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Evidence for Changes to the Northeast Pacific Wave Climate

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ABSTRACT

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A large database of deep water wave buoy measurements over a 24-year period is created for four regions comprising the West Coast of the United States. The regional monthly mean significant wave height (MMSWH) is selected as the defining wave climate parameter and averaging multiple data sources within a region is found to significantly reduce data gaps. Two 12-year periods are compared, showing significant temporal variability but high correlation between regions, allowing the further collapse of the data to a northern and a southern region. Correlations between MMSWH records with three global-scale climate indices are investigated and only the North Pacific Index (NPI), a measure of atmospheric pressure in the Gulf of Alaska, shows strong correlation. The Multivariate ENSO Index (MEI) is less correlated and the Pacific Decadal Index (PDO), which is a measure of ocean surface temperature, provides no significant correlation.

A method for displaying multiple correlations is developed that shows the mean of all MMSWH records that occur at unique temporal combinations of two climate indices. The graphics depicting the mean wave height as a function of NPI and MEI for the two 12-year periods are shown to be very instructive in establishing why the two periods are so different. On the contrary, the same procedure with PDO substituted for MEI produces uniform distributions with little interpretive value.

Century-scale variation in the climate indices is investigated, and significant linear trends are found for NPI and MEI, both consistent with causing increases in mean wave energy in these regions. Causal relationships for the observed correlations are discussed, and conclusions are reached indicating that global warming is a likely contributor to observed increases in wave intensity in the North Pacific.

ADDITIONAL INDEX WORDS: *Waves, wave climate, Pacific Ocean, ENSO, NPI, PDO, MEI, buoy, climate change.*

INTRODUCTION

Coastlines on the eastern boundaries of large ocean basins are typically subject to the more energetic wave climates that are produced by predominantly westerly winds. The U.S. West Coast has consistently provided the highest wave energy levels in the country and, as a result, has been the subject of a large body of scientific and engineering studies on its wave climate and the impacts of these waves on the shoreline.

The earliest works in wave climatology in this region involved rudimentary hindcasts (Marine Advisers,1960; Meteorology International, 1977) made prior to the installation of the first wave measurement buoys in the late 1970s. These estimates were hampered by low spatial and temporal resolution of the atmospheric pressure data from which winds were inferred as well as highly simplified models dictated by a lack of computing capability. Seymour *et al.* (1984) contains a more refined hindcast of wave events exceeding 3-m H_{m0} off central California from 1905 to 1981. The estimates in this series prior to the 1970s suffered from the data deficiencies previously described but did correct for procedural problems in the earlier studies. This paper was motivated by the seven instances of waves over 6 m H_{m0} during the winter of 1982–83, which were concurrent with a strong ENSO (El Nino–Southern Oscillation) and was the first to establish the twentieth century correlation between very energetic waves on the West Coast and El Ninos. The 1984 catalogue of Southern California major wave events was extended for a decade in Seymour (1996) using measured data. The continuing influence of El Ninos on wave energy intensity was demonstrated, particularly the storms associated with the El Nino event of 1986–87. The ENSO condition was measured by the southern oscillation index (SOI). A second index, multivariate ENSO index (MEI) developed in 1993, combines sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky with SOI to characterize the ENSO (Wolter and Timlin, 1998). MEI is often employed in current research to characterize the ENSO condition. Although negative SOIs indicate an El Nino condition, the MEI reverses the sign convention.

Wolter and Timlin (1998) showed that the El Nino of 1982–83 was the strongest such event in the past 50 years, followed very closely by the El Nino of 1997–98. The significant 1997–98 event resulted in a number of studies related to the impacts of ENSOs on the West Coast wave climate (Allan and Komar, 2000; Seymour, 1998, 2002; and Storlazzi and Griggs, 2000).

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Graham and Diaz (2001) undertook a hindcast of the winter season forcing winds in this area over a 50-year period (1948–1998) and found a steadily increasing trend. They conjectured that the cause could be related both to ENSO cycles and Pacific decadal oscillation (PDO) (an index of ocean surface temperature; see Mantua and Hare, 2002). They concluded that the climate modeling at that time could not predict the observed increase from consideration of anthropogenic greenhouse gas warming. Graham and Diaz found the increase in the winds was greatest in the southern region and lessened toward the north. Allan and Komar (2006) found overall increasing trends in average wave heights but with an inverse distribution yielding the higher values in the north and diminishing toward the south. Bromirski, Cayan, and Flick (2005) used data from 10 NOAA/NDBC buoys over the 23-year interval from 1981 to 2003 and employed empirical orthogonal function (EOF) analysis to show a consistent pattern in mean wave energy at all frequencies decreasing from north to south along this coast, confirming Allan and Komar. They also found an increase in overall storminess over time and identified a north–south variation in intensity associated with ENSO cycles such that extreme waves were more likely in the south during El Nino conditions and in the north during La Nina. Adams, Inman, and Graham (2008) used a 50-year (1948–1998) hindcast at one location offshore of Southern California to provide the longest view of any of the studies. Changes at decadal time scales were observed to be correlated with SOI and PDO. La Nina cycles appeared to have no influence on hindcast wave energy at this site, regardless of the PDO value (warm or cool), while El Nino events produced more energetic waves and the energy increased with increasing values of PDO (warmer). A linearly increasing trend in winter mean monthly wave heights as well as mean monthly peak periods were detected over the 50-year interval.

Allan and Komar (2006) provide a comprehensive review of the state of West Coast wave climatology research. They introduce the concept of climate controls, implying a loose relationship rather than a strict cause–effect. They revisit the previous controls of ENSOs and PDO, long the staples of understanding wave activity on this coast. They also reintroduce the control associated with atmospheric pressure differences between Hawaii and Alaska. In Allan and Komar (2000), the East Pacific Teleconnection Index (EPI) (differences at an altitude of about 4 km) was invoked with limited success. In their 2006 paper, the sea level differences (North Pacific Index [NPI]; Trenberth and Hurrell, 1994) were found to be a better predictor of the Northwest wave climate. MEI and NPI were found to have comparable skills in predicting annual wave height. One weakness in this study is in its inferences about a particular reach of the coastline using only the data from a single NOAA/NDBC buoy. Whereas all the more northern locations showed similar upward trends in wave energy with time (which were consistent with the findings of the other papers discussed), the Point Arguello data suggests a reduction in the middle of the study interval with a return at the end to approximately the conditions at the beginning. This buoy, as is typical of others utilized, was out of service for a total of 13 winter months during the period of this study. Seymour (2008) addresses this problem by utilizing the mean of many

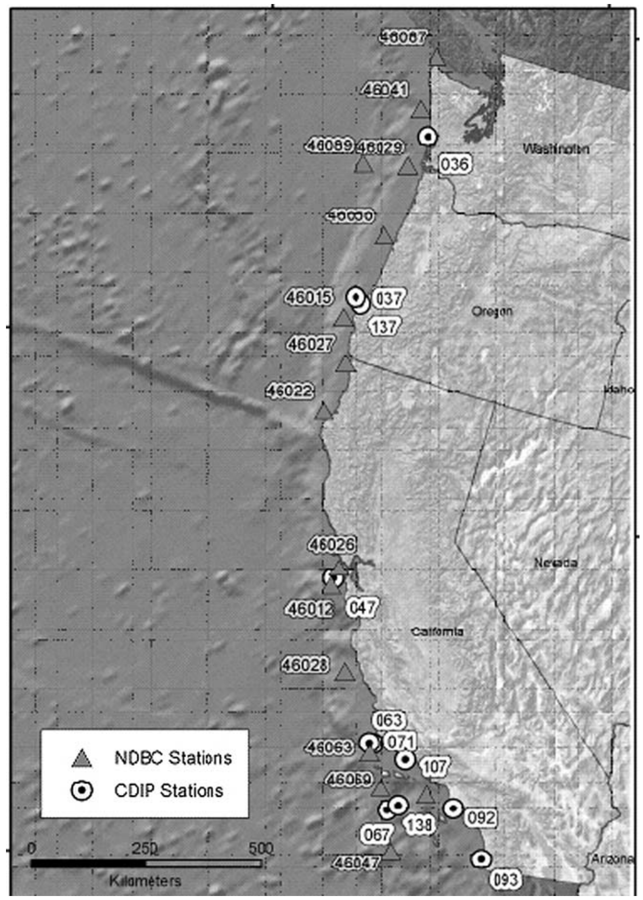

Figure 1. Location of wave measurement buoys used in this study.

buoys within a region to characterize the wave climate of that region.

WAVE DATA SOURCES FOR THIS STUDY

A total of 26 wave measurement buoys were employed to define the West Coast wave climate over a 24-year period. Of these, 15 were operated and maintained by NOAA's National Data Buoy Center (NDBC) and 11 by the Coastal Data Information Program (CDIP) of the Scripps Institution of Oceanography (SIO.) The study divided the approximately 2000 km long coastline into four regions. The buoy locations and affiliations are shown in Figure 1 and the boundaries of the regions in Figure 2. Having multiple data sources within each region allowed for pooling data and eliminated any significant data outage problems as discussed in the previous section. Because of the many islands and banks in the Southern California Bight, only those buoys that were offshore of these obstacles (CDIP 063, 067, and 071 and NDBC 46047, 46063, and 46069) were chosen to represent this region, when available.

The wave observation record selected began in 1984 and ended with 2007, divided into two equal periods. Hourly wave parameters were downloaded from the NDBC and the CDIP

Figure 2. Definition of regions.

Web sites (http://www.ndbc.noaa.gov/) (http://cdip.ucsd.edu/) for the complete 24-year period. The hourly values were then averaged for each day. The resulting data set contains approximately 100,000 daily-averaged wave parameter listings. An almost identical data set was used in Seymour (2008). Each listing contains the mean H_{m0}, the maximum hourly value of H_{m0} during that day, the peak period, and, for those buoys with directional capabilities, the mean direction.

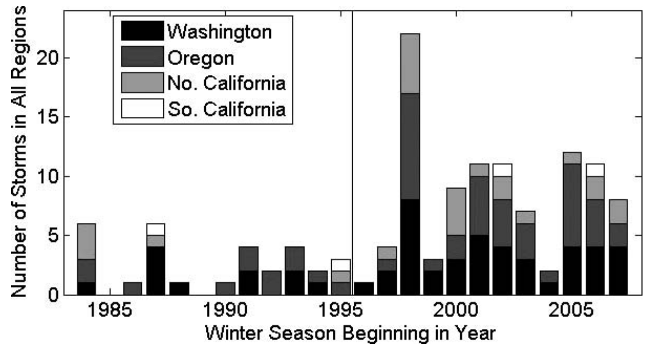

Figure 3. Occurrence by region of wave events with H_{m0} greater than 6 m for 24 hours (after Seymour, 2008).

REGIONAL AND TEMPORAL DIFFERENCES IN STORMINESS

Seymour (2008) set a threshold for major storms that required the H_{m0} to exceed 6 m for at least 24 hours. Figure 3 shows the numbers of such storms by region. It is obvious that a substantial change in the wave storminess occurred between the first and second 12-year epoch. Oregon has the largest number of these events (12/37) followed by Washington (11/36), Northern California (4/19), and Southern California (2/2.) If the threshold value for Southern California is reduced from 6 m to 5 m, the number of major storms increases to 5/25, again emphasizing the significant change in storminess between these 12-year epochs. Although statistics based on numbers of storms exceeding an arbitrary limit are attractively compact, they can mask important trends, as illustrated by the very significant departure of the Southern California data. Therefore, this paper uses the metric of the mean monthly significant wave height (MMSWH) for establishing trends and investigating potential causes. Values for this parameter for each of the 12-year epochs are shown in Figure 4. There were occasional breaks in the regional time series for the northern regions (Washington, Oregon, and Northern California) during the first few years of the record. As shown in Figure 4, these three regions experienced very similar MMSWH histories throughout both periods. Because the intent of this work is to assess and understand processes in the northeast Pacific Basin rather than to provide a historical record of regional wave climate, the records from the three northern regions were averaged to provide a single time series. This simplification provided for the elimination of all but a very few relatively brief data gaps. Southern California clearly experiences a significantly different wave climate from the northern regions. This results, at least in part, because of an increase in travel distance from Gulf of Alaska storms and from the significant sheltering offered by the abrupt change in coastal orientation at Point Conception. Table 1 shows some statistical comparisons between the North Region (Washington, Oregon, and Northern California) and the Southern California region.

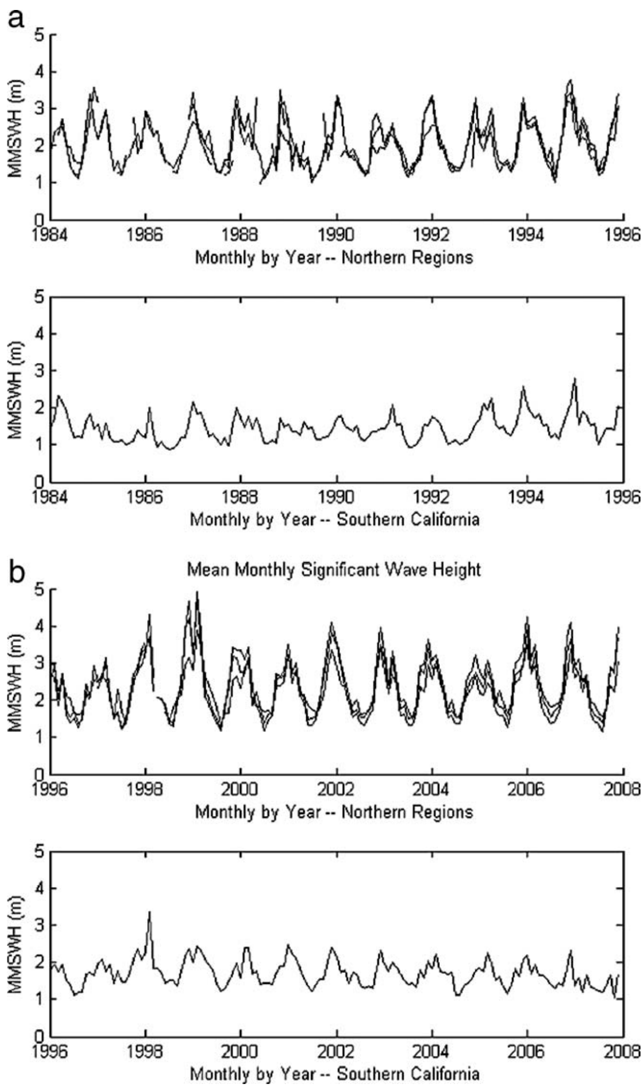

Figure 4. (a). MMSWH values for northern regions and Southern California, 1984–95. (b). MMSWH values for northern regions and Southern California, 1996–2008.

CORRELATIONS BETWEEN MMSWH AND CLIMATE INDICES

Three indices have been proposed in the referenced sources for predicting wave energy along this coast—PDO, MEI (or SOI), and NPI. Monthly mean values of these indices were downloaded from the Internet sources referenced previously.

Table 1. *Means and correlations between northern region and Southern California.*

	1984–1995	1986–2007
Northern region	Mean H_{m0} = 2.03 m	Mean H_{m0} = 2.34 m
Southern California	Mean H_{m0} = 1.45 m	Mean H_{m0} = 1.70 m
Correlation coefficient	R = 0.71	R = 0.80
Confidence level	99%+	99%+

Table 2. *Correlations between MMSWH and climate indices.*

Era	Region	Index	R	Limit
1984–1995	North	NPI	−0.599	>99%
1984–1995	So. Calif.	NPI	−0.538	>99%
1996–2007	North	NPI	−0.714	>99%
1996–2007	So. Calif.	NPI	−0.671	>99%
1996–2007	So. Calif	PDO	0.163	95%
1984–1995	So. Calif.	MEI	0.125	>85%
1996–2007	North	MEI	−0.134	>85%

Using monthly means of H_{m0} extracted from the wave data set for each of the two consolidated regions, all statistically significant correlations among MMSWH and these three indices are shown in Table 2.

Inspection of Table 2 clearly shows the strong predictive capability that the NPI index has for mean wave height over both regions and times (low pressure produces larger waves.) However, neither of the other two climate indices yields very significant correlations.

A semipermanent low pressure system was situated over the Aleutian Islands during the winter (CCSP, 2008). As an example of the influence of atmospheric pressure in the northern Pacific, Figure 5 shows a massive low pressure system south of the Aleutian Islands during mid-December, 2002. The monthly mean NPI value was 3.3, which was moderately low. (Note that the NPI is the atmospheric pressure in millibars minus1000, so that the mean for December 2002 was 1003.3 mbar.) This huge low had a NPI index of −20 (980 mbar) and resulted in values of H_{m0} exceeding 6 m from Canada to Mexico on a single day (Seymour, 2008).

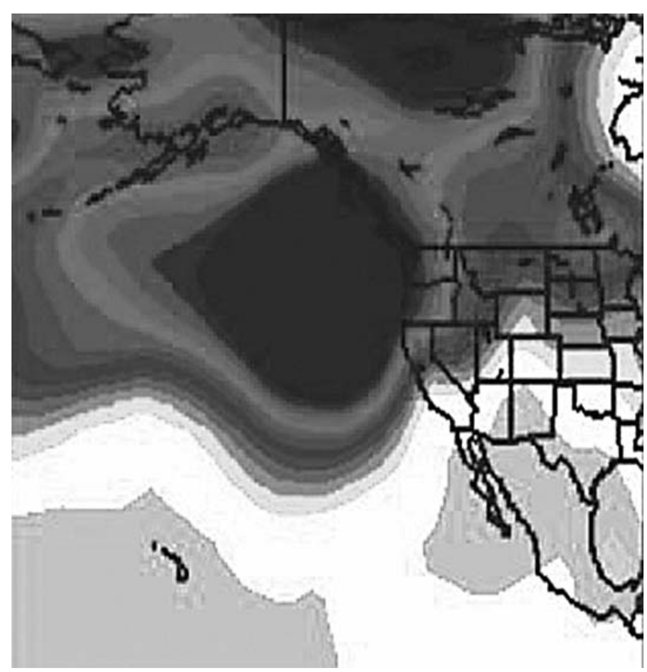

Figure 5. Gulf of Alaska low pressure area, December 16, 2002 (after Seymour, 2008).

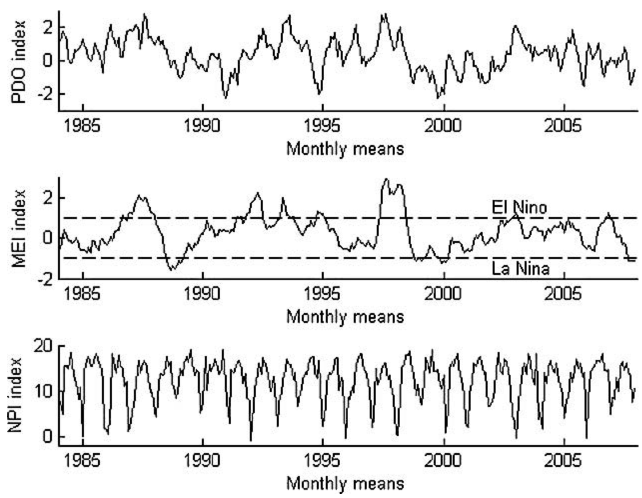

Figure 6. Variation in climate indices during the period 1984–2007.

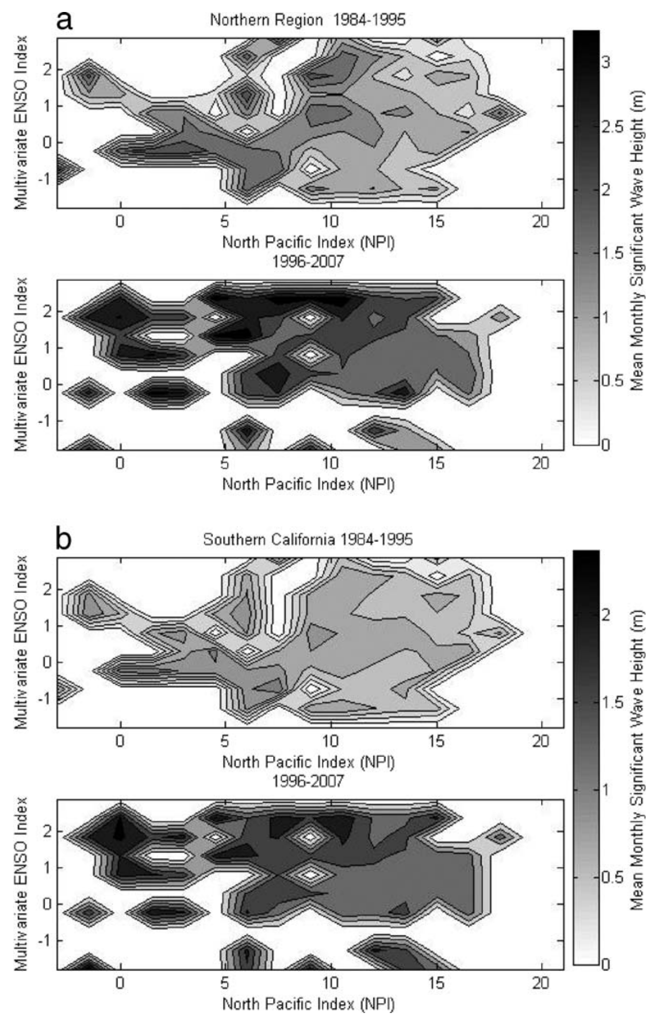

Figure 7(a). Distribution of MMSWH means from the consolidated northern regions at coincident occurrences of MEI and NPI values over two periods. (b). Distribution of MMSWH means from the Southern California region at coincident occurrences of MEI and NPI values over two periods.

Figure 6 illustrates the significant variability, both year to year and seasonally, in all three candidate indices. Although the northern atmospheric pressure index, NPI, appears to have significant skill as a predictor of MMSWH along the whole West Coast, some of the correlation could be coincidental because both time series have a well defined annual cycle. Both the temperature change and the ENSO condition indicators vary on much longer time scales. Their influence could conceivably be important in producing extremes in the wave height record caused by coincidence with each other or with the atmospheric pressure in the Gulf of Alaska. Therefore, it is instructive to investigate the possibility of correlations among indices.

Table 3 shows the significant correlations among the three indices. NPI is weakly and negatively correlated with PDO, but only in the 1996–2007 period, significant at the 95% confidence level (*i.e.*, atmospheric pressure near the Aleutian Islands trends toward lower values when Pacific water is warmer, in the most recent years). The other combinations with NPI show no significant correlations. However, PDO and MEI are correlated in both periods (R = 0.32 in 1984–1995 and R = 0.64 in 1996–2007, both significant at greater than the 99% confidence level). As previous research has shown, El Nino conditions often coexist with warm Pacific water.

Although the correlation data provide an opportunity for investigating the relationship between a chosen pair of time series, they do not allow for simultaneous viewing of how any combination of these climate indices might influence wave height. Figures 7a and 7b are designed to explore the possible significance of combinations of ENSO conditions and Gulf of Alaska atmospheric pressure levels in establishing the wave climates along the West Coast. They are quasi-three-dimensional in that the time-averaged MMWSH value at the intersection of two climate index pairs is depicted through shading, darker denoting larger mean values of MMSWH. MEI and NPI were selected on the basis of their correlations with wave energy. The figures for each of the regions are divided into the two periods used throughout this article. The overall increase in wave intensity between the two periods is emphasized by the darker shades in the Figure 7b (1997–2007) panels.

Table 3. *Significant correlations among climate indices.*

Era	Index pair	R	Limit
1984–1995	MEI/PDO	0.316	>99%
1996–2007	MEI/PDO	0.637	>99%
1996–2007	NPI/PDO	−0.164	>95%

The Figure 7 panels show the anticipated differences between the northern regions and Southern California as indicated by the maximum mean values on the scales at the right-hand side of the figures. However, the patterns of the responses of MMSWH to the combinations of NPI and MEI are remarkably similar. By comparing either pair of figures, we can deduce the following:

- MMSWH values are higher in all areas of the NPI/MEI space during the 1996–2007 era than in 1984–1995.
- The 84–95 period has very few instances of wave activity at values of MEI less than −1 (typically the threshold for a strong La Nina condition). The 1996–2007 period exhibits a significant number of these occurrences.
- The 1996–2007 period has essentially no activity between the MEI values of 0 and −1 (neutral to mild La Nina) at any value of NPI, whereas the 84–95 period has substantial activity in this band over the full range of NPI.
- In either period, the wave energy is dominantly at MEI values greater than 0 and at NPI values greater than 5.
- At NPI values less than 5, activity is more evenly distributed in MEI space. However the 1996–2007 period shows a much broader range of extremes of MEI.
- The centroid of the wave occurrences in the earlier period was located at an NPI value of about 10 while the centroid of the later period was at about 6.

Using the same techniques as were used to produce Figures 7a and 7b, similar plots were made substituting PDO for MEI on the vertical axis (Figures 8a and 8b) and plotting MEI and PDO together (Figures 9a and 9b). In both the Figure 8 and 9 panels, the distributions are mirrored in both regions and the intensities differ significantly, as in Figure 7. In all of the Figure 8 panels, it can be seen that the lowest values of PDO (less than −1) coincide with very high levels of NPI, in the range of 13 to 16. Similarly, in all of the Figure 9 panels, the lowest PDO (cool) values are accompanied by very high MEI values, signifying a strong El Nino. Typically, strong El Ninos are associated with warmer water, as suggested by the MEI/PDO correlations in Table 3. The low values of mean MMSWH associated with this particular combination may be an indicator of its relative scarcity in the record.

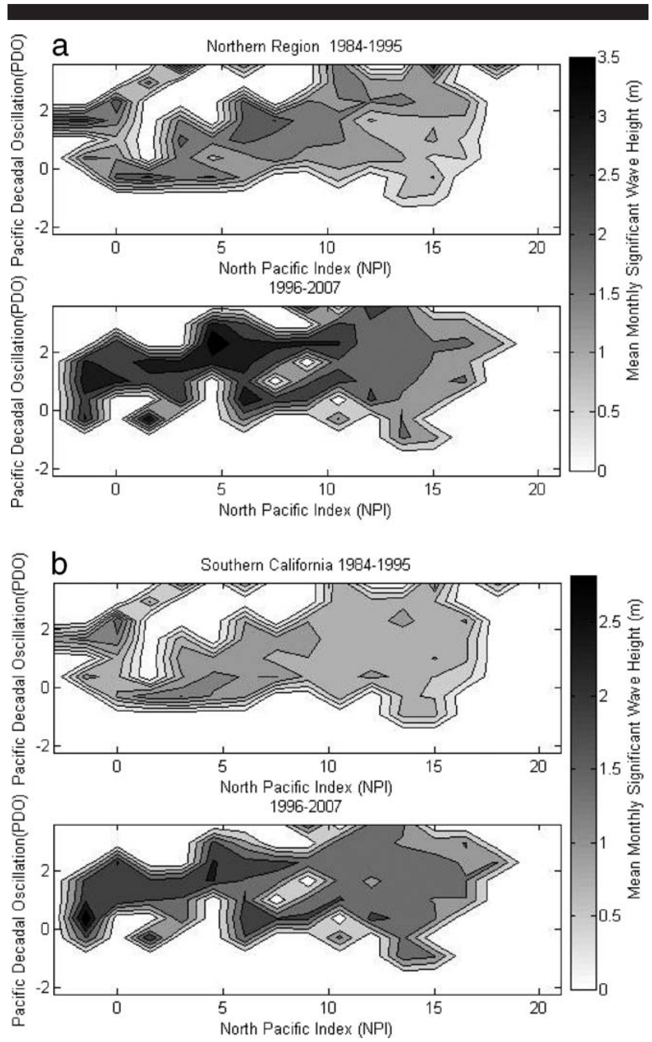

Figure 8. (a). Distribution of MMSWH means from the consolidated northern regions at coincident occurrences of PDO and NPI values over two periods. (b). Distribution of MMSWH means from the Southern California region at coincident occurrences of PDO and NPI values over two periods.

DISCUSSION

There is a marked similarity in the Figure 7 patterns between the two regions in either period, even though there was a significant reduction in intensity in Southern California in each case. Figures generated in the same fashion individually for each of the three northern regions (Washington, Oregon, and Northern California) are nearly identical. Increasing the resolution of these plots by reducing the size of the NPI/MEI cells results in the same similarity but blurs the shading significantly. This extraordinary similarity establishes a very important finding. To a remarkable degree, the regional wave climates of the entire West Coast respond as a system to particular combinations of atmospheric pressure in the Gulf of Alaska and position in the ENSO cycle.

The significant increase that was observed in wave storm occurrence between two 12-year periods over the last quarter century (Seymour, 2008), and in the corresponding data in this work on an increase in the mean wave height climate between the same periods, can possibly be entirely explained by normal variability. Within the climate modeling community there is presently a high level of confidence in the potential for human-induced climate change affecting tropical storms at sea (IPCC, 2007). In light of this, it would appear worthwhile to investigate what portion, if any, of the variation reported here concerning higher latitude storminess might be attributed to a changing global climate.

The span of time when measurement of waves in this area was available is relatively short—probably too short to unequivocally distinguish the effects of global warming from the data alone given its high intrinsic variability. However, those climate indices that are candidates for prediction of wave intensity have much longer time spans and can be inspected for linear trends over century-scale intervals. The annual incident wave energy in this area is dominated by events in the traditional winter season (November through April of the following year). Therefore, the mean value of the climate indices during the winter season, rather than the annual means, will be considered here.

Figure 10 shows a plot of the mean winter values of NPI since 1900. Although highly variable on a year-to-year basis,

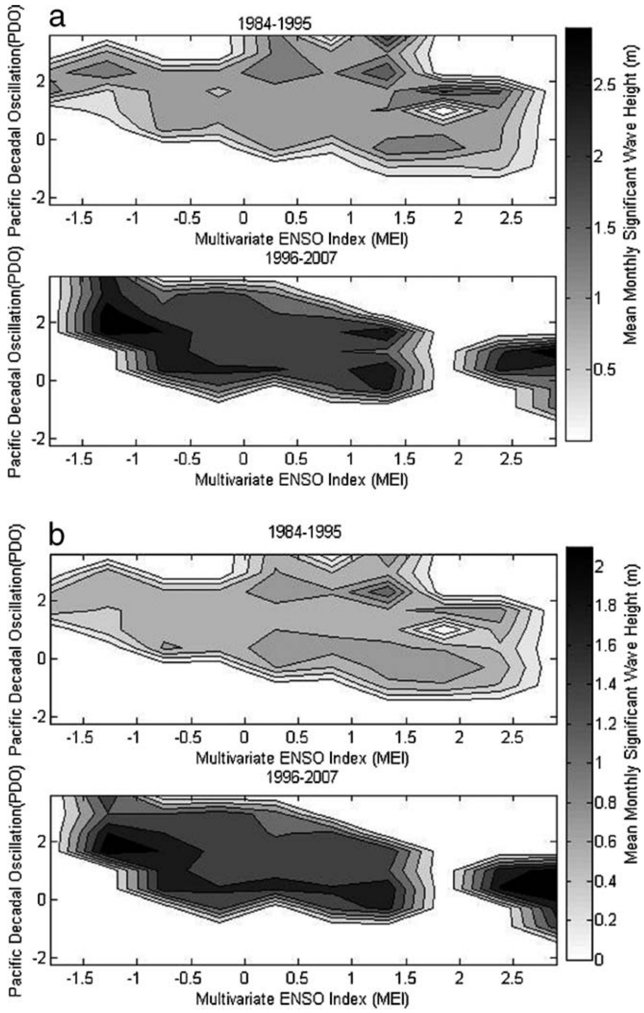

Figure 9. (a). Distribution of MMSWH means from the consolidated northern regions at coincident occurrences of MEI and PDO values over two periods. (b). Distribution of MMSWH means from the Southern California region at coincident occurrences of MEI and PDO values over two periods.

NPI displays a clear linear downward trend. The magnitude of this reduction over a century approximates one standard deviation in the record, indicating that the mean winter atmospheric pressure near the Aleutians has been diminishing significantly. Further, the peak winter values are presently approaching the long term mean. Reducing surface atmospheric pressure would be expected to result in higher wind speeds or increased fetch lengths, or both, in a critical generation area for waves affecting the West Coast of the United States. The remarkably high correlation between NPI and MMSWH for the entire region does not, of itself, prove causation. However, in this case a clear causation linkage from low pressure to wind fields and then to waves exists, and the high correlation means that NPI is likely to remain a robust predictor of waves in the North Pacific. The lowering of the mean winter NPI values over the last century may be causally linked to global warming (Overland, Adams, and Mofjeld, 2000). If so, the chain between greenhouse gases and bigger waves in the North Pacific will have been completed.

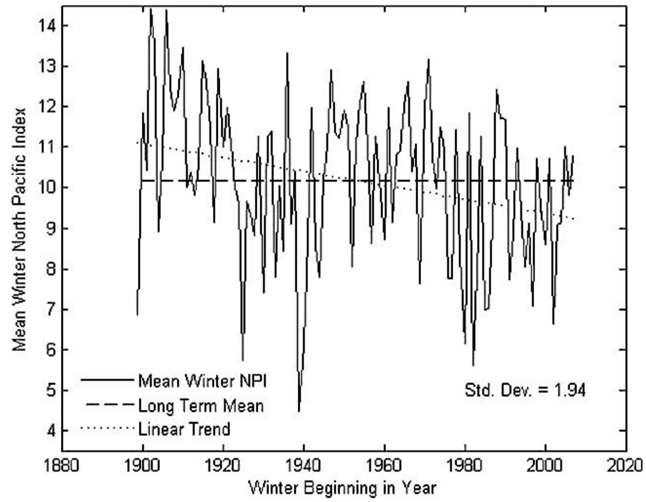

Figure 10. Long term variation in the mean winter season values of the North Pacific Index.

Figure 11 shows a similar display of the trends in the ENSO index, MEI. In this case the linear trend is upward. The increase is at a rate of 1.4 standard deviations per century. Some of the variability in wave energy between the two 12–year periods appears to be explained by the positive peak in 1996 that almost matches the record-setting El Nino of 1982–83 and also by the multiyear La Nina event immediately following. Wind patterns over the North Pacific are significantly altered during ENSO cycles (Seager *et al.*, 2009). During strong El Ninos, winds at midlatitude reverse the normal pattern and become more westerly. This enhances wave

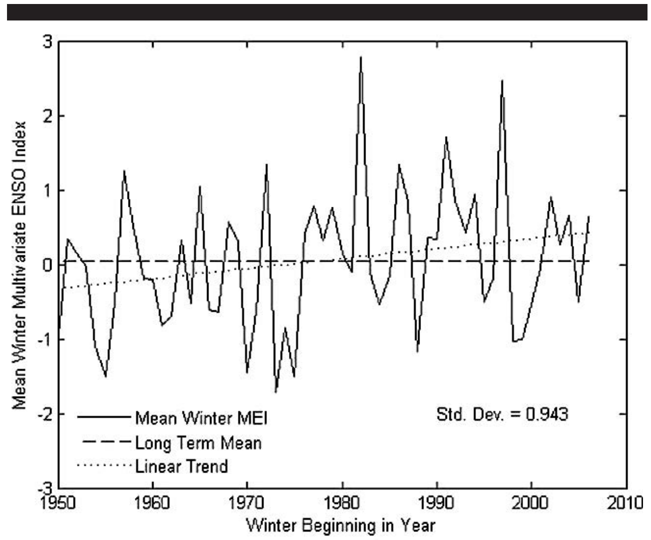

Figure 11. Long term variation in the mean winter season values of the Multivariate ENSO Index.

propagation toward California, and to a slightly lesser degree, the northern regions. Strong La Nina conditions reverse this, diminishing the waves to the south slightly while enhancing those propagating toward the north. Notice that either ENSO extreme is likely to increase the wave intensity, as clearly shown in Figure 7. Because only the ENSO extremes have significant impact on North Pacific waves and because these extremes occur very rarely, the long term correlation between MEI and waves is expected to be low, as documented in Table 2. The casual relationship between extremes in MEI and wave intensity has clearly been established. The trend toward more, or stronger, or longer El Ninos and some comparable reduction in La Ninas as shown in Figure 9 could be a result of global climate change. Recent modeling results predict this trend (Merryfield, 2006).

Water temperature, as represented by PDO, is highly variable but shows no significant trend over the last century or any strong correlation with MMSWH observations. For these reasons, it has not been considered in this work as a candidate for transmitting global climate change effects to the North Pacific wave climate.

A major increase in wave energy affecting the West Coast of the United States has been shown to occur over the interval of a quarter century. During the same period, there was a monotonic increase in the positive (El Nino) portion of the ENSO cycle and a monotonic decline in the atmospheric pressure in the Gulf of Alaska. Both of these changes would be expected to produce higher wave energy levels and both have been identified as resulting, at least in part, from global climate change. The wave height record appears to be too noisy and too short to establish an estimate of a probable contribution from the changes to global climate.

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