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SPATIAL AND TEMPORAL VARIATIONS IN THE WAVE CLIMATE OF THE NORTH PACIFIC

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ABSTRACT

Analyses of wave statistics from a series of six offshore NDBC buoys in the North Pacific, extending from the Gulf of Alaska to Southern California, demonstrate that the heights of storm-generated waves have increased during the past three decades. The greatest increase has taken place off the coast of Washington, where winter waves on average have increased by 0.88 meters since 1976 when the buoy was installed, with the largest storm waves having increased by 2.0 meters. Slightly smaller increases are found offshore from Oregon and Northern California, while no significant increase has occurred on the coast of Southern California or in the Gulf of Alaska. The increased wave heights at mid-latitudes reflect the growing intensities of storms that cross the Pacific Northwest and Northern California during the winter, and are of concern since the risks from coastal erosion and inundation also increase, as do the costs associated with responding to these hazards. Ship observations of winds in the North Pacific do show a roughly parallel increase during the past 25 years. However, we have been unsuccessful in attempts to account for the increase through comparisons with large-scale climate indicators such as the East Pacific index, a measure of the north-to-south pressure difference between the Aleutian Low and Hawaiian High atmospheric systems. That index does account for the annual variations in the wave conditions above and below the long-term trends.

Superimposed on the progressive increase in storm-wave heights are inter-annual cycles associated with El Niño/La Niña - Southern Oscillation events, which also show a latitude variation along the West Coast of North America. Comparisons between the wave height residuals and the Multivariate ENSO Index (MEI) demonstrate that larger waves tend to be generated during strong El Niños and La Niñas, while smaller waves occur during intermediate or "normal" years. However, intermediate or "normal" years can result in large waves being produced offshore from Washington, and to a lesser extent the Oregon coast. The correlations demonstrate the regional influence of El Niño/La Niña - Southern Oscillation events, so that major El Niños correspond to years of higher wave conditions in California and along the Oregon coast, while moderate events result in considerable scatter in the heights of the waves, and especially offshore from the Pacific Northwest. Furthermore, such events do not appear to significantly influence the wave climate north of Washington. Conversely, La Niñas appear to dominate the buoy measurements in the Pacific Northwest, but can generate large wave conditions as far south as Pt. Arguello (Southern California), as occurred during 1998-99. This suggests that the greater intensities of both El Niños and La Niñas compensate for the increased distances of the storm systems, respectively from the Pacific Northwest and California coasts. Notwithstanding this, the increased frequency of major storms and higher wave energies between 1997 and 1999 in the North Pacific, may in fact be a function of the recent strong positive phases of the EP Pattern. Accordingly, it is unclear how the Southern Oscillation controls the heights of waves in the North Pacific and their latitude variations, beyond the effects of the EP Pattern. At present with such a short record of wave measurements, during which only a few significant El Niños and La Niñas have occurred, the relative roles of the EP Pattern and the Southern Oscillation cannot be separated. It appears that many climatic factors interact to control wave energy levels in the North Pacific, and it is important to establish the relative contributions since the increasing wave energies are a significant cause of coastal erosion.

INTRODUCTION

The ocean wave climate, and especially the occurrence of high wave energy levels generated by severe storms, is important to the operation and safety of shipping, and to the occurrence of erosion in the coastal zone. The latter concern has been the impetus for initiating the present investigation. Major beach and property erosion occurred along the West Coast of the United States (U.S.) during the El Niño winter of 1997-98, followed by unusually intense wave conditions and additional erosion during the 1998-99 La Niña. We have completed a detailed investigation of the largest storms that occurred during those two winters, involving analyses of the hourly variations of the measured tides plus the runup of storm waves on beaches, with a comparison between the total water levels and the erosional cutback of dunes and properties backing the beaches (Komar et al., in review). That investigation raised broader questions concerning the dependence of annual wave conditions on the climate spectrum ranging between El Niños and La Niñas, that is, on the status of the Southern Oscillation. Furthermore, the wave-energy levels of storms experienced during those two winters, and particularly during the 1998-99 La Niña, greatly exceeded previous projections of the expected most severe storm waves. Based on 25 years of wave data for the Oregon coast, we had projected a 100-year deep-water significant wave height of approximately 10 m (Ruggiero et al., 1996; Tillotson and Komar, 1997). This 10-m height was exceeded by one storm during the 1997-98 El Niño, and by four storms during the 1998-99 La Niña, with one storm (2-4 March 1999) having generated a deep-water significant wave height of 14 m (Komar et al., in review). Those recent occurrences of unusually severe storms raise the question of whether there has been a progressive increase in wave-energy levels in the North Pacific, comparable to those that have been experienced in the North Atlantic and North Sea (Carter and Draper, 1988; Bacon and Carter, 1991).

Severe erosion occurred along the U.S. West Coast during the 1982-83 and 1997-98 major El Niño events. There has been a number of investigations of the erosion impacts and causative processes, with the processes including elevated mean water levels that enhance the heights of tides, and the southerly shift of storm systems that increased wave-energy levels (Earle et al., 1984; Komar, 1986; Seymour, 1998; Flick, 1998; Storlazzi and Griggs, in press; Komar et al., in review). The most detailed investigation of wave conditions during El Niño has been undertaken by Seymour (1998). He demonstrated the occurrence of increased wave energies in California, and suggested that the southerly shift of the storm tracks would generally reduce wave conditions further to the north, on the coasts of Washington and Oregon (the Pacific Northwest). However, as noted above, the 1997-98 El Niño brought one 100-year storm to the Pacific Northwest, suggesting that the greater intensity of El Niño storms may compensate for the increased distances of the storms from the Northwest. There have been no previous investigations of La Niña related storm waves, studies that might offer an explanation for the extraordinary number of severe storms that occurred during the 1998-99 La Niña. It is known that the storms tracks pass more directly over the Pacific Northwest, bringing higher rainfalls. The northward shift of the La Niña storm paths might be expected to decrease wave conditions in Southern California, while raising them in the Pacific Northwest, but the question remains as to why the 1998-99 La Niña produced a series of such extreme storms.

It is possible that in addition to the cycle between El Niño and La Niña and their controls on wave conditions in the North Pacific, there is also a longer-term progressive increase in wave-energy levels. Studies in the North Atlantic and North Sea have shown that mean ocean wave heights have been increasing since the 1950s (e.g., Carter and Draper, 1988; Bacon and Carter, 1991; WASA, 1995; Kushnir et al., 1997). Wave measurements at Land's End in the United Kingdom, using a Ship-borne Wave Recorder fitted in the Seven Stones Light Vessel, has yielded one of the longest-running wave records in the world. Carter and Draper (1988) analyzed the data collected between 1962 and 1983, and found that the significant wave height had increased at a rate of 0.034 $m.yr^{-1}$; this amounts to an overall increase in the significant wave height by 0.71 m during those 21 years. Bacon and Carter (1991) provided a revised estimate, using a new and more accurate pressure sensor depth correction function, and included data up to 1986. Their analysis revealed an increase in the significant wave height of 0.022 $m.yr^{-1}$, which amounts to an overall increase in the wave height by 0.53 m. This 24-year progressive increase in wave-energy levels in the North Atlantic has been convincingly related to a simultaneous increase in the north-south sea-level atmospheric pressure gradient between Iceland and the Azores (Bacon and Carter, 1993; Kushnir et al., 1997). It is uncertain whether this represents a natural fluctuation, or a progressive climatic shift.

Little attention has been given to similar long-term shifts in the wave climate of the North Pacific, largely because of, until recently, the lack of sufficiently long data sets to investigate such trends. The study by Seymour (1996) represents the only previous attempt, based on wave data derived from a variety of instruments between 1977 and 1994 along the California coast. He identified two measurement sites in Southern California, Scripps Pier and Oceanside, where there was an apparent increase in wave heights over time (though he does not report the amount of increase), while the majority of sites (7) showed a decrease in wave height. As a result, he concluded that there is no general trend toward increasing wave intensity, at least on the California coast.

The objective of this report is to present detailed analyses of wave buoy data for the North Pacific, covering the region between the Gulf of Alaska and Southern California. The analyses demonstrate the expected latitude variations in the wave climate (significant wave heights and wave periods), and show that there has been a systematic increase in wave heights since the 1970s, with the greatest rates of increase having been experienced in the Gulf of Alaska and Pacific Northwest, while a nearly negligible increase is found for Southern California. The analyses further document the dependence of the wave climate on the occurrence of El Niños and La Niñas, a dependence on the Southern Oscillation Index.

SOURCES OF WAVE MEASUREMENTS

Wave statistics (heights and periods) and some meteorological information have been measured in the North Pacific using wave buoys and sensor arrays. The data have been collected by the National Oceanic and Atmospheric Administration (NOAA), which operates the National Data Buoy Center (NDBC), and by the Coastal Data Information Program (CDIP) of Scripps Institution of Oceanography. The buoys cover the region between the Gulf of Alaska and Southern California, and are located in both deep and shallow water. The NDBC operates some 30 stations along the West Coast of North America, while CDIP has at various times carried out wave measurements at 80 stations. By far the greatest concentration of wave measurement sites is located off the California coast, with comparatively fewer stations to the north.

The majority of wave buoys were installed during the 1980s, while a few sites have data that extend back to the mid 1970s. Since it is our objective to present a long-term account of the wave climate, we have relied mainly on buoys that have been in operation since the 1970s. Because there are no deep-water CDIP wave sites that have been installed for a sufficiently long period, we have based our analyses on wave data derived from the NDBC wave buoy network. Wave measurements by NDBC are obtained hourly, and are transmitted via satellite to the laboratory for analysis of the wave energy spectra, significant wave heights, average zero-up-crossing wave periods, and the peak spectral wave periods.

Data from the six NDBC buoy station sites identified in Figure 1 have been used in this study. Three of the buoys have been in operation since the mid to late 1970s, while the remaining three have data that extend back to the early 1980s. Table 1 describes the general characteristics of each buoy site, including the water depth, location, and period of operation. As can be seen from Figure 1, the chosen sites are distributed relatively evenly along the West Coast of North America. The three northern-most sites, in the Gulf of Alaska and offshore from the Pacific Northwest, are located well out into the Pacific Ocean, while the sites along the California coast, Pt. Arena, Half Moon Bay, and Pt. Arguello, are located closer inshore. Apart from buoy #46012 (Half Moon Bay), all of the sites are in deep-water. The Half Moon Bay buoy is in 88-m water depth, which technically is deep-water for waves having periods less than 15 sec; waves between 15 and 20 sec are in intermediate water, and their correction to deep-water equivalents involves on average a factor of 1.04, a 4% increase. This correction for the rare, long-period waves is small, so in our analyses for buoy #46012 we have worked with the original buoy measurements without correction.

The hourly wave data for each buoy site were obtained from NDBC, and compiled in an EXCEL spreadsheet for detailed analyses. To describe the variability of the wave climate over a range of temporal scales, representative measures of the wave statistics were calculated from the hourly data. These included:

- Mean monthly averages of the significant wave height (H_S), maximum significant wave height (MAX H_S), peak spectral period (T_P), and maximum peak spectral period (MAX T_P);
- Annual mean significant wave height, and peak spectral period;
- Annual mean winter significant wave height (WH_S), maximum winter significant wave height (MAX WH_S), winter peak spectral period (WT_P), and maximum winter peak spectral period (MAX T_P). Winter means were derived by averaging the wave statistics for the months of October to March; and,
- Annual maximum significant wave height, and maximum peak spectral period.

The annual mean wave statistics were derived from the mean of the 12 consecutive monthly means of the data. In addition, we have relied on only those years in which all 12 consecutive months have hourly data return ≥ 90 per cent. This approach is consistent with the analysis of Carter and Draper (1988), and is slightly more rigorous than Bacon and Carter (1991), who relied on a data return of ≥ 80 per cent. Where data were missing, or did not exceed or equal the threshold, wave data measured from another buoy was used, located as close as possible to the main buoy of interest. This approach proved successful for the California stations, where a number of alternative buoys are located along the coast. However, because of the absence of sufficient buoys in the north, this approach was not possible and the monthly data was left blank.

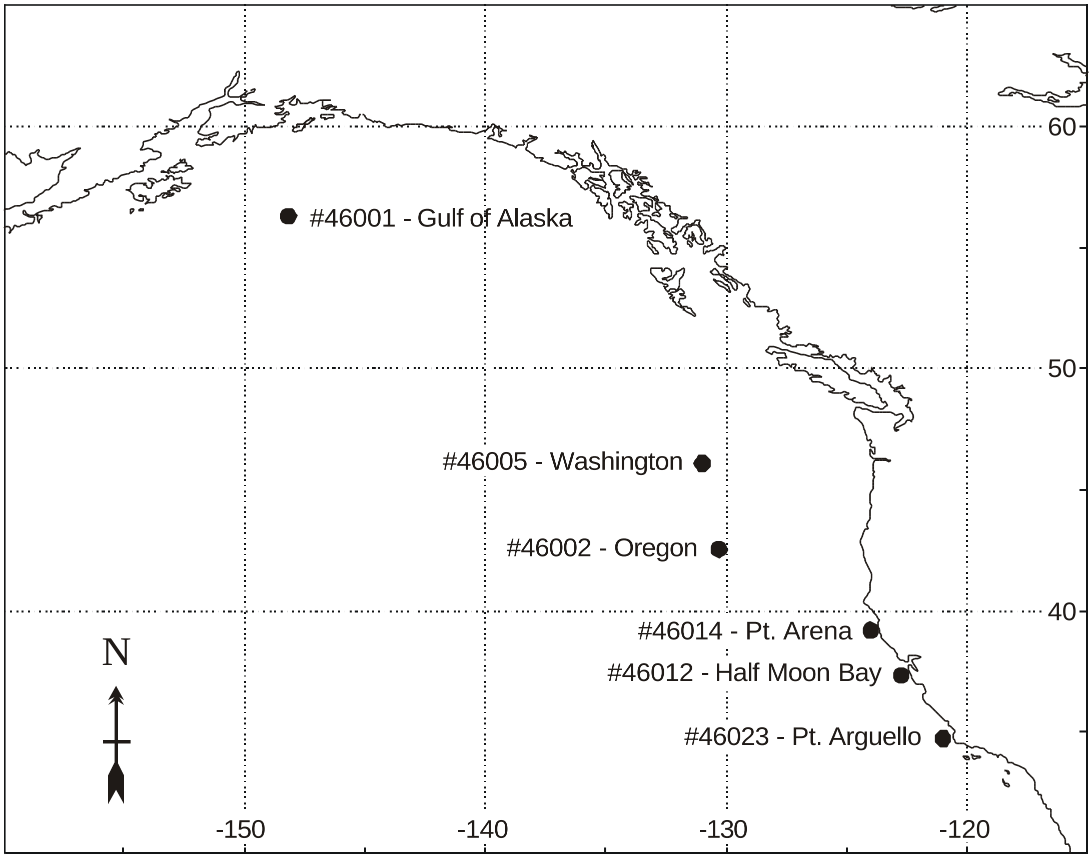

Figure 1 Locations of the NDBC wave buoys in the North Pacific, and analyzed in the present study.

Table 1 Wave buoy site characteristics.

Station Name	Location	Water Depth (m)	Period of Operation	System
46001	Gulf of Alaska (Lat. 56°17'44"N; long. 148°10'19"W)	4,206	1972 - present	6-meter NOMAD buoy
46005	Washington (Lat. 46°05'00"N; Long. 131°00'00"W)	2,853	1976 - present	6-meter NOMAD buoy
46002	Oregon (Lat. 42°31'37"N; Long. 130°15'37"W)	3,420	1975 - present	6-meter NOMAD buoy
46014	Pt. Arena (Lat. 39°13'00" N; Long. 123°57'57" W)	265	1981 - present	3-meter discus buoy
46012	Half Moon Bay (Lat. 37° 23' 12"N; Long. 122°43'36" W)	88	1980 - present	3-meter discus buoy
46023	Pt. Arguello (Lat. 34°42'50"N; Long. 120°58'00"W)	384	1982 - present	10-meter discus buoy

LATITUDE VARIATIONS IN WAVE CONDITIONS

Comparison of Seasonal Wave Conditions

There is a strong seasonality to the wave climate in the North Pacific, with the strongest storms and largest generated waves occurring in the winter months. This has been shown, for example, by Tillotson and Komar (1997) for the Oregon coast. The objective here is to expand the analysis to the six buoy sites in Figure 1.

Figure 2 documents the seasonal nature of wave conditions (heights and periods) for the West Coast of North America. The graphs clearly show a prominent cycle in the mean monthly wave heights and peak wave periods. Waves are characteristically smallest (<2.0 m) between May and August (late spring to summer), reaching a minimum in August at four of the buoy sites, while the two northern buoys (#46001 and #46005) reach a minimum in July (Figure 2A). It is also apparent that there is little difference in the wave heights between the northern and southern buoys during May through August. The range of wave heights during these months is generally less than 0.4 m. This suggests that during the summer, the West Coast is characterized by relatively similar conditions for wave generation, likely by local winds that blow over short fetches.

A similar pattern can be seen for the peak wave periods, Figure 2B, such that during the summer the periods are typically less than 10 sec. The range between the different buoys is again small (< 1 sec). However, Figure 2B reveals evidence for a slight spatial variability between the north and south wave buoys, not apparent in Figure 2A for the wave heights. In the Gulf of Alaska (#46001), the peak wave periods are the lowest for the six sites (typically < 9 sec). Wave periods increase gradually to the south, so that the Southern California wave buoys (#46012 and #46023) are characterized by slightly longer periods compared with those in the north. It is possible that these longer period waves in Southern California are arriving from winter storms in the Southern Hemisphere.

Between August and November waves in the North Pacific rapidly increase in heights, Figure 2A, reaching a peak in December. This transformation reflects the propagation of storm systems in a southeasterly direction towards the West Coast of North America. These storms generate strong winds that blow over large fetch areas. On average, the peak monthly winter wave heights range from 3.6 to 3.8 m in the north (#46001, #46005, and #46002), while the southern buoys are characterized by much lower wave heights that range from 2.5 to 3.0 m. The waves remain high throughout the winter months (December to February). With the onset of spring in March, they gradually decrease in height. Two further characteristics can be identified from Figure 2A. First, the difference in the average monthly wave heights between the buoys in the north, compared with those measured in the south, amounts to approximately 1 m. Second, it can be seen from the diagram that the waves rapidly increase in height in the north during the transition from summer to winter (given by the slopes of the lines), while the rate of increase in the south is more gradual.

In keeping with the change in wave heights between August and November, the peak wave periods also increase during the winter, Figure 2B, though the rate of change is less than that observed for the wave heights. The longest wave periods occur in January for Southern California, and one month later for the northern buoys. The latitudinal variation in the wave periods identified for the summer months is even more strongly developed during the winter. In the north, the Gulf of Alaska buoy exhibits the lowest winter peak periods (typically around 11 sec), while the buoys located in Southern California are characterized by longer wave periods (up to 14 sec). These differences suggest that in the Gulf of Alaska, the waves remain strongly influenced by locally generated storm systems having relatively short fetches. Because the wave heights are large relative to waves measured off the Oregon and Washington coasts, while the wave periods are lower, the waves in the Gulf of Alaska tend to be much steeper, suggesting that they are locally generated by extremely strong winds. Further to the south, the buoys become increasingly influenced by far-field storm systems in the North Pacific, storms having larger fetches and durations than in the Gulf of Alaska. Wave dispersion during travel across the wide expanse of the central North Pacific would also enhance the development of long-period swell.

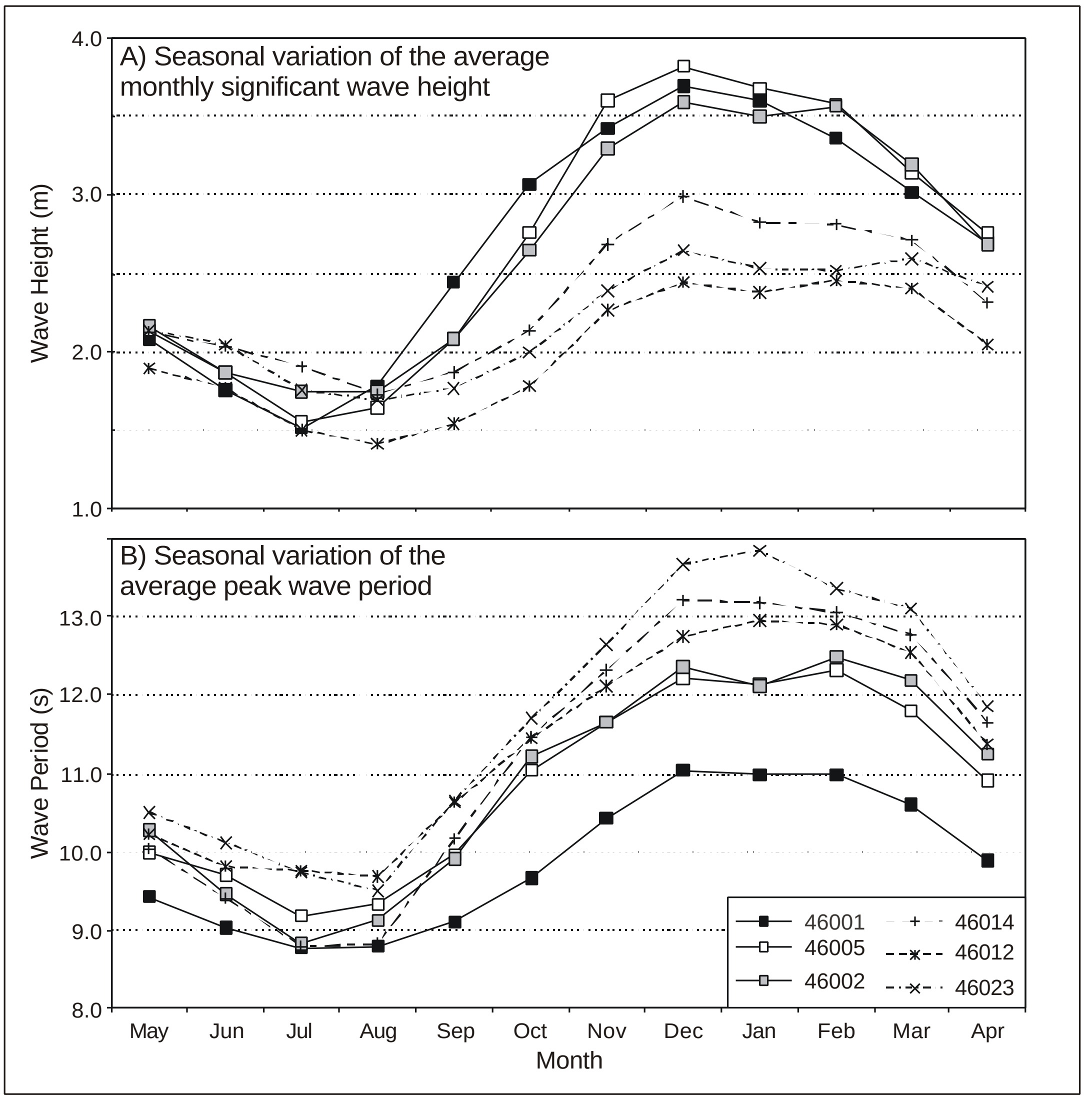

Figure 2 Seasonal variability of the wave climate in the North Pacific. A) Mean monthly significant wave height; B) Mean monthly peak wave period.

Latitude Differences in the Wave Climate

Latitude variations in the significant wave heights and peak wave periods for the North Pacific are further highlighted in Figures 3 and 4. Figure 3A shows the spatial variability of the average significant wave height (H_S) and the average wave height during the winter (WH_S) derived from the six buoys, while Figure 3B graphs the average maximum significant wave height (MAX H_S) for all years and the maximum significant wave measured at each buoy during its operating life. Figure 4 presents a similar analysis for the peak wave periods. The variance for each buoy site is shown, and provides an indication of the range of wave heights and periods measured at the buoy.

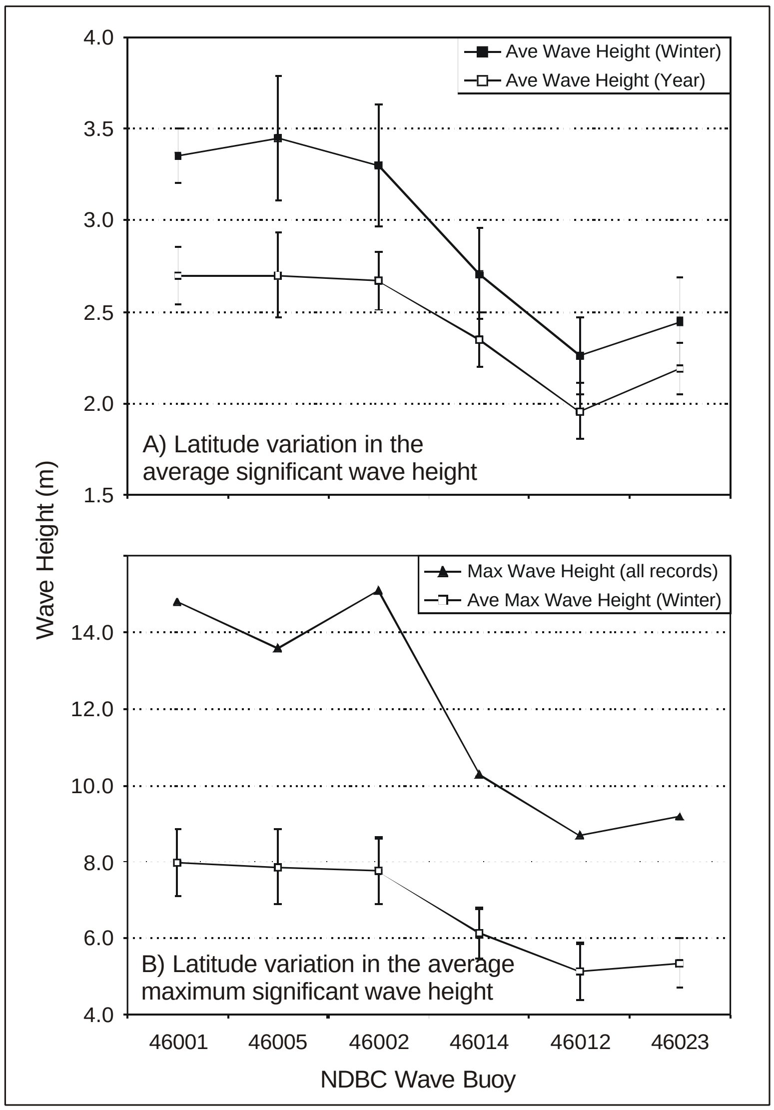

Figure 3 Spatial variability of wave heights in the North Pacific; A) Average yearly and winter significant wave heights; B) Average maximum wave heights.

The overwhelming characteristic of Figure 3 is that wave heights observed in the north are substantially greater than those in the south along the California coast. The average yearly significant wave height in the north is 2.7 m, compared with 2.2 m in the south. The differences are much greater when considering only the winter months. Waves in the north reach an average height of some 3.3 to 3.5 m during the winter, while the southern sites range from 2.3 to 2.7 m. This represents an average increase in the northern wave heights of 0.7 m from summer to winter, compared with 0.3 m in the south. In contrast, Figure 4 reveals a systematic increase in the peak wave periods from north to south along the West Coast, with the highest peak periods occurring in Southern California. Nevertheless, it can be seen that apart from buoy #46001 in the Gulf of Alaska, the maximum wave periods (MAX T_P) among the remaining buoys are broadly similar (20 to 21.4 sec).

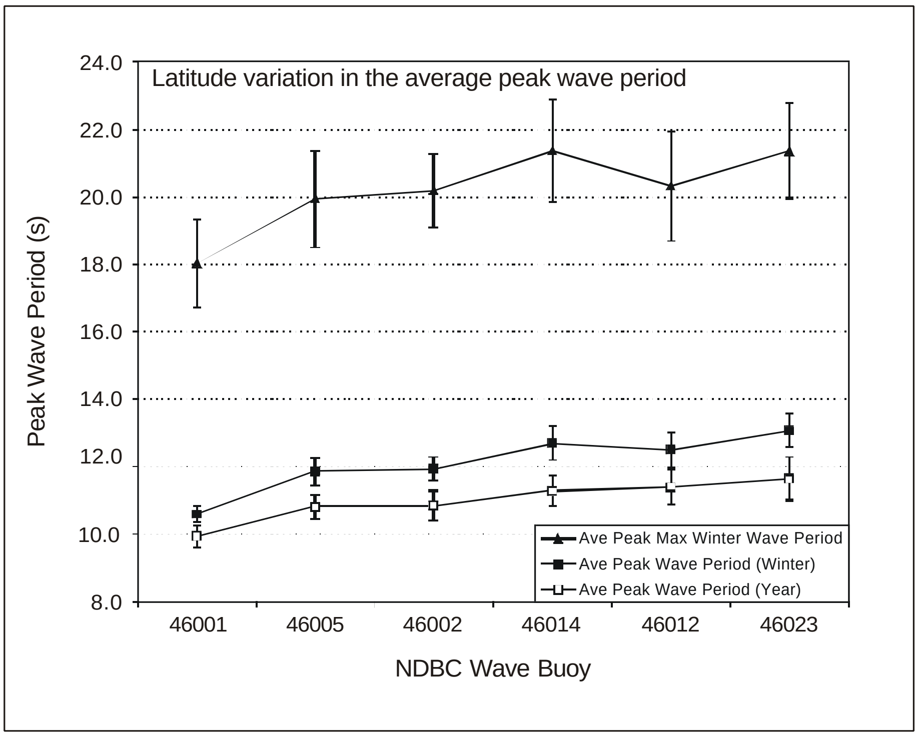

Figure 4 Spatial variability of peak wave periods in the North Pacific.

From the Gulf of Alaska to Oregon, it has been shown that the yearly averages of the measured wave heights are relatively uniform, with only minor differences between the three stations (Figure 3A). However, during the winter these differences become more apparent, with the average WH_S winter wave heights being greatest off the Washington coast (#46005), while waves in the Gulf of Alaska and off the Oregon coast are slightly smaller on average. The largest significant wave height measured by the buoys reached 15.1 m, and was measured by the Oregon buoy (Figure 3B). Typically though, the height of the maximum significant wave (MAX H_S) averages around 8.0 m. In contrast, the wave climate in the south is considerably milder. The average heights of the winter maximum waves range from 5.1 to 6.1 m, while the MAX H_S has not exceeded 10 m in Southern California. Furthermore, these results suggest that the region near Pt. Arena (#46014) represents the transition between the extremely energetic wave climate of the north, and the milder wave conditions to the south. Although peak wave periods are slightly lower in the north, the combination of very large waves that occur north of Pt. Arena together with relatively long wave periods results in wave powers (energy fluxes) that are at least twice as great as those observed in Southern California.

DECADE-LONG TRENDS IN WAVE CONDITIONS

The characterization of the wave climate for the North Pacific, undertaken in the preceding section, is somewhat misleading due to the existence of long-term trends of increasing wave heights present in some of the data sets. These trends are comparable to that observed in the North Atlantic and North Sea (Carter and Draper, 1988; Bacon and Carter, 1991), but the North Pacific wave date for the six buoys show interesting latitude variations in the wave-height trends.

Long-Term Trends in Annual Mean and Winter Wave Heights

Annual mean values of the significant wave heights (H_S) and the mean winter significant wave heights (WH_S) determined for each of the buoys (in which all 12 consecutive months have hourly data returns $\geq$ 90 per cent) are plotted against time in Figure 5; linear regression lines have been fitted to the data, to distinguish the broad temporal patterns. Also identified on the graphs are two time periods, 1982-83 and 1997-98, which correspond to the occurrences of the two strongest El Niño events of the past three decades. Table 2 lists the regression slopes and statistical significance of the regression lines determined by an analysis of variance (ANOVA), for each data plot. The ANOVA test performs a simple analysis of the variance ratios determined for a sample population, to determine whether or not there are significant differences among the means of several observations, where each group is assumed to be normally distributed.

The Gulf of Alaska buoy (#46001), located in the far North Pacific, shows a small increase in the annual average H_S and the WH_S since 1972 (Figure 5A). However, the ANOVA test reveals that these trends are not statistically significant at the 0.05% level (Table 2). The graph does provide some insight into the inter-annual variability of wave heights in the Gulf of Alaska, indicated by the variance of the waves about the regression line, as well as possible decadal variability in wave heights. In general, wave heights were generally lower during the mid 1970s, around 3.0 m during the winter months, and there followed a progressive increase in the wave heights that peaked around 3.7 m during the latter half of the 1980s. Throughout the 1990s, wave heights decreased slightly, though remaining higher than those measured during the latter half of the 1970s. Figure 5A also reveals that El Niño events appear to have had a negligible influence on the wave height statistics in the Gulf of Alaska, a finding that is consistent with the southerly shift of storm tracks during those events.

Further south, the Washington (#46005) and Oregon (#46002) buoys are characterized by marked increases in the annual average H_S and average winter WH_S, indicated by the prominent upward sloping regression lines (Figure 5B and 5C). These trends are statistically significant at the 0.006% level or lower for each of the buoys (Table 2); the one exception is that the Oregon buoy shows no statistically significant trend in its annual average H_S, possibly produced by the large gaps in the data record for the annual averages (Figure 5C).

The annual average H_S for the Washington buoy increased at a rate of 0.027 $m.yr^{-1}$ since 1978, the slope of the regression line (standard error of 0.007; Table 2), while the annual winter average WH_S increased by 0.042 $m.yr^{-1}$ (standard error of 0.011). This corresponds to an overall increase in the annual average H_S of 0.54 m for the 21-year time span, while the annual average WH_S grew by 0.88 m. The annual average WH_S measured at the Oregon buoy increased at a rate 0.031 $m.yr^{-1}$ (standard error of 0.009), which amounts to an overall increase in the winter wave heights of 0.65 m since 1977.

The plotted data for both buoys reveal a significant jump in the wave heights from 1977 to the early 1980s (Figure 5B and 5C). From the mid 1980s to 1994, the average WH_S gradually decreased with time, while the annual average H_S increased. This suggests that the heights of the waves during spring and summer were on average higher than normal during those years. Since 1994, the wave heights again increased significantly, reaching prominent highs during 1998, associated with 1997-98 El Niño, followed by a larger peak in 1999 related to the 1998-99 La Niña (Figure 5B and 5C).

The wave climate at Pt. Arena (#46014) in Northern California is also characterized by a long-term increase in the average H_S (Figure 5D). Since 1981 the average H_S has increased at a rate of 0.017 $m.yr^{-1}$ (standard error of 0.007), and is statistically significant at the 0.03% level (Table 3). This corresponds to an overall increase of 0.27 m in the wave heights for the 18-year period. The lower wave height increase identified at Pt. Arena compared with those to the north reinforces the evidence for a transformation in the wave climate between Oregon and California, a finding here that is consistent with the seasonal and latitude variability of waves identified previously. Although the average WH_S reveal a long-term increase that parallels the average H_S, the trend is not significant at the 0.05% level. Figure 5D also highlights the increasing role of El Niño and La Niña events with the southward progress along the West Coast of North America. As can be seen in that diagram, the 1997-98 El Niño and 1998-99 La Niña stand out as having generated the largest average wave heights at Pt. Arena since installation of the buoy in 1981. Also prominent, though not as significant as the 1997-98 El Niño and 1998-99 La Niña, is an increase in the average annual WH_S in 1982-83, associated with the strong El Niño at that time.

Along the Southern California coast, buoys #46012 and #46023 show little evidence for an increase in the annual average H_S or of the average winter WH_S (Figures 5E and 5F). The negatively sloping regression line fitted to the Half Moon Bay data (#46012) suggests that the annual average H_S has declined with time at this particular site. However, for each record the regression lines are not statistically significant at the 0.05% level (Table 2). Furthermore, the apparent decrease in the annual average H_S identified at Half Moon Bay should be viewed with caution, given the absence of wave height data measured during the 1997-98 El Niño and 1998-99 La Niña winters. The other important feature of Figures 5E and 5F is the much larger average wave heights produced by the 1982-83 and 1997-98 El Niños, while the 1998-99 La Niña also generated above average wave conditions along the Southern California coast.

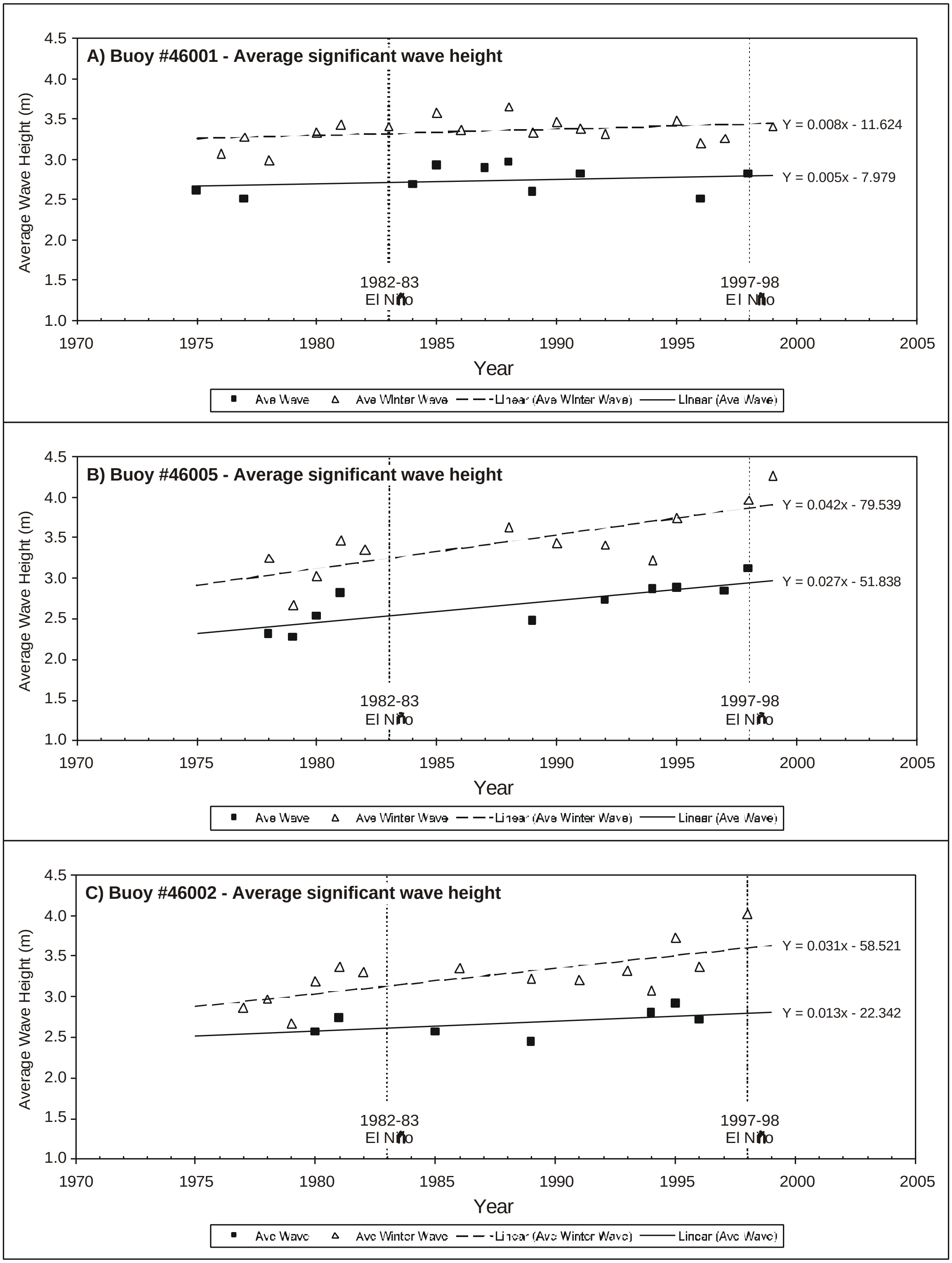

Figure 5 Long-term trends in the annual average significant wave heights (H_S) and the annual average winter (October through January) wave heights (WH_S) for the North Pacific buoys.

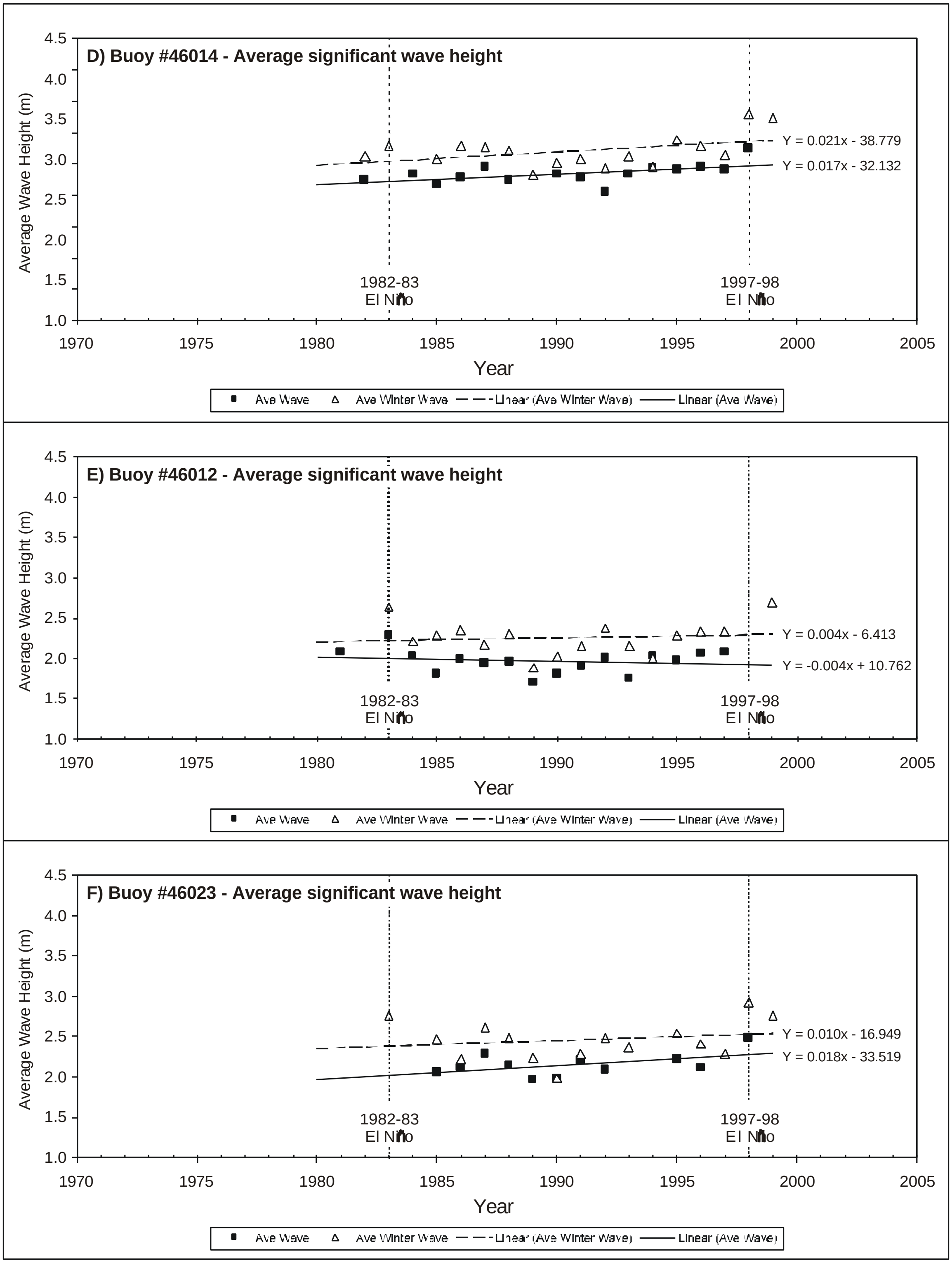

Figure 5 (Cont.) Long-term trends in the annual average significant wave heights (H_S) and the annual average winter (October through January) wave heights (WH_S) for the North Pacific buoys.

Table 2 Linear regression analysis results for the annual average significant wave height (H_S) and the annual average winter significant wave height (WH_S).

Station	Name	N	Slope	Standard Error	Pearson's R	F Statistic	Significance F
46001	H_S	10	+0.005	0.008	0.22	0.434	N.S
	WH_S	17	+0.008	0.006	0.33	1.852	N.S
46005	H_S	10	+0.027	0.007	0.79	13.489	0.006
	WH_S	12	+0.042	0.011	0.77	15.033	0.003
46002	H_S	7	+0.013	0.009	0.51	1.765	N.S
	WH_S	14	+0.031	0.009	0.70	11.314	0.006
46014	H_S	15	+0.017	0.007	0.56	5.811	0.030
	WH_S	17	+0.021	0.011	0.43	3.366	N.S
46012	H_S	16	+0.004	0.008	0.15	0.313	N.S
	WH_S	16	-0.004	0.011	0.10	0.147	N.S
46023	H_S	11	+0.018	0.010	0.51	3.222	N.S
	WH_S	15	+0.010	0.013	0.20	0.531	N.S

Note N.S denotes Not Significant at the 0.05% level.

The statistical significance of the long-term trends shown in Figure 5 has been further assessed using a non-parametric ranking test, the Wilcoxon rank-sum test, used by Carter and Draper (1988) and Bacon and Carter (1991) in their analyses of wave data from the North Atlantic. This particular test is based on the assumption that the distribution of the first-half of a population compared with the second half of a population, are the same *[Johnson and Leone, 1977]*. Unlike the ANOVA statistical test, which assumes that the sample population is normally distributed, the Wilcoxon rank-sum test is distribution-free and is particularly good for dealing with small population samples. The annual mean significant wave heights and the annual mean winter significant wave heights for each of the wave buoys are sorted into ascending order, and ranked from lowest to highest. Table 3 provides an example of this approach for the Washington buoy (#46005). In this example the annual averages of the significant wave heights are divided into two periods, 1978 to 1989 and 1990 to 1999, while the first half of the winter averages range from 1978 to 1988 and the second half covers 1989 to 1999. These divisions are essentially determined by the length of the wave buoy record, and by the absence of data in the late 1980s. The sum of the ranks for the first half of the data set is derived, and compared with the distribution of the sum assuming no trend defined in statistical tables. The hypothesis of no trend is rejected at the 0.05% level. Results from the Wilcoxon rank-sum test are given in Table 4. The test reinforces the findings of statistical significance identified for the Washington buoy (#46005), while rejecting all other sites, indicating no long-term temporal trend at these sites. Despite the lack of correlation determined by the Wilcoxon rank-sum test for the Oregon and Pt. Arena buoys, the similarity of the trends and systematic southward drop in the rate of increase in the wave-height statistics along the West Coast suggests that the results are meaningful.

Table 3 Annual mean values of the significant wave height, and winter significant wave height for buoy #46005.

Data Period 21 Years	Mean H_S (m)	Rank	Mean Winter H_S (m)	Rank
1978	2.307	2	3.239	4
1979	2.278	1	2.679	1
1980	2.522	4	3.027	2
1981	2.831	6	3.472	8
1982	-		3.360	5
1988	-		3.626	9
1989	2.465	3	-	
1990	-		3.440	7
1992	2.723	5	3.415	6
1994	2.865	8	3.231	3
1995	2.872	9	3.743	10
1997	2.834	7	-	
1998	3.126	10	3.965	11
1999	-		4.253	12
N	10		12	

Decadal Trends in Maximum Wave Heights

Similar analyses have been undertaken of the maximum significant wave heights measured each month at the six buoy locations. The results are presented in Figure 6 as annual averages of the monthly maximum heights, MAX H_S, and as averages for the winter months, WMAX H_S (October through March).

While the data are more scattered, the trends established by the buoy measurements in the Gulf of Alaska and off the coasts of Washington and Oregon are similar to those seen in Figure 5 for the monthly-averaged wave heights, but displaced upward to greater heights. Apart from the Washington maximum winter wave height data, which is characterized by a long-term increase that is statistically significant at the 0.03% level, all other regressions fitted to the data in Figure 6 are not statistically significant due to the high degree of scatter. Nevertheless, the similarity of the trends shown in the MAX H_S and the MAX WH_S to the results in Figure 5 suggests that the trends are meaningful.

Table 4 Wilcoxon rank-sum statistical analysis results for the annual average significant wave height (H_S) and the annual average winter significant wave height (WH_S).

Station	Name	N	Slope	Standard Error	Significance
46001	H_S	10	+0.005	0.008	N.S
	WH_S	17	+0.008	0.006	N.S
46005	H_S	10	+0.027	0.007	0.005
	WH_S	12	+0.042	0.011	0.050
46002	H_S	7	+0.013	0.009	N.S
	WH_S	14	+0.031	0.009	N.S
46014	H_S	15	+0.017	0.007	N.S
	WH_S	17	+0.021	0.011	N.S
46012	H_S	16	+0.004	0.008	N.S
	WH_S	16	-0.004	0.011	N.S
46023	H_S	11	+0.018	0.010	N.S
	WH_S	15	+0.010	0.013	N.S

Note: N.S denotes Not Significant at the 0.05% level.

Of the three buoy sites in the north (#46001, #46005 and #46002), Figure 6 shows the greatest upward trend for the Washington buoy. Since we are dealing with maximum waves, it is not surprising that the trend is strongest for the winter months. The rate of increase for the Washington buoy is 0.094 $m.yr^{-1}$ ($R = 0.62$), an overall increase of 2.0 m in the maximum winter wave heights for the 21-year record. This rate of increase is more than double that found for the average winter waves (0.042 $m.yr^{-1}$) in Figure 5C.

Data from the California buoys, Figures 6D through 6F, show unusual trends in averages of the monthly maximum wave heights. In contrast to the linear trends found for monthly averages of the daily significant wave heights, Figure 5, the maximum heights show a reduction centered on about 1990, lower by about 1 m compared with the highest waves during the early 1980s and again in the late 1990s. Accordingly, the regression curves through the data have polynomial equations. Here again we have a distinct difference between the wave climate of California, versus sites to the north off the coasts of Washington and Oregon.

Trends in Wave Periods

Analyses also have been undertaken to examine long-term trends in the peak spectral wave periods (T_P) measured hourly by the NDBC buoys. The results are give in Figure 7 for averages covering the entire year, the winter months, and for the maximum wave periods that were measured. Upward trends are found, indicating progressive increases in average annual and winter wave periods, with perhaps a suggestion of increases in the maximum periods as well. There is no distinct latitude pattern as found for the wave heights, and no apparent transition between California versus Oregon and Washington.

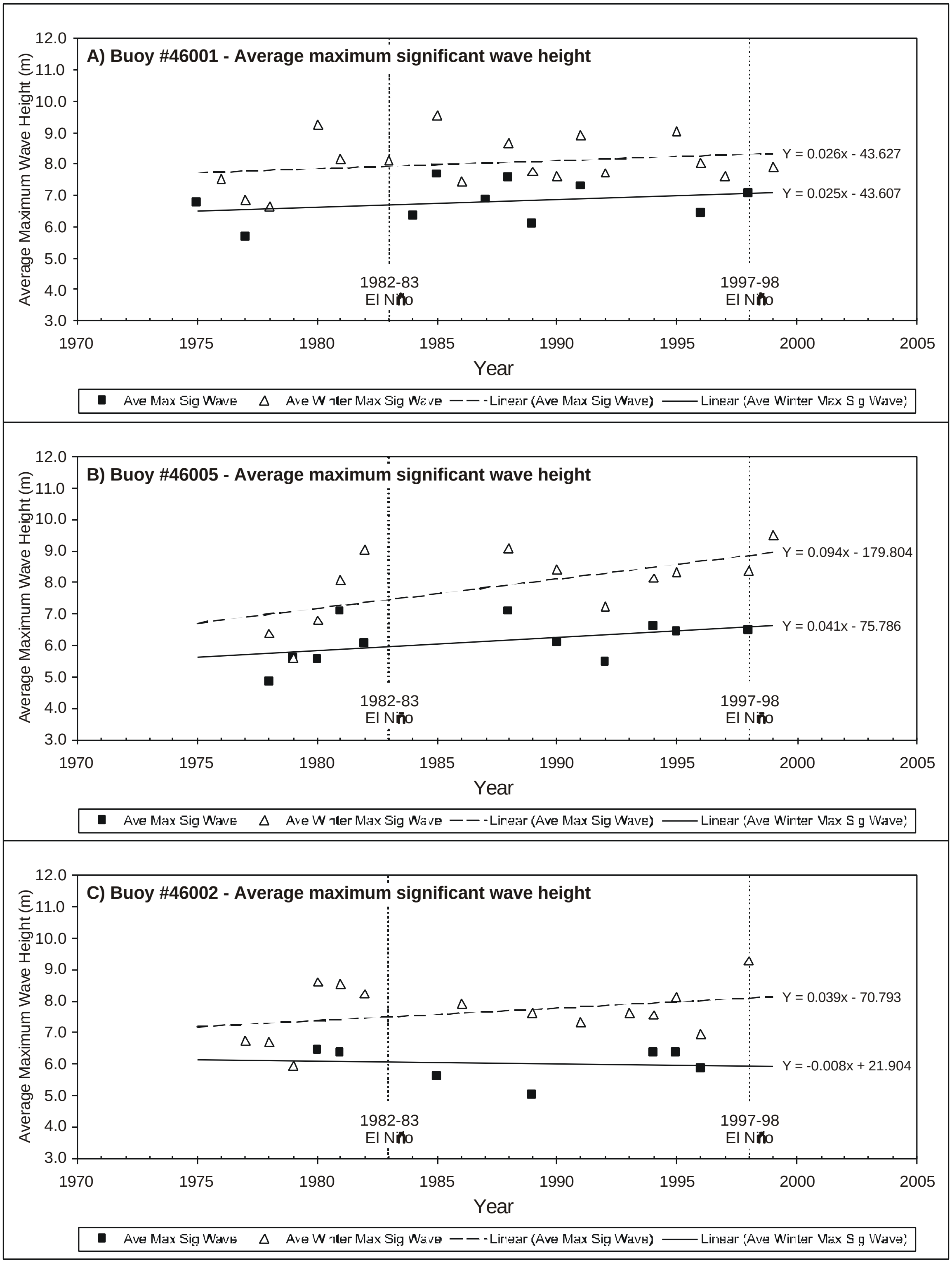

Figure 6 Long-term trends in the annual average maximum significant wave heights (MAX H_S) and the average winter (October through January) maximum wave heights (MAX WH_S) for the North Pacific buoys.

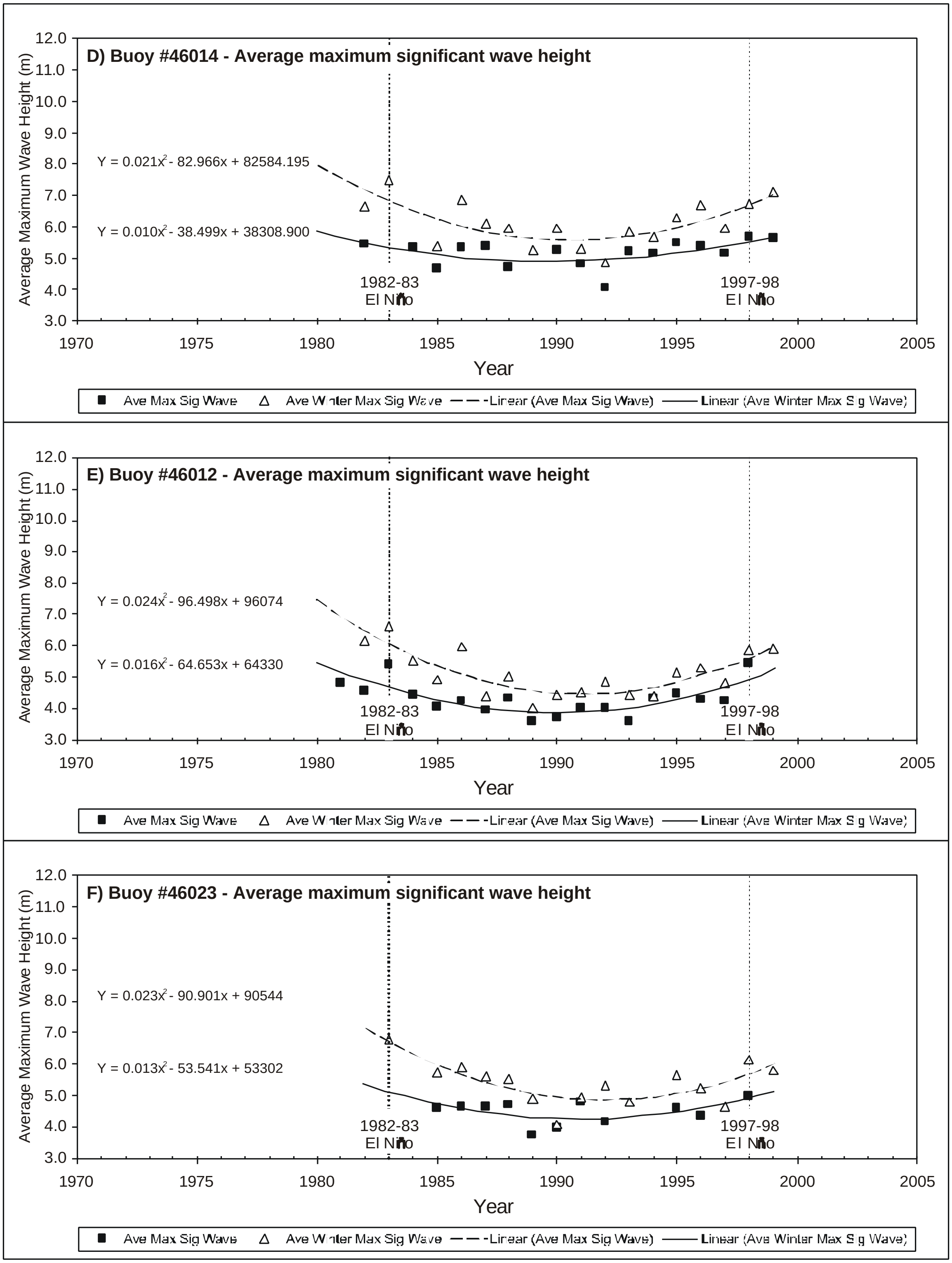

Figure 6 (Cont.) Long-term trends in the annual average maximum significant wave heights (MAX H_S) and the average winter (October through January) maximum wave heights (MAX WH_S) for the North Pacific buoys.

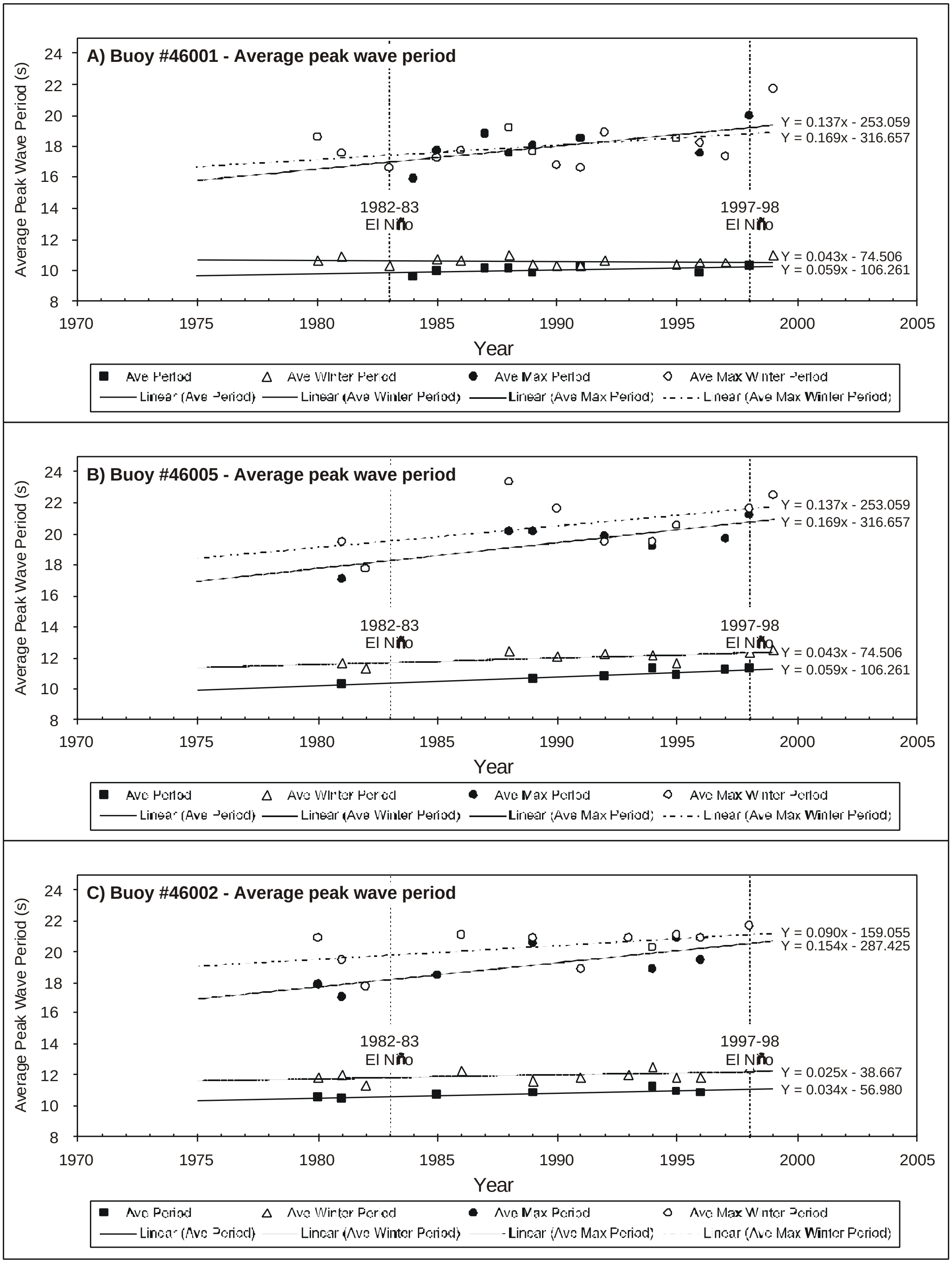

Figure 7 Long-term trends in the annual average peak spectral wave period (T_P) and the average winter (October through January) peak spectral wave period (WT_P) for the North Pacific buoys.

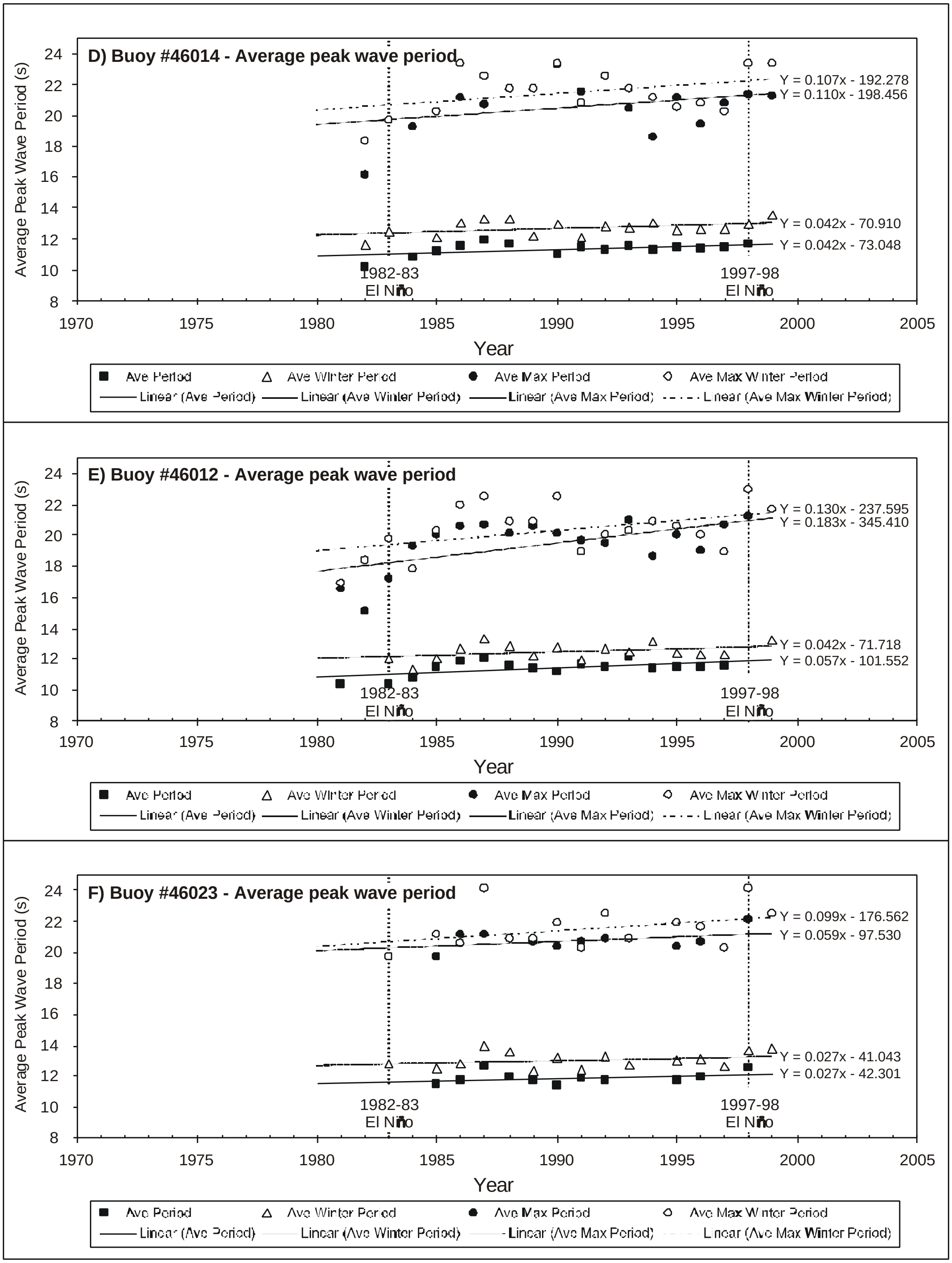

Figure 7 (Cont.) Long-term trends in the annual average peak spectral wave period (T_P) and the average winter (October through January) peak spectral wave period (WT_P) for the North Pacific buoys.

Statistical analysis of the wave period trends observed at each of the wave buoy sites is presented in Table 5. As shown in the Table, the rise in the annual average peak wave periods (T_P) and the annual average winter peak periods (WT_P) is statistically significant at the 0.043% level or lower for the Washington and Oregon buoys; again the one exception is the Oregon buoy which shows no statistically significant trend in its annual average T_P. Further, the annual average T_P trends for the Pt. Arena (#46014) and Half Moon Bay (#46023) buoys are also statistically significant at the 0.046% level or lower. Data for the Washington buoy yield a rate of increase for the annual average T_P of 0.059 $sec.yr^{-1}$, while WT_P grew by 0.043 $sec.yr^{-1}$. This amounts to an overall increase in the annual average peak period T_P by 1.1 sec during the 19-year record, and 0.82 sec for WT_P. In contrast, the T_P for the Pt. Arena (#46014) and Half Moon Bay (#46023) buoys increased at a rate of 0.042 $sec.yr^{-1}$ to 0.057 $sec.yr^{-1}$, yielding an overall increase in the T_P of between 0.67 - 0.91 sec since 1981. These findings are consistent with the regional changes identified in the wave height data presented above. However, because of the few wave period data points available for the Washington and Oregon buoys, Table 5, the trends and rates should be viewed with some caution.

Station	Name	N	Slope	Standard Error	Pearson's R	F Statistic	Significance F
46001	T_P	10	+0.025	0.017	0.51	2.151	N.S
	WT_P	17	-0.004	0.011	0.09	0.107	N.S
46005	T_P	7	+0.059	0.010	0.93	31.668	0.002
	WT_P	9	+0.043	0.018	0.68	6.111	0.043
46002	T_P	7	+0.034	0.010	0.83	10.910	0.021
	WT_P	11	+0.025	0.018	0.43	2.022	N.S
46014	T_P	15	+0.042	0.019	0.52	4.843	0.046
	WT_P	17	+0.042	0.021	0.45	3.886	N.S
46012	T_P	16	+0.057	0.024	0.53	5.581	0.033
	WT_P	16	+0.042	0.027	0.39	2.523	N.S
46023	T_P	15	+0.027	0.028	0.31	0.959	N.S
	WT_P	17	+0.027	0.027	0.26	0.977	N.S

Note N.S denotes Not Significant at the 0.05% level.

Table 5 Linear regression analysis results for the annual average peak wave period (T_P) and the annual average winter peak wave period (WT_P).

Trends in Storm Frequency

Accompanying the long-term trends of increasing wave heights and periods offshore from the Pacific Northwest, are variations in the numbers of storms. It is recalled that during the 1997-98 El Niño, the Pacific Northwest received one large storm that generated significant wave heights greater than 10 m, while the recent 1998-99 La Niña produced four storms, with one storm (March 2-4, 1999) having generated a deep-water significant wave height of 14 m (Komar et al., in review). These storms have greatly exceeded previous projections of the expected most severe storm waves for the Pacific Northwest, suggesting that larger magnitude storms may have increased in frequency in the North Pacific.

Analyses have been carried out on the frequency of storms, Figure 8, for the Washington (#46005) and Oregon (#46002) wave buoys located off the Pacific Northwest coast. Storms were defined as those events when the significant wave height exceeded 6 m for a duration of 9 hours or more, an approach that is similar to that used by Seymour (1996). Unlike the linear trends of increasing wave heights and periods, there are marked cycles in the number of storms that have occurred over the past three decades. During the late 1970s, Figure 8, the frequency of large storm events was generally low, averaging about 2 to 5 storms. The incidence of storms increased throughout the early to mid 1980s, reaching a maximum of 12 events during the winters of 1982-83 and 1987-88. Between 1988 and the mid 1990s, the frequency of large storms steadily decreased, reaching a low of 3 to 5 storms during the 1996-97 winter. Of great significance however, is the dramatic increase in the number of large storm events that have occurred during the two most recent winters. As can be seen from the graph, the 1997-98 El Niño and 1998-99 La Niña winters were both characterized with more than 20 events, in which the heights of the waves exceeded 6 m or more. Clearly, this represents the highest incidence of severe storms during the past three decades.

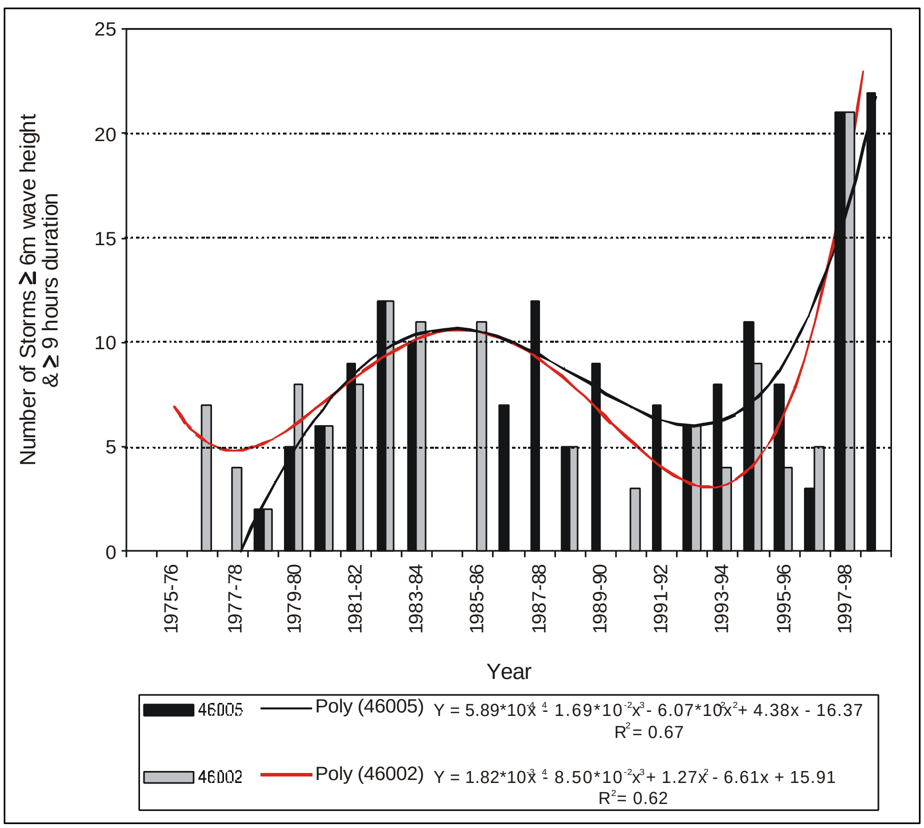

Figure 8 Temporal plot of the number of storm events that occurred in the Pacific Northwest between 1975 and 1999. Large storms were defined as those events that exceeded 6 m significant wave heights for durations of 9 hours or more.

Possible Causes of the Long-Term Trends

The long-term changes in wave statistics found in the North Pacific demonstrate the development of a significant increase in the wave energy and power (proportional to the square of the wave heights and peak periods) since the late 1970s, with the greatest change having occurred in the Pacific Northwest (Washington and Oregon). Such changes are of concern since the risks from coastal erosion and inundation also increase, as do the costs associated with responding to these hazards. In addition, our analyses have revealed a cyclical nature to the incidence of large storms off the Pacific Northwest coast, with the greatest frequency of large events having occurred during the two most recent winters. This raises the question of whether these trends can be expected to continue in the future, resulting in progressively greater impacts to our coasts. To answer this question, we need to understand the possible causes of the long-term trends of increasing wave energies.

Changes in the North Pacific wave climate should reflect some form of adjustment in the parameters important to wave generation - the strength of the wind, the storm duration, and available fetch length. Several questions can be asked that relate to possible long-term changes in these parameters. For example, have wind speeds noticeably increased during the past three decades? Is there evidence for an increase in the duration in which strong winds blow across the North Pacific? Have the paths of storm systems changed since the 1970s? We are not yet in a position to answer the last two questions, but can provide some insight into the question of whether wind speeds have strengthened in the North Pacific.

The most logical cause of the temporal trends identified in the wave statistics might be a simple relationship to a parallel increase in wind speeds over time. Analyses of the average annual wind speeds and the winter wind speeds were carried out for each of the NDBC buoys. The method of data analysis is identical to that undertaken for the wave heights and periods. Here, we will focus on the trends identified in the annual winter wind speeds, since those data have the most complete temporal record. Figure 9 is a graph of the annual winter wind speeds measured at each of the buoys, plotted against time. Since the data exhibit distinct curvilinear patterns, 2nd order polynomial equations have been fitted to the data. It is seen that average annual winter wind speeds tended to be highest during the latter half of the 1970s, and progressively decreased to a minimum in the late 1980s. This pattern appears to be consistent along the entire West Coast of North America (Figure 9). Since the late 1980s, wind speeds at each of the buoys have steadily increased in strength with time. The graph also highlights the latitude variation in wind speeds, such that the northern buoys are characterized by much stronger average wind speeds, compared with the buoys located along the coast of Southern California. This difference in wind strength is likely to be a major factor influencing the latitude variations observed in the significant wave heights described above. When the long-term linear trends identified in the wave height data, Figure 5, are compared with the patterns found for the wind speeds, Figure 9, it is clear that they are not directly related. In reality, this finding is not surprising since the wave climate in any given region of the Pacific Ocean is a complex function of waves generated by distant storms, plus those associated with near-field storm systems or locally generated winds. Thus, it is necessary to derive some alternative measure of winds for the North Pacific.

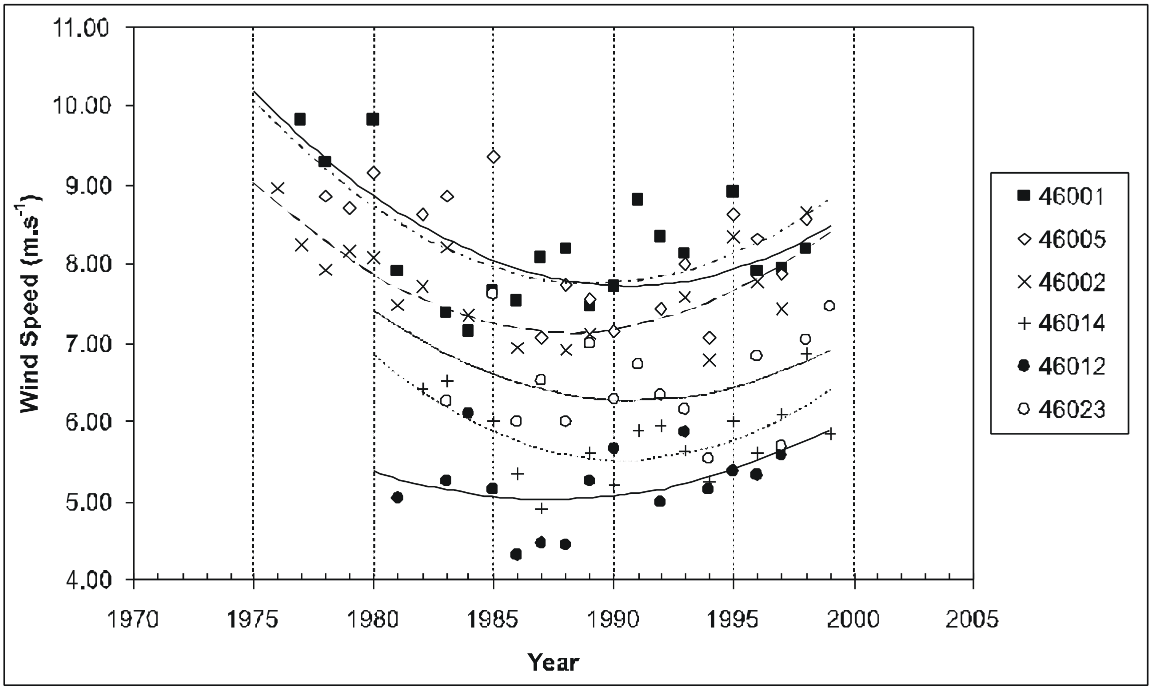

Figure 9 Long-term trends in the annual average winter (October through January) wind speeds for the North Pacific buoys.

Bacon and Carter (1993) and Kushnir et al. (1997) convincingly demonstrated a link between the increase in significant wave heights observed in the North Atlantic and North Sea, with a simultaneous increase in the north-south sea-level atmospheric pressure gradient between Iceland and the Azores. This pressure gradient was used as a surrogate of the strength of the westerly winds that drive the wave climate in the North Atlantic, the steeper the gradient the stronger the winds. Furthermore, Bacon and Carter (1993) noted that the rise in the pressure gradient between Iceland and the Azores was related to a dramatic decrease in the central pressure of the Iceland Low since the 1950s, corresponding approximately to the documented increase in wave heights.

We have undertaken a similar analysis for the North Pacific. Data relating to the East Pacific Teleconnection Pattern (EP) were obtained from the Climate Prediction Center (CPC) [http://www.cpc.noaa.gov/data/teledoc/telecontents.html]. This index reflects a north-south dipole of monthly mean 700-mb pressure height anomalies over the eastern part of the North Pacific. The northern center reflects the position of the Aleutian Low, located in the vicinity of the Gulf of Alaska and the west coast of Canada, while the southern center is of opposite sign and is found near, or east of, Hawaii. According to the CPC, when the EP Pattern is strongly positive, the Aleutian Low is characterized by a deeper than normal trough located in the vicinity of the Gulf of Alaska/western North America, while positive height anomalies are observed farther south near Hawaii. This phase of the pattern is associated with a pronounced northeastward extension of the Pacific jet stream toward western North America. During this phase, westerly winds are enhanced, and the storm systems are directed toward the Pacific Northwest and northern California. Conversely, during strong negative phases of the EP Pattern, a pronounced split-flow configuration occurs over the eastern North Pacific, which results in reduced westerly winds throughout the region. In addition to the EP Pattern, the areaweighted barometric sea level pressure (SLP) averaged over the region of 30°N-65°N, 160°E-140°W, were also utilized in our analyses. These data characterize the North Pacific Index (NPI), a measure of the relative strength of the Aleutian Low for the period 1899-1999. The data were obtained from the National Center for Atmospheric Research, [http://www.cgd.ucar.edu/cas/climind/np.html].

Figure 10 is a graph of the annual averages of the winter EP Pattern (October through March) from 1960 to 1999, and the NPI for the period 1899 to 1999. A 2-year moving average has been fitted to the EP data set, while the NPI is fitted with a 3-year moving average. As can be seen from Figure 10A, the EP Pattern is characterized by a number of prominent climate regime shifts in the past three decades. During the early half of the 1970s the EP was in a strong positive phase - the strongest positive phase since the index began in 1950. This would suggest that the Pacific Northwest and Northern California were subjected to a strong westerly wind regime during the early 1970s. This conclusion is supported somewhat by the graph of the wind speeds, Figure 9, which indicates that the average annual winter winds were highest during the mid-1970s. The NPI is also characterized with a number of decadal and interdecadal regime shifts that have occurred over the past century. Further, over the complete record it can be seen that the NPI has steadily decreased, suggesting that the Aleutian Low has intensified.

In 1975, the EP Pattern altered from a strong positive phase, to a moderately negative phase that peaked in 1979. The Aleutian Low deepened throughout this period, and continued to deepen until the winter of 1982-83. This finding is consistent with the data analyses of Ward and Hoskins (1996) and Mantua et al. (1997). In particular, Ward and Hoskins observed that the Aleutian Low was deeper during the 1980s than in the preceding decades, and noted that this would have lead to more intense near-surface circulations to the south.

From 1979 to 1984, the EP Pattern strengthened and returned to a positive phase, while the NPI remained negative until about 1987 (Figure 10). As described above, the positive EP phase reflects periods in which the westerly winds are enhanced over the Pacific Northwest and Northern California. It is of interest to note that these changes approximately coincided with the initial rapid phase in the increase of WH_S measured by the Pacific Northwest wave buoys during the late 1970s and early 1980s (Figure 5). In addition, the analyses of Ward and Hoskins (1996) revealed that wind speeds increased throughout this period in the North Pacific. A similar increase in wind speeds was identified for the North Atlantic by Ward and Hoskins, although this latter trend was not as statistically significant as the rise in wind speeds measured in the North Pacific. Nevertheless, it is apparent that the wave climate changes observed in the North Pacific closely parallel the trends previously reported for the North Atlantic and North Sea by Carter and Draper (1988), Bacon and Carter (1991), and Kushnir et al. (1997).

Throughout the 1980s the EP Pattern gradually decreased, Figure 10A, though remained in a positive phase until 1990. By 1992, the EP Pattern had become strongly negative, implying a reduction in the westerly winds, while the NPI entered a positive phase, characterized by higher atmospheric pressures. These changes are somewhat reinforced by the decrease in the wind speeds measured at the wave buoys during the late 1980s. As shown in Figures 5B and 5C, the winter wave heights are characterized by a decrease from the late 1980s to about 1994, consistent with the change in the EP and NPI patterns. However, the rate of change in the EP Pattern is not matched by the rate of decrease in the wave heights, and may reflect some form of lag effect, or is related to a rapid deepening of the Aleutian Low after 1993 (Figure 10B). Since 1993, the EP Pattern gradually increased, Figure 10A, while the NPI rapidly decreased. As a result, during the latter half of the 1990s, the Aleutian Low deepened and intensified. This latter phase may explain the rise in wave heights observed throughout the latter half of the 1990s. By 1998-99, the EP Pattern had re-entered a strong positive phase, one of the strongest on record (Figure 10A).

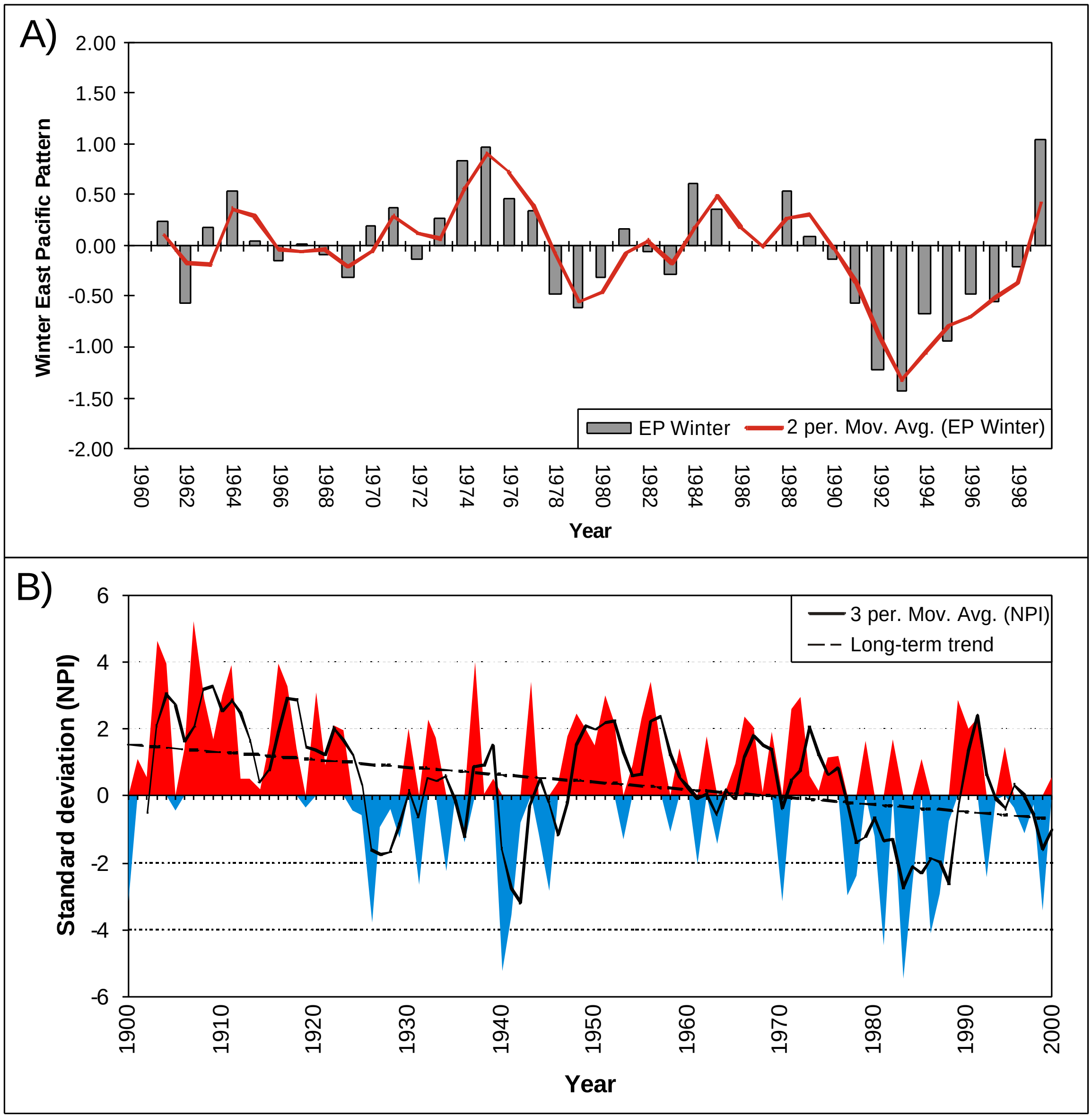

Figure 10 A) East Pacific (EP) Teleconnection Pattern for the North Pacific, 1960-1999; B) The North Pacific Index (NPI), 1900-1999.

The pattern of variation in the EP and NPI since the mid-1970s, Figure 10, is remarkably similar to the variations in the storm events that have occurred on the Pacific Northwest coast, Figure 8. The large numbers of storms that occurred between 1997 and 1999 correspond to a marked increase in EP values, becoming strongly positive in 1999 following several years of negative EP values when the number of storms in the Pacific Northwest was much lower. This reinforces the close association that exists between the North Pacific wave climate and the predominant climatological regime.

To extend the argument for a relationship between the EP Pattern and the increase in the North Pacific wave heights, the annual average winter wave heights measured at the Washington and Oregon buoys were correlated with the EP. Unfortunately, no statistically significant correlation was discernable. This analysis is closest to that undertaken in the North Atlantic where good correlations were found (Bacon and Carter 1991, Kushnir et al., 1997). However, in using the EP index our analyses account for only the north-south pressure difference, as opposed to a true pressure gradient as used in the North Atlantic studies. Despite this, it is unlikely that the use of a true pressure gradient would have contributed to a significant improvement in the correlation. Similar analyses were carried out with the NPI. However, although this index reveals that the Aleutian Low has deepened since 1900, correlations with the annual average winter wave height values revealed no statistically significant trend. Nevertheless, the long-term pattern towards a deeper more intense Aleutian Low is similar to changes that have been identified in the NA, where the Iceland Low has also deepened over time (Bacon and Carter, 1993). Intuitively, such changes should be reflected in the North Pacific wave climate.

Although we have been unable to find a link between the EP Pattern and NPI with the annual average winter wave heights, a correlation is found with the EP if the wave-height data is de-trended, that is, the value for the linear trend of increasing heights with time is subtracted from the measured WH_S for each year. Wave data measured by the Washington buoy were used in the correlation since it is characterized by the largest temporal increase in the winter wave heights. Although the data in Figure 11 exhibit some scatter, a relatively good correlation is achieved between the EP index and the WH_S residuals ($R = 0.68$), which is significant at the 0.015% level. Of importance, the graph reveals that positive phases of the EP Pattern, associated with stronger winds in the North Pacific and with the jet stream passing over the Pacific Northwest, correspond to positive WH_S values, higher than usual waves, while negative EP values correspond to lower wave heights. This pattern is therefore consistent with the qualitative descriptions provided above. However, because the regression accounts for only 46% of the data variation in Figure 11, this suggests that other factors such as possible shifts in the tracks of storms or changes in the persistence of winds, may also account for some of the long-term increase in wave heights that have occurred in the Pacific Northwest. Therefore, although the EP index did not account for the long-term average trends of increasing wave heights, it does account for part of the annual variations in the wave conditions above or below that average trend.

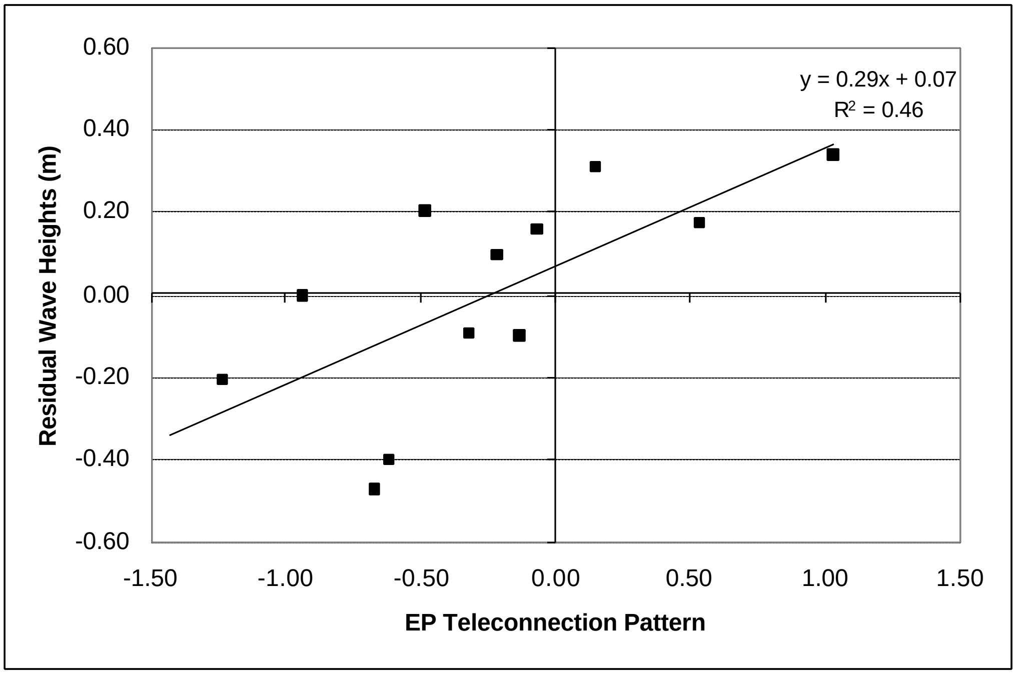

Figure 11 Correlation of the EP Teleconnection Pattern and the winter wave height residuals determined for the Washington (#46005) buoy.

The North Pacific is also characterized by interdecadal fluctuations, or regime shifts, that have occurred since at least the 1920s. These fluctuations have been given the name the Pacific Decadal Oscillation (PDO) by Mantua et al. (1997), and reflect a close association between the ocean and atmosphere environments. Figure 12 presents a graph of the PDO, derived from sea surface temperature anomalies. These data have been obtained from the University of Washington, Climate Impacts Group web site [ftp://ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/PDO.latest]. Mantua et al. (1997) correlated the PDO with a variety of indices, including the SOI and SLP. They found that the PDO correlated well, particularly with the SLP index. They further demonstrated that positive (negative) phases of the PDO tended to coincide with warm- (cold) phase El Niño-like (La Niña) conditions; conversely, positive phases of the PDO tended to be characterized by negative SLP anomalies, that is by an intensification of the Aleutian Low. Since 1977, the PDO has been in a predominantly positive phase, Figure 12, reinforcing the link between the increase in wave statistics during the past three decades, and the predominant climatological regime of the North Pacific since about 1977. Previously, the PDO was in a positive phase between 1925 and 1946, and a negative phase from 1946 to 1976. It is interesting to speculate about the characteristics of the wave climate during those periods [i.e. higher wave energy conditions between 1925 and 1946], compared with lower energy conditions during the negative phase. Unfortunately, no correlations could be found with the long-term trends of increasing wave statistics.

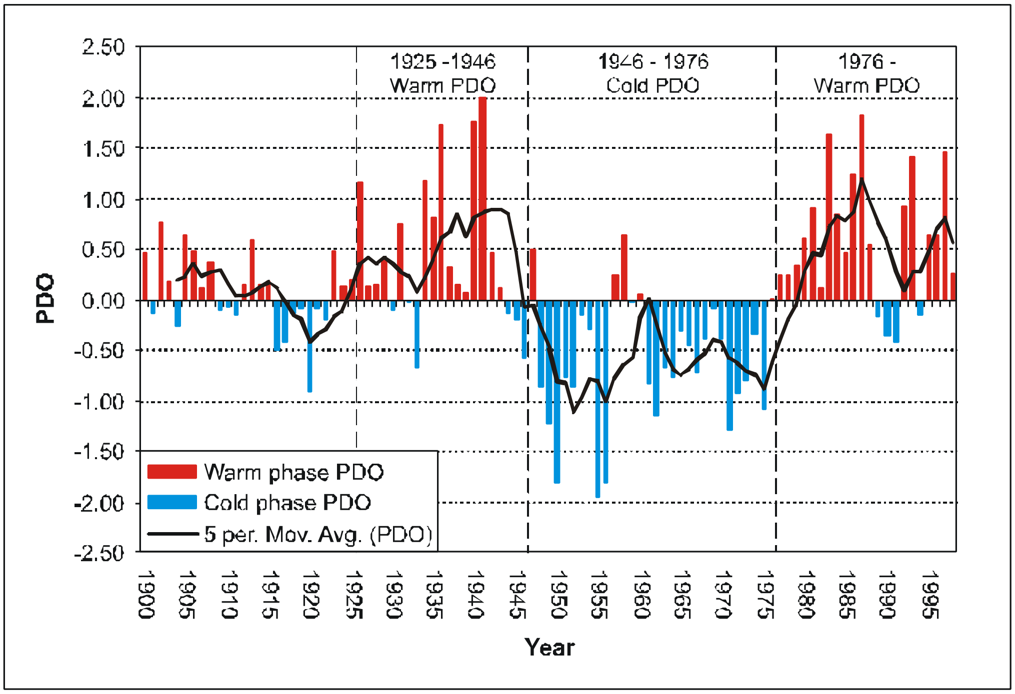

Figure 12 The Pacific Decadal Oscillation (PDO) climate index, 1900-1999.

Finally, it is also possible that the increase in the wave statistics might be related to global warming, caused by the increase in Greenhouse gases in the atmosphere. According to Mann and Park (1996) and Livezey and Smith (1999), mean surface temperatures observed around the globe have increased significantly since the 1960s, in response to anthropogenic effects. As a result, the change in wave statistics in the North Pacific, and those identified in the North Atlantic and North Sea, may be related to some form of global climate change. However, given the shortness of wave and climate records, this hypothesis is not easily demonstrated, and remains highly contentious. Notwithstanding this, recent work on the impacts of global climate change on the Pacific Northwest, undertaken by the JISAO/SMA Climate Impacts Group (1999), has revealed through the use of climate models that large-scale climate changes are predicted to occur over the Pacific Ocean during the next 50 to 100 years. In particular, their models reveal that the Aleutian Low is likely to continue to deepen and move southward, Figure 13, resulting in an increase in wind speeds along the West Coast of North America. These changes are likely to result in a higher incidence of situations similar to the 1982-83 and 1997-98 El Niño events [JISAO/SMA Climate Impacts Group (1999)]. As a result, it is possible that the ensuing decades could be characterized by stormier conditions, and further increases in North Pacific wave energies.

Our inability to relate the long-term trends of increasing wave statistics in the North Pacific to one of the climate indices is surprising considering this was accomplished in the North Atlantic (Bacon and Carter 1991, Kushnir et al., 1997). Moreover, it is known that there has been a corresponding long-term trend of increasing winds in both the North Atlantic and North Pacific, with the latter having the stronger trend (Ward and Hoskins 1996). Evidence for this comes from the millions of ship observations of near-surface winds that have accumulated over the years. However, there has been some debate concerning the quality of this data, and whether the apparent increase in wind speeds may have resulted from the shift from visual estimates to the increasing use of anemometers. In a detailed comparison between the wind measurements and those calculated from mean sea-level pressure gradients, Ward and Hoskins (1996) concluded that on a global basis there has been no significant trend of increasing wind strengths between 1949 and 1988. However, they did find regional patterns of increasing winds, most significantly in the extratropical North Pacific. During the time frame corresponding to our wave-data analyses, the wind speeds have shown an upward trend that amounted to an increase of about 4 ms^{-1} but with considerable interannual variability superimposed on this trend.

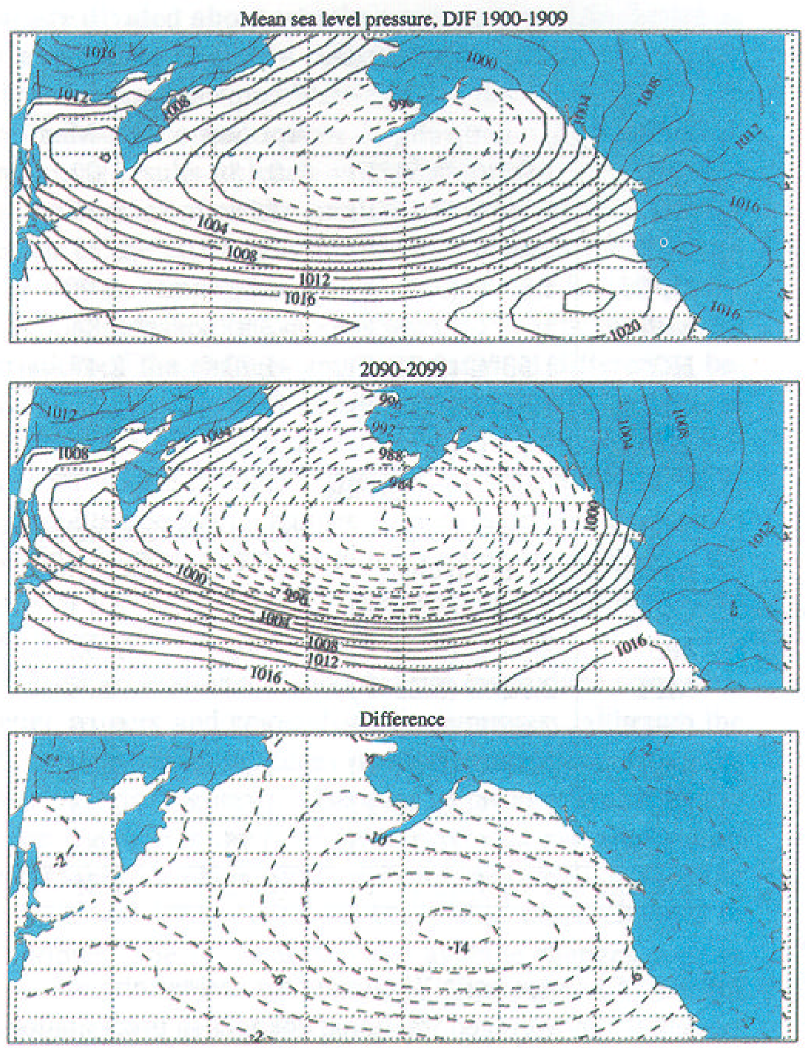

Figure 13 Simulated sea level pressure field for A) 1900's; B) 2090's; and C) the difference. Contour interval is 2-mb. Dashed contours represent pressures below 1000-mb in the top two panels, and represent pressure decreases in the bottom panel *[From JISAO/SMA Climate Impacts Group, 1999, p22]*.

DEPENDENCE ON EL NIÑO AND LA NIÑA

The previous section has identified long-term temporal patterns in the North Pacific wave height statistics that parallel wave climate changes that have occurred in the North Atlantic and North Sea. In addition, the analyses have revealed a systematic increase in the significant wave heights along the West Coast of North America, produced by the 1982-83 and 1997-98 El Niños, and more recently by the 1998-99 La Niña which generated above average wave conditions along much of the West Coast of North America, including Southern California (Figure 5). This suggests a dependence of the annual wave conditions in the North Pacific on the climatic spectrum ranging between El Niños and La Niñas, that is, on the status of the Southern Oscillation. However, the above analyses have also demonstrated that the recent increased wave conditions between 1997 and 1999 may be related to the development of strong positive EP values.

Characteristics of El Niño and La Niña Events

Previous studies of the characteristics of waves in the North Pacific have revealed that the wave climate is strongly influenced by climate changes that occur in response to the El Niño/La Niña - Southern Oscillation climatic anomaly (Earle et al., 1984; Komar, 1986; Seymour, 1998; Storlazzi and Griggs, in press). These climate fluctuations occur interannually with dominant periods of 5 to 6 years (Ghil and Vautard, 1991), but may occur over a range of intervals from 2 to 7 years (Kleeman et al., 1996).

The effects of El Niños on the West Coast first became apparent during the 1982-83 event, and more recently in 1997-98, when it resulted in considerable erosion on the coast of California (Earle et al., 1984; Flick, 1998; Seymour, 1998; Storlazzi and Griggs, in press), and in the Pacific Northwest (Komar, 1986; Komar et al., in review). While these erosion responses are related to an increase in wave energy and a rise in mean water levels along the coast during an El Niño, they also reflect a shift in the predominant direction in which the waves approach the shore, resulting in "hotspot" coastal erosion (Komar, 1986). More recently, Komar et al. (in review) analyzed the processes of erosion associated with the La Niña climatic anomaly. Their findings revealed a significant increase in wave energy levels during the 1998-99 La Niña, that were substantially higher than the El Niño winters. As a result of the present investigation, it has been suggested above that the increase in wave energy levels and the frequency of storms during the1998-99 La Niña may be related to an abrupt climate shift identified in the EP and PDO patterns.

El Niños and La Niñas can be viewed as opposite extremes in an otherwise continuum of atmospheric and oceanic conditions, with intermediate "normal" or "average" conditions generally prevailing (Komar et al., in review). During "average" years the eastern equatorial Pacific is dominated by a region of high atmospheric pressure, while conversely a low atmospheric pressure characterizes the western equatorial Pacific. As a result of the pressure gradient between these two regions, easterly and southeasterly Trade Winds are generated along the equator. These winds elevate the level of the sea in the western equatorial Pacific, while ocean upwelling occurs along the West Coasts of North and South America.

With the onset of an El Niño, the easterly and southeasterly Trade Winds break down due to a reversal in the pressure gradient along the equatorial Pacific. As a result, the potential energy of the sloping water surface is released, causing a wave-like bulge in the sea level to propagate eastward along the equator, together with a pool of warm water. Wyrtki (1977) has followed the propagation of the sea-level bulge through analyses of tide gauges located along the equator. His results revealed that during an El Niño, mean water levels are raised by up to 50 cm, and that the rise in water levels occurs rapidly.

As the sea-level bulge arrives on the coast of South America, it splits, with the separate parts respectively moving north and south along the coast. The sea-level wave is now held by the inclination of the continental shelf and slope, by the combined effects of refraction and the Coriolis force. These processes prevent the sea-level wave from flowing out to sea and dissipating. Enfield and Allen (1980) have analyzed tide gauge records along the West Coast of North America, and have shown that the sea-level wave is capable of traveling as far north as Alaska. In addition, they demonstrated that the sea-level wave looses relatively little height as it propagates along the coast due to the increasing effect of the Coriolis force at higher latitudes. In terms of the change in water elevations caused by the sea-level wave, Flick (1998) has demonstrated that the 1982-83 and 1997-98 El Niños resulted in mean water levels being raised by up to 35 cm on the central California coast, while analyses of tide gauges in the Pacific Northwest indicated that the monthly average water level is raised by 60 to 70 cm (Komar et al., in review).

Aside from changes to the mean water levels on the coast, the tracks and intensities of storm systems are also altered during an El Niño. In particular, the paths of the polar and subtropical jet streams are changed from their courses during “average” years (Taylor, 1998; Storlazzi and Griggs, in press). During an El Niño, the paths of the jets split; the polar jet stream follows a more northerly course, dipping southward over the North Pacific and then veering northward into Alaska, while the subtropical jet is directed over the California coast. It is recalled from above that when the EP Pattern is in a negative phase, a pronounced split-flow configuration occurs in the jet stream over the eastern North Pacific. This type of situation occurred during the 1982-83 El Niño, while much of the 1990s (an El Niño period) was also characterized by a strong negative EP phase. Because the subtropical jet is centered over California, a larger number of high magnitude storm systems cross the California coast. These storms generate higher than average wave energy levels. Accordingly, it is this combination of high wave energy levels and above average mean water levels that produces widespread erosion in Southern California during an El Niño. In contrast, due to the split flow regime in the jet stream, fewer large storms are thought to reach the Pacific Northwest. As a result, Seymour (1998) hypothesized that the Pacific Northwest would experience generally lowered wave energies during El Niños.

The La Niña phase of the Southern Oscillation, and its associated processes, is poorly understood when compared with the El Niño phenomena. Nevertheless, its influence in terms of causing widespread coastal erosion is no less significant than that caused by El Niño (Komar et al., in review). In general, La Niñas tend to be characterized by Trade Winds that are stronger than average, which results in the enhancement of upwelling along the equator. Due to the increased ocean upwelling, a pronounced east-west temperature gradient develops along the equator, with the western Pacific characterized by much warmer water temperatures, while the eastern Pacific experiences on average colder water temperatures. Despite the temperature gradient in the sea surface temperatures, there is no sea-level wave that is released. As a result, unlike El Niños, La Niñas tend to be characterized by mean water elevations that are close to normal.

Unlike the El Niño phase, which is dominated by a split-flow configuration in the jet streams, during a La Niña the polar jet follows a more northerly course toward the Bering Straight and then to the southeast, toward the Pacific Northwest (Taylor, 1999; Storlazzi and Griggs, in press). The position of the subtropical jet is also altered so that it merges with the polar jet, producing intense extratropical storms, as a result of the mixing of warm tropical air with the cold polar air, that are directed at the Pacific Northwest coast. Due to these characteristics, one might expect that La Niñas would result in higher wave energies along the Pacific Northwest coast, with comparatively smaller wave energies occurring along the California and Alaska coasts.

Indices of the Southern Oscillation Phenomena

A variety of indices are available that characterise the status of the Southern Oscillation. These include the Southern Oscillation Index (SOI) monitored by the Climate Prediction Center, a Multivariate ENSO Index (MEI) proposed by Wolter and Timlin (1993), and a revised ENSO Index (REI) proposed by Storlazzi and Griggs (In press).

The SOI is based on the difference in barometric SLP anomalies between Darwin and Tahiti, and has been normalized by the standard deviation of the monthly values of the respective index for all months combined for the years 1951 to 1980. In contrast, the MEI is derived from six variables that are observed over the tropical Pacific. These include the sea-level pressure (SLP), zonal (U) and meridional (V) components of the surface wind, sea surface temperature (S), surface air temperature (A), and total cloudiness fraction of the sky (C). The MEI is computed separately for each of twelve sliding bi-monthly seasons (Dec/Jan, Jan/Feb,... Nov/Dec), and is calculated as the first unrotated Principal Component (PC) of all six observed fields combined. According to Wolter and Timlin (1993), all seasonal values are standardized with respect to each season, and to the 1950-93 reference period.

The REI index developed by Storlazzi and Griggs (in press) is based essentially on the relative index of Quinn et al. (1987), but has been extended to include “average” years, and years during which La Niñas have occurred. This was accomplished by evaluating the fluctuations in the SOI, the MEI, and two other indices, relative to the Quinn et al. (1987) index. As a result of this approach, the REI index is characterized by two extremes; strong El Niños are represented by a value of 6, while La Niñas have the value -1. Storlazzi and Griggs (in press) demonstrated that their index correlates strongly with El Niño events. However, a notable limitation of the REI index is that the La Niña years have been standardized to the same -1 value, irrespective of differences in the strengths of the La Niñas. As a result, the index is not able to differentiate between moderate or strong La Niñas.

Southern Oscillation Effects on the North Pacific Wave Climate

Since there are clear problems in the ability of the REI index to differentiate between the contrasting strengths of La Niñas, we have relied on the MEI index of Wolter and Timlin (1993) in our analyses of the effect of the Southern Oscillation on the North Pacific wave climate. This particular index is considered to be more robust than the SOI, since it encompasses six variables, including the zonal and meridional components of the surface wind that are likely to be important in influencing the wave climate of the North Pacific. Figure 14 presents a temporal plot of the MEI index since 1950. Positive values of the MEI represent El Niño events, while negative values represent the La Niña phase. As can be seen from the graph, El Niños have tended to dominate much of the climate spectrum since about 1976, while La Niñas were more frequent prior to 1976. These patterns are thus consistent with the descriptions presented above concerning the recent warm (El Niño) PDO phase, and the cold (La Niña) PDO phase that existed between 1946 and 1976.

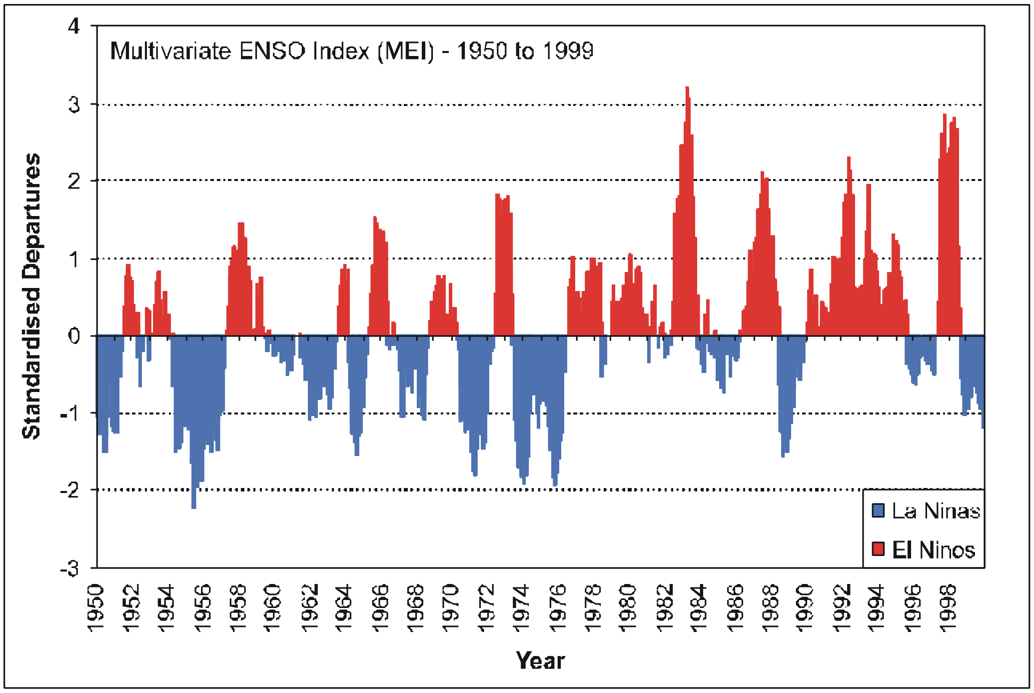

Figure 14 Multivariate ENSO index (MEI) depicting the incidence of El Niños and La Niñas since 1950.

To identify the relative influence of the Southern Oscillation on the North Pacific wave climate, the annual winter wave height residuals (WH_{SR}), the deviation of the wave heights from the linear regression temporal plots, for each of the NDBC wave buoys were correlated against the MEI (Figure 15). Since the data appear to be characterized by non-linear trends, 2nd order polynomial equations have been fitted to the data. The 1988-89 La Niña, the strongest during the period of study in terms of the MEI index, deviates markedly from the remaining data, and for this reason was not included in the regression curves. That La Niña winter also corresponded to a time with a positive EP, yet it was a year of unusually low wave conditions. This is in direct contrast with the 1998-99 La Niña, which also occurred at a time of positive EP values, but having unusually high waves along the West Coast. These differences raise an important question as to the relative roles of the EP Pattern and the MEI on the wave climate of the North Pacific.

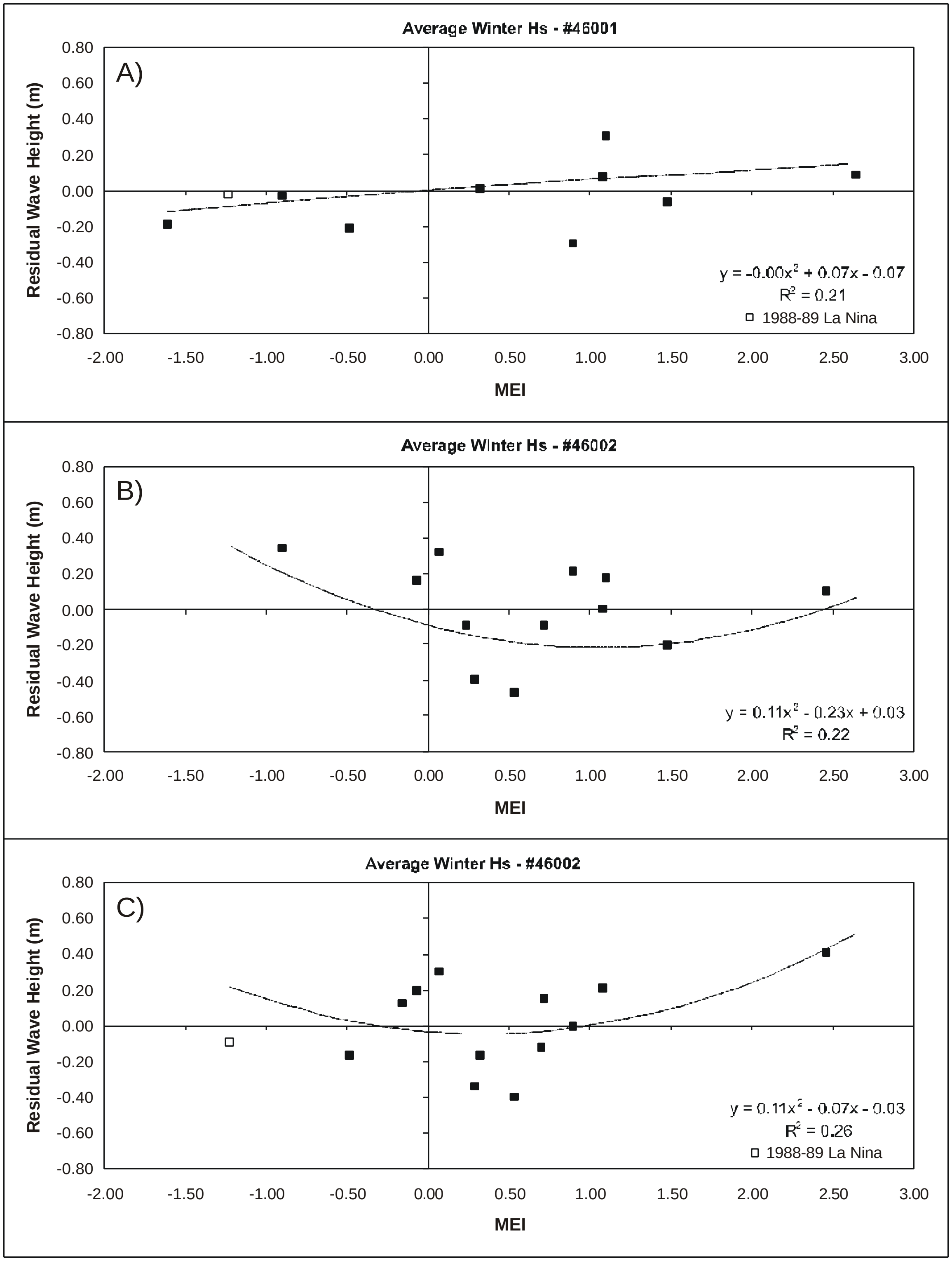

Figure 15 Correlation analyses of the MEI index and the annual winter residual wave heights.

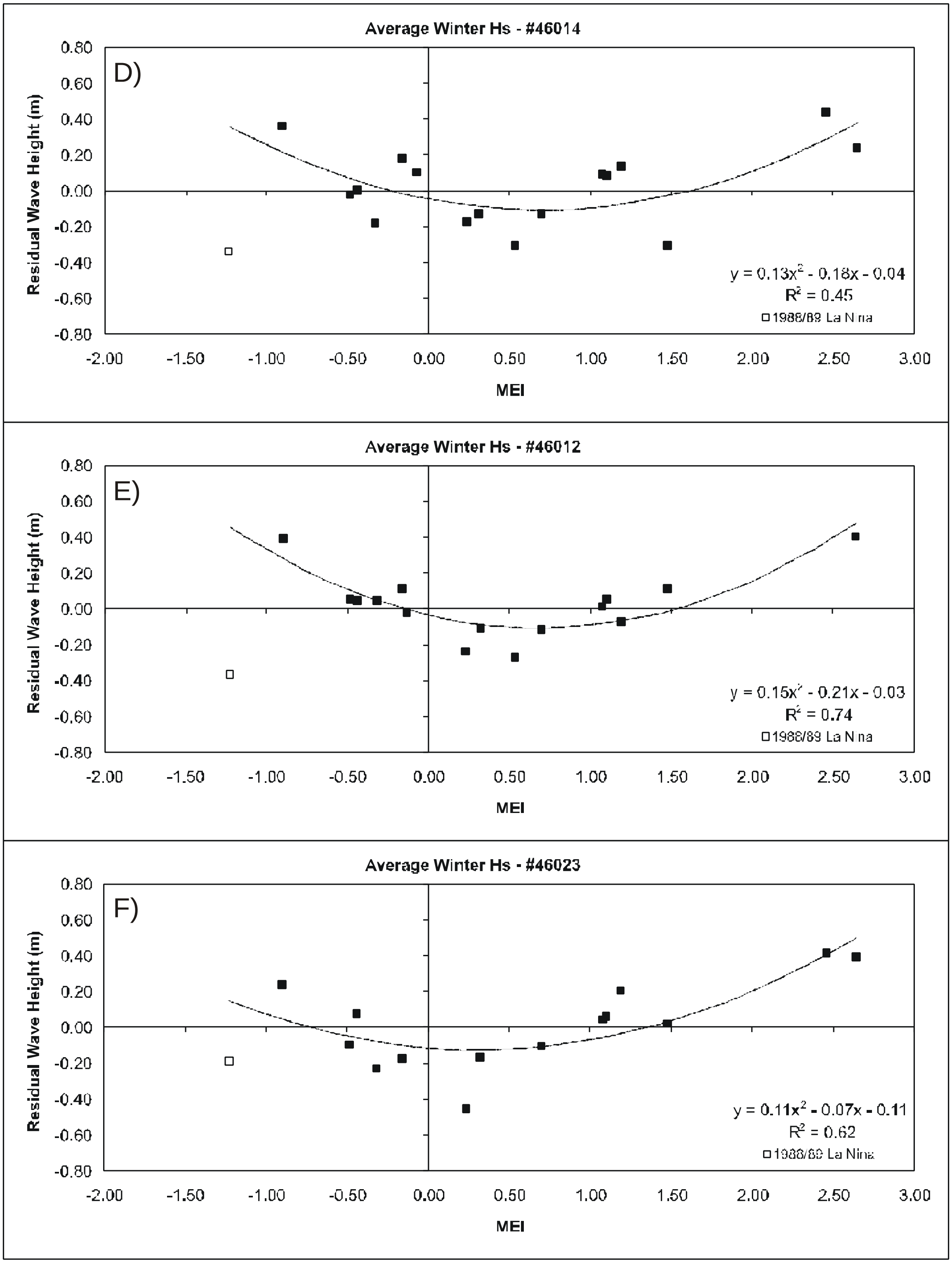

Figure 15 (Cont.) Correlation analyses of the MEI index and the annual winter residual wave heights.

Although there is considerable scatter in the Gulf of Alaska (#46001) wave data, it can be seen from Figure 15A that the Southern Oscillation phenomena does not appear to significantly influence the wave climate in the far north. Apart from the moderately strong 1987-88 El Niño, which caused a significant increase in the winter wave heights in the Gulf of Alaska, the very strong 1982-83 El Niño did not result in a comparable increase. Unfortunately, due to a problem with the instrument during the recent 1997-98 El Niño, there is no available data to assess the influence of this event on the wave climate. In addition, Figure 15A indicates that strong La Niñas (particularly the 1975-76 La Niña) resulted in much smaller waves being measured in the Gulf of Alaska. These findings therefore reinforce the perception that the wave climate in the Gulf of Alaska is strongly controlled by the locally generated winds and short fetches, as opposed to any influence from the Southern Oscillation.

Further south at the Washington wave buoy (#46005), an improvement in the correlation ($R = 0.47$) between the MEI index and the wave height residuals can be seen (Figure 15B). This suggests that the Southern Oscillation does influence the wave climate off the Washington coast, though the effect is relatively weak. As indicated in Figure 15B, there is considerable scatter in the WH_{SR}, especially at low MEI values. The general pattern shown by the curvilinear trend indicates that strong La Niñas result in larger wave heights, while strong El Niños do not appear to generate a comparable increase in the wave height residuals. However, due to the absence of similar strong El Niños (e.g. 1982-83) and La Niñas (e.g. 1975-76) in other years, this trend should be viewed with some caution. The positive increases in the WH_{SR} shown in Figure 15B for the low MEI values, also suggests that this region is influenced by large storm events during "average" years, events that can exceed any influence associated with strong El Niño phases. This finding is further reinforced by a similar correlation carried out between the MEI index and the annual average maximum winter wave height residuals (MAX WH_{SR}). Results from this latter correlation demonstrate that "average" years contribute to significantly greater increases in the MAX WH_{SR}, than occurs during El Niño and La Niña years. This finding is thus consistent with the hypothesis of Seymour (1998) that the Pacific Northwest is characterized by much larger wave energies during "average" years. However, our results reveal that this phenomenon is confined to the region north of Washington. Despite this, it is apparent that El Niño/La Niña - Southern Oscillation events, particularly La Niñas, can significantly influence the wave climate as far north as Washington.

Further south, at the Oregon (#46002) and Pt. Arena (#46014) wave buoys, El Niño/La Niña - Southern Oscillation events begin to increasingly influence the wave climate. As shown in Figure 15C and 15D, strong El Niño phases are characterized by significant increases in the wave height residuals at both buoys. Similarly, the strong La Niña of 1998-99 resulted in a significant increase in the WH_{SR} in Northern California, while the absence of a similar rise in the Oregon buoy is due to a problem with the instrument. It is interesting to note that these patterns are also consistent along the Southern California coast. As can be seen from Figure 15E and 15F, the Half Moon Bay (#46012) and Pt. Arguello (#46023) wave buoys are also characterized by prominent increases in the WH_{SR} during strong El Niños (1982-83 and 1997-98) and La Niña (1998-99) phases. Further, it can be seen from Figures 15E and 15F that there is less scatter in the residual data at low MEI values compared with those buoys located north of Pt. Arena. Interestingly, Figures 15D through 15F also indicate that very strong La Niñas can result in much smaller waves being measured. Such a phenomena occurred during the 1988-89 La Niña, and may have been related to climate changes associated with the EP

Pattern and the PDO (Figures 9 and 12). In contrast, the northern wave buoys reveal a small decrease in the wave heights for the same event.

The present analyses demonstrate that the relationship between El Niño/La Niña - Southern Oscillation events and the wave climate of the North Pacific is far from simple, a function of the complex association that exists between the ocean-atmosphere environments. In general, the regional influence of El Niño/La Niña - Southern Oscillation events has been demonstrated above. In particular, there is strong evidence in Figure 15 to suggest that major El Niños, correspond to years of higher wave conditions, in California and along the Oregon coast, while moderate events result in considerable scatter in the heights of the waves, and especially off the Pacific Northwest. Furthermore, such events do not appear to significantly influence the wave climate north of Washington.

At the other extreme, La Niñas appear to dominate the buoy measurements in the Pacific Northwest. However, it is also evident that given the right climatic conditions, strong La Niñas, as occurred during 1998-99, can generate large wave conditions as far south as Pt. Arguello located near Southern California. This suggests that the greater intensities of both El Niños and La Niñas clearly compensate for the increased distances of the storm systems, respectively from the Pacific Northwest and California coasts. However, these latter occurrences are likely to be related also to the recent positive phases of the EP Pattern, as demonstrated for the last two El Niño/La Niña - Southern Oscillation events. Based on those recent occurrences, it therefore becomes unclear how the Southern Oscillation controls the heights of waves in the North Pacific and their latitude variations, beyond the effects of the EP Pattern. At present with such a short record of wave measurements, during which only a few significant El Niños and La Niñas have occurred, the relative roles of the EP Pattern and the Southern Oscillation cannot be separated adequately enough.

SUMMARY AND DISCUSSION

Since 1997, the North Pacific has been characterized by unusually intense wave conditions that have resulted in extensive beach and property erosion along the West Coast of North America. Due to the severity of the storms and their coincidence with the 1997-98 El Niño and 1998-99 La Niña winters, important questions were raised. First, has there been a progressive increase in wave-energy levels in the North Pacific, comparable to those that have been experienced in the North Atlantic and North Sea? Second, to what extent is the North Pacific wave climate dependent on the status of the Southern Oscillation, known to be associated with the El Niño/La Niña cycle? In order to answer these questions, we have completed analyses of the temporal and spatial characteristics of wave statistics (heights and periods) derived from six NDBC wave buoys, located between the Gulf of Alaska and Southern California, for the period 1975 to 1999. The analyses demonstrate a number of important characteristics and findings concerning the seasonality, latitude variations, and long-term trends in the wave climate of the North Pacific. In particular, the study has revealed that:

- The North Pacific is characterized by a distinct tripartite wave climate system, consisting of significantly higher wave energy levels in the Pacific Northwest (Washington and Oregon) and in the far north Pacific, while much lower wave energy levels are observed along the coast of Southern California. Between Oregon and Southern California, a zone of transition occurs centered at Pt. Arena;
- A pronounced seasonality occurs in the wave climate, with the greatest change between summer and winter occurring in the Pacific Northwest and Gulf of Alaska;
- During the Spring-Summer months, the wave climate along the West Coast of North America is characterized by relatively similar conditions for wave generation, likely by locally generated winds that blow over short fetches. Annual average wave heights during these months are typically less than 2.0 m, with peak periods less than 10 sec.;
- Between August and November, wave energy levels rapidly increase, reaching a peak in December. This occurs due to an intensification of the Aleutian Low during the winter, and the southeasterly propagation of storm systems towards the West Coast. Further, the wave height increase occurs more rapidly in the north, compared with the southern wave buoys;
- The strongest storms and largest generated waves occur in the winter months (October through March). During the winter, the average WH_S ranges from 3.3 to 3.5 m in the north, with slightly larger winter wave heights being observed along the Washington coast, while the Southern California wave buoys experience average WH_S that range from 2.3 to 2.7 m;
- The largest significant wave height measured by the NDBC wave buoys reached 15.1 m, and was measured by the Oregon buoy. Typically though, the height of the MAX WH_S averages around 8.0 m north of Pt. Arena, and ranges from 5.1 to 6.1 m along the Southern and Northern California coasts;
- Peak wave periods increase systematically north to south along the West Coast, with the highest peak periods occurring in Southern California. However, excluding the Gulf of Alaska wave buoy, the maximum peak winter periods among the remaining buoys reveal only slight variations (20 to 21.4 sec);
- The systematic increase in the peak wave periods suggests that further to the south, the buoys become increasingly influenced by far-field storm systems in the North Pacific. Wave dispersion during travel across the wide expanse of the central North Pacific would also enhance the development of long-period swell;
- During winter, wave powers (energy fluxes) are at least twice as large in the Pacific Northwest (Washington and Oregon) and in the Gulf of Alaska, compared with those observed in Southern California;
- The period from 1997 to 1999 is characterized by a dramatic increase in the number of large storm events that have occurred offshore from the Pacific Northwest. In particular, the 1997-98 El Niño and 1998-99 La Niña winters were both characterized with more than 20 events, in which the heights of the waves exceeded 6 m or more. This represents the highest incidence of severe storms during the past three decades.

Our analyses also reveal the existence of long-term trends of increasing wave heights in the North Pacific that are comparable to increases identified in the North Atlantic and North Sea. Furthermore, these long-term trends show evidence for a systematic variation in the rate of wave height increase along the West Coast of North America, that complements the latitude differences in the wave statistics found between the Pacific Northwest buoys and those in Southern California. The specific differences between long-term trends identified among the six NDBC buoys include:

- In the Gulf of Alaska:
  - The wave buoy exhibits no statistically significant evidence for an increase in its wave statistics (heights and periods) since 1975.
- Offshore from Washington:
  - The annual average H_S increased at a rate of 0.027 $m.yr^{-1}$ since 1978, while the average WH_S increased by 0.042 $m.yr^{-1}$. As a result, the wave climate has undergone an overall increase in the annual average H_S of 0.54 m, while the average WH_S grew by 0.88 m for the 21-year record.
  - Similarly, the average MAX WH_S for the Washington buoy increased at a rate of 0.094 $m.yr^{-1}$. This represents an overall increase of 2.0 m in the maximum significant wave height since 1978.
  - The annual average T_P increased at a rate of 0.059 $sec.yr^{-1}$, while the WT_P grew by 0.043 $sec.yr^{-1}$. This reflects an overall increase in the T_P by 1.1 seconds during the 19-year record, and 0.82 seconds for WT_P.
- Offshore from Oregon:
  - The annual average WH_S measured at the Oregon buoy increased at a rate of 0.031 $m.yr^{-1}$. This amounts to an overall increase in the winter wave heights of 0.65 m since 1977.
  - In contrast, the annual average H_S exhibits no statistically significant evidence for an increase in its wave height. However, the absence of a trend may result from the large gaps in the wave record.
  - Although the remaining wave statistics reveal long-term trends, they are not statistically significant.
- In Northern California (Pt. Arena):
  - The annual average H_S increased at a rate of 0.017 $m.yr^{-1}$, which corresponds to an overall increase of 0.27 m since 1982. Although the average WH_S reveal a long-term increase that parallels the average H_S, the trend is not statistically significant at the 0.05% level.
- In Southern California:
  - The wave buoys reveal no statistically significant evidence for an increase in the wave statistics (heights and periods) since 1981.
  - The California wave buoys show unusual trends in averages of the monthly maximum significant wave heights. In contrast to the linear trends found for monthly averages of the daily significant wave heights for the more northerly buoys, the maximum heights show a reduction

centered on about 1990, lower by about 1 m compared with the highest waves during the early 1980s and again in the late 1990s.

The exact cause of the rise in North Pacific wave heights remains unclear, though there are several possibilities. In particular, analyses of the East Pacific Teleconnection Pattern (EP), a measure of the strength of the westerly winds and the position of the jet stream, reveal an apparent close association between the long-term trends and the broader climatology of the North Pacific. This relationship has been further strengthened through the analyses of temporal records of SLP associated with the Aleutian Low, and the Pacific Decadal Oscillation (PDO). When the EP is in a positive phase, the jet stream is directed at the Pacific Northwest and Northern California, and the westerly winds tend to be enhanced. In contrast, a negative EP phase results in a split-flow configuration in the jet and a decrease in the strength of the westerly winds. Our analyses reveal that:

- The initial increase in wave heights between 1979 and 1984 may be related to the transformation of the EP, from a moderate negative phase to a positive phase that peaked in 1984. In addition, from 1972 to 1983, the Aleutian Low deepened significantly, leading to an increase in the strength of the westerly winds and an intensification of near-surface circulations;
- The slight decrease in the wave heights during the late 1980s and early 1990s is consistent with a transformation of the EP, from a moderate positive phase to a strongly negative phase that peaked in 1993. Furthermore, this period was characterized by an increase in SLP, and a decrease in the wind speeds;
- Between 1993 and 1999, the strength of the negative EP phase decreased. By 1998-99, the EP had reverted to a strongly positive phase, one of the strongest on record. Further, SLP deepened appreciably throughout this period.
- We have been unable to account for the long-term increase in the wave heights through comparisons with a variety of climate indices, including the EP Pattern, NPI, or the PDO;
- However, our analyses did reveal a moderately good correlation ($R = 0.68$) between the EP and the de-trended wave-height data. As a result, positive phases of the EP Pattern, associated with stronger winds in the North Pacific and with the jet stream passing over the Pacific Northwest, correspond to positive WH_S values, higher than usual waves, while negative EP values correspond to lower wave heights. Therefore, although the EP did not account for the long-term trends of increasing wave heights, it appears to account for the annual variations in the wave conditions above or below the average trend;
- Detailed analyses of wind speeds from around the globe by Ward and Hoskins (1996), demonstrated that wind strengths have increased in the extratropical North Pacific. During the time frame corresponding to our wave-data analyses, the wind speeds have shown an upward trend that amounted to an increase of about 4 ms^{-1} but with considerable interannual variability superimposed on this trend.
- The pattern of variations in the EP Pattern since the mid-1970s is remarkably similar to the variations in the number of storm events that have occurred along the Pacific Northwest coast. The large numbers of storms that occurred during 1997-99 correspond to a marked increase in EP values, becoming strongly positive in

1999 following several years of negative EP values when the number of storms in the Pacific Northwest was much lower;

It is also possible that the increase in the wave statistics in the North Pacific since the late 1970s, and those identified in the North Atlantic and North Sea since the 1950s, may be related to some form of global climate change, caused by the increase in Greenhouse gases in the atmosphere. Recent modeling of the effects of climate change in the Pacific Northwest has revealed that significant climate changes are predicted to occur over the Pacific Ocean during the next 50 to 100 years. In particular, the models predict that the Aleutian Low is likely to deepen and move southwards, which may contribute to further increases in wind speeds along the West Coast of North America. As a result, it is possible that the ensuing decades could be characterized by stormier conditions, and further increases in North Pacific wave energies.

Analyses of the temporal and spatial variability of the wave statistics has also demonstrated a dependence of the annual wave conditions in the North Pacific on the climatic spectrum ranging between El Niños and La Niñas, that is, on the status of the Southern Oscillation. This relationship has been established by correlating the annual winter wave height residuals (WH_{SR}), against the Multivariate ENSO Index (MEI), a measure of the relative strength of the Southern Oscillation phenomena. The analyses demonstrate:

- There does appear to be a regional influence of El Niño/La Niña - Southern Oscillation events along the West Coast of North America;
- The far North Pacific (Gulf of Alaska) is not significantly influenced by the Southern Oscillation phenomena;
- There is strong evidence to suggest that major El Niños correspond to years of higher wave conditions in California and along the Oregon coast, while moderate events result in considerable scatter in the heights of the waves, and especially off the Pacific Northwest;
- La Niñas appear to dominate the buoy measurements in the Pacific Northwest;
- Given the right climatic conditions, strong La Niñas, as occurred during 1998-99, can generate large wave conditions as far south as Pt. Arguello (Southern California);
- There is some suggestion that the greater intensities of both El Niños and La Niñas may compensate for the increased distances of the storm systems, respectively from the Pacific Northwest and California coasts.

Although our analyses demonstrate an apparent dependence of the wave climate on El Niño/La Niña - Southern Oscillation events, the increased frequency of major storms and larger wave conditions that occurred off the Pacific Northwest between 1997 and 1999, initially thought to be related to the 1997-98 El Niño and 1998-99 La Niña, may in fact be related to the recent strong positive phases of the EP Pattern. At present, we are uncertain as to how the Southern Oscillation controls the heights of waves in the North Pacific and their latitude variations, beyond the effects of the EP Pattern. Since the record of wave measurements in the North Pacific is short, during which only a few significant El Niños and La Niñas have occurred, the relative roles of the EP Pattern and the Southern Oscillation cannot be separated adequately enough.

Our findings clearly demonstrate that the North Pacific Ocean, particularly offshore from Washington and Oregon, is characterized by a significant increase in the wave energy and power (proportional to the square of the wave heights and peak periods) since the late 1970s. Furthermore, we have established that the identified changes in the wave statistics closely parallel the trends previously reported for the North Atlantic and North Sea by Carter and Draper (1988), Bacon and Carter (1991), and Kushnir et al. (1997). These changes should be of concern to coastal managers since the risks from coastal erosion and inundation also increase, as do the costs associated with responding to these hazards. Unlike the North Atlantic studies, we have been unable to adequately explain the cause of the long-term increase in the wave heights and periods in the North Pacific. This is despite there being a corresponding long-term trend of increasing winds in both the North Atlantic and North Pacific, with the latter having the stronger trend.

Superimposed on the progressive increase in storm-wave heights are inter-annual cycles associated with El Niño/La Niña - Southern Oscillation events, that can generate large wave conditions along the West Coast of the U.S. However, what remains unclear is how the Southern Oscillation controls the heights of waves in the North Pacific and their latitude variations, beyond the effects of the EP Pattern. It is likely that more focus needs to be made on their effects on the strengths of winds over the North Pacific, the primary factor important to the generation of waves. With a much longer record of winds than of waves, it is more likely that the large-scale climate controls can be established, with an inference of the wave conditions further into the past than is provided by the direct measurements, and perhaps with a projection into the future.

This report has provided insight into the characteristics and vagrancies of the wave climate of the North Pacific. However, in doing this, additional questions have been raised that remain unanswered. In particular, what is the cause of the long-term trends of increasing wave heights, periods and wind speeds in the North Pacific? Is there evidence for an increase in the duration with which strong winds blow across the North Pacific? Have the paths of storm systems changed since the 1970s? Further efforts are needed to answer these questions.

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