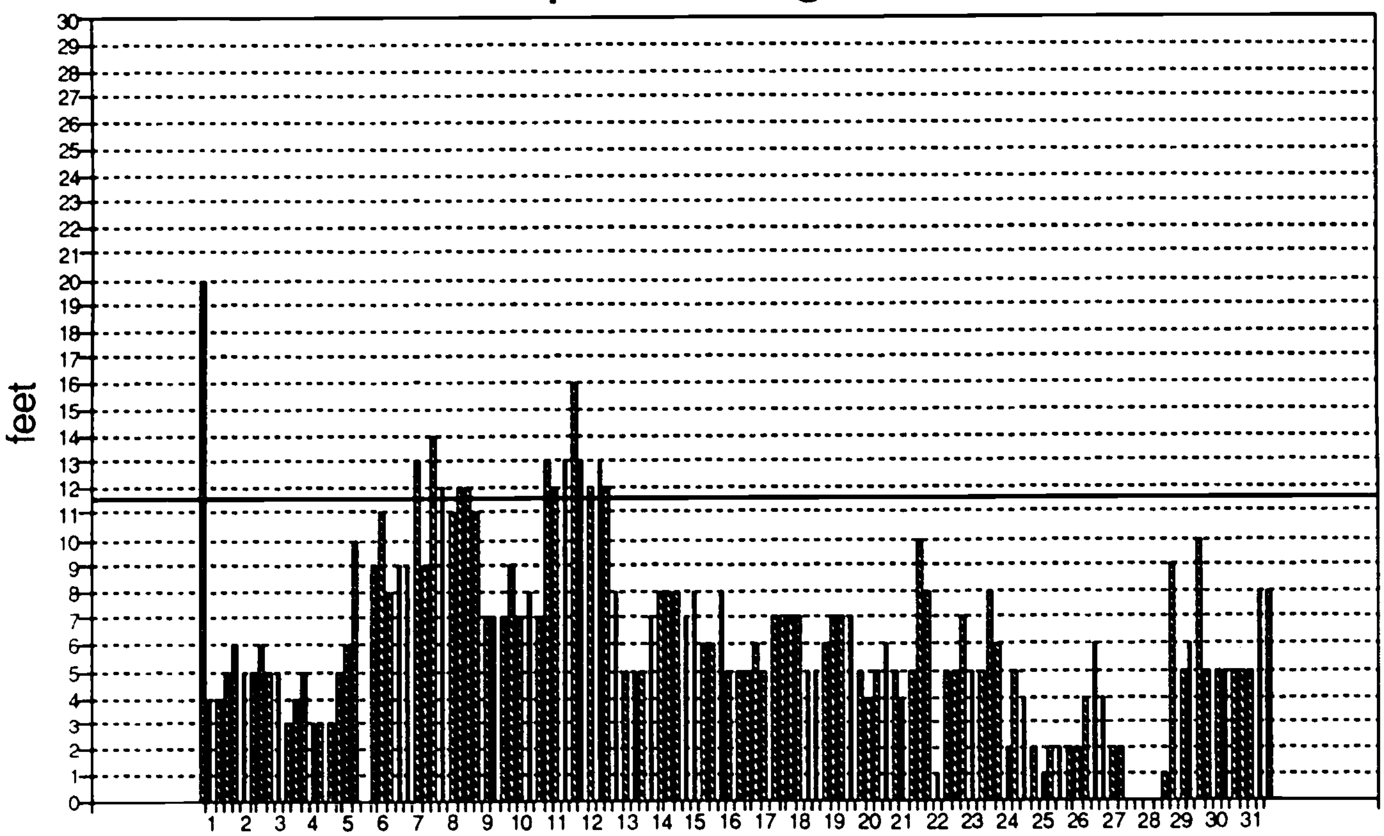
data: Hatfield Marine Science Center microseismometer

Daily Wave Height February 1990
Newport, Oregon



data: Hatfield Marine Science Center microseismometer

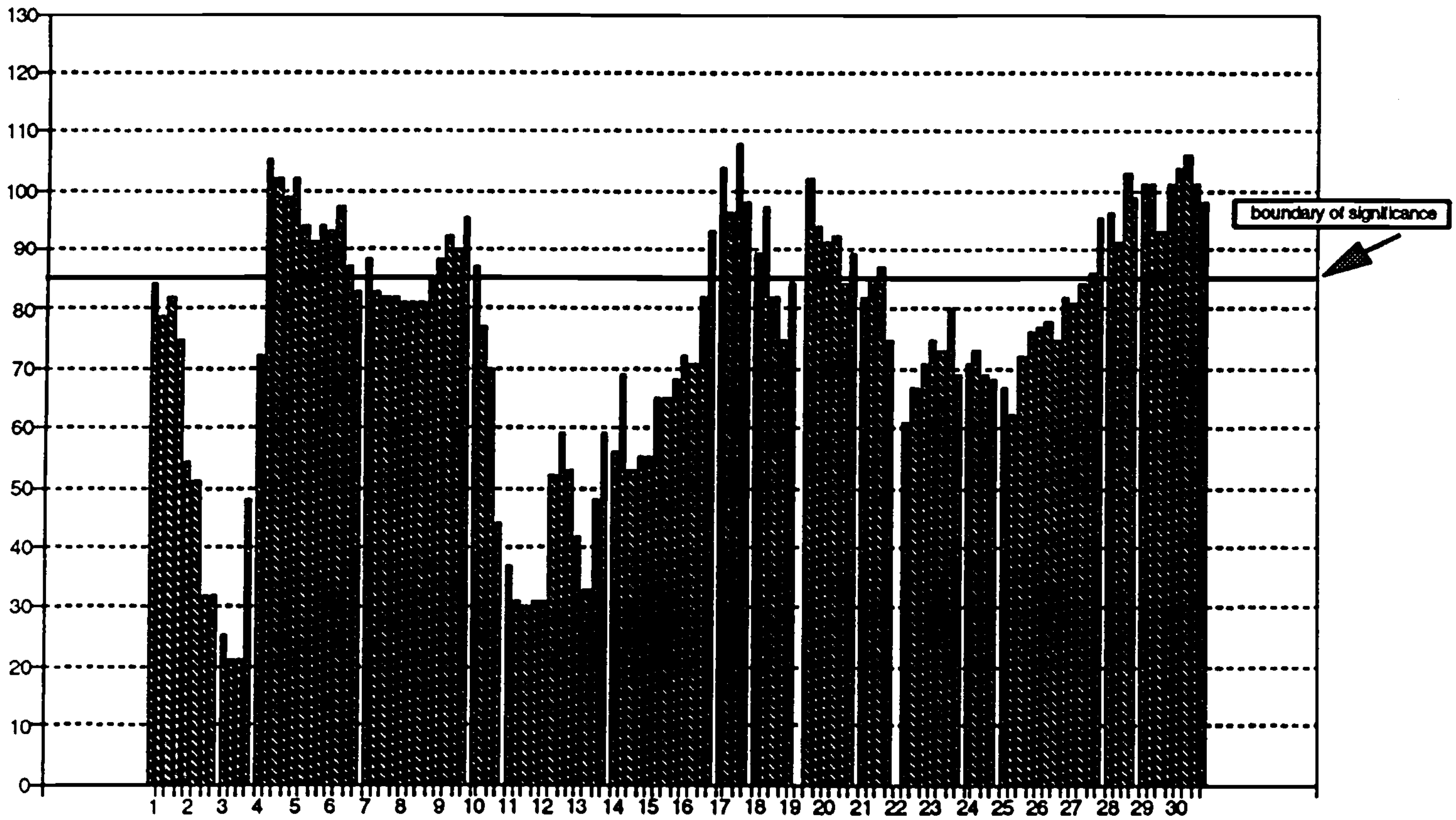
Daily Wave Height March 1990
Newport, Oregon



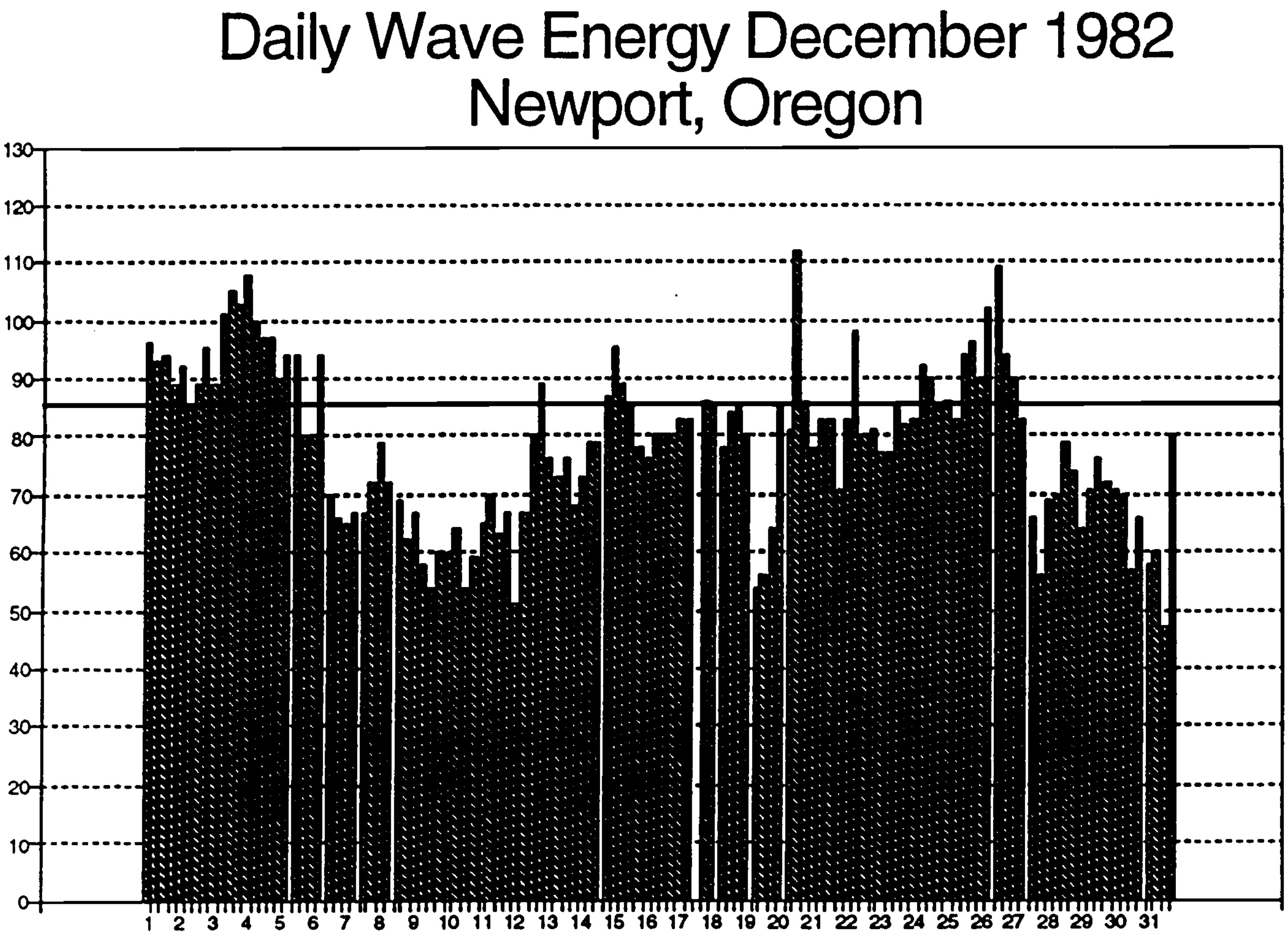
data: Hatfield Marine Science Center microseismometer

Appendix 3.
Data on Energy

Daily Wave Energy November 1982
Newport, Oregon

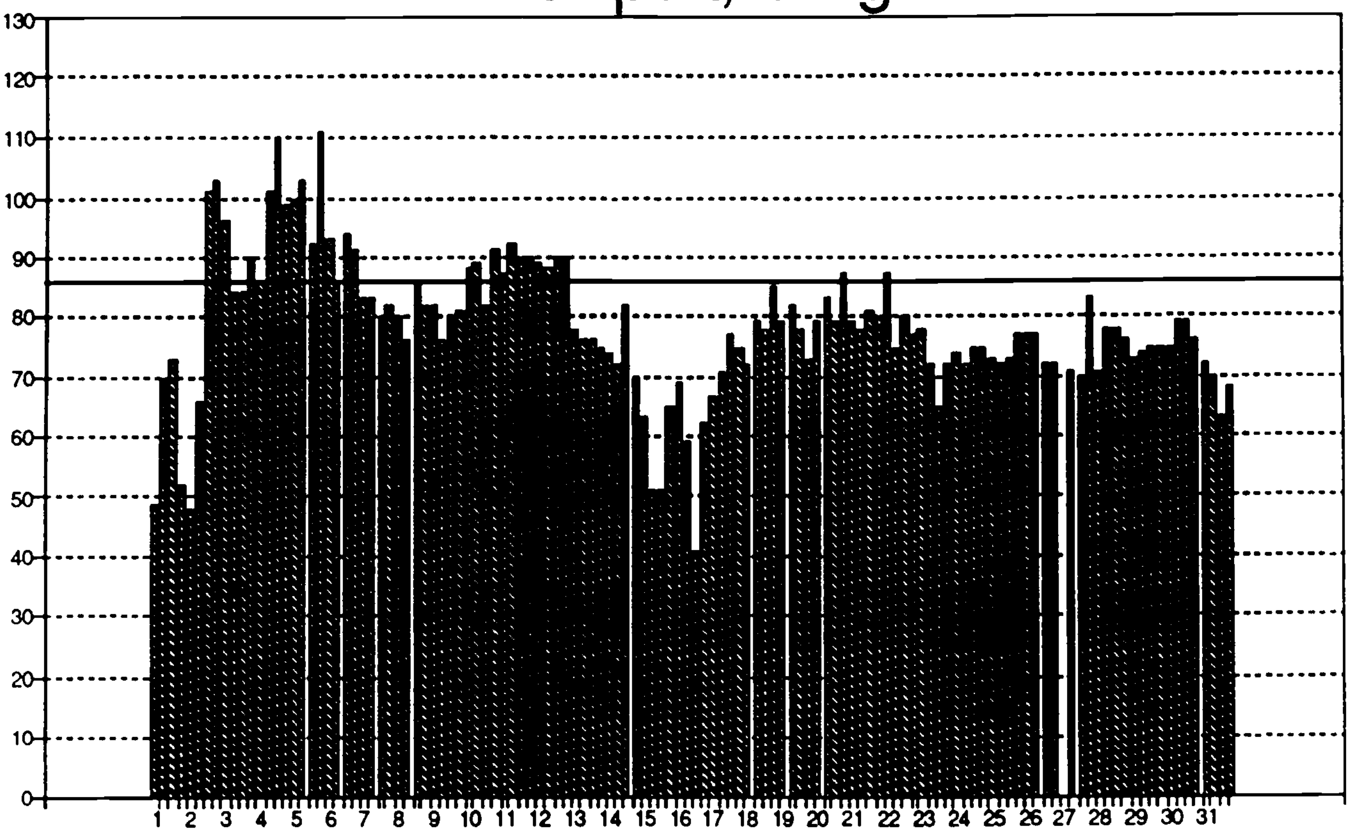


data: Hatfield Marine Science Center microseismometer



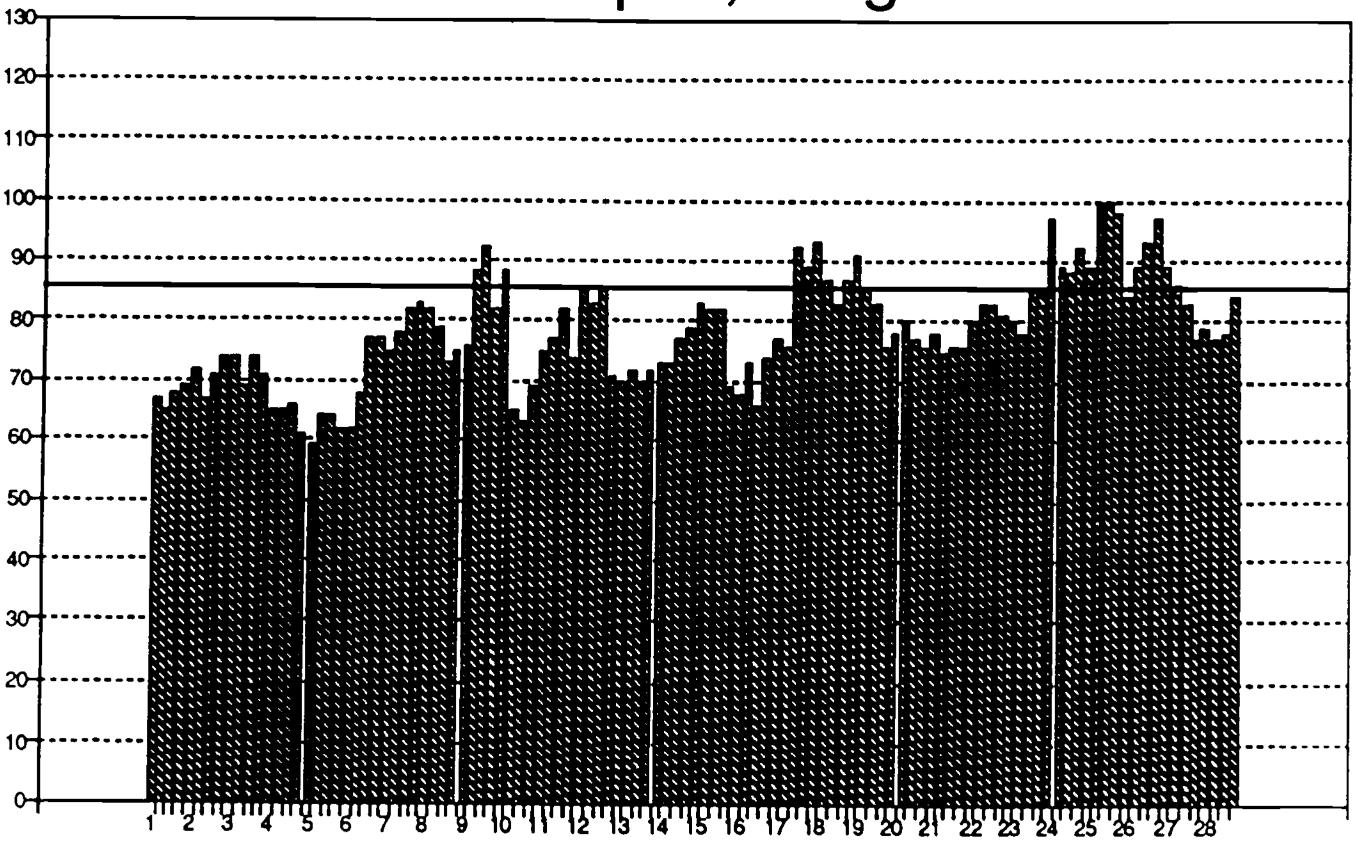
data: Hatfield Marine Science Center microseismometer .

Daily Wave Energy January 1983
Newport, Oregon



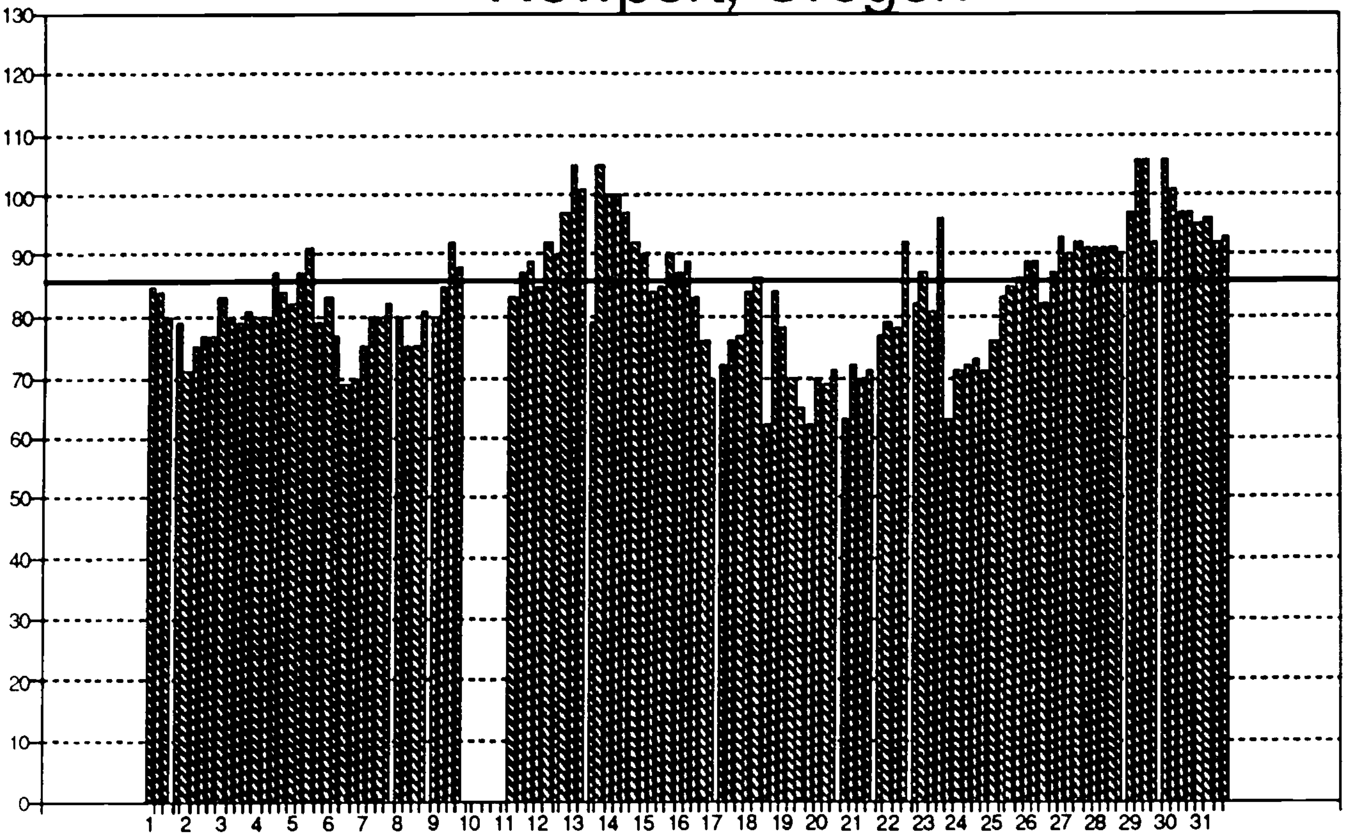
data: Hatfield Marine Science Center microseismometer

Daily Wave Energy February 1983
Newport, Oregon



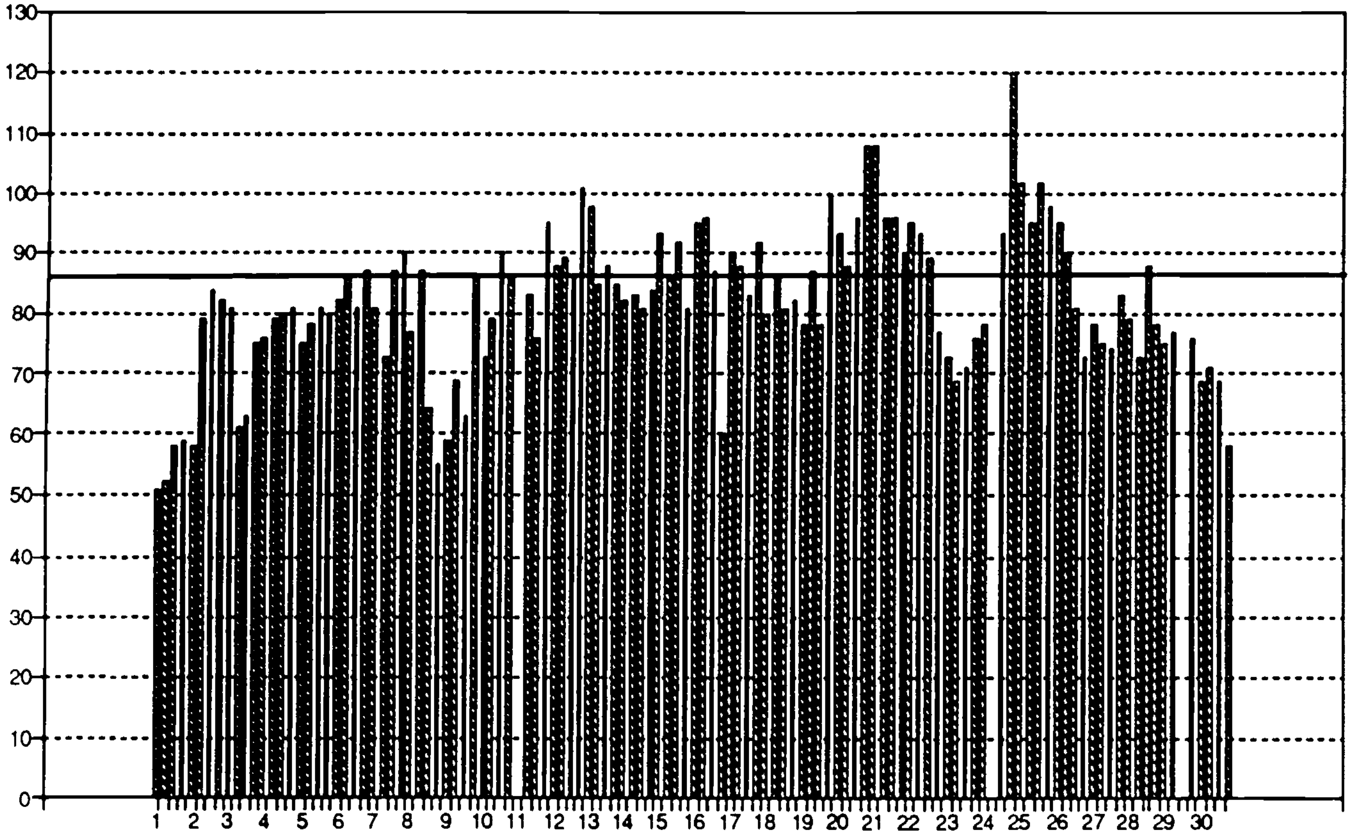
data: Hatfield Marine Science Center microseismometer

Daily Wave Energy March 1983
Newport, Oregon



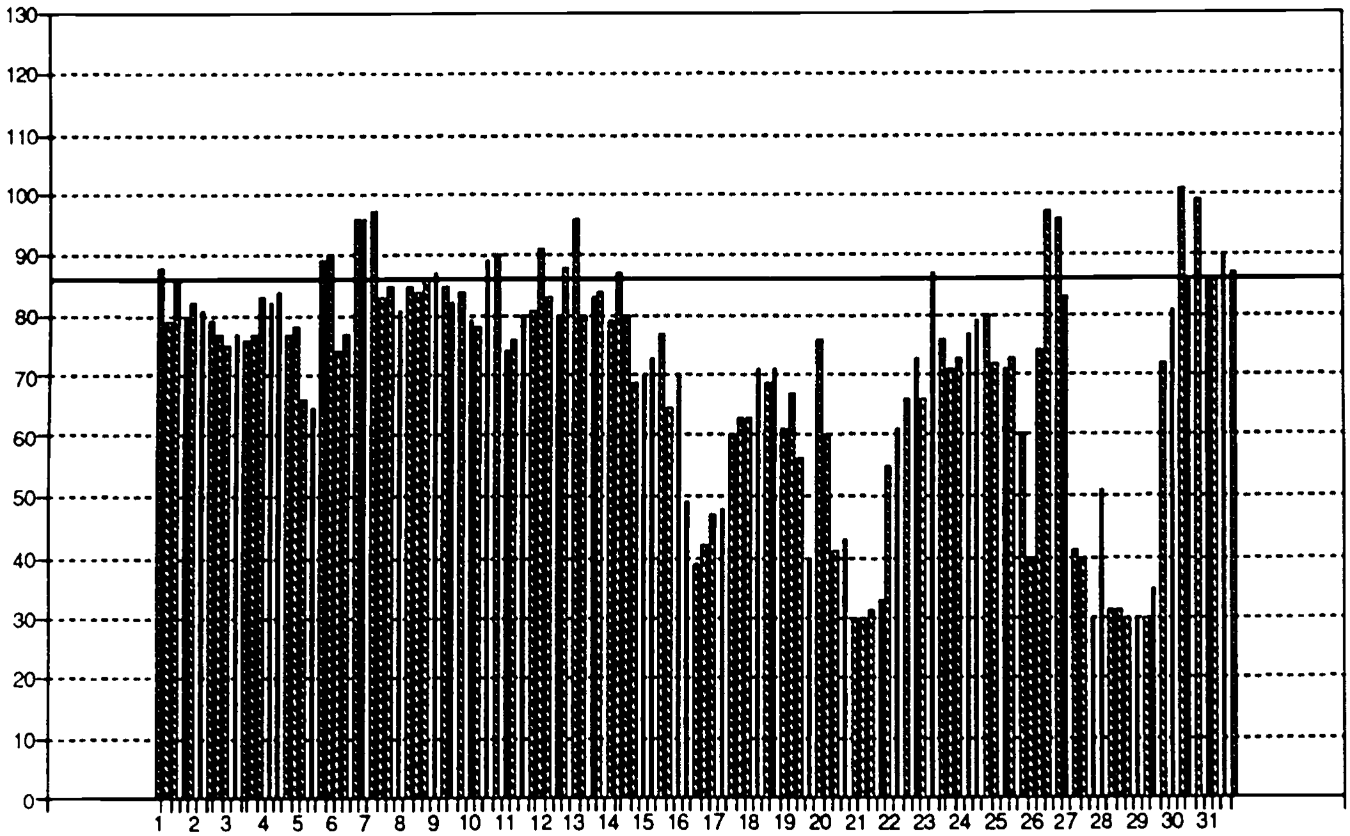
data: Hatfield Marine Science Center microseismometer

Daily Winter Wave Energy November 1983
Newport, Oregon



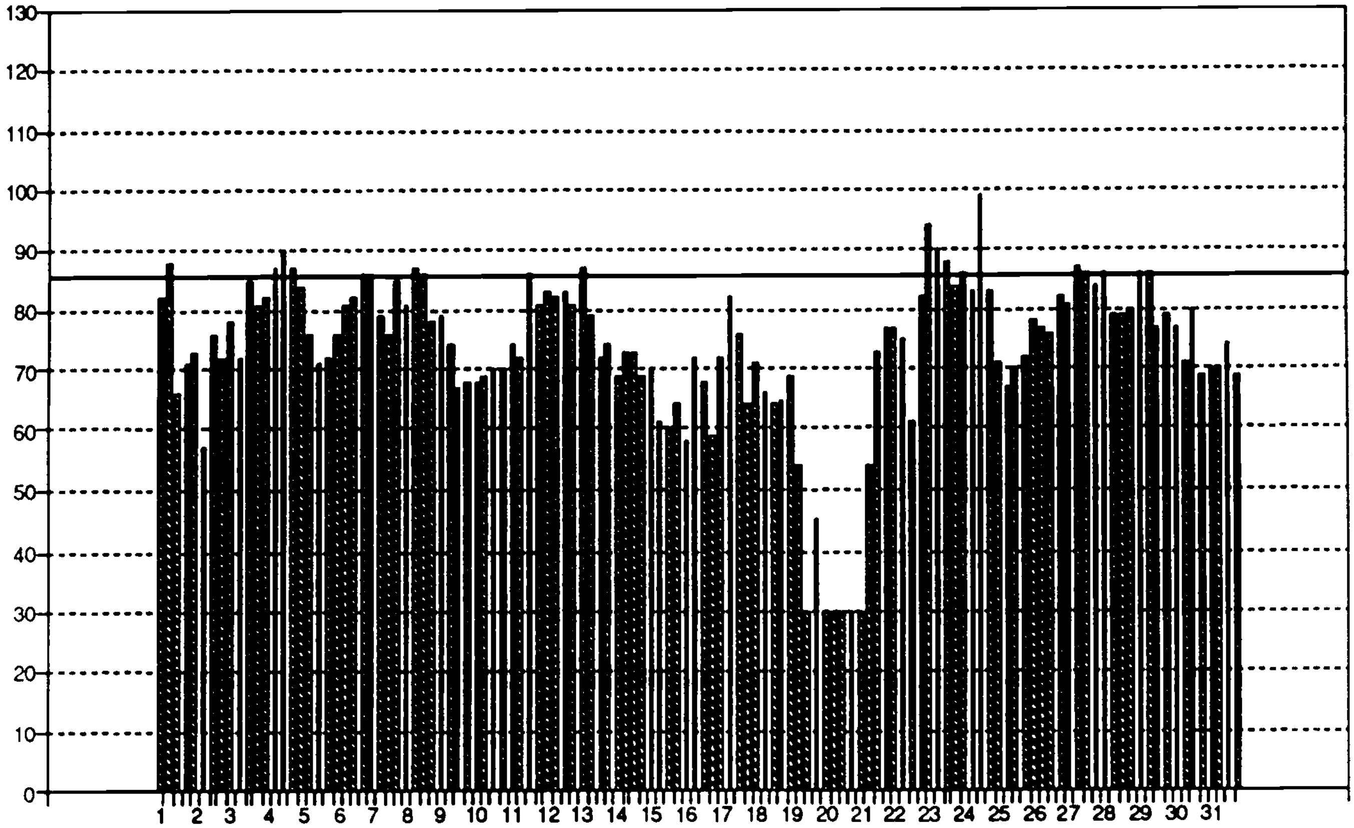
data: Hatfield Marine Science Center microseismometer

Daily Winter Wave Energy December 1983
Newport, Oregon



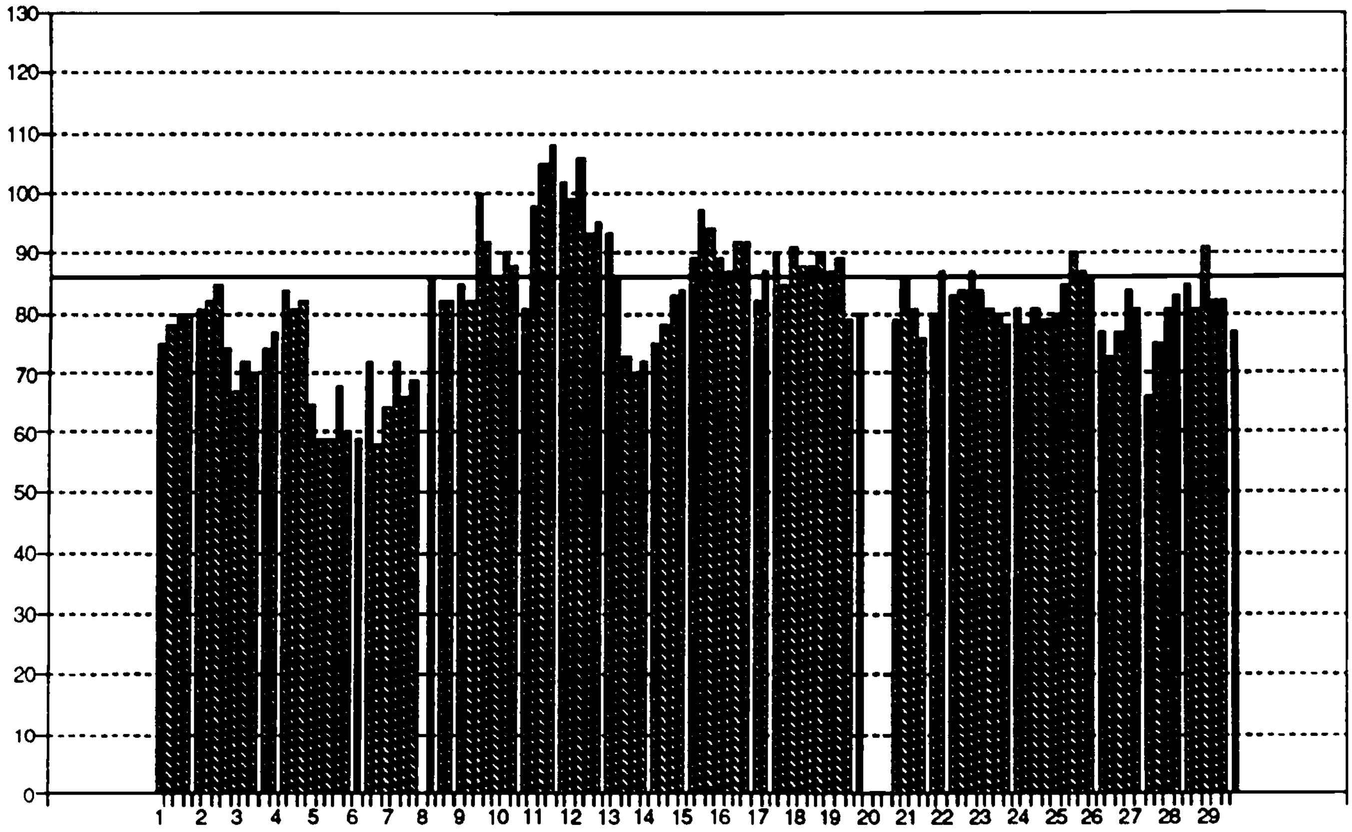
data: Hatfield Marine Science Center microseismometer

Daily Winter Wave Energy January 1984
Newport, Oregon



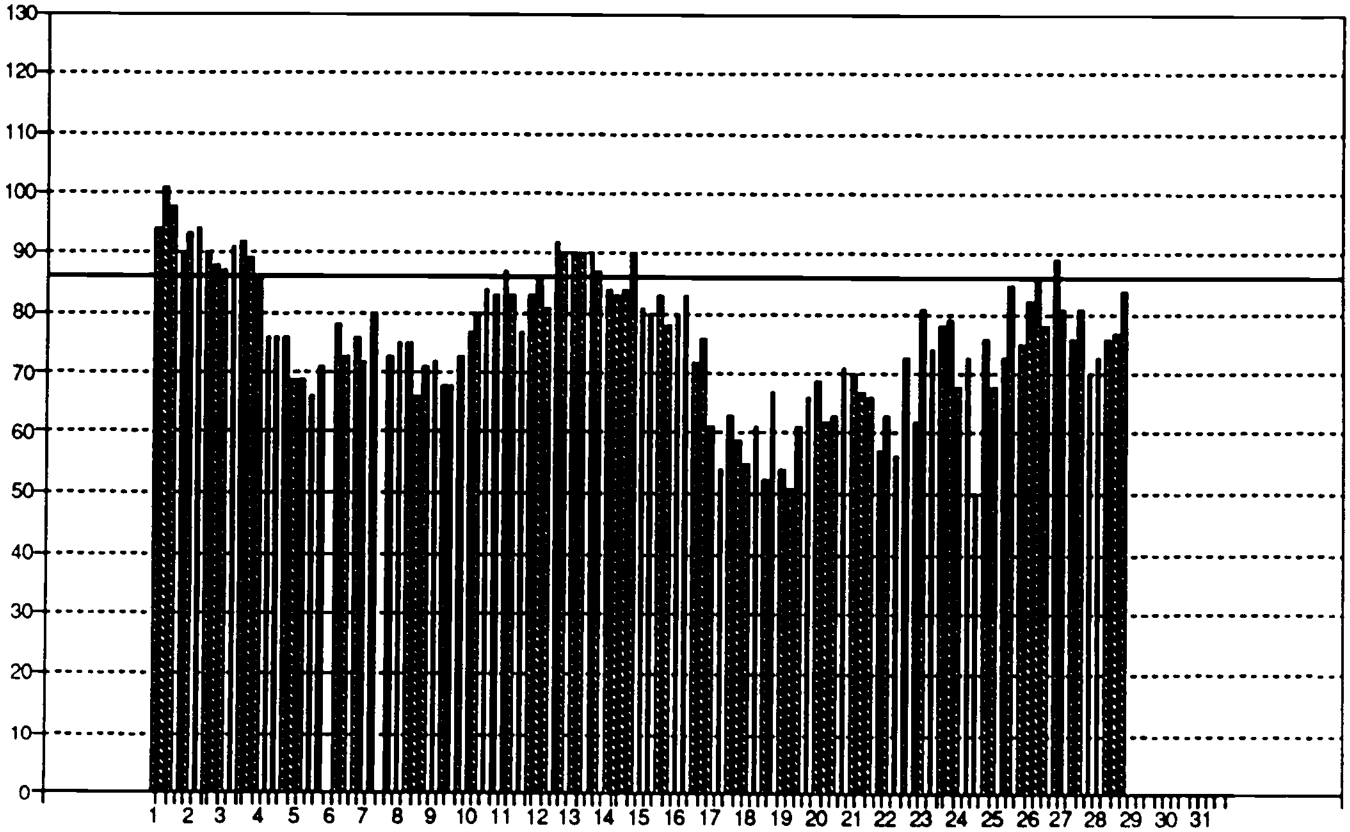
data: Hatfield Marine Science Center microseismometer

Daily Winter Wave Energy February 1984
Newport, Oregon



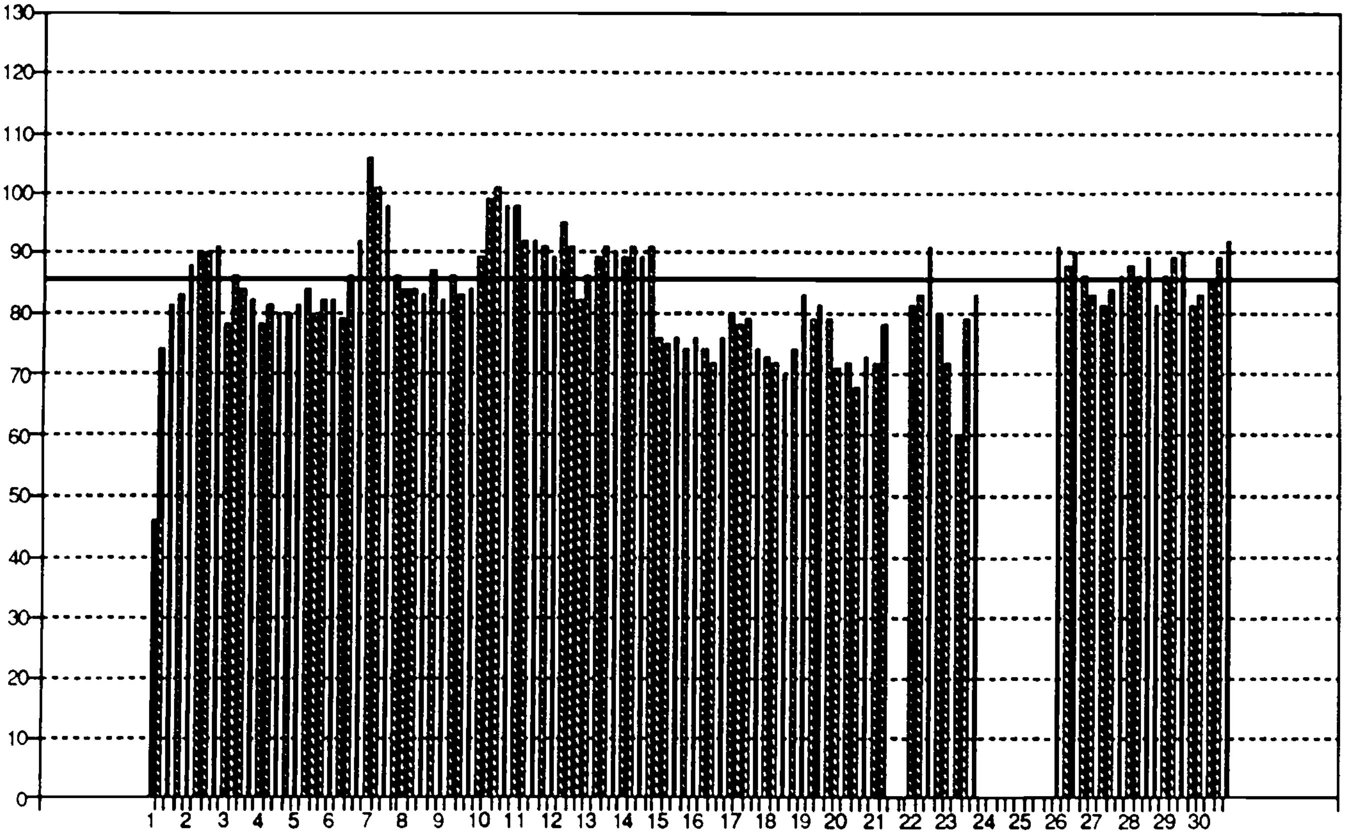
data: Hatfield Marine Science Center microseismometer

Daily Winter Wave Energy March 1984
Newport, Oregon



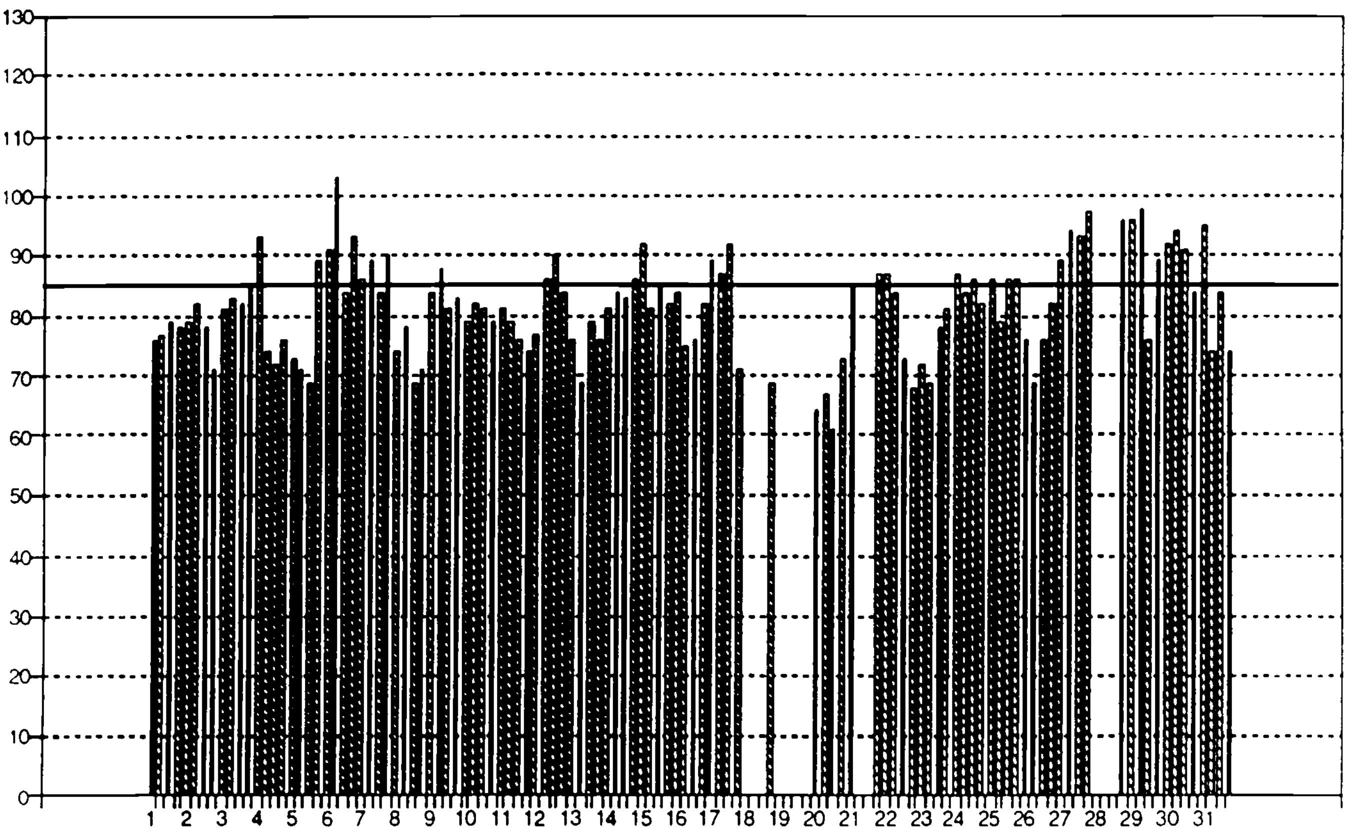
data: Hatfield Marine Science Center microseismometer

Daily Wave Energy November 1984
Newport, Oregon



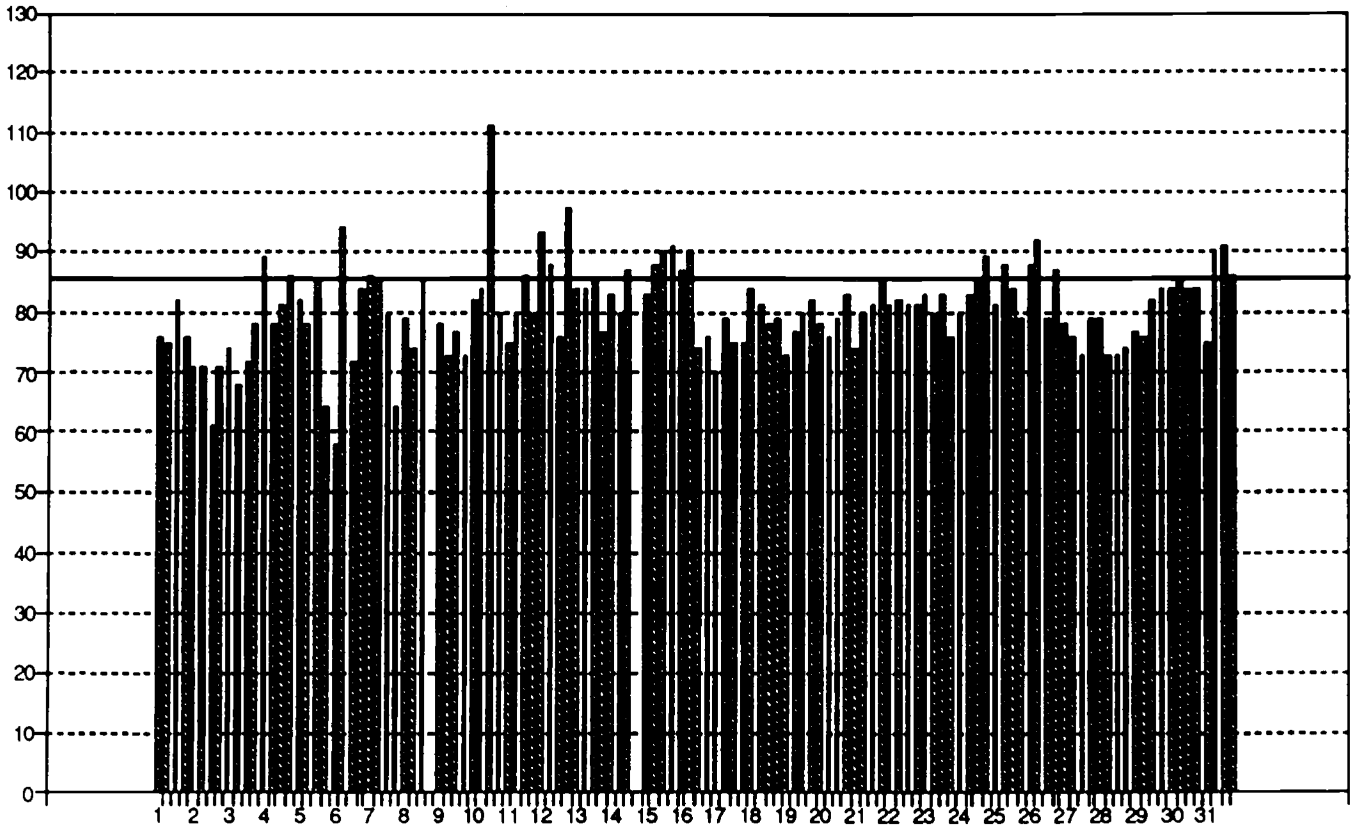
data: Hatfileld Marine Science Center seismometer

Daily Wave Energy December 1984
Newport, Oregon



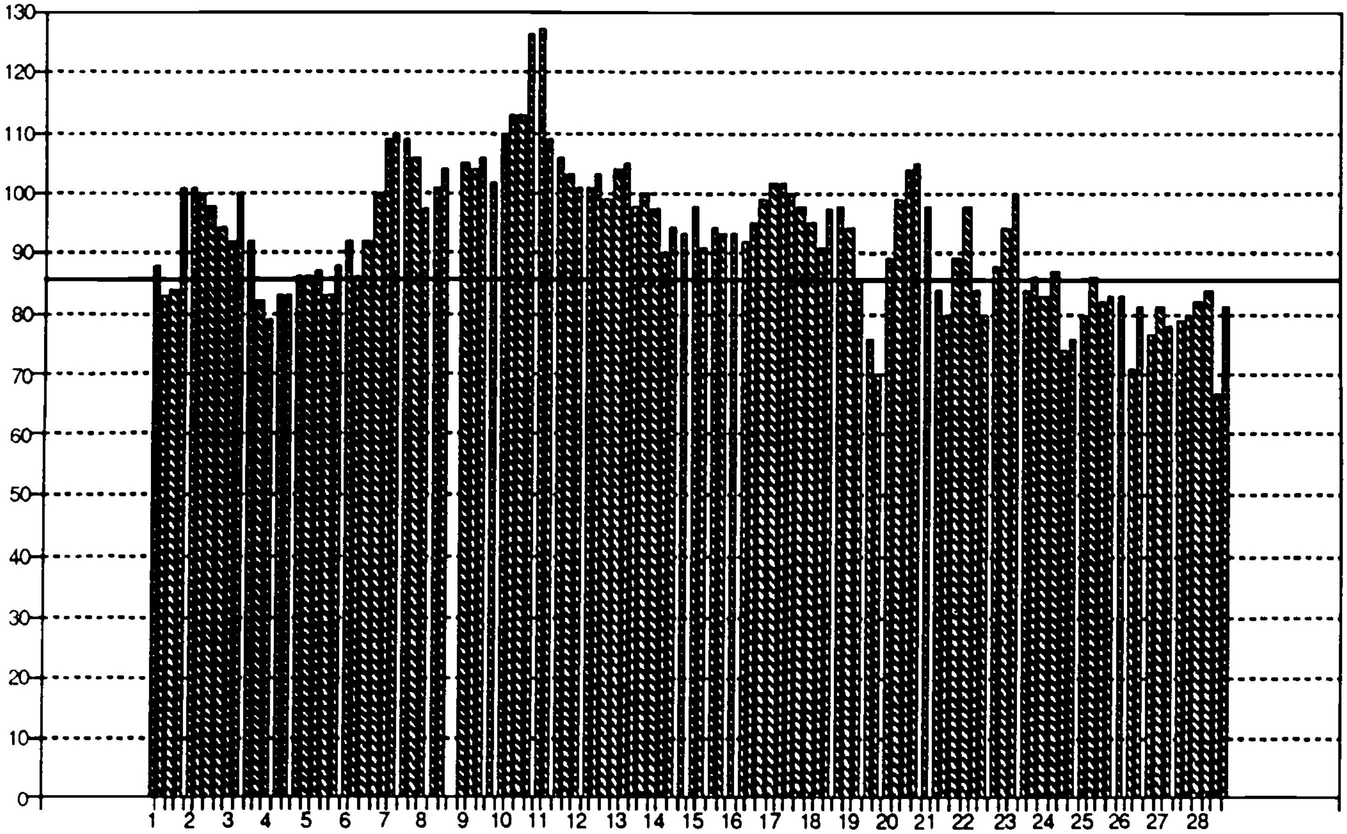
data: Hatfileld Marine Science Center seismometer

Daily Wave Energy January 1985
Newport, Oregon



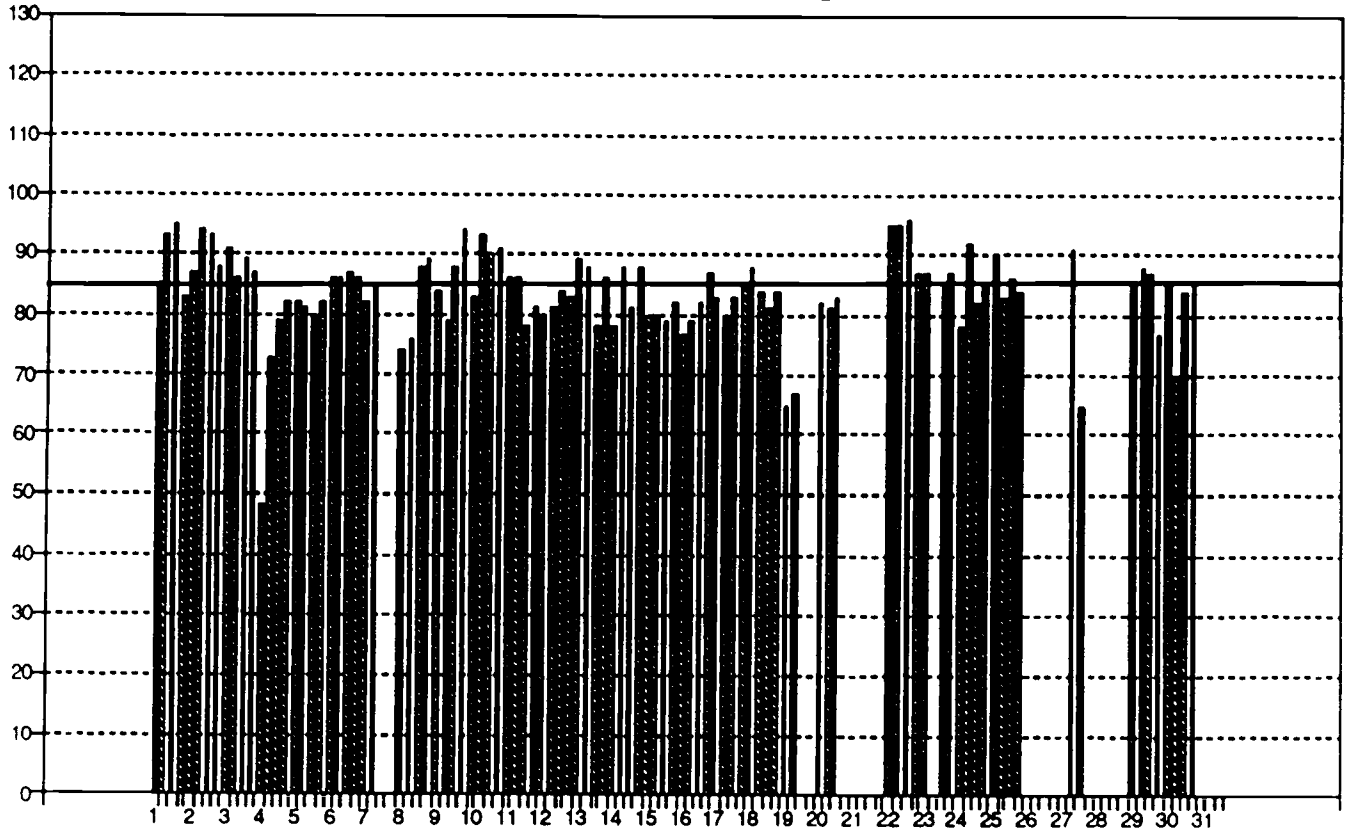
data: Hatfileld Marine Science Center seismometer

Daily Wave Energy February 1985
Newport, Oregon



data: Hatfileld Marine Science Center seismometer

Daily Wave Energy March 1985
Newport, Oregon



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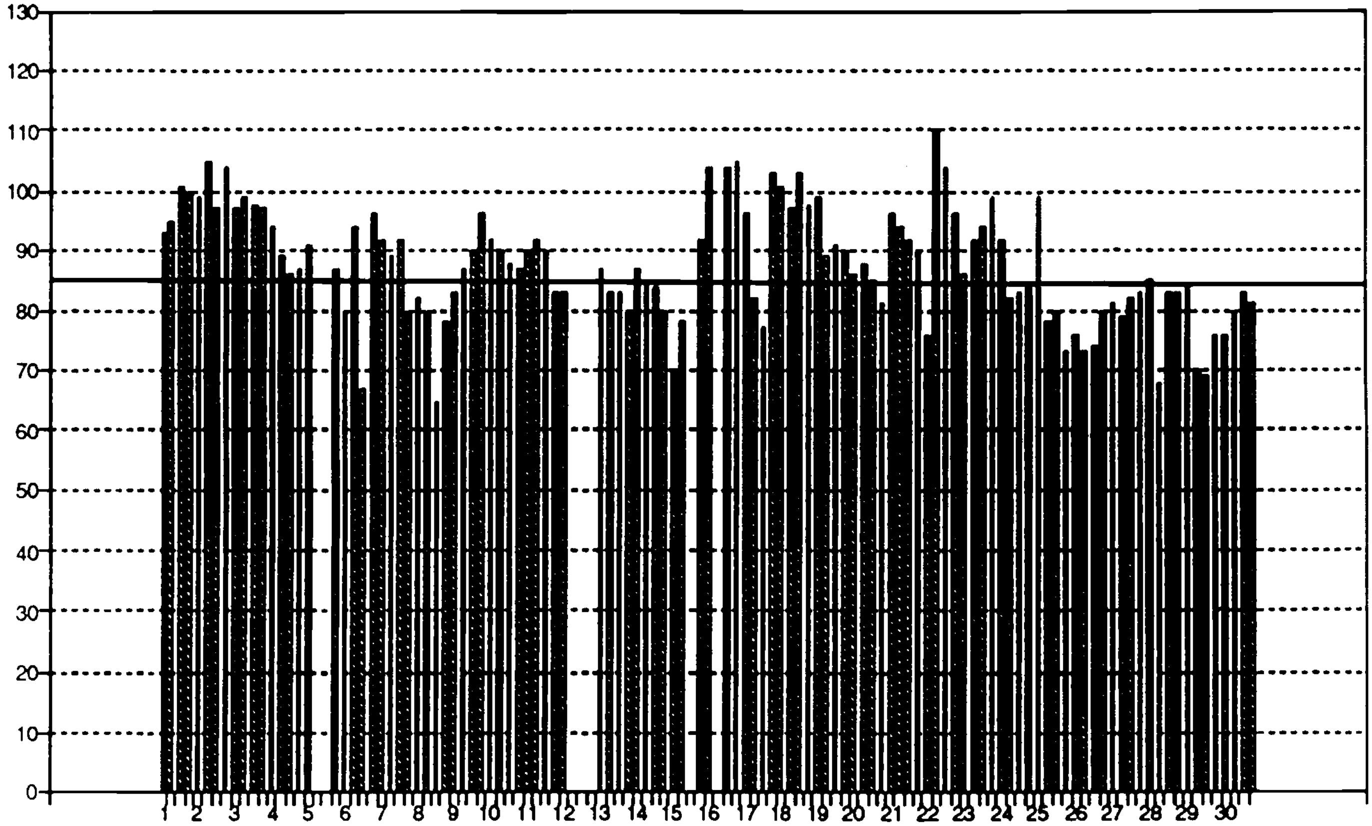
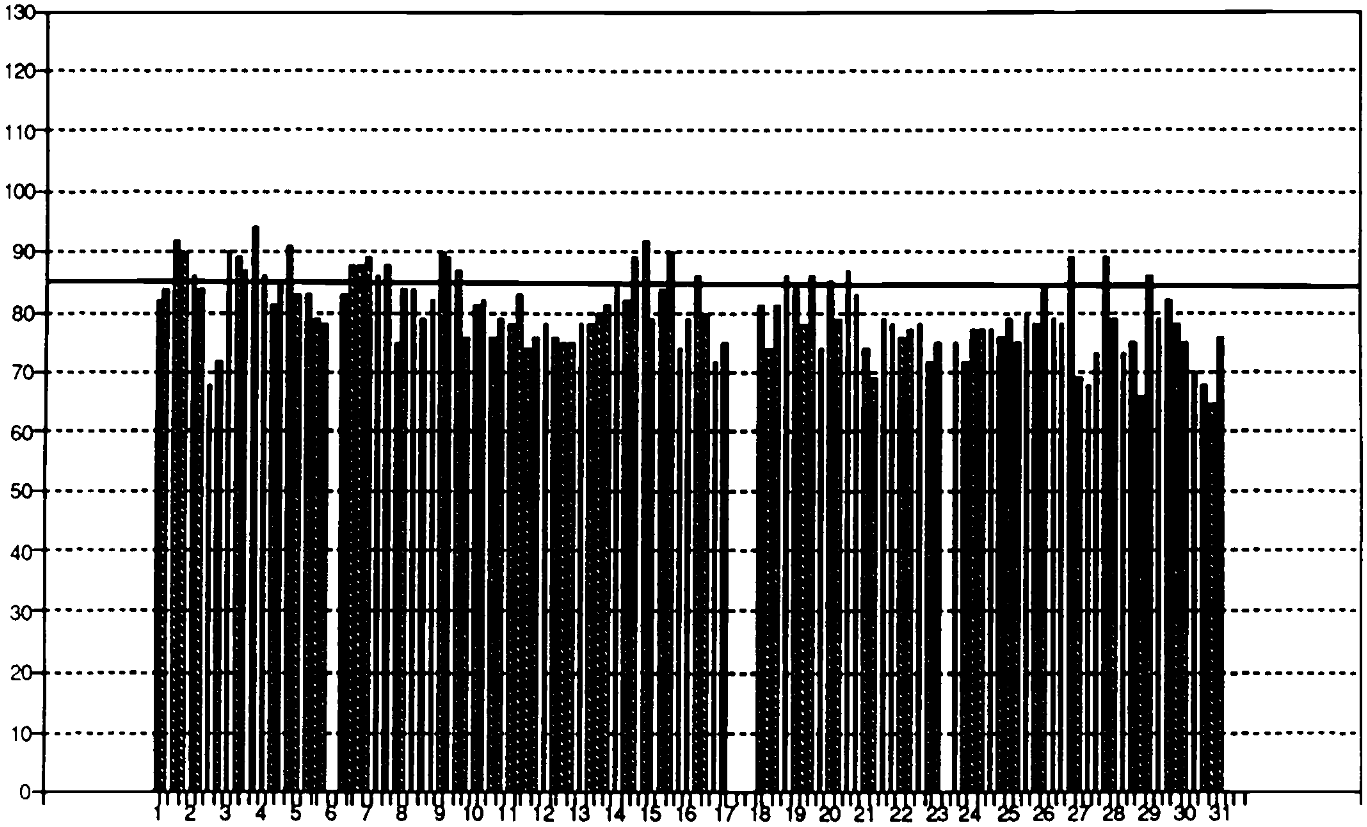
Daily Wave Energy November 1985
Newport, Oregon



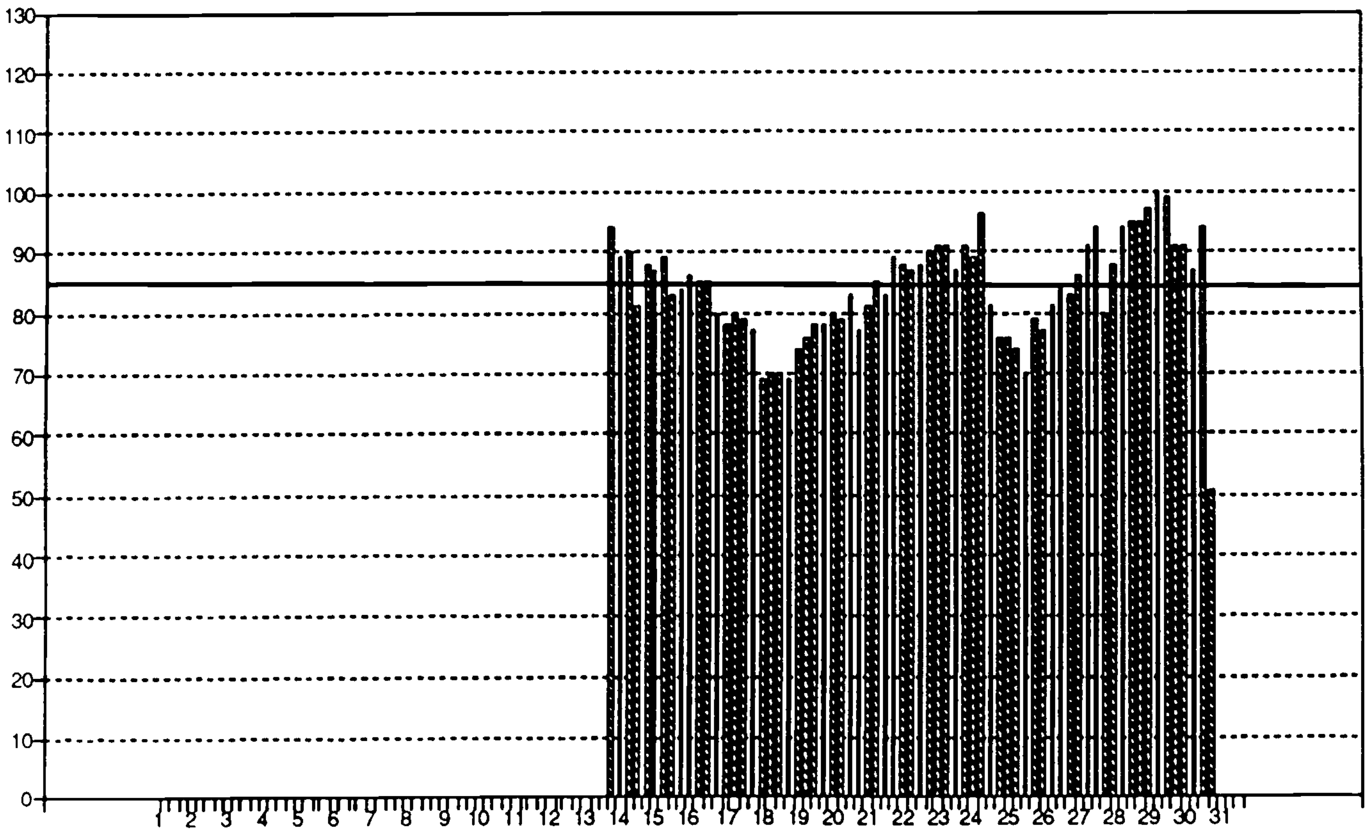
data: Hatfield Marine Science Center microseismometer

Daily Wave Energy December 1985
Newport, Oregon



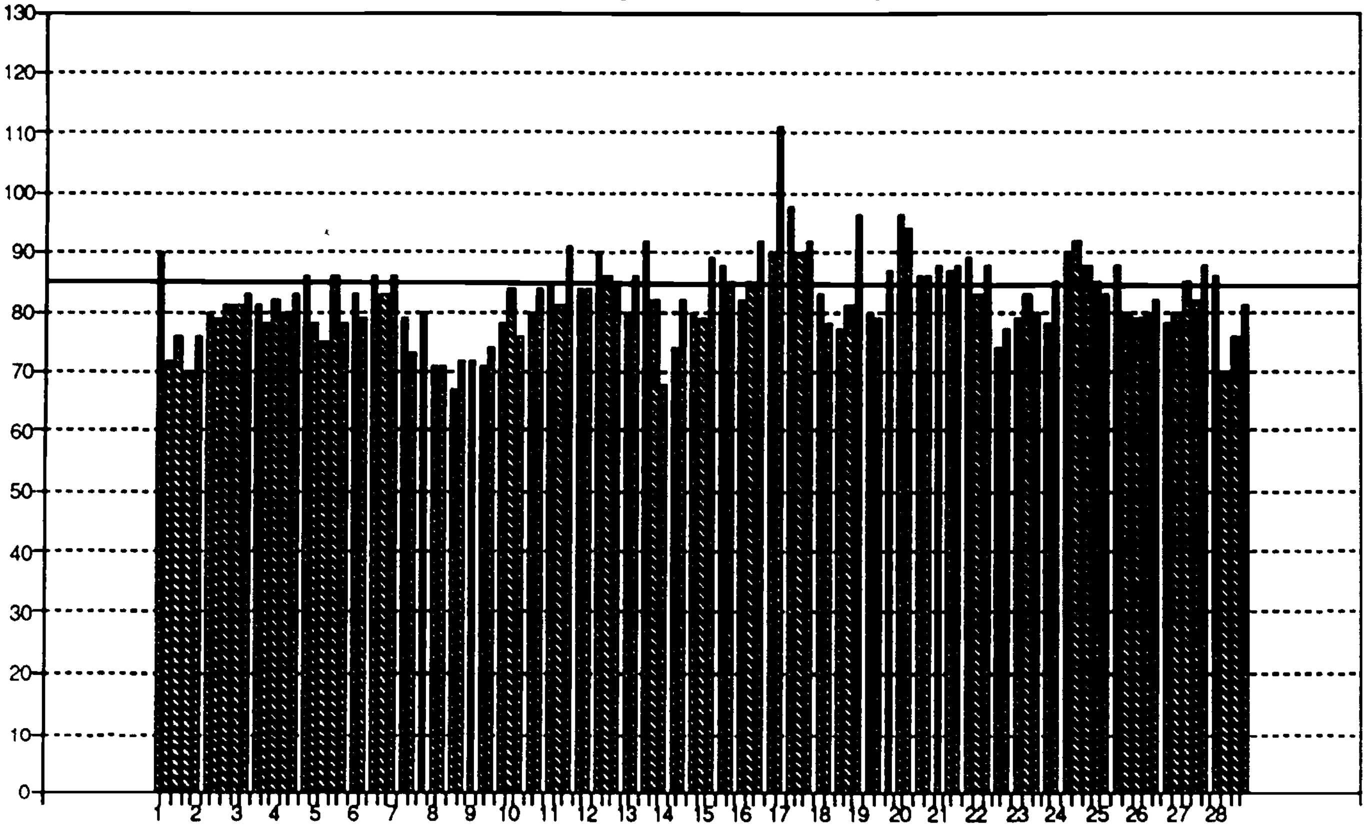
data: Hatfield Marine Science Center microseismometer

Daily Wave Energy January 1986
Newport, Oregon



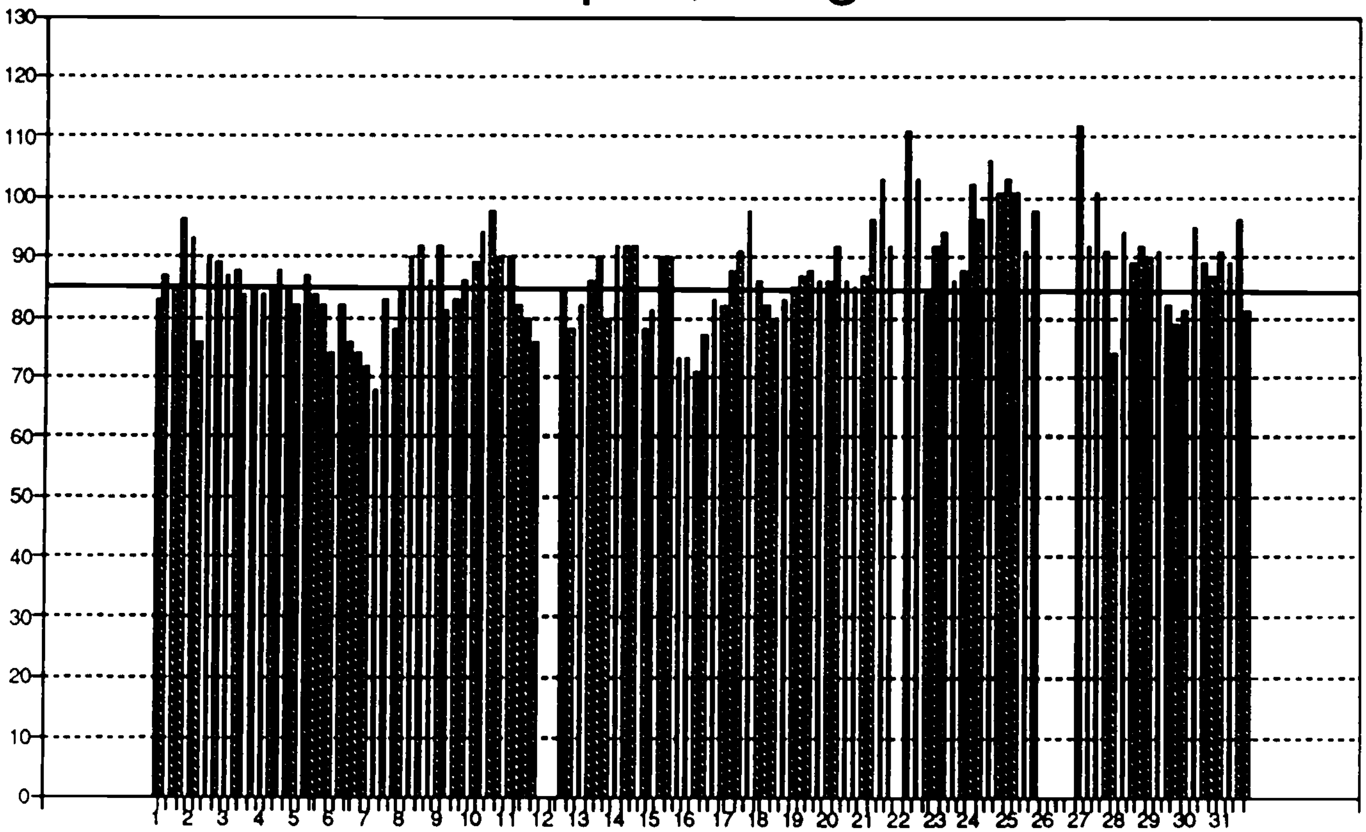
data: Hatfield Marine Science Center microseismometer

Daily Wave Energy February 1986
Newport, Oregon



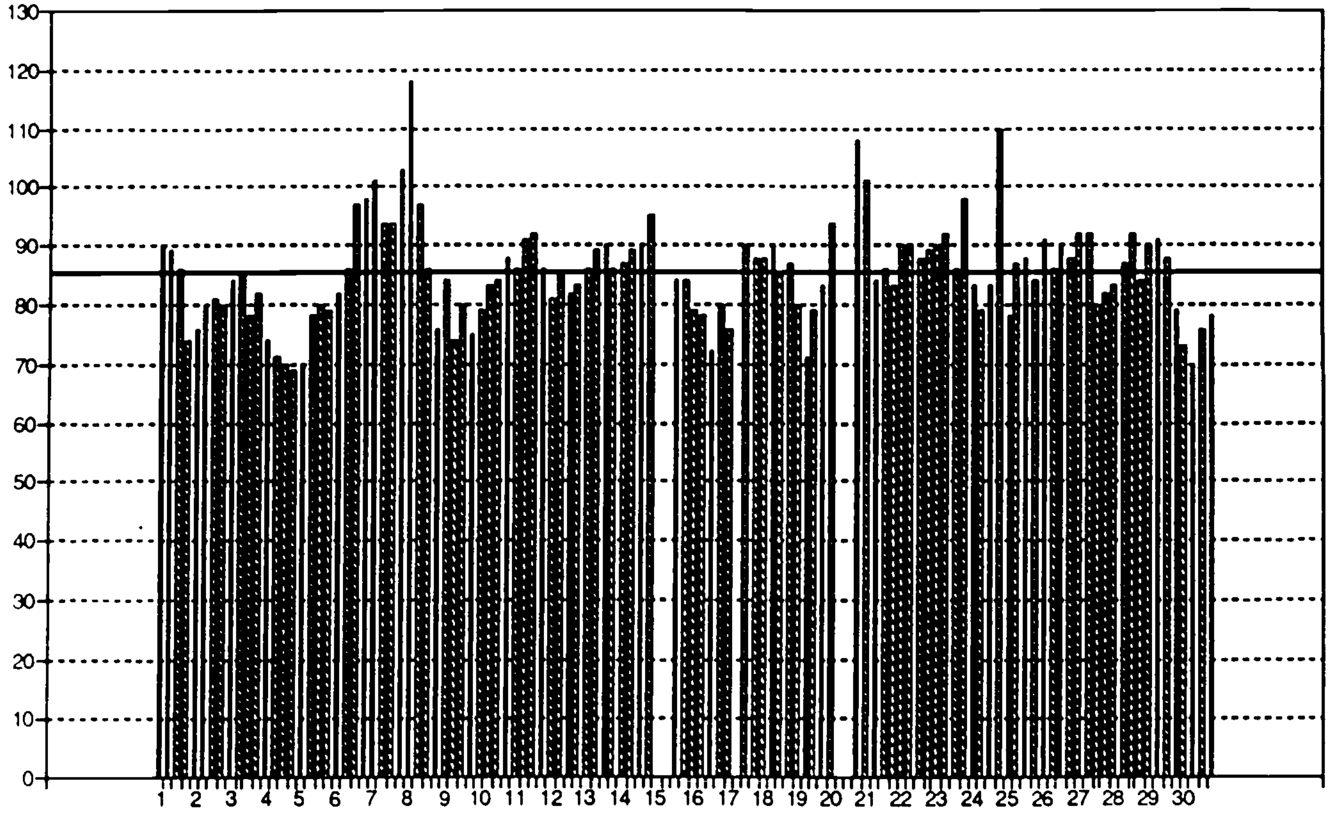
data: Hatfield Marine Science Center microseismometer

Daily Wave Energy March 1986
Newport, Oregon



data: Hatfield Marine Science Center microseismometer

Daily Wave Energy November 1986
Newport, Oregon



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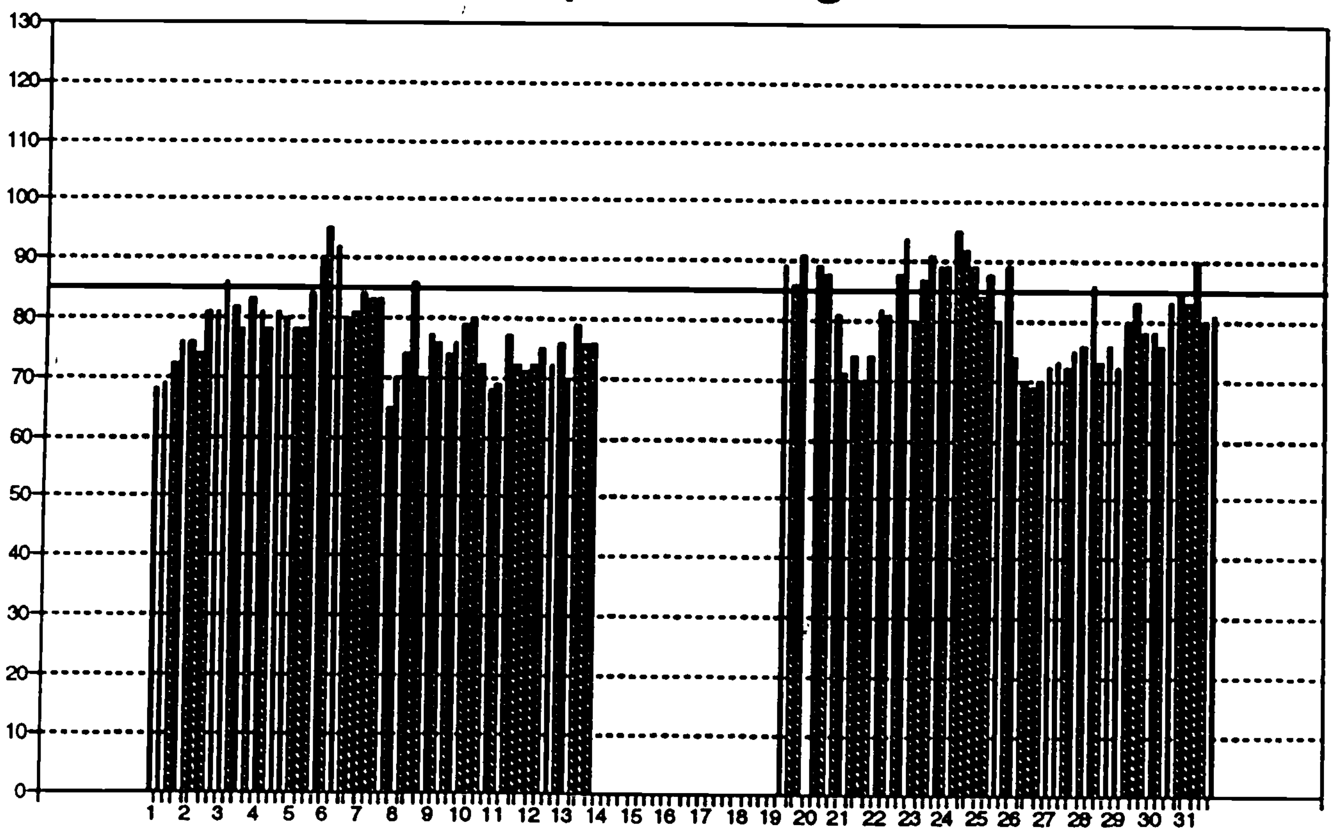
Daily Wave Energy December 1986
Newport, Oregon



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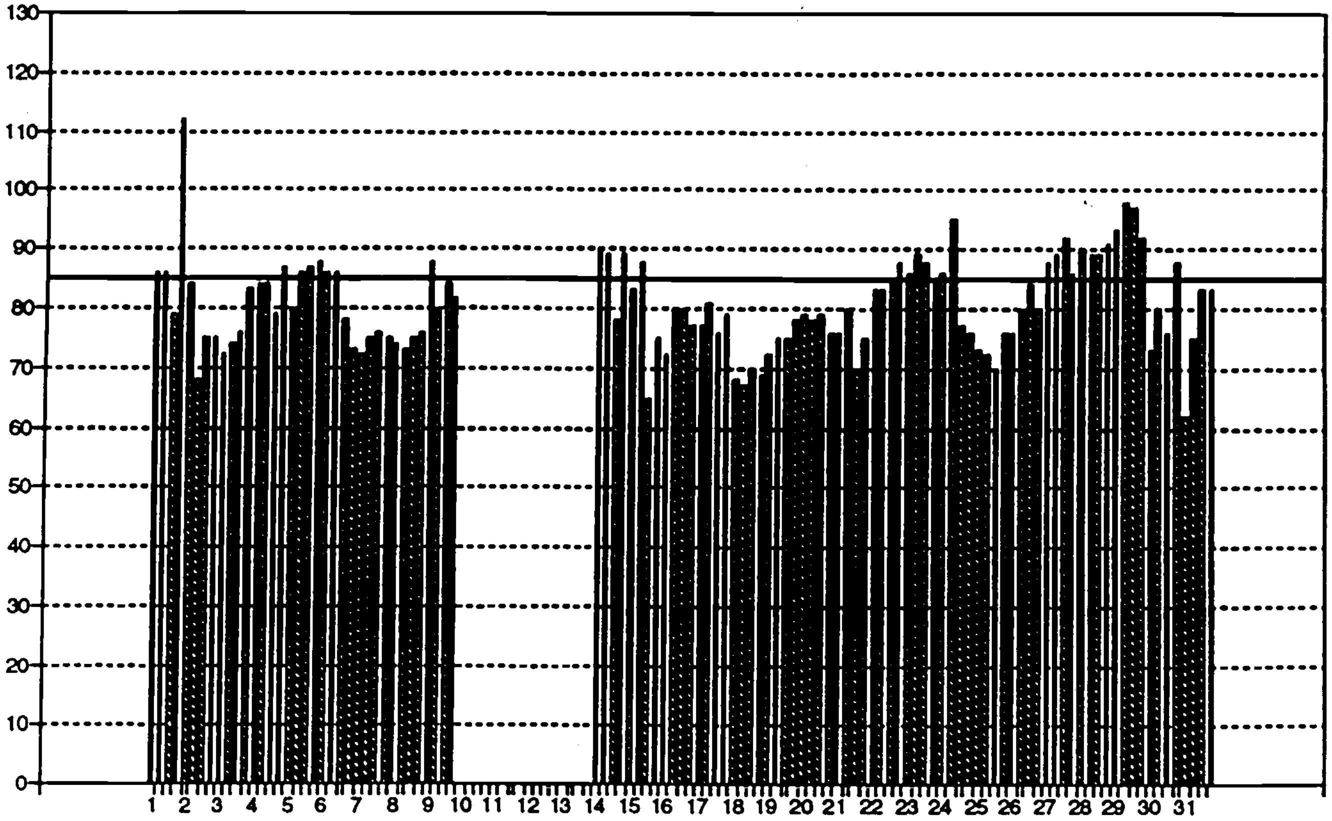
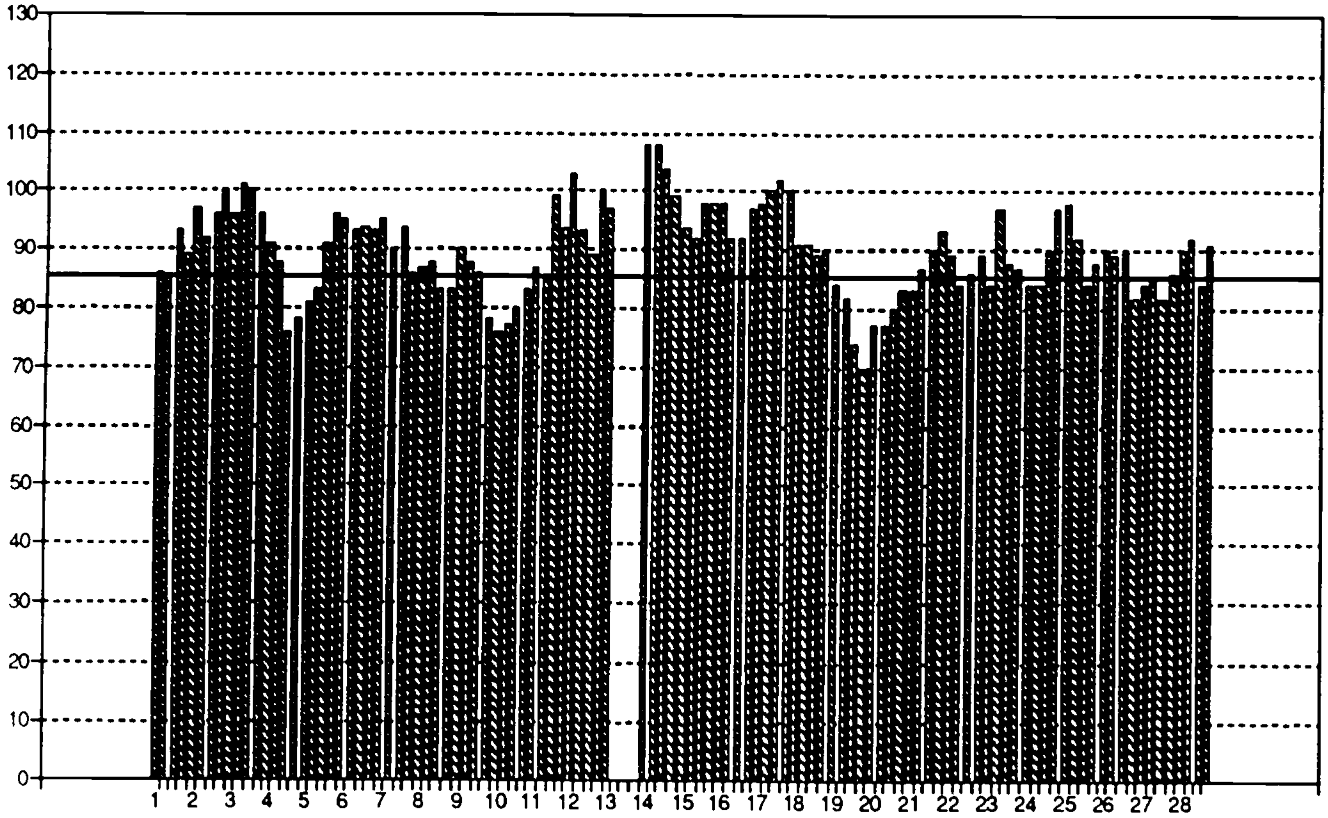
Daily Wave Energy January 1987
Newport, Oregon



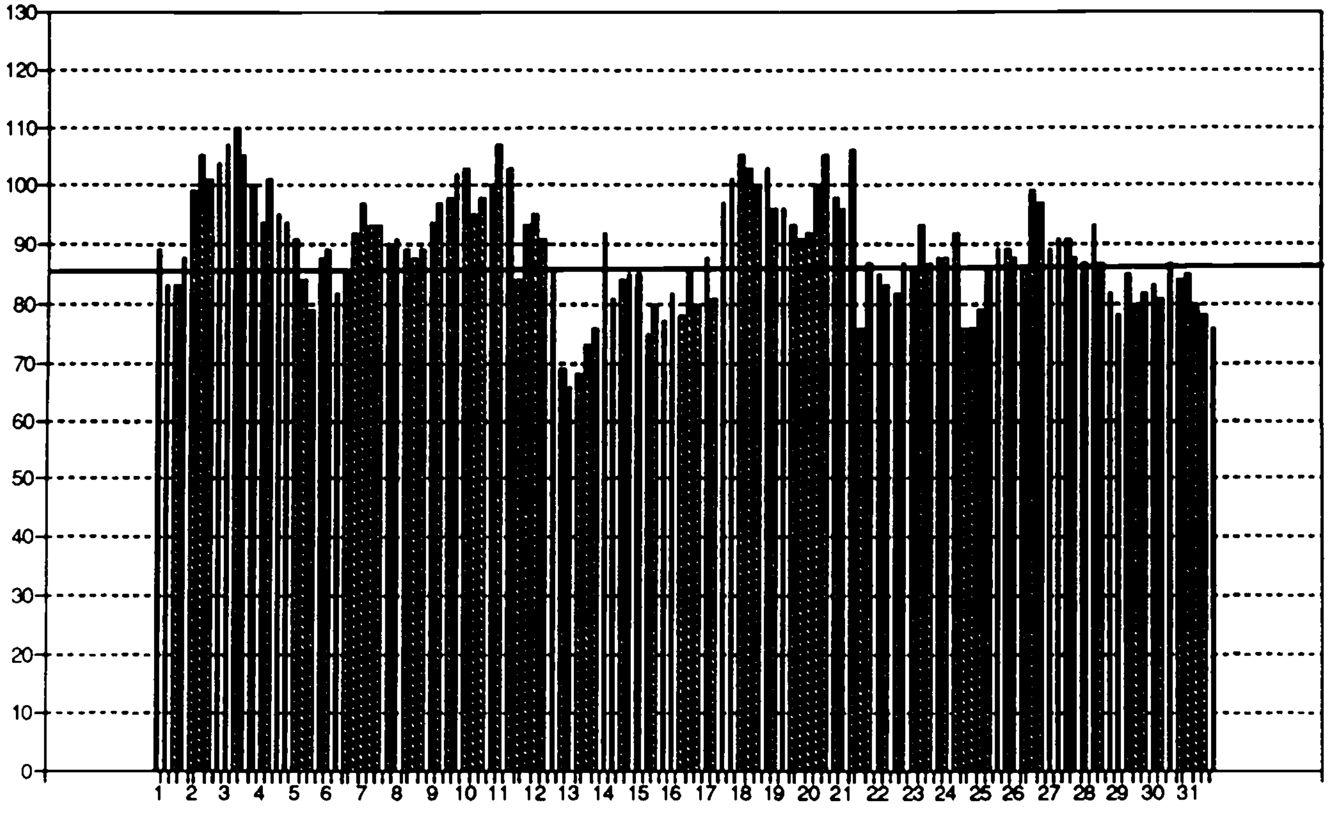
data: Hatfield Marine Science Center microseismometer

Daily Wave Energy February 1987
Newport, Oregon



data: Hatfield Marine Science Center microseismometer

Daily Wave Energy March 1987
Newport, Oregon



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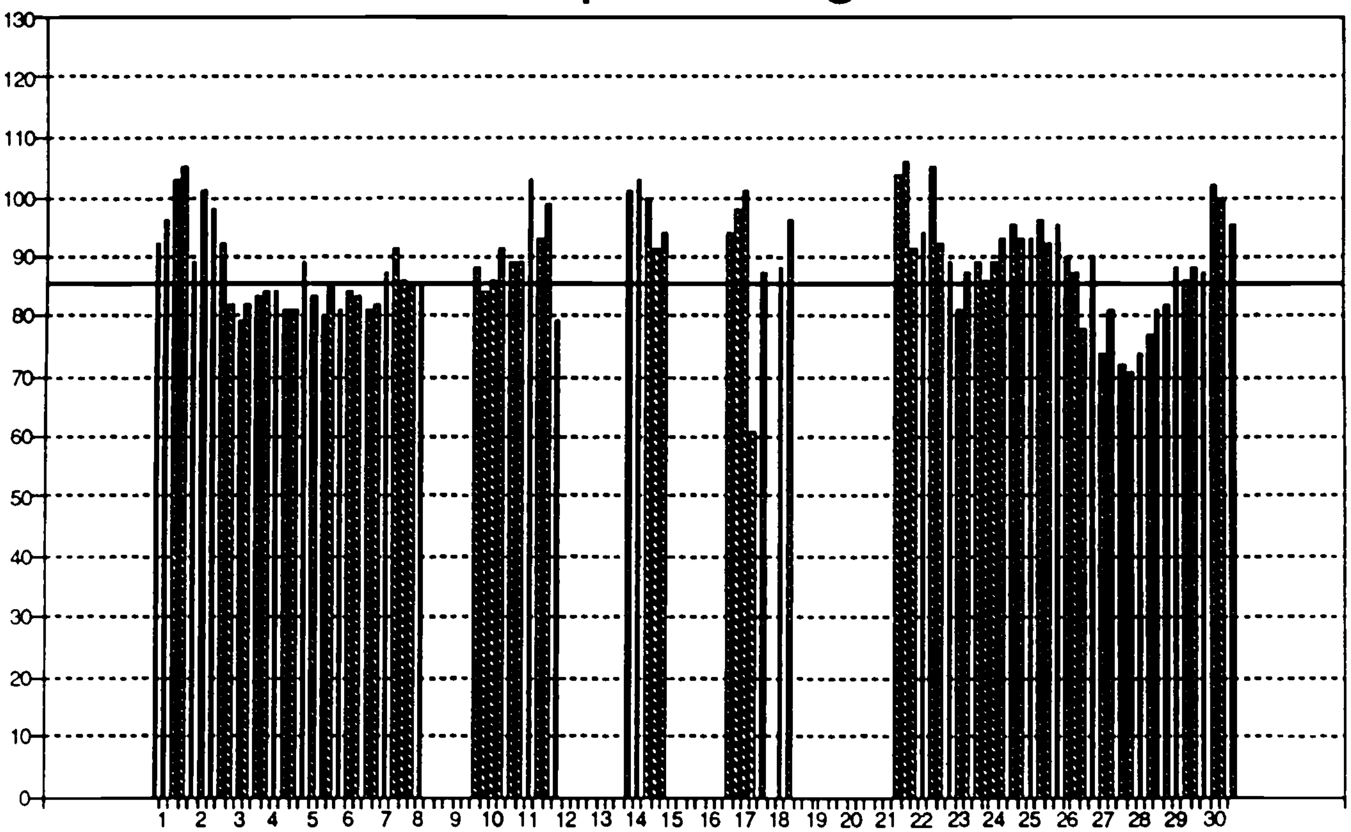
Daily Wave Energy November 1987
Newport, Oregon



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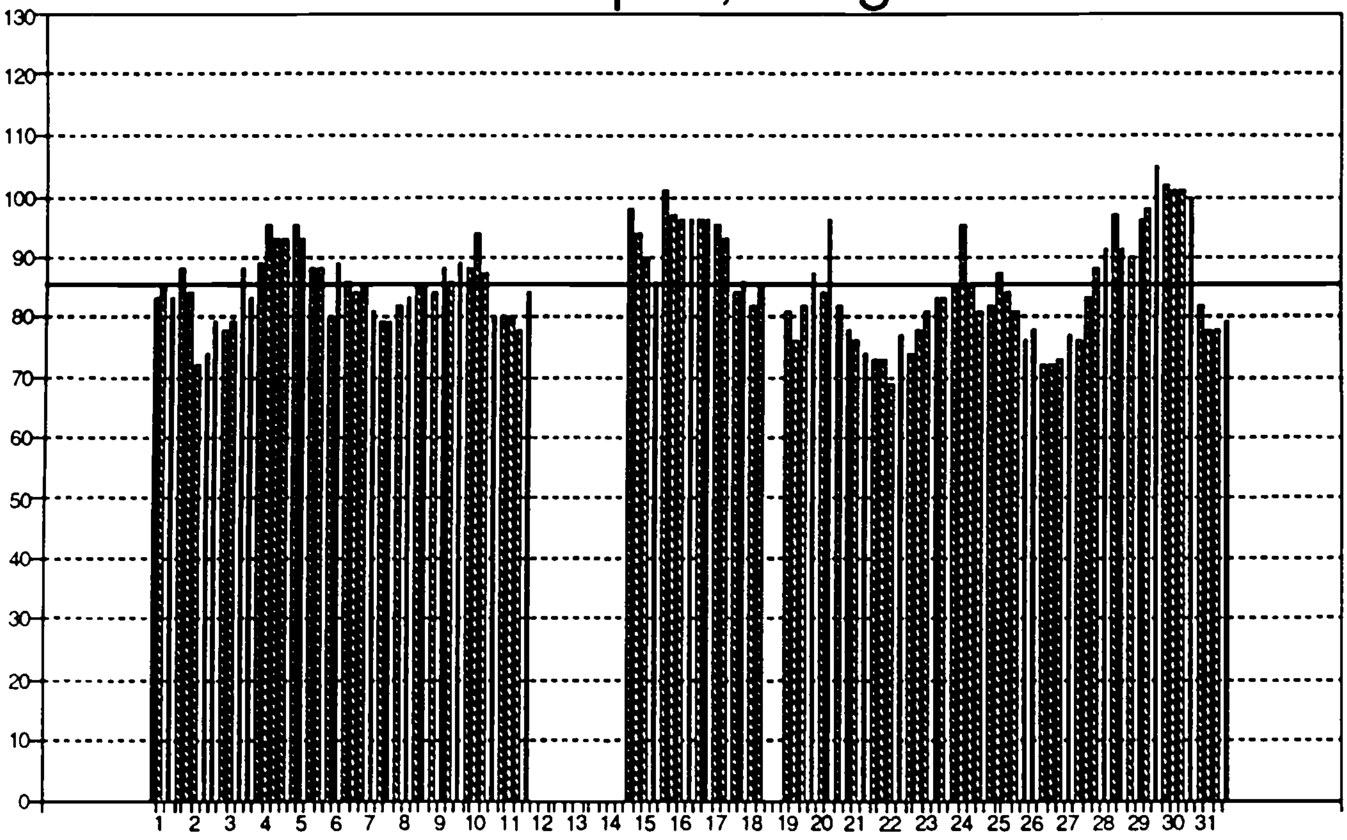
Daily Wave Energy December 1987
Newport, Oregon



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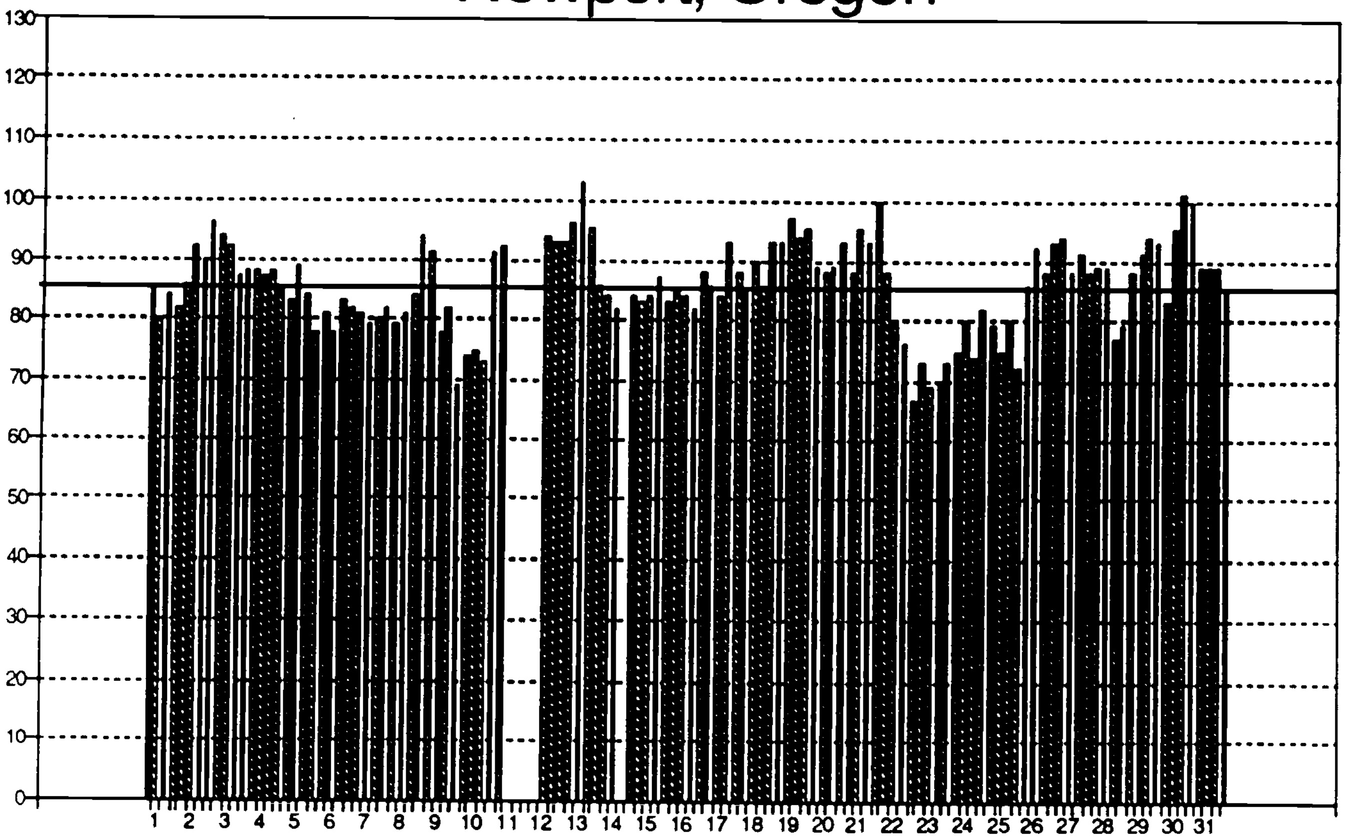
Daily Wave Energy January 1988
Newport, Oregon



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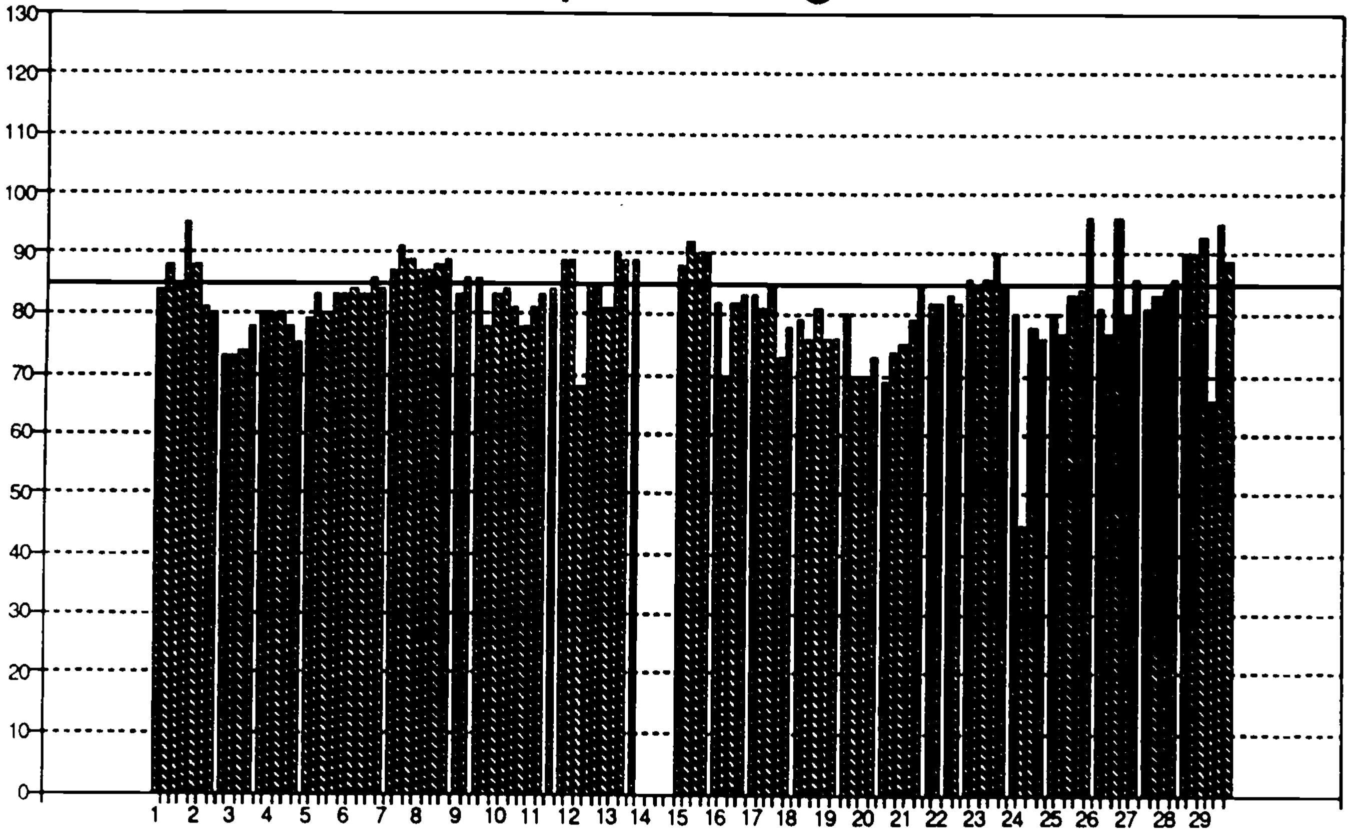
Daily Wave Energy February 1988
Newport, Oregon



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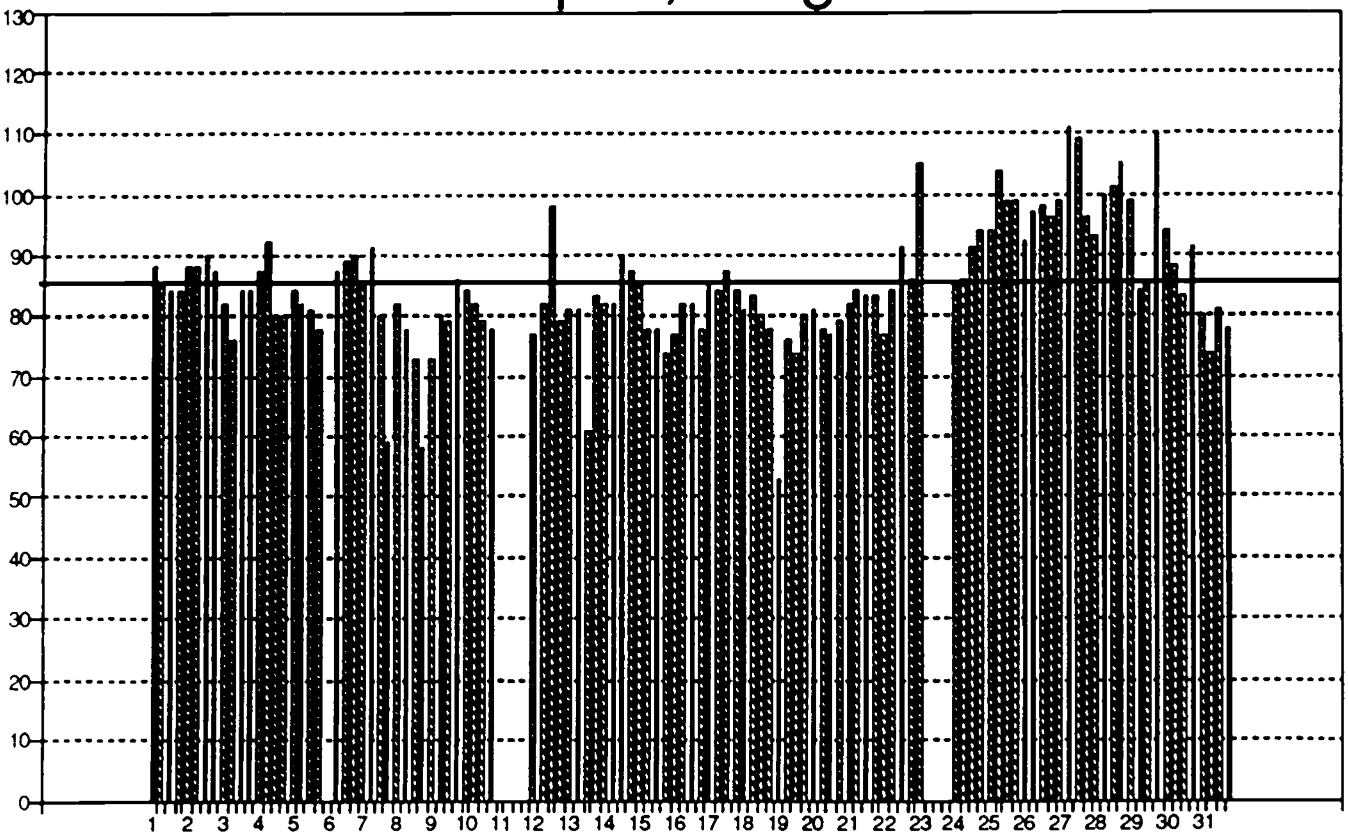
Daily Wave Energy March 1988
Newport, Oregon



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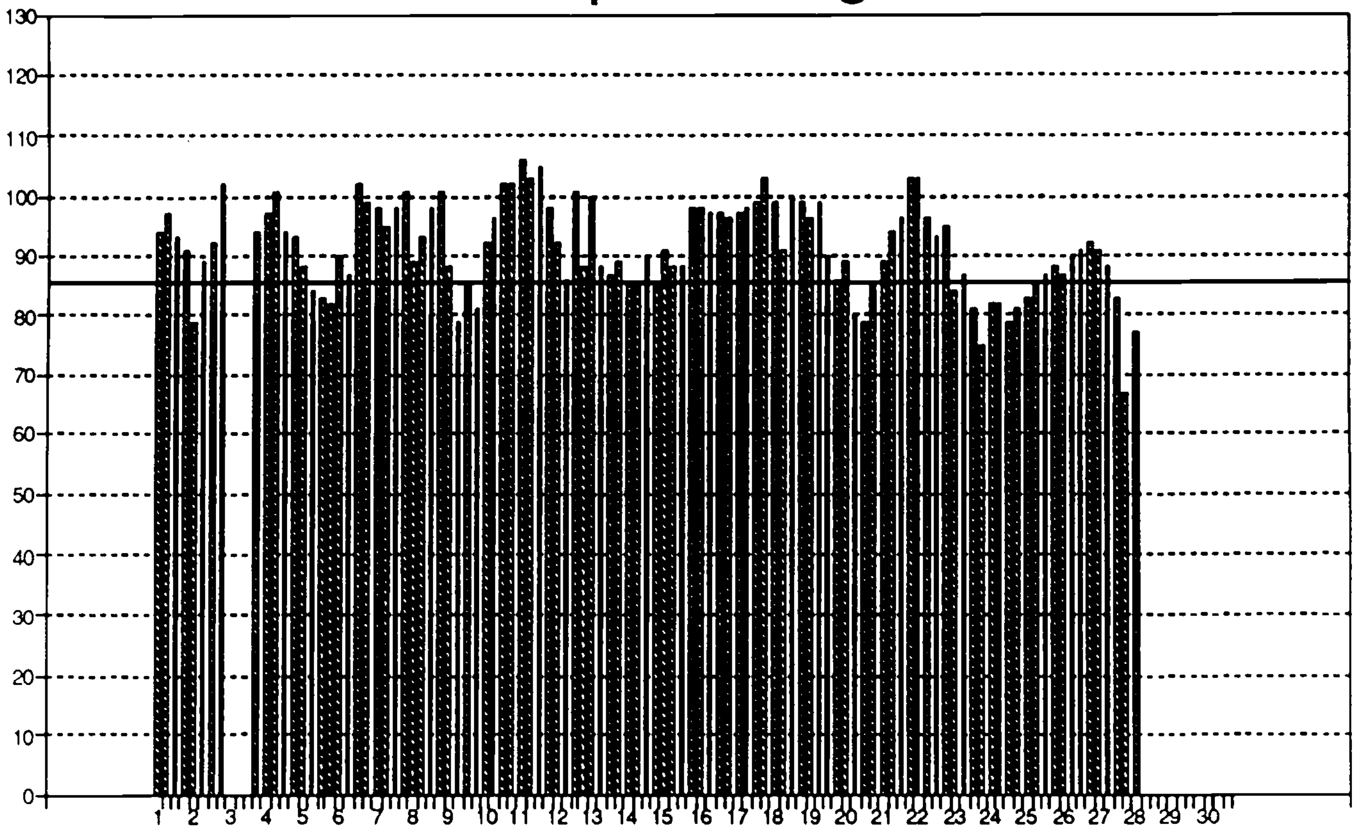
Daily Wave Energy November 1988
Newport, Oregon



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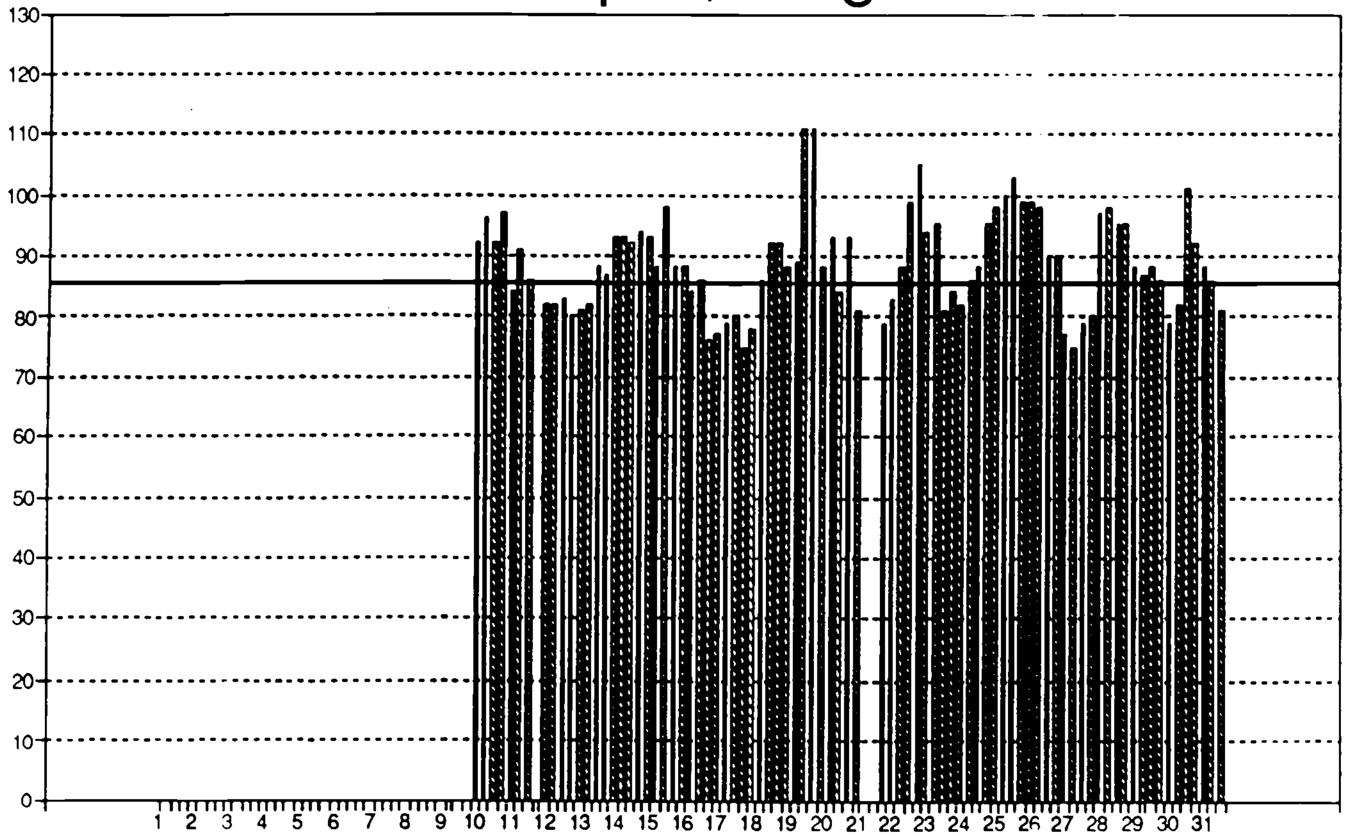
Daily Wave Energy December 1988
Newport, Oregon



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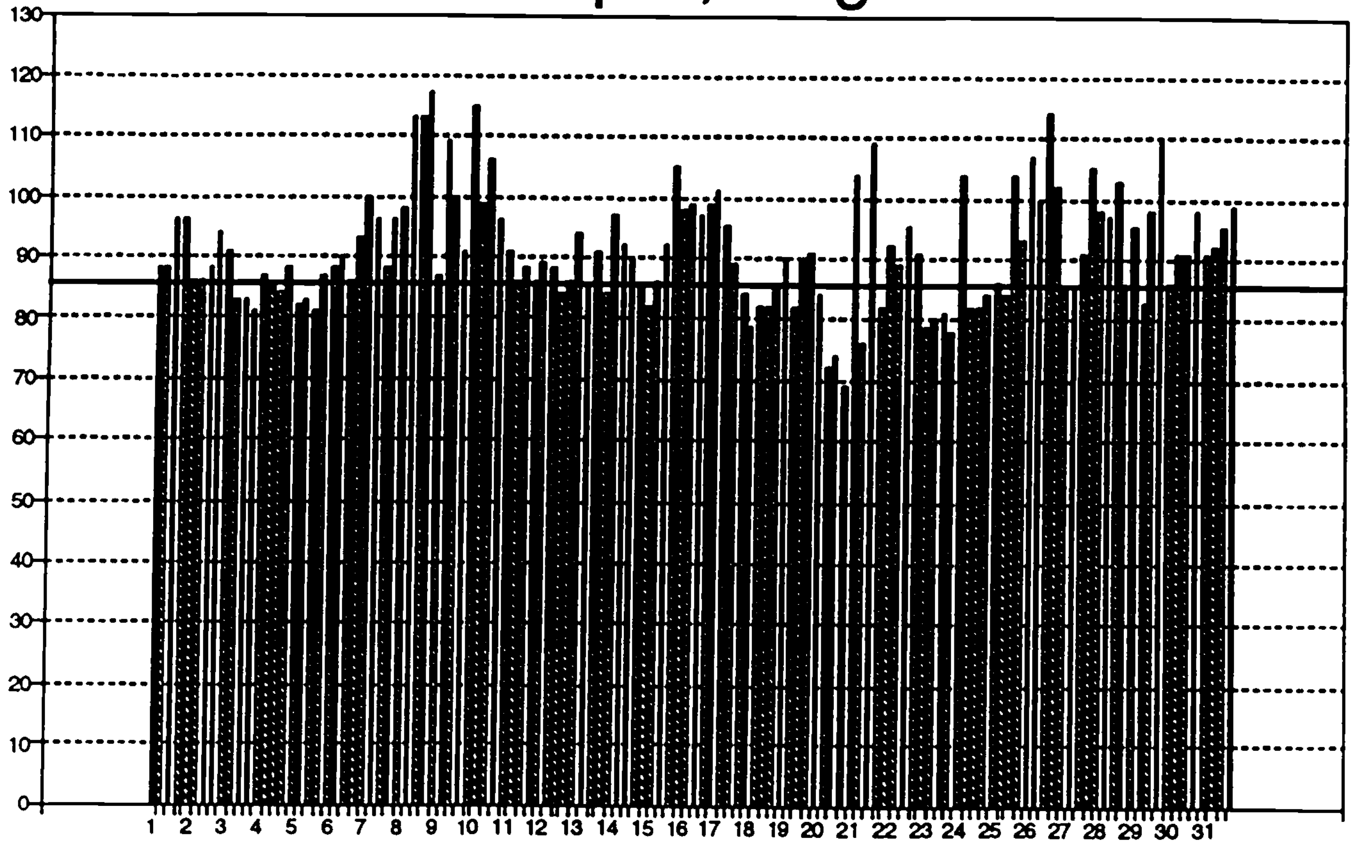
Daily Wave Energy January 1989
Newport, Oregon



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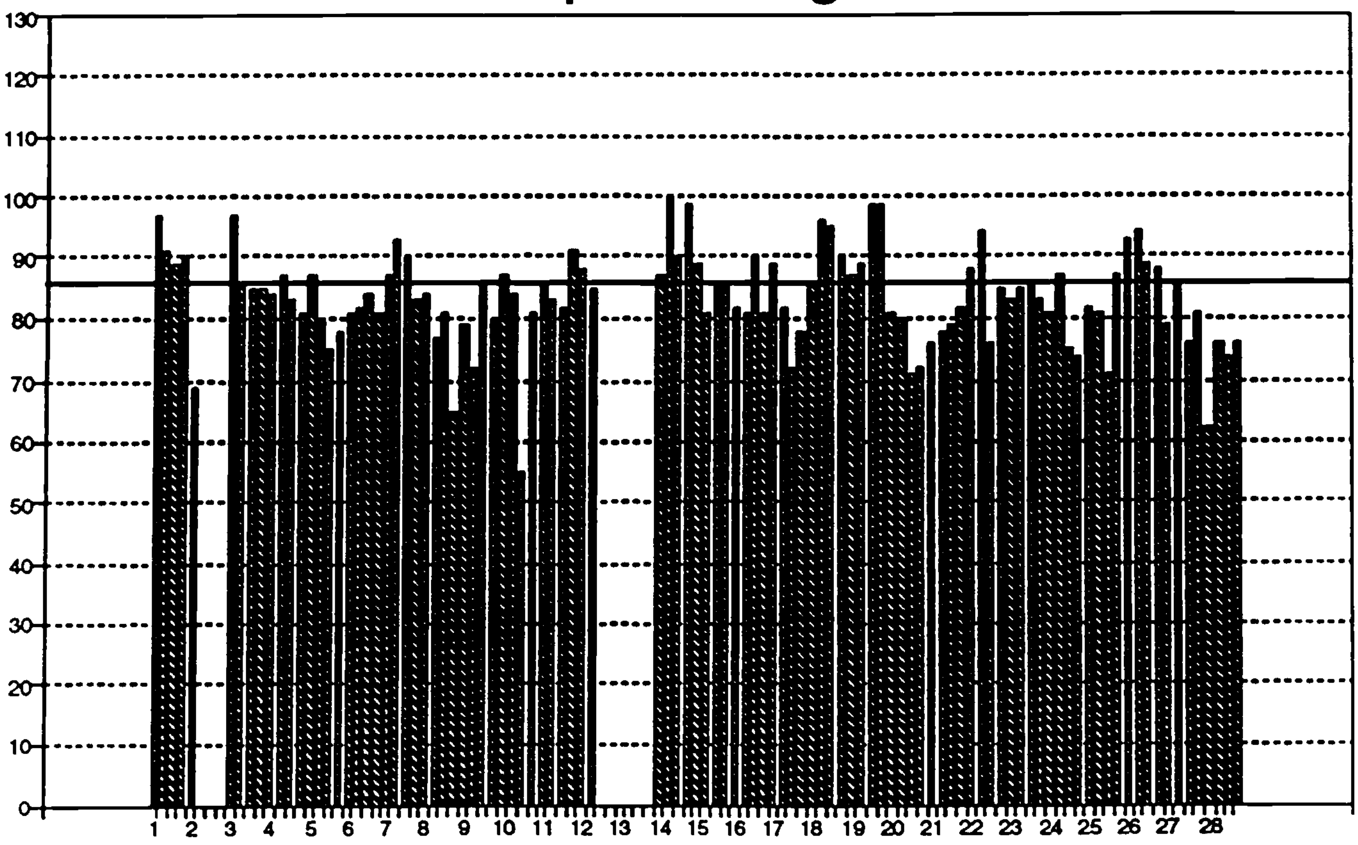
Daily Wave Energy February 1989
Newport, Oregon



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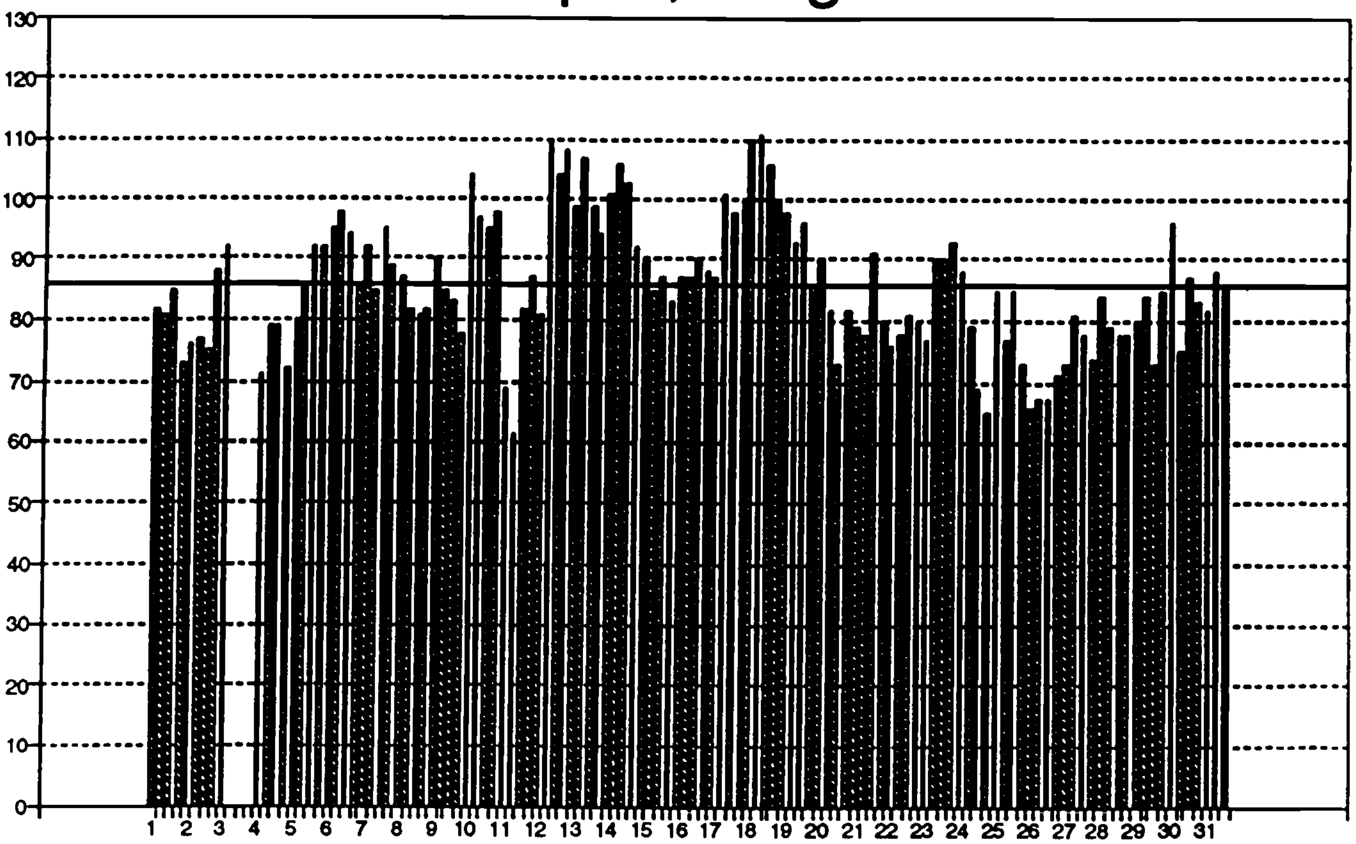
Daily Wave Energy March 1989
Newport, Oregon



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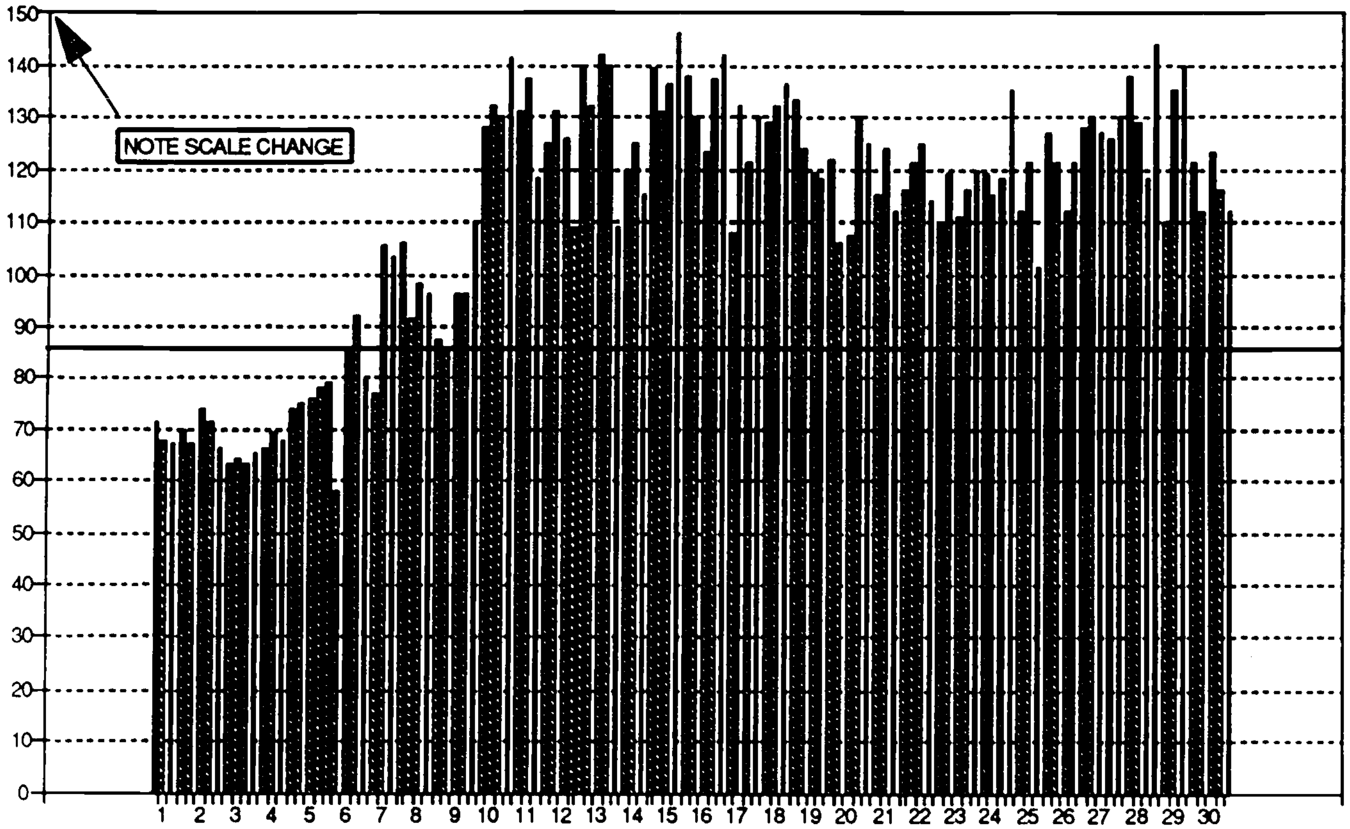
Daily Wave Energy November 1989
Newport, Oregon



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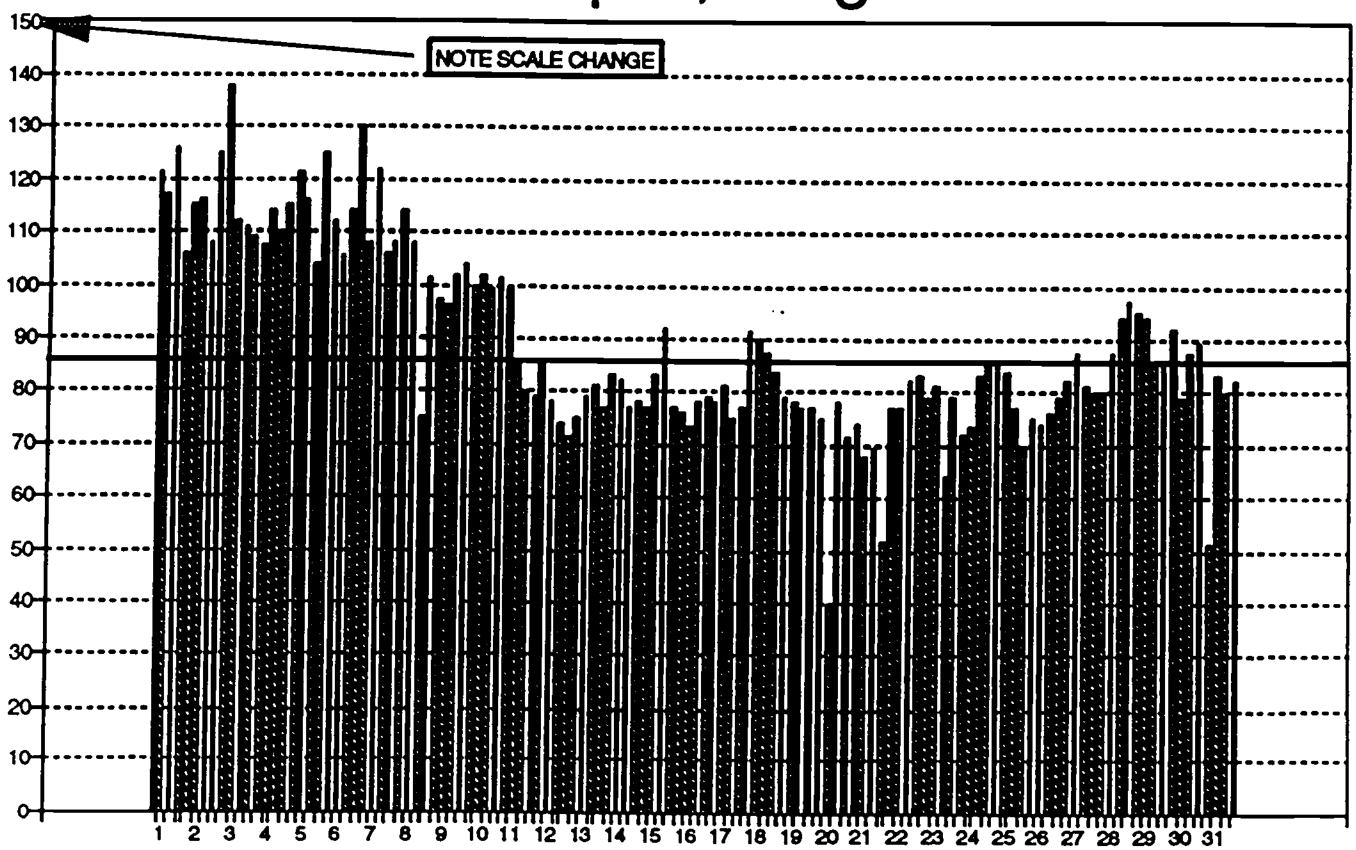
Daily Wave Energy December 1989
Newport, Oregon



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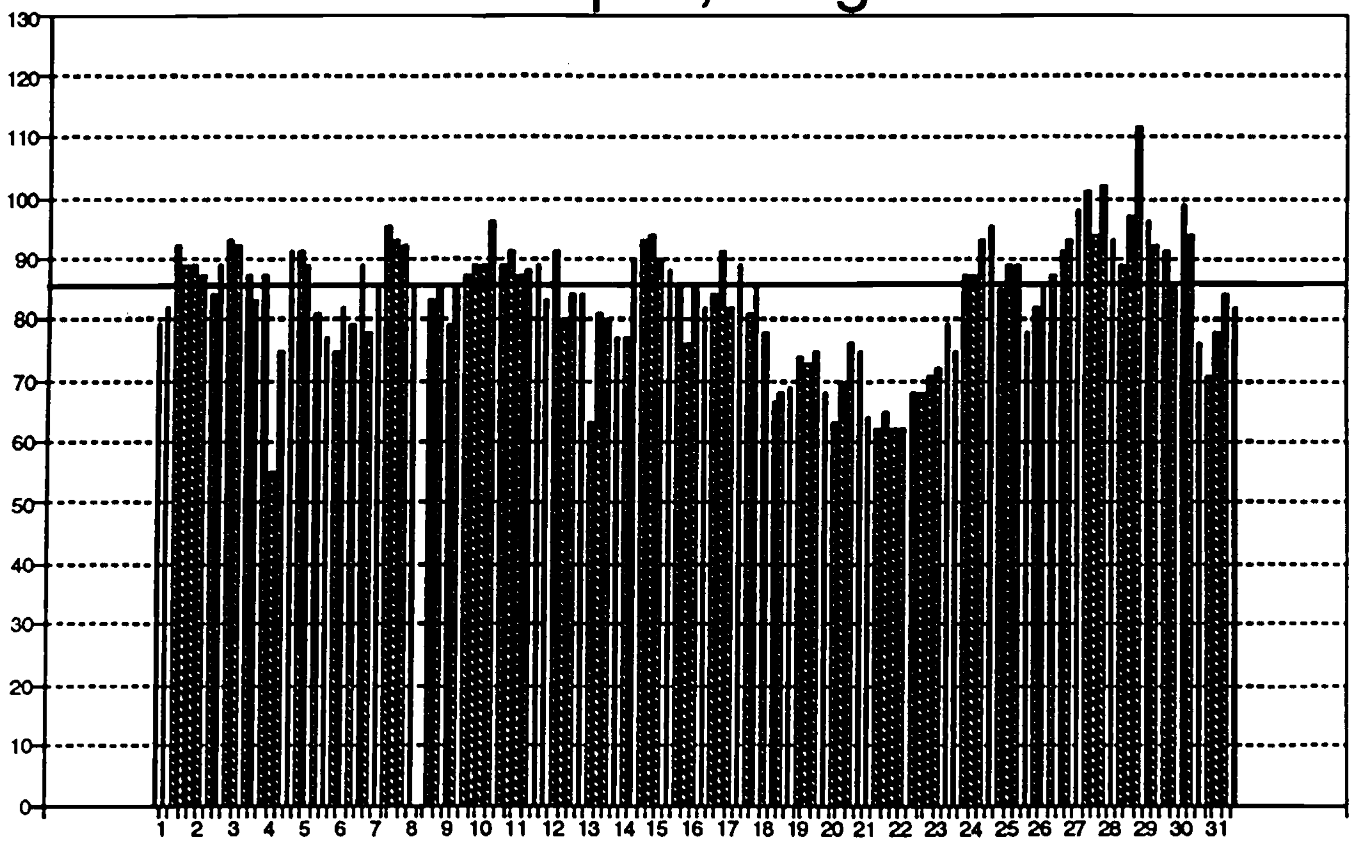
Daily Wave Energy January 1990
Newport, Oregon



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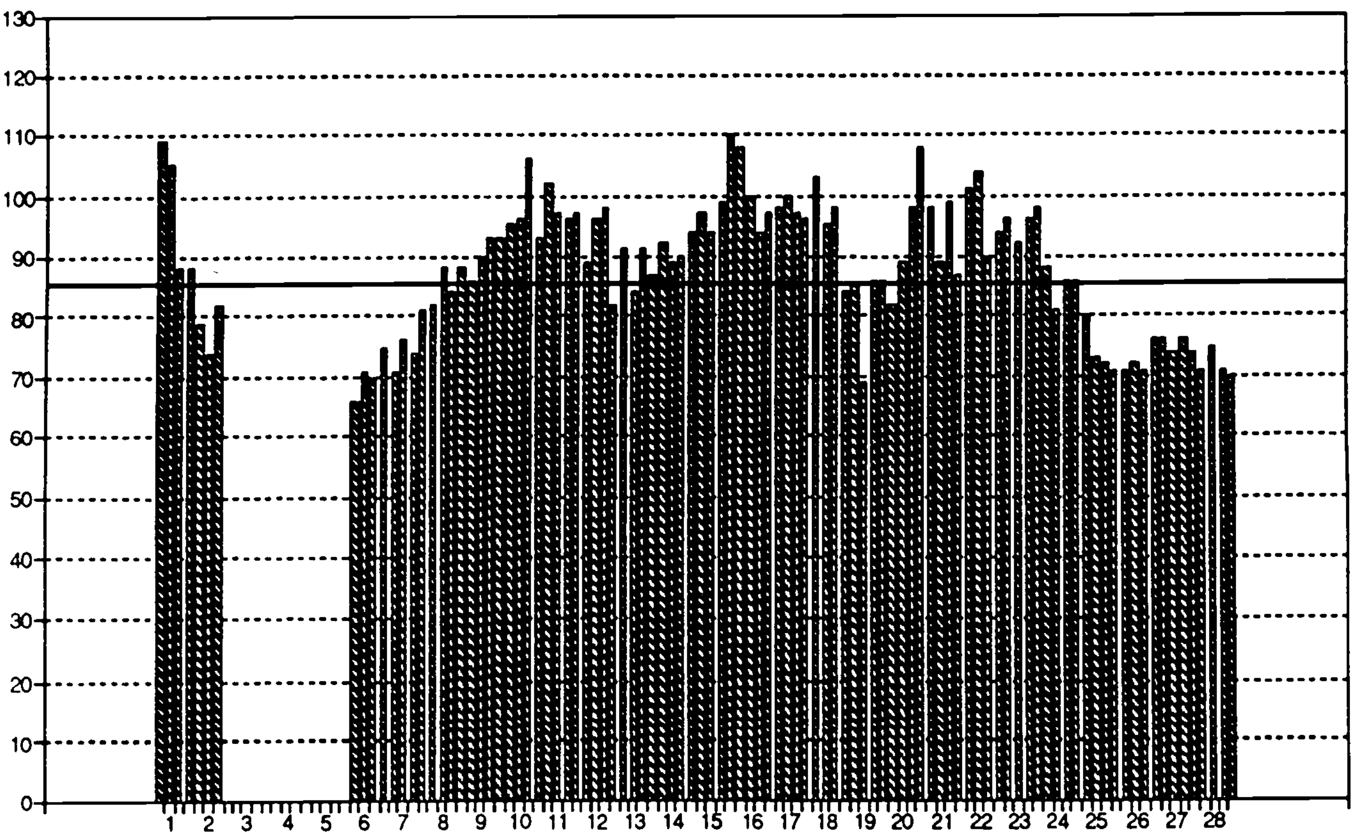
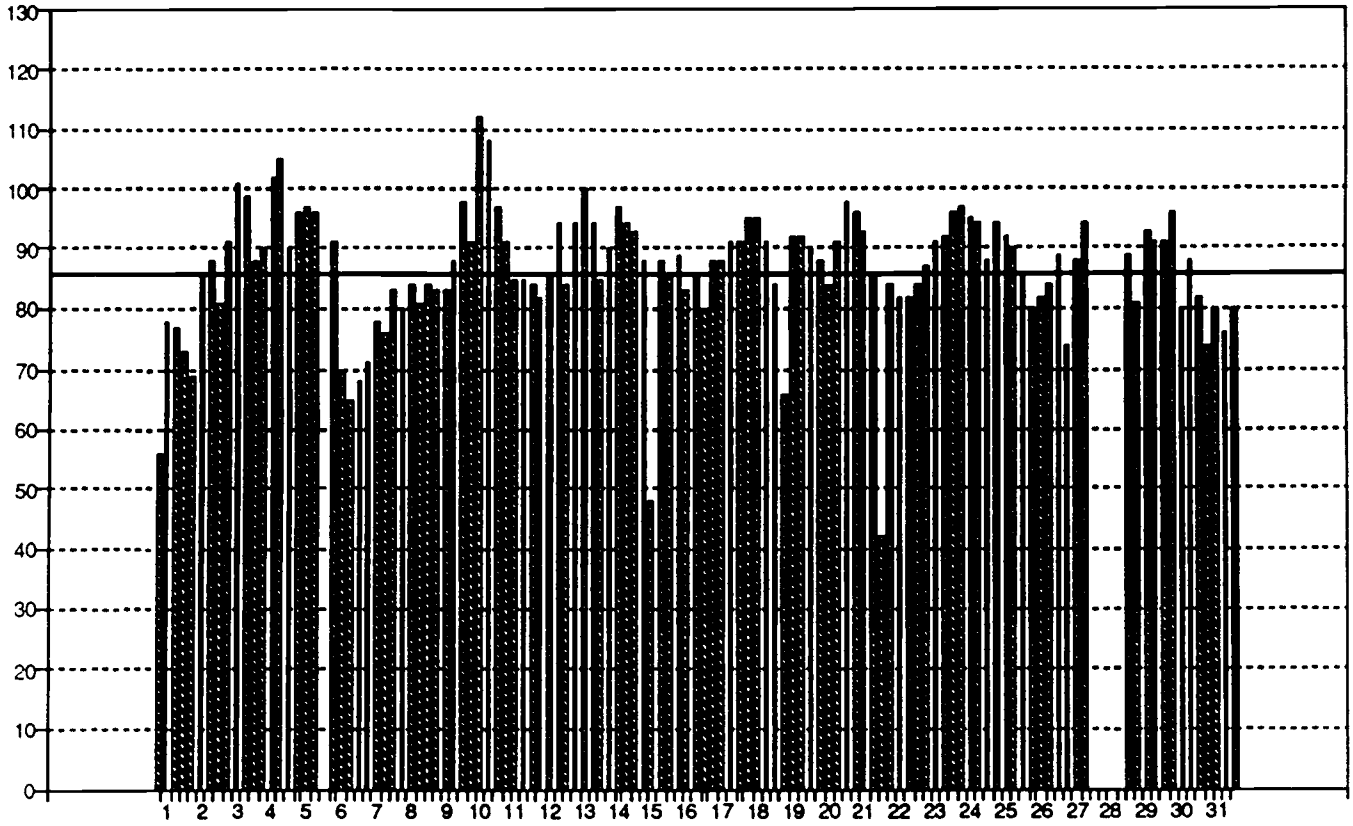
Daily Wave Energy February 1990
Newport, Oregon



data: Hatfield Marine Science Center microseismometer

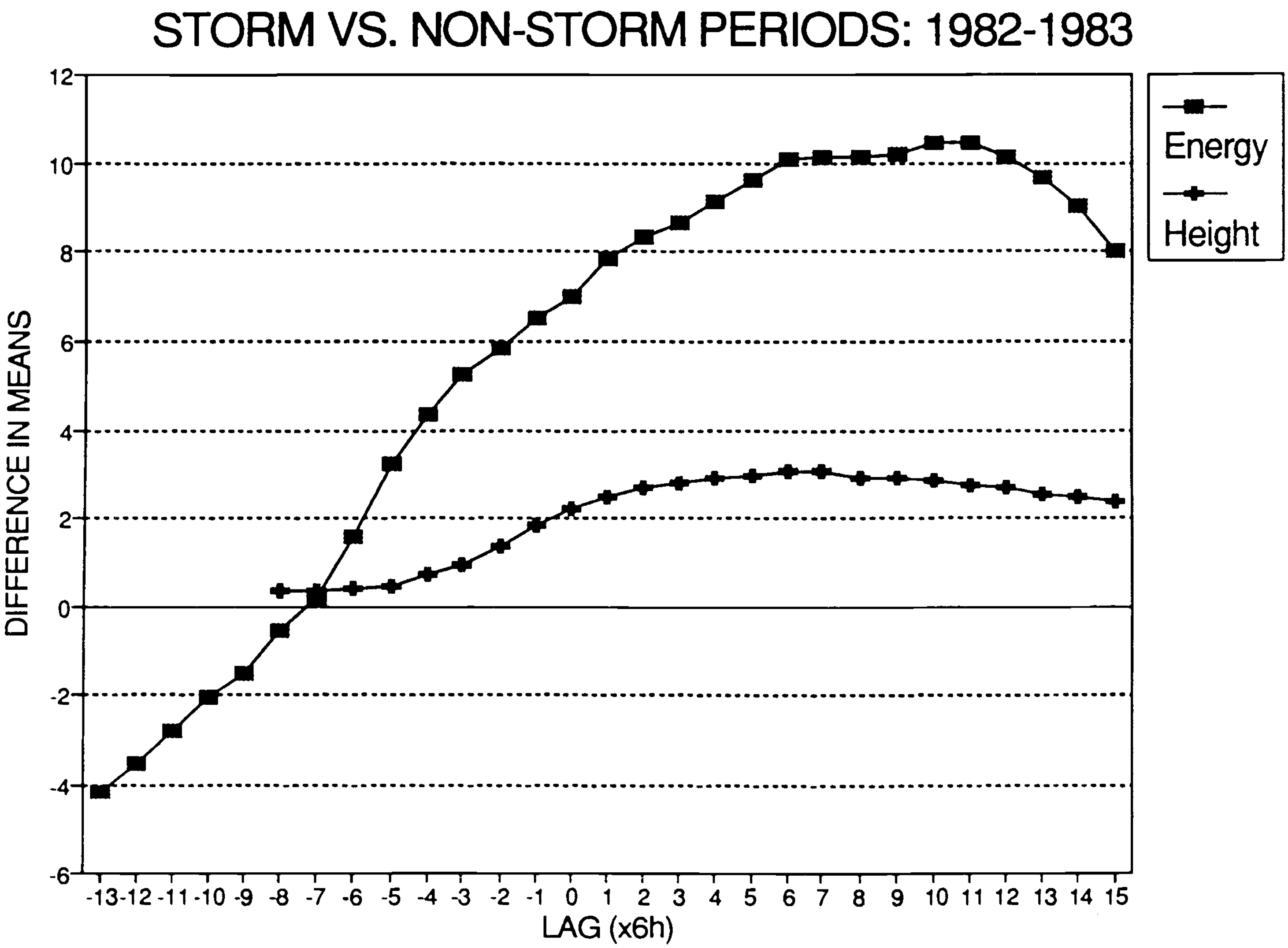
Daily Wave Energy March 1990
Newport, Oregon



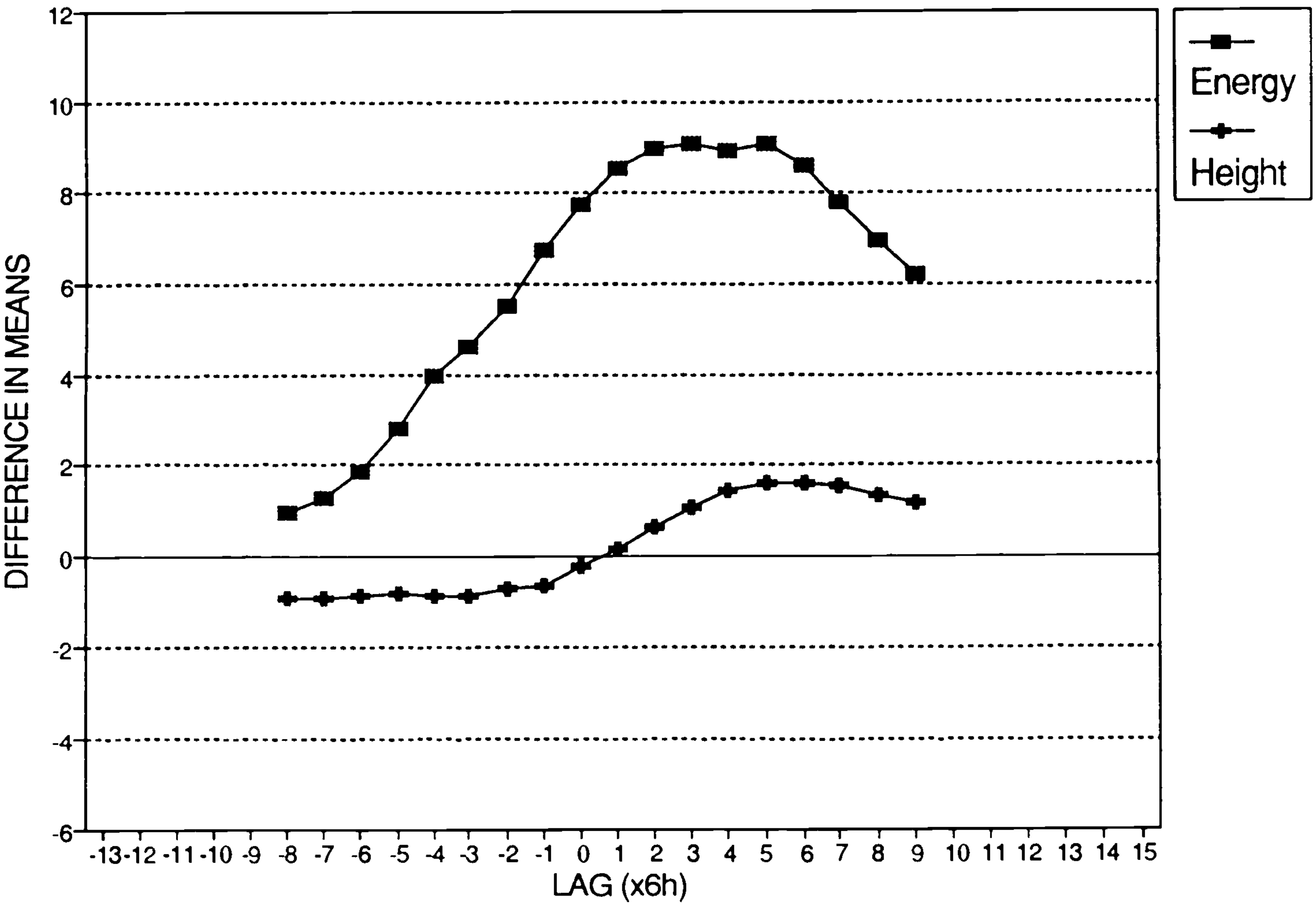
data: Hatfield Marine Science Center microseismometer

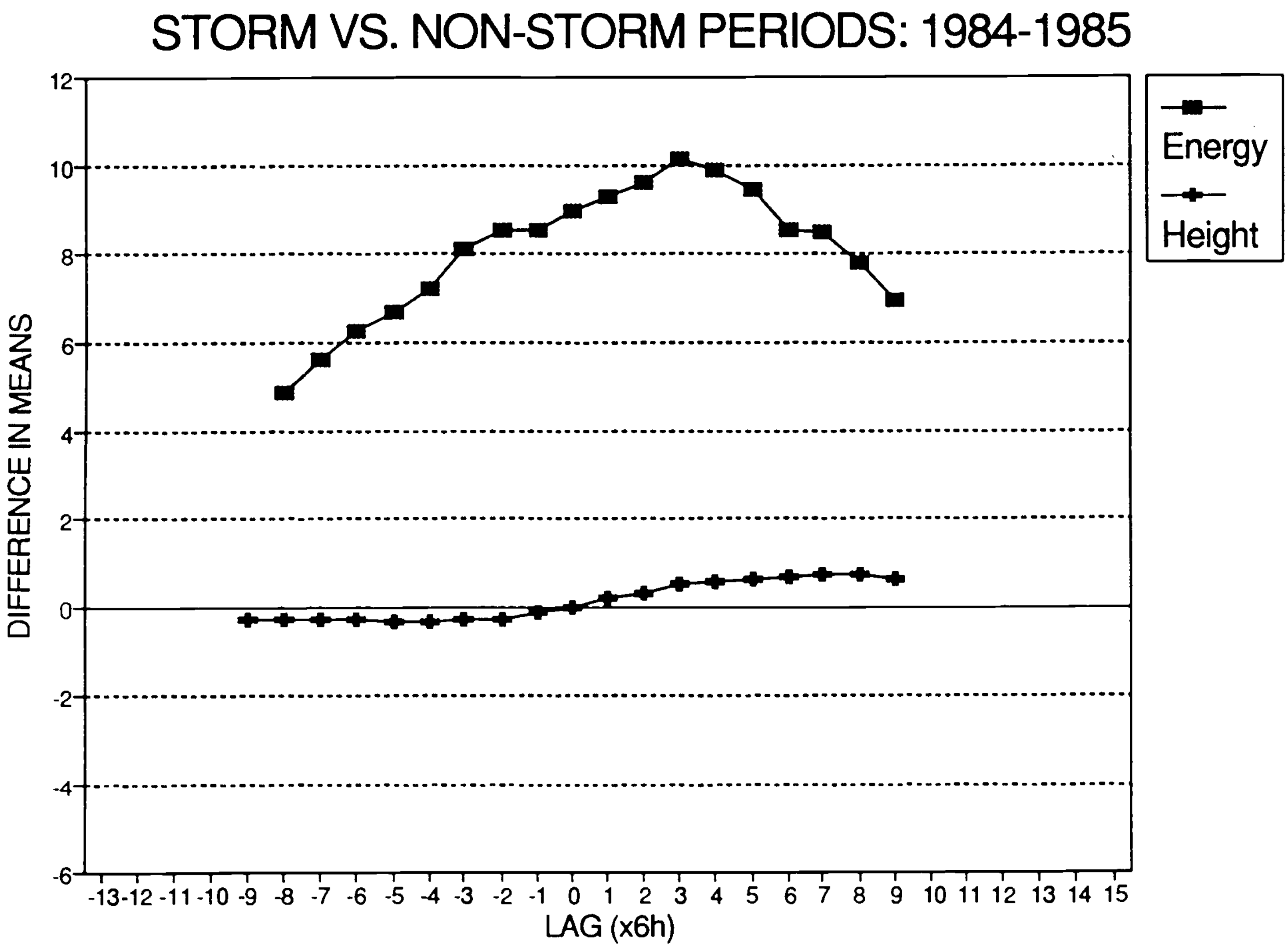
Appendix 4.

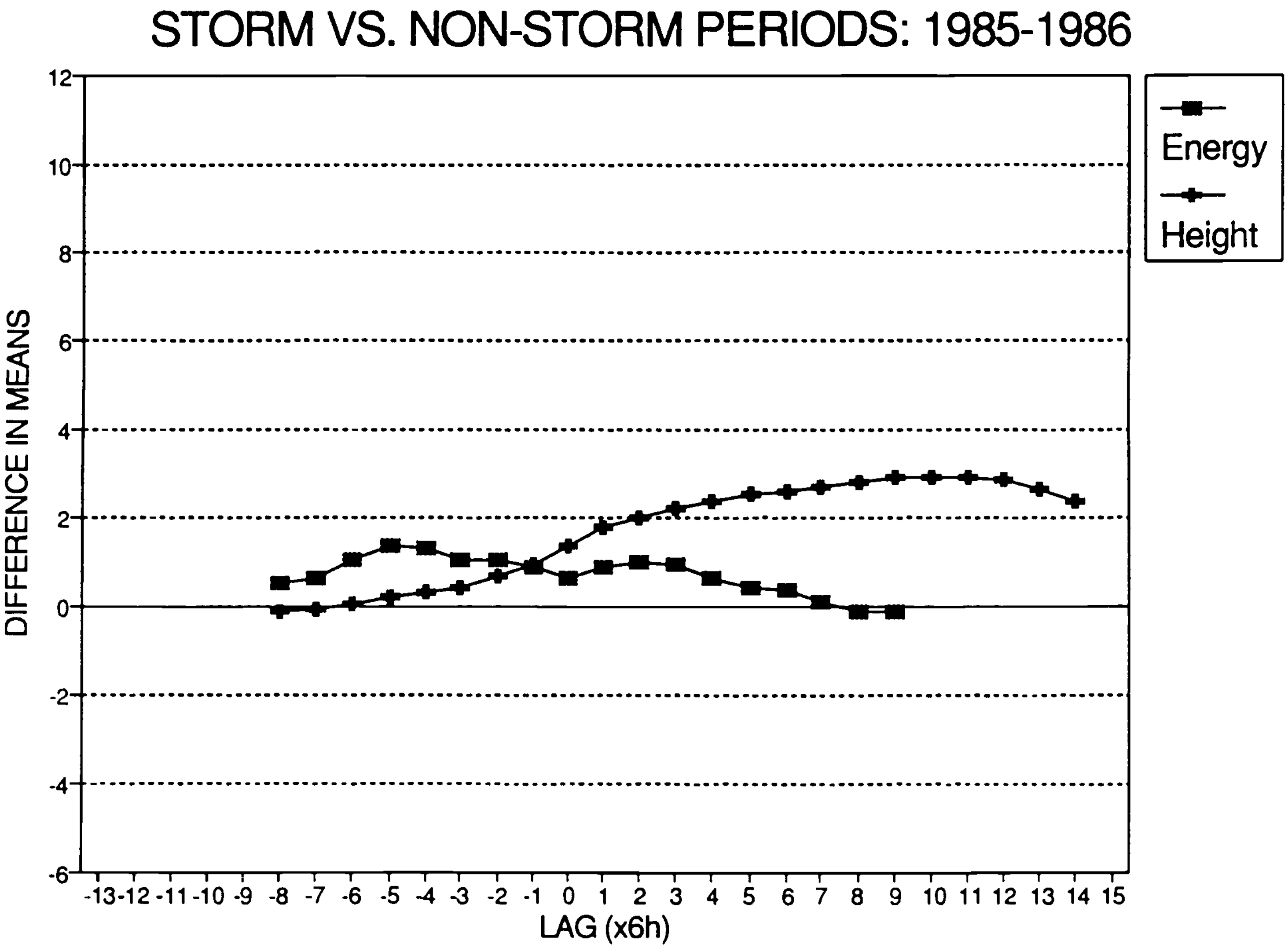
Difference in Mean Height and Energy Values between Storm and Non-Storm Events by Year

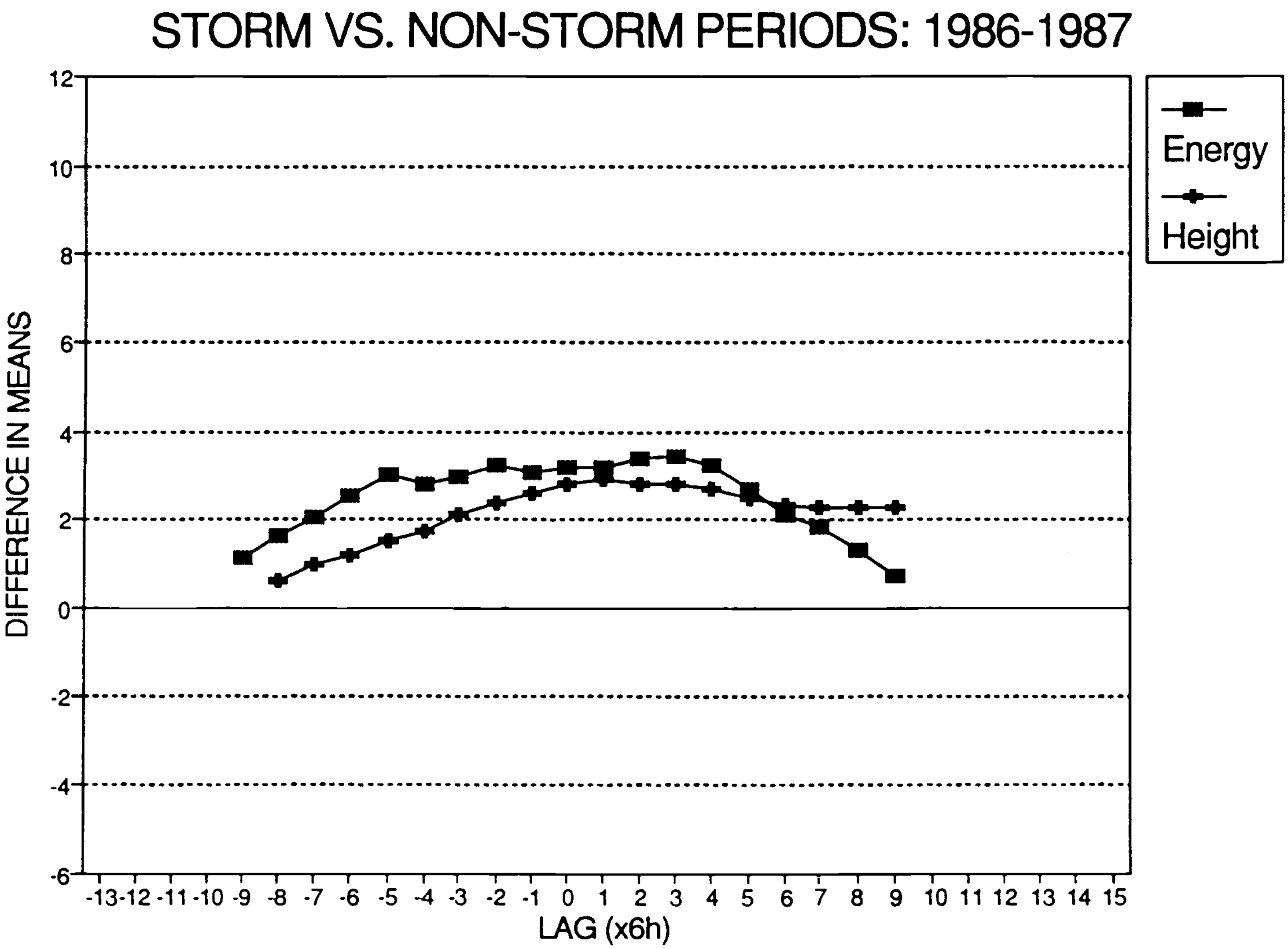

STORM VS. NON-STORM PERIODS: 1982-1983
12
10
8
6
4
2
0
-2
-4
-6
DIFFERENCE IN MEANS
-13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
LAG (x6h)
Energy
Height

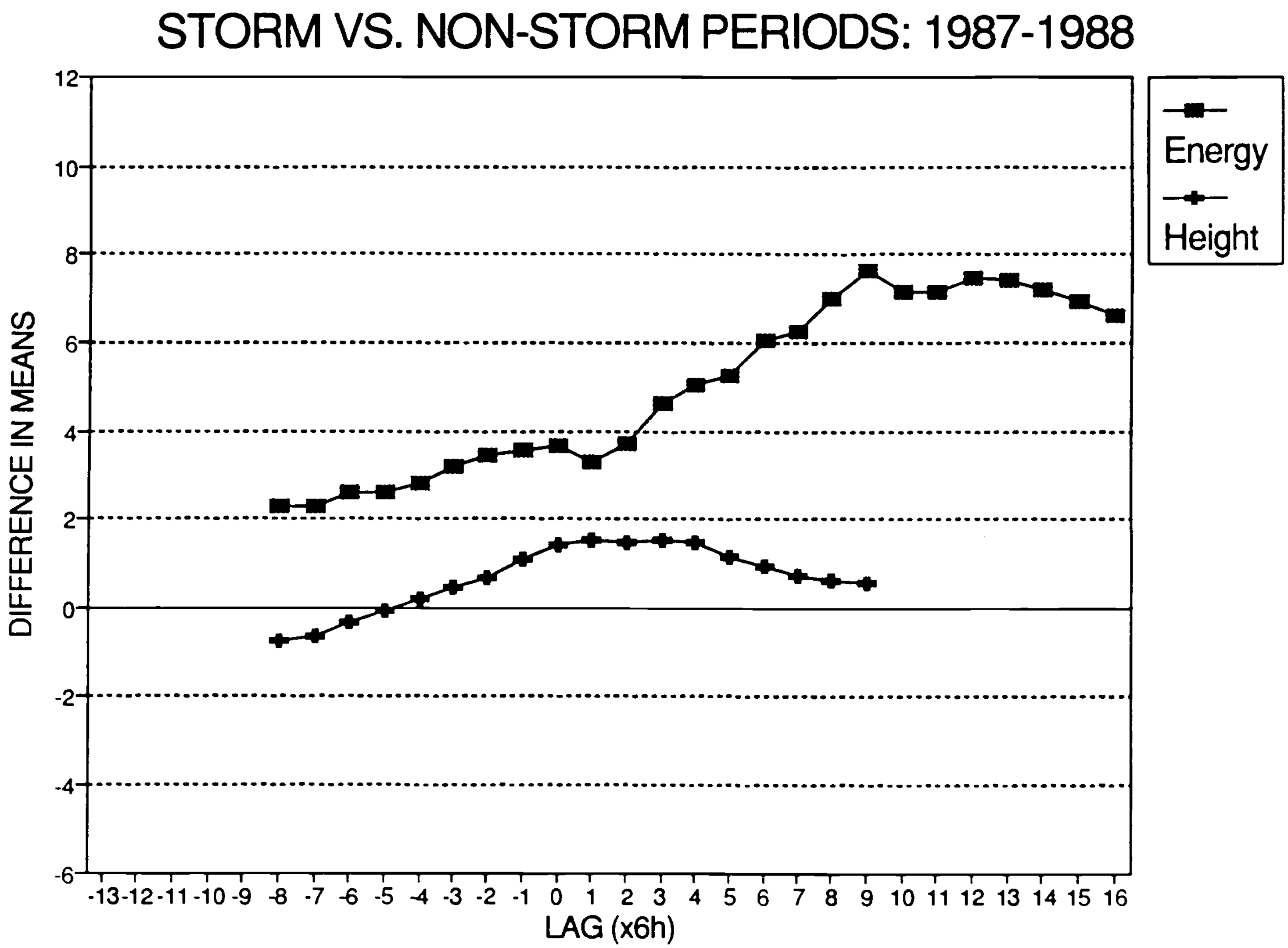
STORM VS. NON-STORM PERIODS: 1983-1984



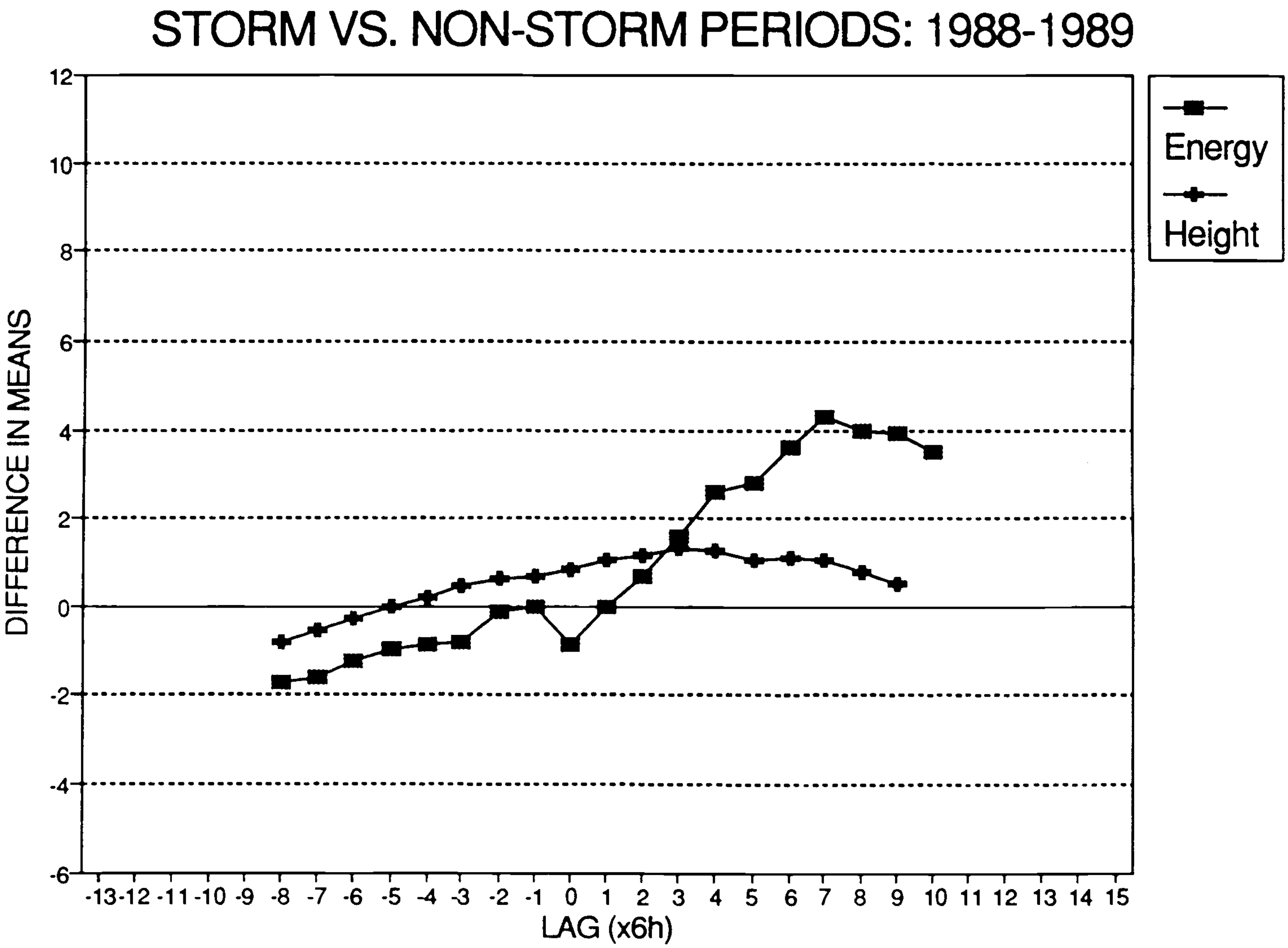

STORM VS. NON-STORM PERIODS: 1984-1985
DIFFERENCE IN MEANS
12
10
8
6
4
2
0
-2
-4
-6
-13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
LAG (x6h)
Energy
Height


STORM VS. NON-STORM PERIODS: 1985-1986
DIFFERENCE IN MEANS
12
10
8
6
4
2
0
-2
-4
-6
-13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
LAG (x6h)
Energy
Height

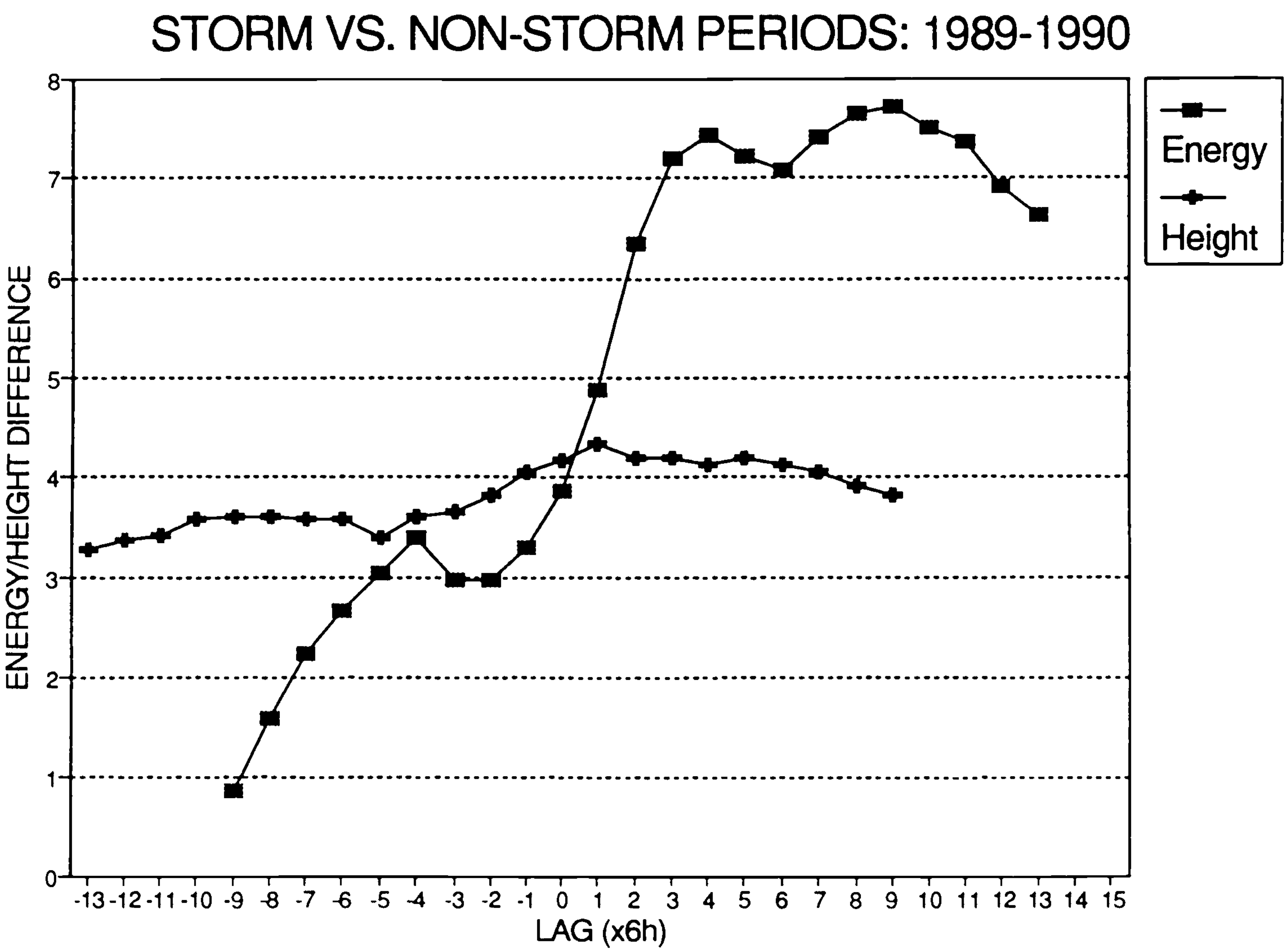

STORM VS. NON-STORM PERIODS: 1986-1987
Energy
Height
DIFFERENCE IN MEANS
12
10
8
6
4
2
0
-2
-4
-6
-13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
LAG (x6h)



STORM VS. NON-STORM PERIODS: 1987-1988
DIFFERENCE IN MEANS
12
10
8
6
4
2
0
-2
-4
-6
-13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
LAG (x6h)
Energy
Height



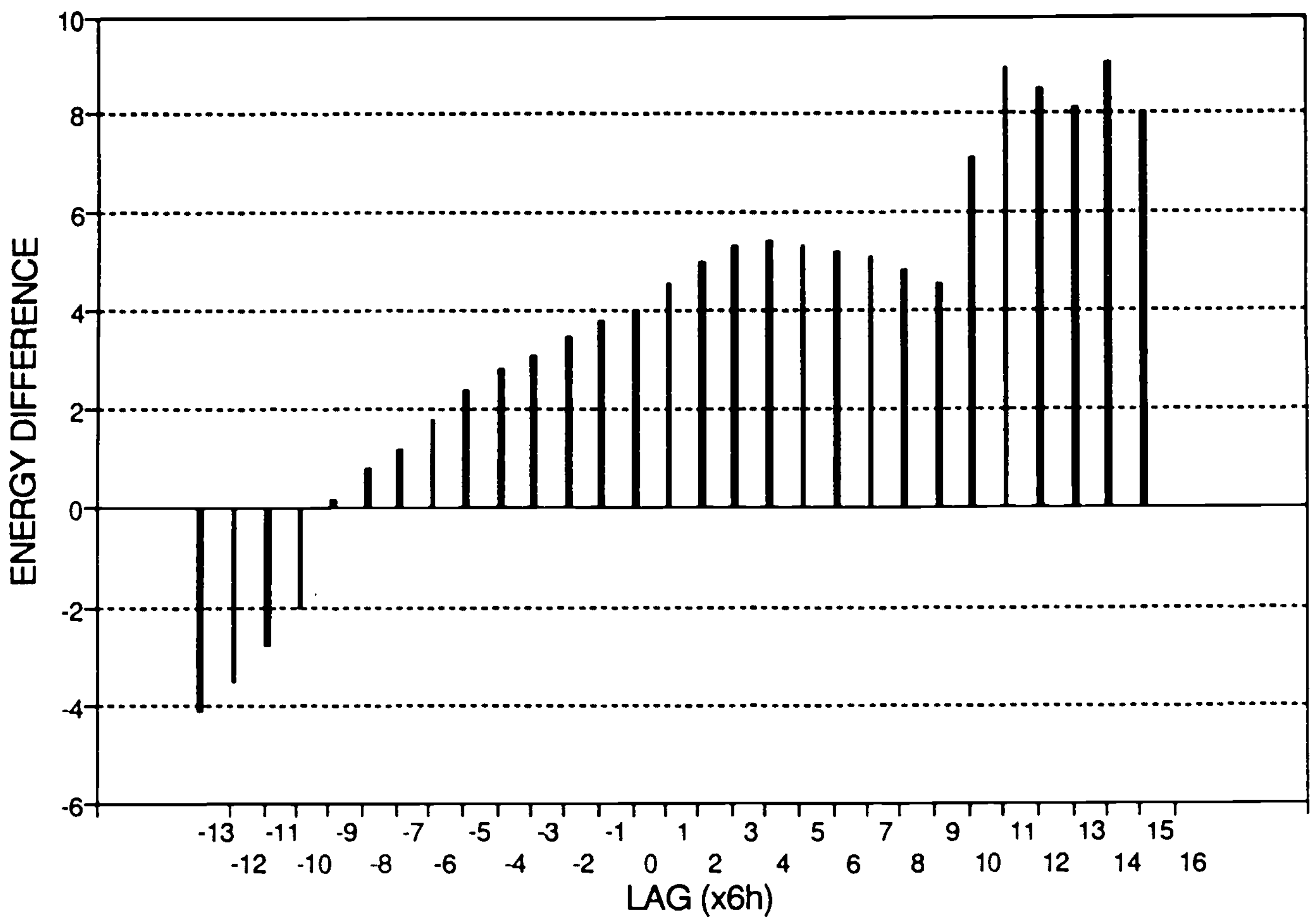
STORM VS. NON-STORM PERIODS: 1988-1989
DIFFERENCE IN MEANS
LAG (x6h)
Energy
Height
12
10
8
6
4
2
0
-2
-4
-6
-13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15


STORM VS. NON-STORM PERIODS: 1989-1990
ENERGY/HEIGHT DIFFERENCE
0
1
2
3
4
5
6
7
8
-13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
LAG (x6h)
Energy
Height

Appendix 5.

Difference in Mean Height and Energy Values between Storm and Non-Storm Events by Lag Period

AVERAGE ENERGY DIFFERENCE BY LAG PERIOD



AVERAGE HEIGHT DIFFERENCE BY LAG PERIOD