The Wave Climate of the Pacific Northwest (Oregon and Washington): A Comparison of Data Sources

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The Wave Climate of the Pacific Northwest (Oregon and Washington): A Comparison of Data Sources

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ABSTRACT

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Wave data for the Pacific Northwest of the United States have been derived from four measurement systems and from wave-hindcast techniques. Direct measurements have come from deep-water buoys of the National Data Buoy Center (NDBC) of NOAA and from shallow-water directional arrays and deep-water buoys installed by the Coastal Data Information Program (CDIP) of the Scripps Institution of Oceanography. The longest series of wave measurements for the Northwest coast has been obtained with a microseismometer system, a technique based on the measurement of microseisms produced by ocean waves. According to theoretical analyses, the microseisms are generated by the pressure field associated with standing waves produced by wave reflection from the coastline. This theory is substantiated by the data collected on the Oregon coast in confirming the expected correlations between the amplitudes and periods of the microseisms and the corresponding ocean-wave parameters. In addition to these direct measurements, wave data also are available from the Wave Information Study (WIS) of the U.S. Army Corps of Engineers, derived from hindcasts based on daily weather charts spanning the years 1956 to 1975. There are some systematic differences between the data sets. The deep-water NDBC buoy tends to yield higher significant wave heights than do the two CDIP buoys; a statistical regression of daily measurements indicates that heights reported by the NDBC buoy are 8% higher. The microseismometer system yields significant wave heights that are in good agreement with the buoy data, but measurements of wave periods are poor. The WIS hindcast data systematically overestimate wave heights, being some 30 to 60 percent larger than measured by the microseismometer and deep-water buoys. The wave data for the Northwest coast establish that during summer months, deep-water significant wave heights range 1.25 to 1.75 meters, increasing on average to 2.0 to 3.0 meters during the winter. Wave periods are on the order of 5 to 10 seconds in the summer when generation is more local, increasing to 10 to 20 seconds during the winter when storm systems are further from the coast and are larger. Major winter storms typically generate waves with deep-water significant heights from 6 to greater than 7 meters, with the calculated equivalent wave-breaker conditions on Northwest beaches reaching heights of 9 to 10 meters. The series of data sets account for the wave conditions on the Northwest coast, data which can be used to establish the extreme-wave parameters. Due to the systematic differences between the directly measured waves and hindcasts by WIS, these data sets had to be analyzed separately. Combining the CDIP deep-water buoy measurements and the microseismometer data, 24 storms with deep-water wave heights in excess of 6 meters were identified within the 23-year total record, with the largest recorded significant wave height having been 7.3 meters. Based on those storm-wave occurrences, extreme-wave analyses yielded a significant wave height of 7.8 meters for the 50-year storm, a statistically reliable estimate, and a less reliable value of 8.2 meters for the 100-year storm.

ADDITIONAL INDEX WORDS: *microseisms, ocean waves, wave measurements, Oregon, Washington.*

INTRODUCTION

The Pacific Northwest of the United States, including the ocean shores of Oregon and Washington (Figure 1), is particularly noted for the severity of its wave conditions. Storm systems in the north Pacific have large fetch areas and strong winds, the two factors that account for the large heights and long periods of the generated waves. During the winter these storm systems move in a southeasterly direction across the ocean and usually achieve landfall in the Pacific Northwest or along the shores of British Columbia in Canada.

There are many examples of the destructive impacts along the Northwest coast of waves generated by storms. Most susceptible to the resulting erosion have been the sand spits, several of which are heavily developed with homes constructed within foredunes backing the beach (KOMAR, 1978, 1983, 1986; KOMAR and REA, 1976; KOMAR and MCKINNEY, 1977). Along much of the coast, the beach is backed by sea cliffs, but they are generally composed of non-resistant sandstones which easily succumb to wave attack (KOMAR and SHIH, 1993; SHIH and KOMAR, 1994). Analyses of specific instances of dune or cliff erosion have relied on direct measurements of the waves, the primary factor in causing the erosion. Wave measurements are also necessary to establish the long-term wave climate of the Northwest coast, a documentation which is needed in ongoing research to develop models that predict the susceptibilities of coastal properties to erosion (SHIH *et al.,* 1994). A knowledge of the wave climate is also important to the engineering design of shore-protection structures, jetties, and sewage outfalls.

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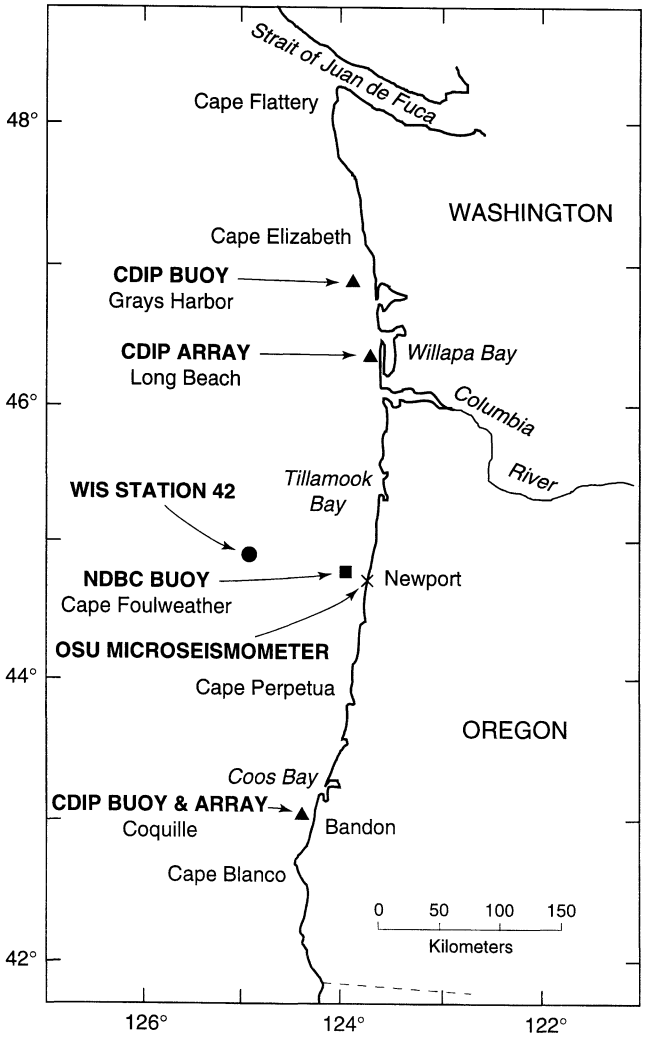

Figure 1. Locations along the ocean coast of the Pacific Northwest of wave-measurement systems and the position of WIS Phase II hindcast data analyzed in this study. Details are given in Table 1.

The broad objective of this study has been to better characterize the wave climate of the Northwest coast. This includes an examination of the monthly changes in the wave conditions so as to establish the seasonal cycle that is important to many coastal processes, undertaking analyses of the statistics of daily measurements of wave heights and periods, and the derivation of estimates for the long-term extreme wave parameters that represent the most severe erosion potential and serve as the design criteria for ocean structures. The pursuit of this objective was complicated by the existence of multiple data sets derived from various wave-measurement systems. This includes deep-water buoys operated by the National Data Buoy Center (NDBC) of NOAA and by the Coastal Data Information Program (CDIP) of the Scripps Institution of Oceanography. The CDIP also operates two inshore directional arrays consisting of four pressure sensors, one array each on the coasts of Oregon and Washington. The longest set of wave measurements in the Northwest, available from 1971 to the present, has been derived from a microseismometer system that is based on the theoretical analysis of LONGUET-HIGGINS (1950) which attributes the generation of microseisms to the pressure field associated with standing waves produced by wave reflection from the coastline. Wave data are also available from the Wave Information Study (WIS) of the U.S. Army Corps of Engineers, derived from hindcasts based on daily weather charts spanning the years 1956 to 1975 (CORSON *et al.*, 1987). As a result of these diverse techniques to measure or to hindcast wave conditions, each covering different intervals of time, the development of a meaningful wave climate for the Northwest necessarily included direct comparisons of the data derived from the several techniques. This effort is particularly important for the wave data obtained with the microseismometer, considering the "remote sensing" nature of that technique, and for the WIS hindcast data, considering that the hindcast techniques have not been tested for such a high-energy environment.

This paper begins with a review of the several measurement systems and the data derived from them. The first analysis involves an examination of the data obtained from deep-water buoys. The measurements from the inshore CDIP arrays in intermediate water depths are then evaluated using linear-wave theory to transform that data to the equivalent deep-water wave parameters to be compared with the buoy data. Calculations are also made of the breaking-wave climate along the coast, important to an understanding of nearshore processes. Our consideration then turns to the microseismometer system, its calibration and analyses of the long-term wave measurements derived from that system. The microseismometer data are also important in serving as a link between the buoy measurements which began in 1981 and the WIS hindcast data which span the years 1956–1975, there being four years of overlap between the microseismometer and WIS data. This overlap provides the opportunity to test the WIS wave-hindcast techniques for this high-energy coast. Finally, the last section of this paper examines the most extreme wave conditions that have occurred during the years covered by these combined data sets, allowing estimates to be made of the expected 50-year and 100-year storm-wave parameters.

MEASUREMENT SYSTEMS AND WAVE-DATA SOURCES

A diversity of wave-measurement systems has been in operation along the Northwest coasts of Oregon and Washington; their positions are identified in Figure 1 and basic information given in Table 1. A deep-water buoy operated by the National Data Buoy Center (NDBC) has been collecting data offshore from Cape Foulweather on the mid-Oregon coast since May 1987. The measurements are obtained hourly and are transmitted via satellite to the laboratory (STEELE and JOHNSON, 1979; NDBC, 1992). Wave data derived from the NDBC buoys are analyzed to yield spectra, the corresponding significant wave heights, and the average zero up-crossing wave periods as well as spectra-peak periods. Deep-water buoys have also been installed by the Coastal Data Infor-

Table 1. *Wave data sources for the northwest coast.*

Program	System	Location	Water Depth (m)	Time Period
CDIP	buoy-1D	Coquille, OR (lat. 43 06.4′N; long. 124 30.4′W)	64	12/81–present
CDIP	directional array	Coquille, OR (lat. 43 07.4′N; long. 124 26.5′W)	11	8/83–present
CDIP	buoy-2D	Grays Harbor, WA (lat. 46 51.1′N; long. 124 14.9′W)	43	12/81–present
CDIP	directional array	Long Beach, WA (lat. 46 23.4′N; long. 124 04.6′W)	10	9/83–present
NDBC	buoy	Cape Foulweather, OR (lat. 44 40.2′N; long. 124 18.4′W)	112	5/87–present
OSU	microseismometer	Newport, OR	20*	5/71–present
WIS	hindcast	Station 42 (lat. 44.8N; long. 125.0W)	deep water	1/56–75

buoy-1D = surface following buoy for deep water wave energy measurements
buoy-2D = surface following buoy for measurement of deep water wave energy and direction
*Depth to which the original calibration corresponds (ZOPF *et al.,* 1976). The new calibration in Figure 11 is directly with a deep-water buoy

mation Program (CDIP) of the Scripps Institution of Oceanography (SEYMOUR *et al.,* 1985) and are located offshore from Grays Harbor, Washington, and the Coquille River at Bandon on the south coast of Oregon (Figure 1). Both have been in operation since November 1981 (Table 1). Wave measurements from buoys are made four times each day, and the analyses include the wave spectra and significant wave parameters.

CDIP also has installed sensor arrays to monitor wave conditions along the U.S. coast (SEYMOUR *et al.,* 1985). Sensor arrays have been in operation since 1983 at a water depth of 9.8-meters offshore from Long Beach, Washington and in 11.0-meters depth offshore from the Coquille River at Bandon (Figure 1). An array consists of four pressure sensors arranged on the corners of a square, held in place by supports that follow the diagonals. This arrangement permits a determination of directions of wave-energy propagation, as well as the periods and heights of the waves. This system is used in water depths less than 15 meters and has a cable from the array to the shore to provide power and to deliver the measured data to a land-based recorder. In the standard mode of operation, each instrument array is interrogated once every 6 hours; the central station at SIO initiates a telephone call to the shore station using an autodialer and normal telephone lines. The shore station responds by answering the call and then transmits the collected data. All data records are subjected to Fourier analysis. The Fourier coefficients derived from the submerged pressure sensors are depth corrected using linear wave theory to yield the equivalent surface coefficients. The coefficients are used to produce an energy spectrum grouped into period bands which are published in the CDIP monthly reports. Since January 1983, directional wave records have been presented in the form of daily two-dimensional energy spectra, together with wave parameters such as the total spectral energy, significant wave height, and peak period.

The above systems that yield direct measurements of wave conditions along the Northwest coast have been in operation at most since the early 1980's (Table 1). Therefore, the record durations are too short to confidently establish the long-term wave climate. Of potential use in this regard is the microseismometer wave-measurement system of Oregon State University that has been in operation since 1971 at the Marine Science Center in Newport. This system is based on the theoretical analysis of LONGUET-HIGGINS (1950) which relates the generation of microseisms to the pressure field on the ocean floor produced by standing waves that result from the interaction of the incident waves and their reflections from the coastline. Since the microseism signal is attributed to standing, reflected waves, the theory predicts that the frequency of the microseisms is exactly twice the frequency of the ocean waves. Based on the LONGUET-HIGGINS analysis, ZOPF *et al.* (1976) showed that

$$H_{seis} = K(H^2_{ocean}/T^3_{seis}) \quad (1)$$

where H_{seis} and H_{ocean} are respectively the height recorded by the peak-to-peak deflection of the seismometer and the height of the ocean waves, and T_{seis} is the seismic signal period, K is an empirical constant. In the system operated by Oregon State University, the seismometer signal is modified by a low-pass filter with a break point at 0.7 Hz to eliminate ambient seismic noise. Another filter with a response between 0.1 and 0.4 Hz is used to remove the wave-period dependence in equation (1). The filters are designed to yield an effectively flat energy spectrum between 0.1 and 0.4 Hz (wave periods from 5 to 20 sec). Therefore, in the filtered signal

$$H_{ocean} = (KH_{seis})^{1/2} \quad (2)$$

providing a simple proportionality between the record of the microseisms and the height of the causative ocean waves.

The empirical coefficient K in equation (2) was determined by simultaneously measuring seismic signal deflections and ocean wave heights (ZOPF *et al.,* 1976). For the initial calibration in 1971, visual observations of wave heights were made from shore against a 4-meter high buoy located in 12-meters water depth. The observer watched waves pass the buoy and estimated the heights of the highest 10% of the waves. The errors associated with these visual observations are discussed by ENFIELD (1973). In addition to the visual observations, 25 records were obtained with a pressure sensor located in 20-meters water depth offshore from Newport. In total, 403 comparison measurements were obtained, establishing that K = 32 in equation (2). The resulting predicted wave heights based on the seismometer records showed good agreement with the heights measured visually and with the pressure sensor; the correlation coefficient was $R^2 = 0.76$ with a standard error of 0.49 m (ZOPF *et al.,* 1976). A similar analysis focused on the seismic period and ocean-wave period and confirmed the expected 2-to-1 ratio for microseisms generated by standing waves produced by wave reflection from the coast.

BODVARSSON (1975) analysed the OSU microseismometer records as a further test of the LONGUET-HIGGINS (1950) theory for microseism generation by standing ocean waves. A roughly linear relationship was found between the root-mean-square amplitudes of the microseisms and the squared product of the local ocean wave heights and frequencies. Calculations were made according to the LONGUET-HIGGINS theory which showed that the microseisms could be accounted for quantitatively by a narrow (roughly 400-meters wide) region of standing-wave generation along the coast, assuming wave reflection coefficients that are on the order of 0.01 to 0.1. Spectra of microseism energy showed essentially no concentration at the frequency of the ocean waves, instead being at double the frequency of the waves as predicted by LONGUET-HIGGINS.

A similar microseismometer system has been used on the coast of New Zealand to measure wave conditions (EWANS, 1984; KIBBLEWHITE and EWANS, 1985; BROWN, 1991; KIBBLEWHITE and BROWN, 1991). Their analyses provide further confimation of the LONGUET-HIGGINS (1950) theory of microseism generation of reflected waves.

From May 1971 to May 1992, the signal of the OSU microseismometer in Newport, Oregon, was recorded directly on a strip-chart recorder for manual analysis of the wave conditions. Manual analysis required a visual estimate of the largest wave packet (group) within the record. A template prepared by the calibration was then placed over the wave group and the peak-to-peak deflection of the largest wave in the group was recorded, providing an estimate of the highest 10% of the waves. The corresponding significant wave height was determined through multiplication by a 0.79 factor (CERC, 1984). The average wave period was determined by counting the number of zero up-crossings, dividing the length of the record by this value, and multiplying the result by 2 because of the 2-to-1 relationship between the seismic period and the wave period. Since May 1992, the signal has been digitally stored in a personal computer to facilitate automated spectral analyses of the wave records, eliminating the laborious manual analysis. The measurements can now be immediately retrieved by phone.

CREECH (1981) compiled the wave data collected by the microseismometer for the 1971–1981 decade, with an analysis of the wave climate. As part of the present study, the unprocessed strip-chart data from 1981 to 1992 were analyzed in order to yield 20 years of measurements upon which to base the wave climate and to identify the most extreme storms during that period. KOMAR *et al.* (1976) used the microseismometer data to calculate the corresponding breaking waves in the nearshore, documenting the seasonal variations and discussing the ramification to nearshore processes. THOMPSON *et al.* (1985) compared two months of microseismometer data with the CDIP pressure-sensor array data derived from the Coquille River site at Bandon. Measurements of wave heights by the microseismometer showed good agreement with the array measurements, but comparisons of wave periods were poor. Measured wave heights were in closer agreement during winter wave conditions than during the summer, which THOMPSON *et al.* explained as resulting from coast-wide storms during the winter as opposed to more locally generated waves in the summer. HOWELL and RHEE (1990) investigated the use of computer analyses of the microseism signal to obtain more reliable estimates of wave periods. Again, the system was found to be most reliable during extreme wave conditions, with spectral estimates of wave periods judged to be as good as assessments derived from zero-crossing analyses.

The Wave Information Study (WIS) was initiated by the U.S. Army Corps of Engineers to yield a long-term wave climate for the U.S. coast (HEMSLEY and BROOKS, 1989) based on hindcast procedures. The WIS analyses have been divided into three main phases. In Phase I, the deep water wave data were hindcast for a spatial grid on the order of 2 degrees along the coast; Phase II utilized the same meteorological information, but at a finer scale (0.5 degrees) to better resolve the sheltering effects of the continental geometry and at a time step of 3 to 6 hours. Phase II wave estimates are available for 17 stations along the ocean coasts of Oregon and Washington. Station 42 positioned in deep water offshore from Newport, Oregon, Figure 1, is employed in the analyses undertaken in the present study. The required data are listed in the report by CORSON *et al.* (1987) and include directional wave spectra as well as significant-wave parameters hindcast at 3-hour intervals for the 20 years from 1956 to 1975. The report also contains summary statistics such as average monthly wave heights and periods and probabilities of extreme-wave statistics such as the significant wave height and period of the projected 100-year storm. Phase III of the WIS analysis involved the transformation of the Phase II wave data into shallow water. Those data were not employed in the present analyses as preference is given to the deep-water conditions provided by the Phase II hindcast data.

A summary of the available wave data for the Pacific Northwest is given in Table 1. Concurrent measurements by the NDBC buoy, the CDIP buoys and arrays, and by the microseismometer system are available only for the five years

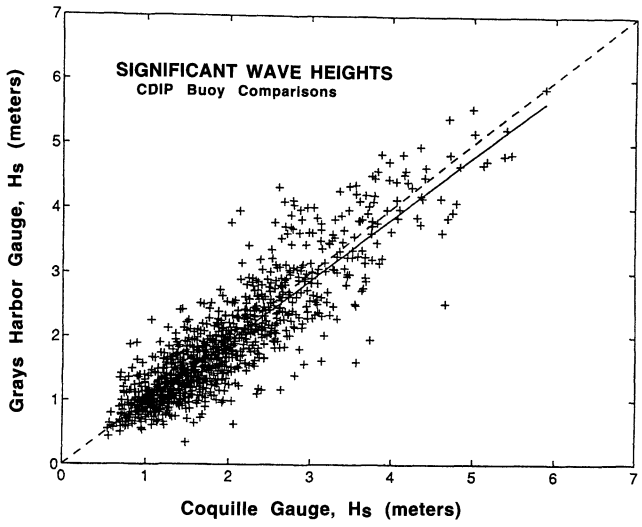

Figure 2. Comparison of the Coquille and Grays Harbor CDIP mean-daily significant wave heights. The dashed line represents perfect agreement, while the solid line is the regression relationship.

from May 1987 to May 1992. Those five years of data from the various systems will be the focus of our comparisons, although the complete data sets are employed to establish the wave climate. The 1956–1975 time frame of the WIS hindcast data provides no overlap with the buoy and array measurements, but there is four years of overlap with the microseismometer data upon which to base a comparison. Collectively, the hindcast WIS data (1956–1975), the microseismometer measurements (1971 to the present), and the buoy and array data (1981 to the present) yield 38 years of wave data upon which to base the wave climate for the Northwest coast.

COMPARISONS OF DEEP-WATER BUOY DATA

Particularly important is the establishment of the deep-water wave climate and this is most-directly accomplished with the buoy data of NDBC and CDIP. These buoys are positioned in water depths of 43 to 112 meters (Table 1), and for the most part, the data can be treated as representing direct measurements of deep-water wave conditions. In rare instances, the wave periods exceed 20 seconds, such that these depths actually represent intermediate water according to the $h/L_o > 1/4$ criterion, where h is the water depth and L_o is the deep-water wave length (KOMAR, 1976; CERC, 1984). However, the correction factors remain small in these rare instances, so the data were uniformly treated as representing deep-water conditions (TILLOTSON, 1994). In addition to using the buoys to establish the overall deep-water wave climate, comparisons between measurements obtained by the NDBC and CDIP systems will be of interest, whether there are discernable north to south variations along the length of the Northwest coast of Oregon and Washington and to what extent seasonal variations exist in the wave parameters.

The mean daily significant wave heights measured by the CDIP buoys respectively at Coquille (Bandon) on the south coast of Oregon and at Grays Harbor, Washington, are nearly identical; this is established by the direct regression of daily measurements shown in Figure 2 for four years of data, and in evaluations of means and standard deviations for the complete data sets (Table 2). The measured wave periods are also the same (TILLOTSON, 1994). This result indicates a near uniformity of the deep-water wave climate along the length of the Northwest coast. Analyses of the measurements by season (winter, spring and summer) also reveal a near uniformity on average of the wave climate. However, the scatter of the data seen in Figure 2 allows for differences in daily wave conditions as measured at Coquille versus Grays Harbor. This is apparent in a day-by-day comparison of the wave conditions, where it is found that in some instances individual winter storm waves reach one buoy a day or two earlier than the other buoy; in some cases they reach the Coquille Buoy first and in other instances the Grays Harbor buoy, depending on the offshore location of the storm and its movement with time. Such differences by a day or two in storm-wave arrival times account for much of the scatter in Figure 2, which simply compares the significant wave heights on a daily basis. Differences in daily wave conditions are also apparent in the summer when more local wind conditions prevail.

Table 2. *Means and standard deviations of significant wave heights and periods measured by the various systems.*

Program & System	Mean Significant Wave Height (m)	Standard Deviation	Mean Significant Wave Period (sec)	Standard Deviation
CDIP Coquille buoy	1.94	0.93	9.7	3.0
CDIP Grays Harbor buoy	1.92	1.01	10.0	3.0
NDBC buoy	2.19	1.14	10.5	3.1
Microseismometer	2.05	1.14	13.0	5.0
WIS (Station 42)	3.25	1.47	11.0	2.5

The measured wave spectral-peak periods derived from the NDPB buoy agree very well with the CDIP measurements, except at times during the summer months of low wave activity. On the other hand, the NDBC measurements of significant wave heights are systematically greater than those measured by the CDIP buoys. The regression comparison in Figure 3 yields a slope of 1.08 with a negligible intercept, indicating that the NDBC measured wave heights are 8% greater; the ratio of the means given in Table 2 based on the entire data sets is 1.13, indicating that the NDBC wave heights are 13% greater. This systematic difference cannot be accounted for by the north-south positions of the respective buoys as the NDBC buoy is located approximately midway between the two CDIP buoys. The NDBC buoy is positioned in a greater wave depth (Table 1), but it is unlikely that bottom friction on the waves over the deep outer shelf can be a factor; also this is evident in the fact that short-period waves show the same height difference measured by the buoys as the long-period waves. The difference likely results from the CDIP versus the NDBC electronics systems which perform the data collection and perhaps in the details of the analysis techniques.

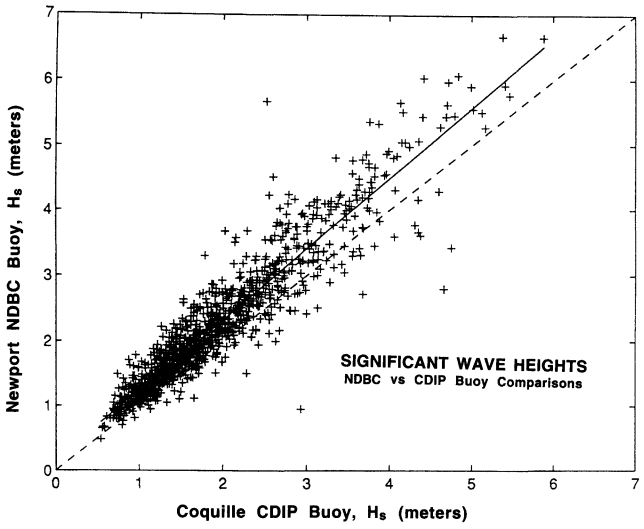

Figure 3. Comparison between the deep-water significant wave height measurements obtained by the CDIP-Coquille buoy offshore from Bandon, Oregon, and the NDBC buoy offshore from Newport. The y = ax + b regression yields coefficients a = 1.08 and b = 0.2 meters, with R^2 = 0.88.

There is a distinct seasonality to the deep-water wave climate as seen in Figure 4 which presents the mean monthly significant wave heights. The systematic differences between the NDBC and CDIP measurements are again apparent. However, both systems demonstrate that wave heights are substantially greater during the winter than in the summer; according to the CDIP data, significant wave heights range 1.25 to 1.75 meters during the summer, increasing on average to 2.0 to 3.0 meters during the winter. There is a gradual

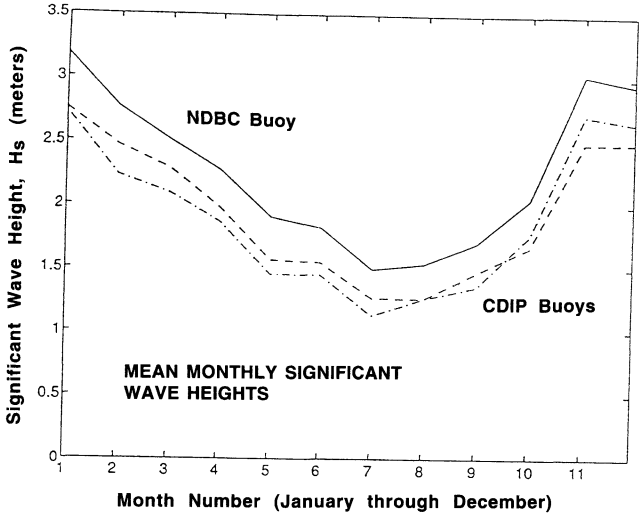

Figure 4. Seasonality of the mean monthly deep-water significant wave heights as measured by the CDIP Coquille and Grays Harbor buoys, and by the NDBC buoy offshore from Newport.

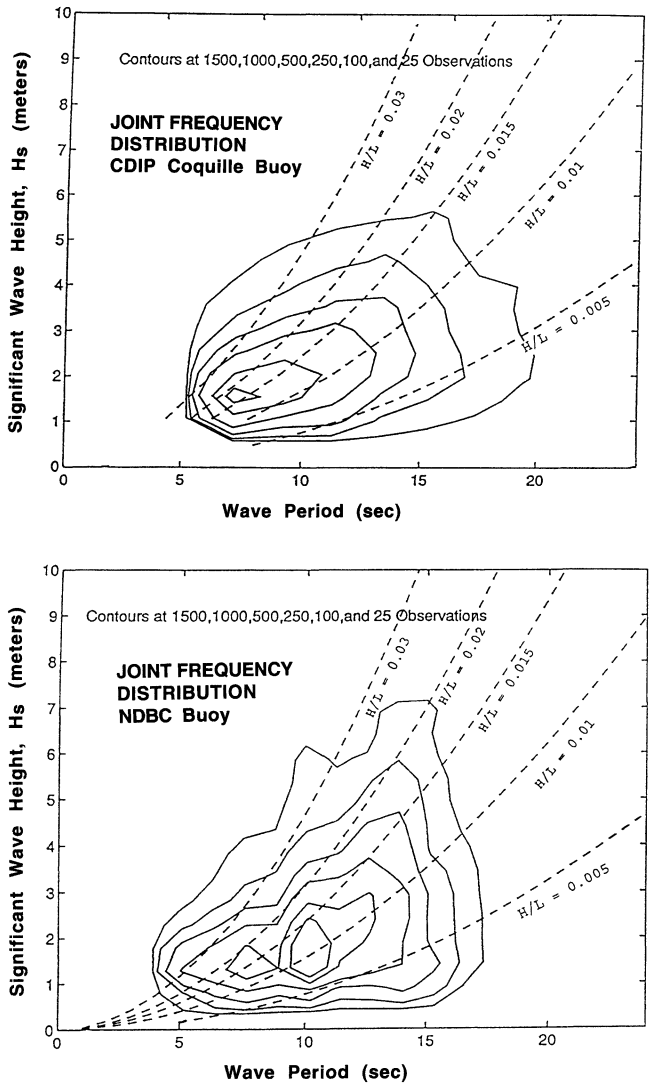

Figure 5. The joint-frequency graphs of significant wave heights versus spectral-peak periods for the measurements derived from the CDIP-Coquille deep-water buoy offshore from Bandon, Oregon, and the NDBC buoy offshore from Newport.

transition during the spring, with a progressive decrease in wave heights from December and January to a minimum in July to August. The onset of higher wave conditions in the fall is more abrupt, with a sharp jump between October to November with the arrival of the first winter storms.

There is an overall positive correlation between significant wave heights and spectral-peak periods, a relationship that has been found in other studies of wave climate (GODA, 1990). This is seen in Figure 5 for both the CDIP deep-water Coquille buoy data and for the NDBC buoy data. The greatest concentration of CDIP observations centers on a significant wave height of about 1.5 meters and corresponding periods between 6 and 7 seconds; the NDBC observations center closer to 2 meters height and a 10-sec wave period. This appears to represent wave generation in the near-coastal zone of the

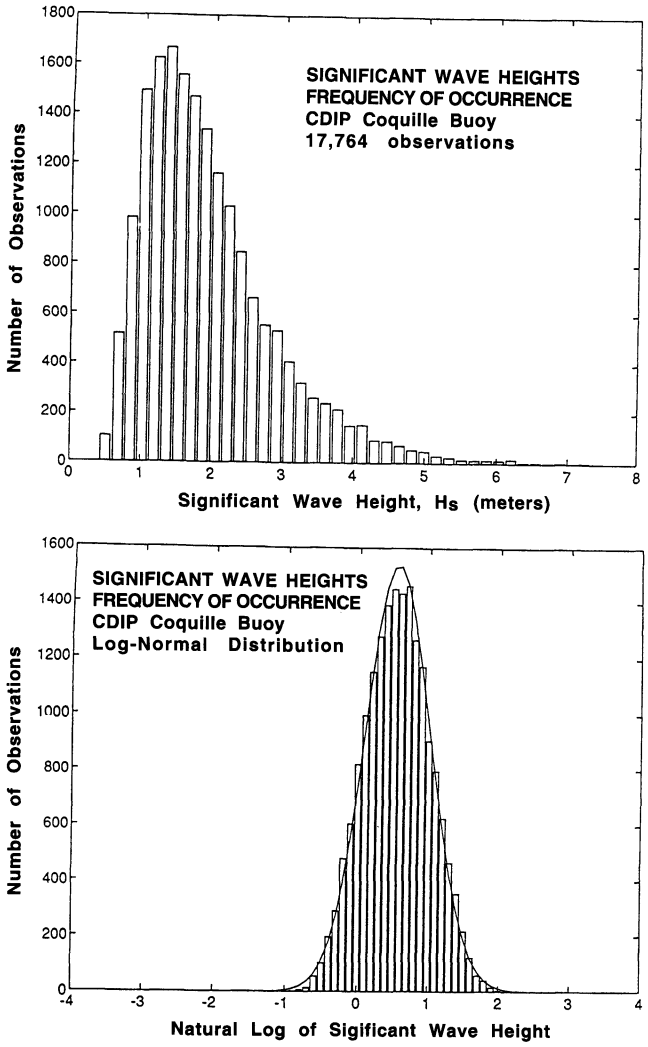

Figure 6. (A) Histogram of daily wave heights measured by the CDIP-Coquille deep-water buoy, and (B) the log-normal distribution of the measurements.

Northwest. The larger wave heights, generated by storms over the north Pacific, correspond to longer wave periods, broadly in the range 10 to 20 seconds. According to the CDIP results, the longest period waves reaching the coast have periods greater than 15 seconds but tend to have slightly lower wave heights (between 1 and 4 meters). For the most part, this must represent distantly-generated swell, also indicated by the correspondingly low values of the wave steepness, H_o/L_o, curves of which are graphed in Figure 5. Storm conditions having the greatest wave heights correspond to wave steepnesses in the range 0.015 to 0.02.

Figure 6A is a histogram of the deep-water significant wave heights measured by the CDIP-Coquille buoy; the results for the other buoys are comparable (TILLOTSON, 1994). The distribution is skewed toward smaller wave heights, with the rare occurrence of large storm waves. The distribution is shifted to the right of zero since the measurements represent signficant wave heights which are not likely to be near zero. Unlike the distribution of wave heights generated by an individual storm, there is no theoretical basis for describing the distribution of daily significant wave heights; therefore, the Rayleigh, normal, and log-normal distributions were given equal consideration in attempts to find an empirical mathematical relationship that would adequately describe the data. Best agreement was obtained with the log-normal distribution as seen in Figure 6B for the Coquille data. Technically, the log-normal distribution is also unsatisfactory as it did not satisfy the Chi-square goodness-of-fit test; however, the number of bins could have been reduced so the mathematical distributions would have a better goodness-of-fit, but the detailed information on the shapes of the distributions would then have been lost. The results do suggest that the log-normal distribution provides the best description of the daily significant wave heights. Further analyses have established that there is a distinct seasonality to these distributions, with changes in the standard deviations and peakedness (kurtosis) of the distributions as well as in the mean wave heights (TILLOTSON, 1994). Histograms of wave periods are more irregular due to there being fewer magnitude bins, but the distributions are roughly normal (TILLOTSON, 1994).

ARRAY DATA AND NEARSHORE WAVE-CLIMATE ANALYSES

The CDIP sensor arrays have been in operation since 1983 offshore from Long Beach, Washington and offshore from the Coquille River at Bandon (Figure 1). The 10 to 11-meter water depths at the array positions (Table 1) represent intermediate to shallow water in terms of wave transformations during shoaling, depending on the wave period. The deep water CDIP buoys are located roughly offshore from the arrays. In order to make comparisons between the two data sets, the daily measurements derived from the arrays were transformed to the equivalent deep-water parameters using linear wave theory (CERC, 1984). Therefore, this comparison assumes the applicability of linear theory, and neglects any energy changes that may have occurred due to continued wave growth by a local storm or losses due to bottom friction or percolation.

Figure 7 provides comparisons between the significant wave heights and spectral-peak periods derived from the Coquille array and transformed to deep-water equivalents, versus those parameters measured by the offshore buoy. The correspondence between the wave heights is good. According to the regression line shown in Figure 7, there is a slight tendency for the transformed wave heights derived from the array to be higher than the significant wave heights recorded by the offshore buoy. This trend is opposite to that expected if wave dissipation by friction were important or the trend that might be produced through the use of linear wave theory rather than a higher-order solution for wave transformations. The amount of scatter in the recorded wave periods, Figure 7, is surprising. Although there is little bias in the array or offshore buoy in systematically recording longer or shorter wave periods; in a few instances on specific days, periods recorded by the two systems differed by as much as 5 to 10 sec.

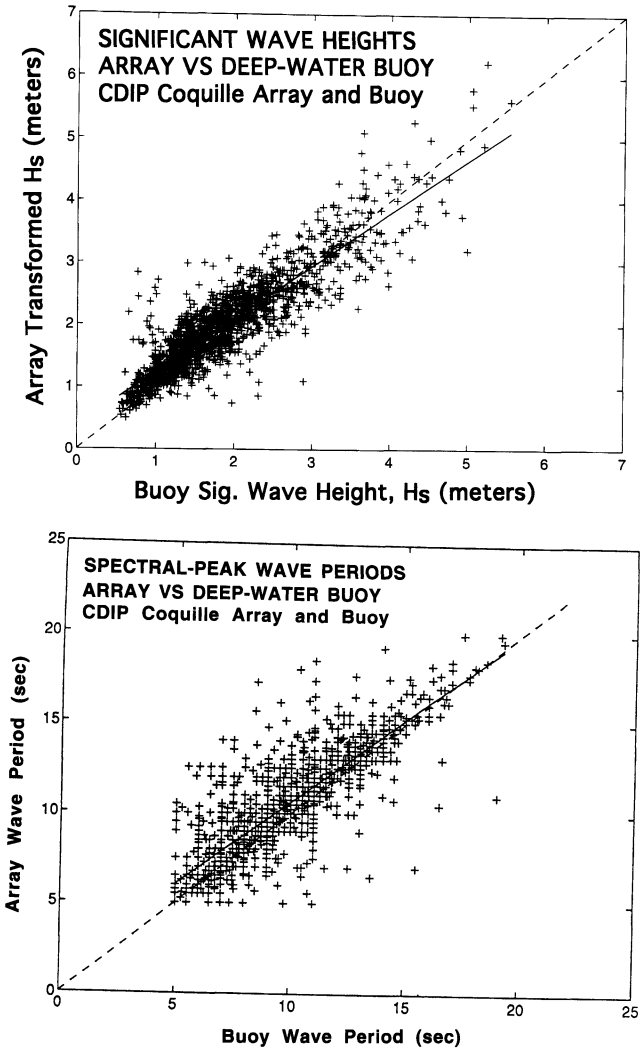

Figure 7. Comparisons of significant wave heights and spectral-peak periods derived from measurements by the CDIP-Coquille array located in 11 meters water depth offshore from Bandon, Oregon versus the offshore deep-water buoy measurements. Significant wave heights derived from the array have been recalculated to yield their deep-water equivalents using linear wave theory. The y = ax + b regression for the wave heights yields coefficients a = 0.94 and b = 0.0005 meters, with R^2 = 0.80.

Comparable results are found in analyses of data from the array and deep-water buoy offshore from Long Beach, Washington.

The 11-meter depths of the arrays place them just outside the breaker zone during all but the most extreme storm-wave conditions. Of interest to analyses of coastal processes are assessments of the breaking wave conditions on the sloping beaches. Direct measurements are unavailable but breaking wave heights can be calculated from the deep-water measurements. This has been done using the formula of KOMAR and GAUGHAN (1973),

$$H_b = 0.39g^{1/5}(TH_o^2)^{2/5} \quad (3)$$

where H_b is the breaker height which depends on the deep-water wave height H_o and period T. The 0.39 coefficient is empirical based on the fit to laboratory and field data. The results are given in Figure 8 for the monthly mean breaker heights, the heights at one standard deviation above and below the means, and the maximum calculated breaker heights which correspond to the most extreme deep-water heights and periods measured by the buoy. The results in Figure 8 are based on the CDIP-Coquille buoy, but the results from the Grays Harbor, Washington, buoy are closely the same (TILLOTSON, 1994). The mean breaker heights reach about 3.5 meters during the winter, decreasing to 2.0 meters during the summer. Individual winter storms generate breaking waves in the nearshore having significant wave heights up to 9 to 10 meters.

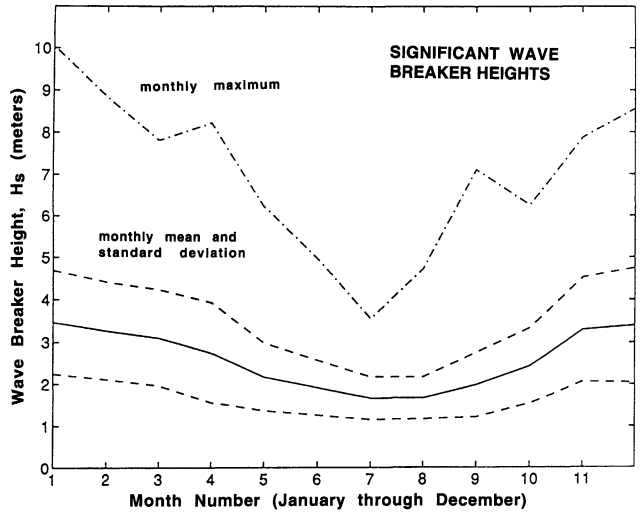

Figure 8. Monthly variations in wave breaker heights, calculated with equation (3) using the deep-water wave measurements from the CDIP-Coquille buoy which began operation in December 1981. The monthly mean values for the 13 years of daily measurements are given by the solid curve, while one standard deviation about the mean is given by the dashed curve. The dot-dashed curve represents the maximum monthly breaker heights calculated from the most extreme wave conditions that have been measured by the deep-water buoy.

THE MICROSEISMOMETER SYSTEM AND DATA

The microseismometer system is important in establishing the wave climate for the Northwest coast, since its 23 years of daily wave measurements provide the longest set of data. However, it is necessary first to reconfirm the validity of this remote-sensing system by direct comparisons with the CDIP and NDBC buoy measurements since their installations in the 1980's. This includes the microseismometer data recorded on strip charts and analyzed manually using the calibration derived by ZOPF *et al.* (1976). The more quantitative calibration involved comparisons between the microseismometer record and wave parameters derived from a pressure sensor in 20-meters water depth. Although this depth is intermediate for many wave periods (T > 7.2 sec), rather than being fully deep water, potential corrections to yield equivalent deep-water wave heights are small and deemed to be unnec-

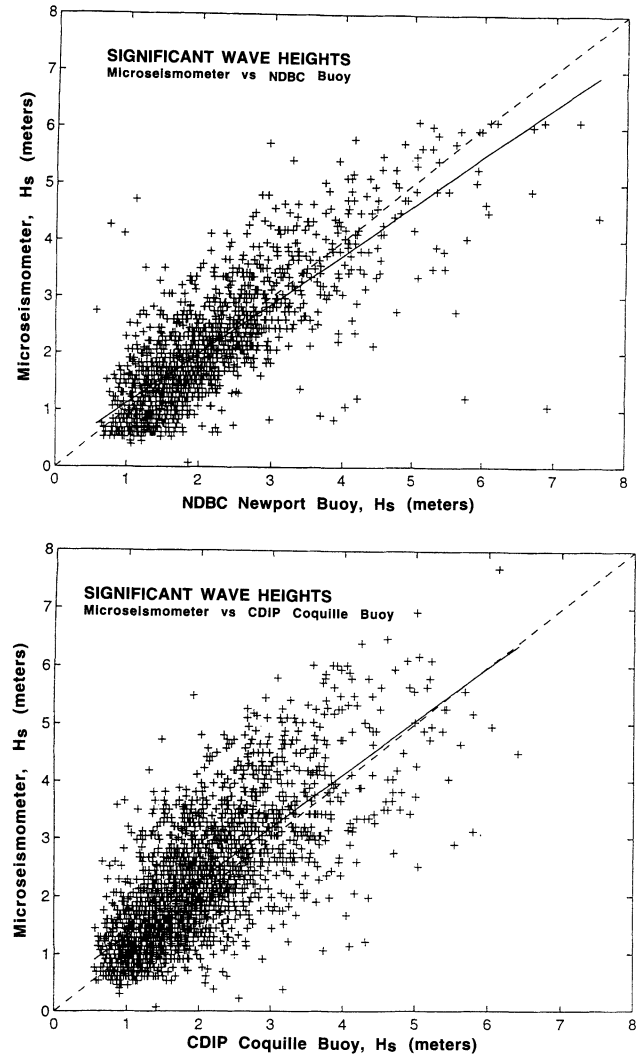

Figure 9. Comparisons of significant wave heights derived from the microseismometer system in Newport, Oregon, with data from the NDBC and CDIP buoys respectively located offshore from Newport and Bandon. The dashed lines represent perfect agreement, while the solid lines are based on regression analyses. The y = ax + b regression between the microseismometer and NDBC wave heights yields coefficients a = 0.87 and b = 0.2 meters, while regression with the CDIP buoy data gives a = 0.93 and b = 0.4 meters.

essary considering the uncertain nature of the microseismometer data. Therefore, the comparisons between the microseismometer wave measurements and data from the NDBC and CDIP buoys were direct, without having made wave-transformation corrections. As discussed above, the microseismometer system was computerized in May 1992, and direct comparisons with the deep-water buoy measurements undertaken here provide a recalibration of the system.

Figure 9 contains daily measurements of significant wave heights obtained from the microseismometer compared with the NDBC buoy located offshore from Newport and with the CDIP-Coquille buoy offshore from Bandon on the southern Oregon coast. In both cases, the correlations are reasonably good. In terms of R^2 values derived from the regressions, the best statistical agreement is found with the NDBC buoy, but that buoy tends to yield somewhat larger wave heights, particularly during the most extreme storm conditions. A couple of data points show the NDBC buoy measuring waves on the order of 6 to 7 meters high, while the microseismometer simultaneously yielded heights on the order of 1 meter. The cause for such a marked disagreement is not known, but it is interesting that there are no comparable extreme diagreements found in the comparison between the microseismometer and the CDIP buoy. The agreement with that buoy is good, Figure 9, with minimal departure of the regression line from the line of perfect agreement. The means of all wave heights measured by the systems are closely similar, Table 2, as are the standard deviations, further demonstrating that the microseismometer and deep-water buoys are effectively documenting the same wave climate for the Northwest coast.

Comparisons between significant wave heights derived from the microseismometer and the deep-water buoys were also undertaken on a seasonal basis (TILLOTSON, 1994). Agreement is good during all seasons, with the best statistical agreement in terms of R^2 values being during the summer, the lowest in the winter. This is contrary to the results of THOMPSON *et al.* (1985) who found best agreement between the microseismometer in Newport and the CDIP-Coquille buoy during the winter, with poor agreement in the summer. However, their results were based on only two months of data, one winter month and one summer month, much less than used in the present study. The results obtained here again indicate that the overall wave climate at Coquille (Bandon) and Newport are much the same; however, the daily wave conditions at these distant sites could be substantially different as suggested by THOMPSON *et al.*, especially during the summer when more locally generated waves prevail.

Comparisons of wave periods obtained from the microseismometer and offshore buoys show poor agreement, Figure 10. The microseismometer typically yields longer periods, centered near 13 to 15 seconds, also seen in the mean for the entire data set (Table 2). Aside from the magnitude differences, there is no discernable trend in the periods measured by the two systems (Figure 10). The microseismometer data show only a small seasonal variation, with a slight tendency for longer periods during the summer compared with the winter; this is the inverse of the more-reasonable trend found by the buoys which measure shorter periods during the summer compared with the winter (TILLOTSON, 1994). The agreement between the two systems is best during the winter, perhaps suggesting that the microseismometer has better success in resolving periods when wave-energy levels are high.

The microseismometer system was computerized in May 1992. Since that time, analyses of significant wave heights have been based on taking the root-mean-square of the raw time-series data, then converting that value into a significant wave height. Wave period analyses are now based on the spectral analysis of each microseism record, where the peak energy in the spectrum is used to infer the dominate wave period according to the 2-to-1 ratio expected from the theory of LONGUET-HIGGINS (1950). Zero-crossing analyses are also

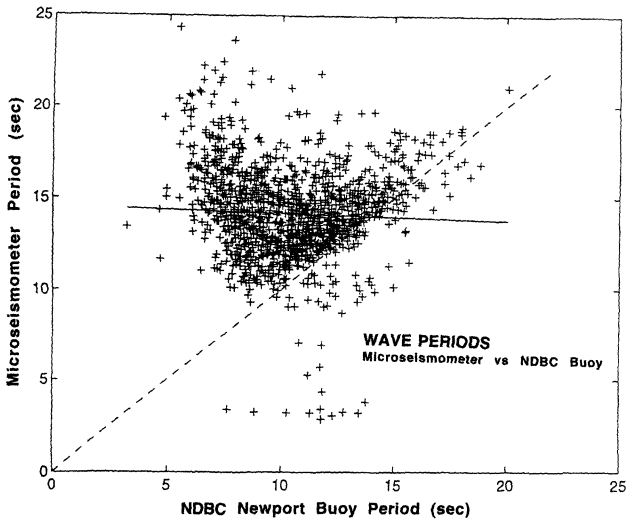

Figure 10. Data comparison showing that there is poor agreement between measurements of wave periods derived from the microseismometer system and the NDBC deep-water buoy.

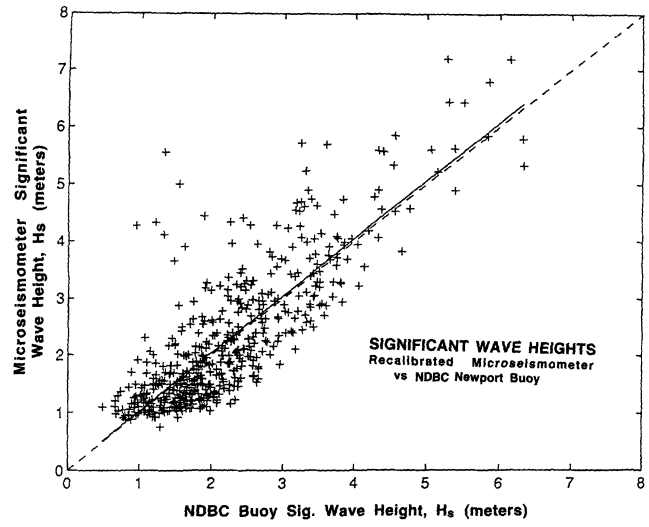

Figure 11. Significant wave heights derived from the recalibrated microseismometer system after its computerization in May 1992, compared with data from the NDBC buoy located in deep water offshore from Newport.

performed on the seismic record to infer a corresponding zero-crossing period of the waves. These modifications required a recalibration of the system which was accomplished by direct comparisons with simultaneous wave measurements on the CDIP and NDBC deep-water buoys. The recalibration regressions are presented in TILLOTSON (1994) and have been incorporated into the software of the microseismometer system. There are seasonal differences in the regressions but these are too small to include in the modified system. Figure 11 compares the significant wave heights derived from the recalibrated microseismometer system and those measured by the NDBC buoy. Agreement is good, showing marked improvement over the results in Figure 9 where the analyses were done manually. The results are slightly different if the recalibration is made with measurements from the CDIP buoys, with predictions of slightly smaller wave heights. This results from the difference between heights reported by the NDBC and CDIP buoys, as noted in Figure 3.

One disappointment is that computerization of the microseismometer system has led to no improvement in measurements of wave periods. The results are equally poor for the period of the dominant energy peak in the spectrum and the zero-crossing period. These two periods show a positive correlation, but neither shows a statistically significant correlation with spectral-peak wave periods measured by the deep-water buoys (TILLOTSON, 1994).

The comparisons undertaken here between the microseismometer system and the deep-water buoys further confirm the usefulness of this system in the routine collection of wave data on high-energy coasts. Measurements of significant wave heights are nearly as reliable as those derived from offshore buoys but measurements of wave periods are poor. In finding a strong correlation between the wave heights inferred from the microseismometer records and waves directly measured offshore, the results further confirm the hypothesis of LONGUET-HIGGINS (1950) as to the association of microseisms with reflected ocean waves, supporting the studies of ZOPF *et al.* (1976) and KIBBLEWHITE and EWANS (1985) that offer more-detailed confirmations of the hypothesis.

HINDCAST DATA FROM THE WAVE INFORMATION STUDY

The 1956–1975 time frame of the WIS hindcast data provides no overlap with the buoy and array measurements but there is four years of overlap (1971–1975) with the microseismometer data. This overlap permits an examination of whether the hindcast procedures employed by WIS yield reasonable estimates of significant wave heights for this high-energy coast.

The comparison between Phase II WIS hindcasts of deep-water significant wave heights and measured significant wave heights obtained with the microseismometer is given in Figure 12. There is a good trend of the data which is statistically significant with $R^2 = 0.64$, but the wave heights derived from the WIS hindcasts are roughly 30% higher than measured by the microseismometer. It already has been shown (Figures 9 and 11; Table 2) that the microseismometer system yields good measurements of deep-water wave heights when compared with buoy measurements. It follows that the WIS hindcast wave heights must also be systematically greater than heights derived from the buoy measurements. This is evident in Table 2 which lists mean values based on the entire data sets. The 3.25-meter mean significant wave height derived from the 20 years of WIS data is on the order of 1 meter greater than obtained by the other systems, indicating that the heights are systematically some 50% too high.

The microseismometer system does not provide adequate measurements of wave periods, Figure 10, eliminating the

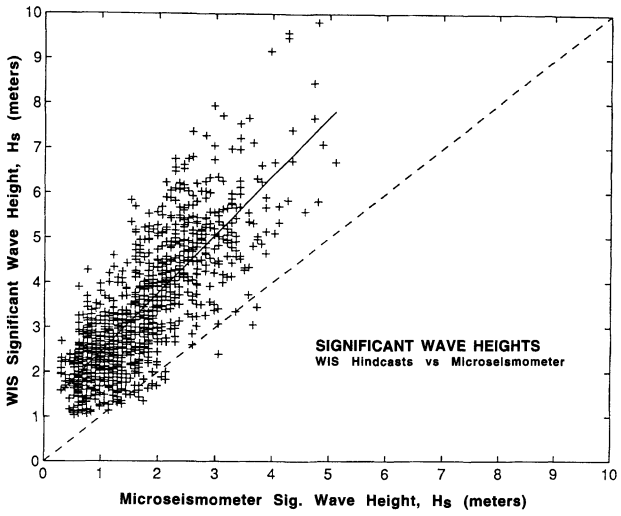

Figure 12. Significant wave heights derived from WIS Phase II hindcast analyses for the years 1973–1975, compared with simultaneous measurements of wave heights derived from the microseismometer system. The microseismometer measurements show good agreement with the buoy data during the 1980's (Figure 9), so the results here imply that the WIS significant wave heights are about 30% higher than directly measured values.

possibility of making direct comparisons with the WIS periods as was done for the significant wave heights. The mean period for the entire WIS data set is 11.0 sec, Table 2, which is reasonably close to the mean periods derived from the buoy measurements, indicating that the WIS hindcast techniques are defining effectively the same wave-period climate.

The results found here in comparisons with the WIS hindcast data are in agreement with the conclusions of HUBERTZ *et al.* (1992) based on hindcasts of deep-water wave conditions for 1988 using the standard WIS techniques and comparing the calculated wave heights and periods to measurements from nearby buoys. The comparisons were with NDBC buoys which covered much of the North Pacific, from California to the Gulf of Alaska and Hawaii. The hindcast wave heights were systematically higher than the measured heights by about 1.0 meter, the root-mean-square difference being 1.3 meters; this difference is on the same order as that found here in the direct regression in Figure 12 and in Table 2 in terms of the mean significant wave heights derived from the WIS data compared with direct measurements by buoys and the microseismometer. HUBERTZ *et al.* found no indication of bias in the wave periods, again in agreement with the present study. However, somewhat different results have been found in comparisons with the WIS hindcast data for the east coast of the U.S., requiring a recalibration of the WIS data (MILLER and JENSEN, 1990; HUBERTZ *et al.*, 1994). Unfortunately, there presently are no plans by the Corps of Engineers to similarly reanalyze the west-coast WIS hindcast data to bring it into better agreement with the buoy measurements. Therefore, the west-coast WIS data must be used with caution and in the recognition of its bias toward significant wave heights that are too large.

MAJOR STORMS AND EXTREME WAVES

Of particular importance are the largest waves measured over the years, since they often serve as the design-wave conditions used in engineering analyses and to establish erosion and flooding zones in coastal-zone management. This usually involves the projection of the 50-year or 100-year extreme-wave conditions, based on wave measurements generally obtained over a much shorter span of time (WANG and LEMEHAUTE, 1983; GODA, 1990; HERBICH, 1990). For such a projection to be statistically valid, it generally is considered that the measured record must be at least one-third the time span of the projected interval; for example to project the 100-year storm-wave conditions, it is necessary to have at least 33 years of wave measurements, while projection of the 50-year conditions requires only 17 years of measurements.

With these guidelines, data derived from the individual wave-measurement programs on the Northwest coast are capable of only modest projections in estimating extreme wave conditions. With little more than a decade of deep-water buoy measurements, the projection would only be to the 30-year condition; the 23 years of accumulated microseismometer data allow for the greatest projection, well beyond the 50-year conditions; although, the 100-year extreme storm could still not be projected with confidence. It was decided that the best projections would be derived from the joint use of the microseismometer data from 1971 to 1981 and the CDIP-Coquille buoy measurements collected since 1981. The measurement comparisons undertaken above indicate that these data sets are comparable in yielding effectively the same deep-water significant-wave heights. In joining these data for the extreme-wave analysis, preference is given to the buoy measurements, with the earlier microseismometer data used to extend the record for a total of 23 years. Within that combined data, 24 storms with deep-water significant wave heights equal to or greater than 6 meters were identified, with the largest recorded significant wave height having been 7.3 meters, measured on 24 Dec. 1972 and 30 Jan. 1990.

The extreme-wave analyses were undertaken using the Automated Coastal Engineering System (ACES) developed by the U.S. Army Corps of Engineers. The program utilizes the methods developed by GODA (1988) to fit input data to five commonly used probability distributions, and information in the form of a correlation coefficient and the sum of squares of the residuals is provided to assist the user in determining which distribution best fits the data. The graphical presentation for the analysis of the combined microseismometer and CDIP buoy data is given in Figure 13, together with the best-fit Weibull distribution and projected extreme wave conditions. The projected 50-year significant wave height is 7.8 meters. The projected 100-year significant wave height is 8.2 meters, which may be used in applications even though it is of questionable validity. Similar analyses were undertaken for all wave occurrences greater than 5 meters, which substantially increased the number of "storms" to 68 in the 23 years of combined data. The projected best-fit Weibull distribution yields 8.2 meters and 8.6 meters respectively for the 50-year and 100-year significant wave heights. The goodness

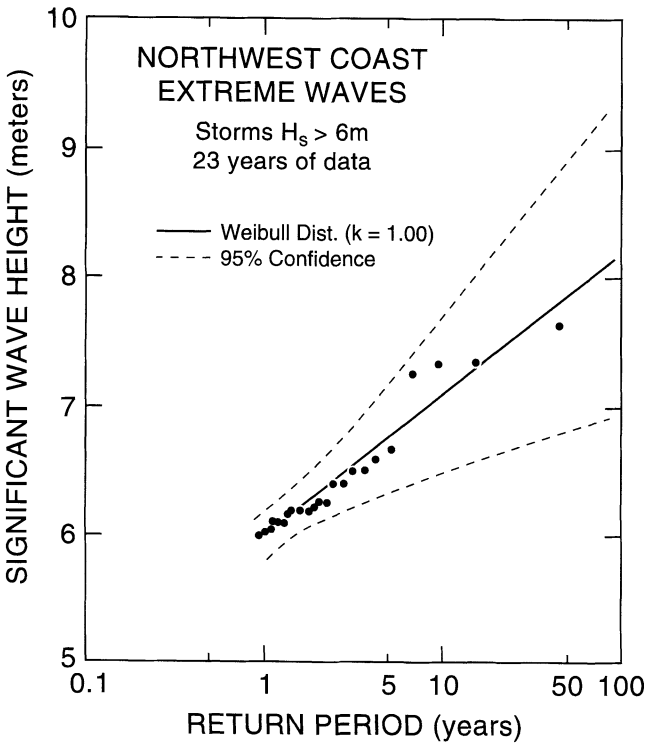

Figure 13. The analysis of the extreme wave conditions based on the occurrence of storms with deep-water significant wave heights in excess of 6 meters in the combined data from the CDIP-Coquille buoy and from the microseismometer wave-measurement system in operation at Newport. The Weibull theoretical curve has been fitted to the measured storm data, and used to project the 50-year and 100-year extreme-wave conditions.

of fit correlations were $R^2 = 0.97$ and 0.98 for these respective Weibull distributions.

The original intention was to combine the above direct measurements of storm waves with the WIS hindcasts which extend back to 1975, yielding a total of 38 years of wave data, which would provide a more confident projection of the 100-year extreme storm conditions. It was seen, however, that the WIS hindcasts yielded significant wave heights that are substantially greater than measured; individual hindcasts yielded significant wave heights close to 10 meters, greatly exceeding the 100-year projection derived from the combined buoy and microseismometer data. An attempt was made to use the regression in Figure 12 between the WIS hindcasts and microseismometer measurements to reevaluate the WIS data, bringing it into average agreement with the microseismometer and buoy measurements. However when this was done, only a few storms remained within the WIS data set where significant wave heights are greater than the 6-meter threshold condition being used in the analyses. It appears that although the WIS hindcasts systematically overestimated the significant wave heights, Figure 12, the analyses actually truncated the predictions during the most extreme storms, underpredicting heights when the data were reanalyzed. Because of such problems, we had to abandon our attempts to combine the WIS data with the more recent direct measurements of the wave climate to provide improved projections of the 100-year conditions.

SUMMARY AND DISCUSSION

The establishment of a wave climate for the Pacific Northwest of the United States has been complicated by the multiplicity of data sets, including direct measurements since the 1980s by the NDBC and CDIP deep-water buoys and shallow-water arrays, remote sensing measurements by a microseismometer system (1971–present), and hindcast data from the Wave Information Study (1956–1975). Overlapping intervals of measurements by the different programs have permitted direct comparisons of the data sets and their joint use to project expected extreme wave conditions. The main conclusions derived in the study include the following.

(1) The deep-water wave climate is essentially uniform in terms of average wave conditions along the length of the Pacific Northwest, although there can be significant differences on a daily basis.
(2) The NDBC deep-water buoy yields significant wave heights that are approximately 8 to 13 percent higher than those derived from the CDIP buoy, while measurements of wave periods are statistically the same.
(3) Wave measurements derived from the CDIP arrays in 11-meters water depth agree with the deep-water buoys when transformed to deep water using linear wave theory.
(4) The microseismometer system yields good measurements of deep-water significant wave heights when compared with the offshore buoys, but little trend is found between the periods which are also systematically too high as derived from the microseismometer system.
(5) Significant wave heights derived from the WIS hindcast procedures are 30 to 60 percent higher than measured by the deep-water buoys and microseismometer.
(6) There is a marked seasonality in the wave climate, with deep-water significant wave heights during the summer months averaging 1.25 to 1.75 meters, increasing to 2.0 to 3.0 meters during the winter months, with individual storms yielding significant wave heights of 6 to over 7 meters.
(7) Calculations of wave-breaker conditions on Northwest beaches yield significant wave heights of 9 to 10 meters for the storm conditions.
(8) The largest storm waves measured during the 23 years of data accumulation with the microseismometer and buoys had a deep-water significant wave height of 7.3 meters, while the projection of the 50-year and 100-year extreme wave conditions for storms with heights in excess of 6 meters yielded significant wave heights of 7.8 meters and 8.2 meters in deep-water.

The results of these analyses further establish the extreme severity of the wave climate along the Northwest coast. The wave data compiled here and the projections of extreme-wave conditions will be useful in coastal-zone management deci-

sions and in the design of engineering structures including jetties, seawalls and sewer outfalls.

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