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Extreme Storms on the Pacific Northwest Coast during the 1997–98 El Niño and 1998–99 La Niña

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ABSTRACT

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Six major storms occurred between 1997 and 2000 offshore from the Pacific Northwest (PNW) of the United States, each generating deep-water significant wave heights greater than 10 m, the approximate height of the 100-year storm event determined from wave data collected up through 1996. Part of this apparent sudden increase in storm-wave heights was found to be associated with a progressive increase that has spanned the past 25 years (ALLAN and KOMAR, 2000), and a progressive increase in the magnitude and frequency of North Pacific cyclones since the late 1940s (GRAHAM and DIAZ, 2001), but also may have been affected by successive occurrences of a strong El Niño (1997–98) and moderate La Niña (1998–99). The objective of this paper is to document in detail the meteorological conditions and wave generation of these recent storms, due to their unusual strengths and because they produced substantial erosion along the coast. The paper focuses primarily on the two severest storms that crossed the PNW coast; the 19–20 November 1997 El Niño storm that generated 10.5 m significant wave heights, and a storm on 2–3 March 1999 (La Niña) that produced 14.1 m significant wave heights. With the presence of several NDBC buoys close offshore, the movement of each storm can be followed as it developed, and there is good spatial documentation of the meteorological conditions and generated waves. The measured wave heights and periods are used to calculate the along-coast variations in wave runup on PNW beaches. In addition, tide gauges permit analyses of the accompanying storm surge produced by the high winds and low atmospheric pressures of the storms. The largest storm surge occurred during the strongest storm in March 1999, which produced a peak surge of 0.6 m along the Oregon coast and 1.6 m on the Washington coast. Important to the resulting coastal erosion are analyses undertaken of the total water levels reached during the storms, produced by the wave runup above and beyond the elevated tides. Analyses of the 19–20 November 1997 El Niño storm and 2–3 March 1999 La Niña storm yielded estimated wave runup elevations that ranged from 2.8 to 4.1 m, while the total water levels (wave runup plus tides) reached 6.4 m relative to the NGVD 1929 vertical datum. These high water levels were a major cause of extreme erosion observed along the coasts of Oregon and Washington.

ADDITIONAL KEY WORDS: *El Niño; La Niña; coastal erosion; extratropical storms; storm surge; wave generation.*

INTRODUCTION

It is important to analyze the characteristics of unusually extreme storms in terms of the heights and periods of waves they generate, of the accompanying storm surge that can elevate tides along the coast, and the total water levels along the shore that result from the superposition of the storm-wave runup on top of the elevated tides. The understanding gained through such analyses can be important to the safety of shipping, and to assessments of erosional impacts along coasts.

In the Atlantic, and particularly along the East Coast of the United States, the main focus has been on the formation and impacts of hurricanes and extratropical storms or "nor'easters" (DAVIS and DOLAN, 1993; DOLAN *et al.*, 1988; DOLAN and DAVIS, 1992a, 1992b, 1993; JENSEN and GARCIA, 1993; JONES and DAVIS, 1995; MAA and WANG, 1995). Fewer analyses have focused on the major extratropical storms that occur in the North Pacific. DANIELSEN *et al.* (1957) analyzed the frequency and intensity of severe storms in the Gulf of Alaska, in connection with the loss of the *S.S. Pennsylvania* during a storm on January 9, 1952 when the deep-water significant wave height reached 14 m. They concluded that the asymmetry of the storm was such that the waves were acted upon by winds from the same direction for a long period of time, accounting for their having acquired a high level of energy. DANIELSEN *et al.* also documented that there had been a great deal of variability in the intensities of storms in the Gulf of Alaska from the 1920s to the early 1950s, with the years having the most severe storms tending to be grouped. EARLE *et al.* (1984) investigated the unusually severe storms off the U.S. West Coast that occurred between January and March 1983, within the time frame of the major 1982–83 El Niño. They analyzed the conditions of wave generation and

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propagation to the coast, where the high waves produced considerable damage.

The 1997–98 major El Niño resulted in a return of high waves along the West Coast of North America, with the occurrence in the Pacific Northwest (PNW), the states of Washington and Oregon, of 20 large storms when the deep-water significant wave heights exceeded 6 m for 9 hours or longer (ALLAN and KOMAR, 2000, in review). Based on wave data collected through 1996, RUGGIERO *et al.* (1996) had projected a 100-year expected significant wave height of approximately 10 m. One storm exceeded that projection during the 1997–98 El Niño, on 19–20 November 1997. The occurrence of such an extreme storm was unexpected in that during an El Niño the storm systems tend to cross the West Coast further to the south in central to southern California, rather than passing directly over the PNW (SEYMOUR, 1996). The severe wave conditions were far worse during the following 1998–99 La Niña winter, when 17 to 22 major storms occurred off the PNW coast, with four having generated deep-water significant wave heights equal to or greater than the 10-m projected 100-year occurrence. The largest storm developed on 2–4 March 1999, generating 14.1-m deep-water significant wave heights. Thus, the PNW received a "one-two punch" from the successive El Niño and La Niña winters, with severe cumulative erosion of the coast. All five storms that generated deep-water significant wave heights in excess of 10 m are classified as "extreme" on the Dolan/Davis scale of extratropical (nor'easter) storm magnitudes proposed for the Atlantic (DOLAN and DAVIS, 1992a).

With this recent development of unexpectedly extreme wave conditions, it was decided to re-examine the wave climate of the PNW in order to up-date the analyses of RUGGIERO *et al.* (1996) and TILLOTSON and KOMAR (1997). In analyses of buoys off the coasts of Washington and Oregon, ALLAN and KOMAR (2000, in review) found that the winter wave heights and periods had progressively increased during the past 25 years, the duration of the buoy measurements. The increase was greatest off the Washington coast, where the averaged winter (October through March) deep-water significant wave heights have increased at a rate of 0.042 m/yr, amounting to an increase of about 1 m during the 25 years of measurements. The largest significant wave heights generated by the yearly strongest storms increased from about 8 to 12 m, a 50% increase. ALLAN and KOMAR (2000, in review) expanded the analysis to include a series of 6 buoys ranging in latitudes from the Gulf of Alaska to Point Arguello in south-central California. A systematic dependence on latitude was found, wherein the greatest increase in wave heights occurred off the coast of Washington, slightly less for Oregon, still less in northern California, and negligible in central California and in the Gulf of Alaska. ALLAN and KOMAR (2000, in review) concluded that the extreme storms and waves experienced off the PNW during the past few winters was part of this long-term progressive increase in wave heights and periods, but were also influenced by the occurrences of the strong El Niño in 1997–98 and La Niña in 1998–99, which affected the paths of storms crossing the coast and apparently also their intensities.

The objective of this paper is to document in detail the meteorological conditions and wave generation of the two largest extratropical storms that occurred off the PNW, respectively during the 1997–98 El Niño and 1998–99 La Niña. This is made possible by the existence of a number of wave buoys, Figure 1, located close offshore. Each buoy records a variety of meteorological data including barometric sea-surface pressures, wind speeds and directions, and wave statistics (heights and periods). With the presence of several buoys, the movement of each storm can be followed as it developed, and insight is gained into the spatial influence of the storm along the length of the PNW coast. In addition, there are two tide gauges on the ocean coasts of Washington and Oregon, Figure 1, that permit analyses of the accompanying storm surge, the super-elevation of mean water levels above the predicted tidal elevations, produced by the high winds and low atmospheric pressures of the storms. The paper concludes with analyses of total water levels that were reached during the storms along the shores of Washington and Oregon, produced by the runup of the storm waves on beaches, above and beyond the elevated tides.

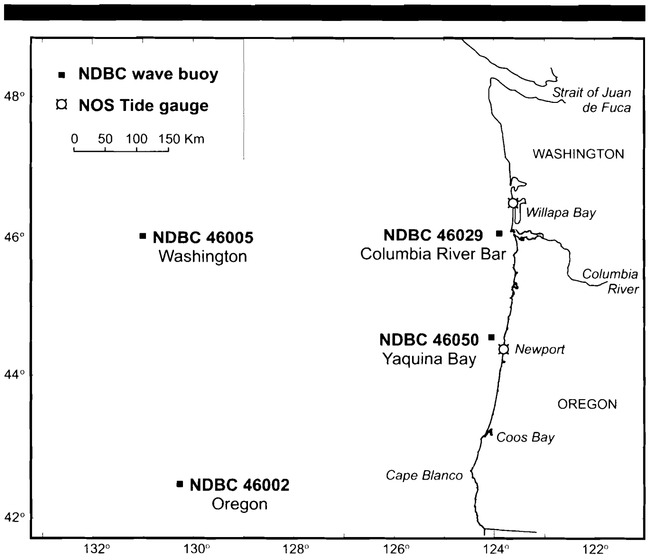

Figure 1. The Pacific Northwest coast, the states of Washington and Oregon, with locations of NDBC wave buoys and tide gauges utilized in this study.

EXTRATROPICAL STORMS

Extratropical storms are essentially low-pressure cyclonic systems—in the Northern Hemisphere, counterclockwise-rotating storms—that develop in regions of unstable conditions. These storm systems form at mid-latitudes, north of about 30 degrees, in response to the mixing of warm, humid air, having its origin in the Tropics, with cooler air that is carried down from the Arctic by the polar jet stream (DAVIS and DOLAN, 1993). The accumulation of tropical air at mid-latitudes results from poleward airflow aloft in the Hadley circulation cells that form either side of the equator (STURMAN and TAPPER, 1996). The descending limb of these cells creates a subtropical belt of high-pressure at the surface. At the same

Table 1. *Wave buoy site characteristics.*

Station Name	Location	Water Depth (m)	Period Of Operation	System
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
46029	Columbia River (Lat. 46°07′00″ N; Long. 124°30′0″ W)	128	1984–present	3-meter discus buoy
46050	Newport (Lat. 44°37′16″N; Long. 124°31′42″W)	130	1991–present	3-meter discus buoy

time, the poleward movement of air aloft is deflected by the Earth's rotation, resulting in westerly winds that are responsible for the pattern of storms that cross the West Coast. This west-to-east propagation of storms is enhanced by the polar jet stream (a concentrated zone of westerly winds), located at an altitude of about 10 km, which is extremely important for the formation of major storms at the surface (REITER, 1967). Although extratropical storms rarely acquire wind strengths comparable to hurricanes, their influence is often more widespread, affecting stretches of coast up to 1,500 km in length (NATIONAL MARINE CONSULTANTS, 1961; DAVIS and DOLAN, 1993). The classic model of extratropical storm development is through cyclogenesis and the frontal wave theory (UCCELLINI, 1990). Of importance is the existence of an upper tropospheric jet, which overlies major frontal regions between subtropical and polar air masses characterized by strong thermal advection patterns and baroclinic zones (UCELLINI, 1990; STURMAN and TAPPER, 1996). In its simplest form, a small wavelike indentation develops along a front that separates two air masses of different density, and hence different temperatures (HSU, 1988). If the system intensifies, lower level air converges around the apex of the wave and a cyclonic circulation pattern will begin to occur. Vertical motions are enhanced as the front becomes unstable due to the superposition of a region of upper level divergence aloft, caused by the strong winds associated with the jet. The jet stream therefore contributes to cyclogenesis by moving mass away from the storm center, allowing the surface pressure to be depressed, with the development of a low-pressure system at the surface. Thus, the greater the divergence of mass in the zone of the jet stream, the stronger the storm system becomes. In addition, the convergence of air at the surface causes the air column to be stretched, which enhances the vorticity or circulation around the low center (STURMAN and TAPPER, 1996). These transformations are frequently produced by wind speed changes associated with the tropospheric jets, as well changes in curvature of the flow. As a result, strong cyclogenesis occurs when both lower level cyclonic vorticity and upper level forcing occur simultaneously. If only one mechanism is in place, cyclogenesis may be weak or nonexistent (LEWIS and HSU, 1992). It is therefore apparent that a strong jet stream is essential for the formation of extratropical storms, while the prevalence of storms is related to seasonal and interannual changes in the position and strength of the jet stream (JONES and DAVIS, 1995).

ALLAN and KOMAR (2000, in review) demonstrated that the inter-annual variability of storms in the North Pacific closely follows the East Pacific (EP) Teleconnection Pattern and the Southern Oscillation. The EP index provides a measure of the strength of the westerly winds and the position of the jet stream, both important for storm formation. When the EP is positive, the westerly winds are enhanced and the jet stream is directed toward the PNW and northern California; a negative EP pattern is characterized by a pronounced split-flow configuration in the jet stream, which results in reduced westerly winds over the eastern North Pacific (CLIMATE PREDICTION CENTER, 1999). ALLAN and KOMAR (2000, in review) showed that the large numbers of storms during 1997 through 1999 corresponded to a marked increase in EP values, becoming strongly positive in 1999, following several years of negative EP values when the numbers of storms were much lower. Furthermore, the relationship was found to be latitude dependent, with the incidence of storms offshore from the PNW being related to the EP index, while storm frequency off the California coast was dependent almost entirely on occurrences of El Niños versus La Niñas, being most frequent during an El Niño.

METEOROLOGICAL AND WAVE CONDITIONS

Analyses of the meteorological conditions associated with the 1997–98 El Niño and 1998–99 La Niña storms have been derived from an examination of North Pacific surface weather charts prepared by the National Oceanic and Atmospheric Administration (NOAA). These charts are prepared on a six hourly basis, and provide good insight into the development and propagation of storms across the North Pacific. The analyses are supplemented by a number of wave buoys located offshore from the PNW, Figure 1, which are operated by the National Data Buoy Center (NDBC) of NOAA. Table 1 describes the general characteristics of each of the wave buoys, and includes their World Meteorological Organization station name, location, water depth, and type of buoy. Due to the severity of wave conditions during both winters, two of the buoys were damaged so they have gaps in their data records. The buoys record a variety of meteorological data, including barometric sea-surface pressures, wind speeds and directions, as well as measuring the heights and periods of the waves. These data are obtained hourly, and are transmitted via satellite to the NDBC laboratory for analyses of the meteorological data, wave-energy spectra, significant wave heights (H_s), average zero-up-crossing wave periods, and peak spectral wave periods (T_p).

The extreme storms of interest in this study are those that generated deep-water significant wave heights equal to or greater than 10 m. As noted above, the 1997–98 El Niño produced one such event, while the 1998–99 La Niña resulted in four events; another occurred during the winter of 1999–2000. While all six storm events have been analyzed, the presentation here will be limited to two storms, the most extreme storm that occurred during the 1997–98 El Niño, and the strongest storm of the 1998–99 La Niña.

El Niños and La Niñas represent opposite extremes in an otherwise continuum of global climate events, with "average" conditions generally prevailing between those extremes. In the past two decades there have been seven El Niños, with the 1982–83 and 1997–98 events having been the strongest on record, while the period between 1990 and 1995 was characterized by persistent EL Niño conditions, the longest on record (TRENBERTH, 1999). During an El Niño, important to coastal erosion are occurrences of elevated mean water levels that cause the measured tides to be much higher than normal, produced by warmer offshore water temperatures, the geostrophic effects of northward flowing currents, and sea-level "waves" emanating from the tropics. During "average" or La Niña years, these processes are not as strong, so that mean water levels along the coast are closer to normal. Also important along the U.S. West Coast are the changing wave conditions between El Niño and La Niña events. During an El Niño there is a southerly shift of the jet stream, which results in a higher incidence of storms that cross the coast of California (KOMAR, 1986; PETERSON *et al.*, 1990; SEYMOUR, 1996, 1998; STORLAZZI and GRIGGS, 2000; KOMAR *et al.*, 2000). Due to this southerly shift of the jet stream, SEYMOUR (1998) has suggested that the PNW would generally experience lower wave energies during El Niños than in normal or La Niña years. However, this is refuted somewhat by the large number of storms that occurred during the 1997–98 El Niño, but does account in part for the still higher number of large storms that struck the PNW during the 1998–99 La Niña (ALLAN and KOMAR, in review).

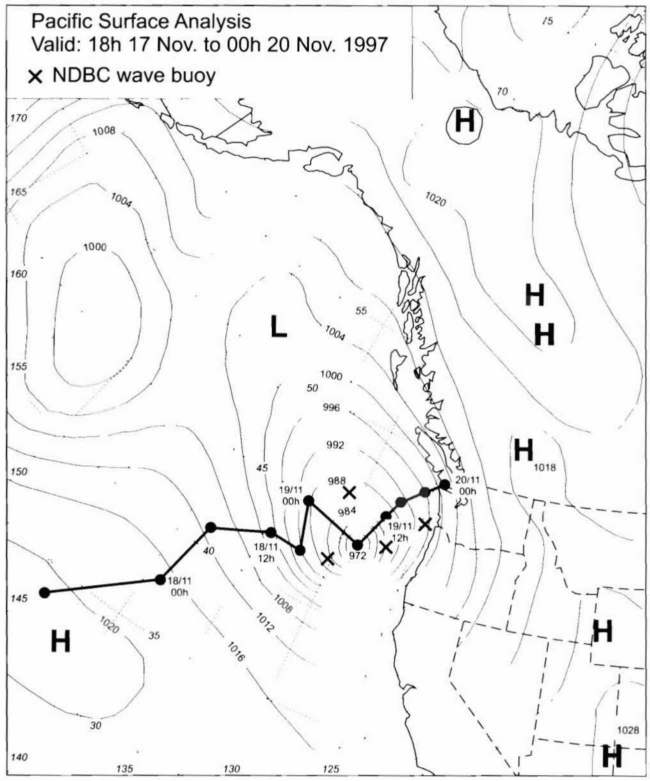

Figure 2. The track of the 17–20 November 1997 El Niño storm, with the pattern of atmospheric pressures on 19 November at the peak of the storm.

The 19–20 November 1997 El Niño Storm

Meteorological conditions during the 1997–98 El Niño were unusual, characterized by a very deep and intense Aleutian Low, while the Hawaiian High atmospheric system was above normal, yielding a strongly positive EP index as noted above. Unlike the 1982–83 El Niño, both atmospheric systems were extremely large in areal extent, with the Aleutian Low centered close to the PNW, encompassing much of the northeast Pacific, while the Hawaiian High expanded toward the coast of Japan and into the Bering Strait. As a result, conditions were ideal for the development of extratropical storms due to the strong temperature and pressure gradients between the Aleutian Low and Hawaiian High. These conditions were further aided by a strong zonal jet stream that fed numerous storms that originated south of Japan, and subsequently moved northeastward into the North Pacific (BANCROFT, 1998). Throughout January–February 1998, the Aleutian Low continued to expand and deepen, reaching 16 mb below normal and eventually covering the entire West Coast. Consistent with previous El Niños, the jet stream progressively shifted to the south so the California coast received a significantly higher incidence of storms during January and February 1998. Close to the West Coast, however, the jet stream adopted a meridional flow pattern, which may account for the larger number of storms that were directed at the PNW coast than is normally expected during an El Niño.

The extreme storm of 19–20 November 1997, which generated the largest waves during the 1997–98 El Niño, first developed well out in the central North Pacific, near 34°N and 144°W. The storm track, Figure 2, as represented by the position of the center of lowest atmospheric pressure, reveals that the depression moved in a northeasterly direction towards the Washington coast. Included in Figure 2 is the synoptic weather situation at 06h GMT on November 19, associated with the peak of the storm.

The storm developed rapidly during 17–18 November, with a pressure drop of over 30 mb in 24 hours, and by 18h GMT on 18 November, wind circulation was occurring around a well-defined low-pressure center. During that 24-hour period, the storm traveled some 1700 km as it intensified, moving at an average rate of over 70 km per hour. Due to the rapid drop in pressure and the speed of storm development, such storms have been referred to as "explosive" or as a "bomb" (SANDERS and GYAKUM, 1980). The development of "explosive" storms is poorly understood compared with the formation of ordinary storms (UCCELLINI, 1991). Furthermore, STRANGE *et al.* (1989) observed that "explosive" storms are relatively uncommon in the eastern Pacific, further demonstrating the extreme nature of this November 1997 storm.

Atmospheric pressures and wind speeds measured at the series of buoys off the PNW, Figure 1, are graphed in Figure 3. At buoy #46005, located off the Washington coast, wind

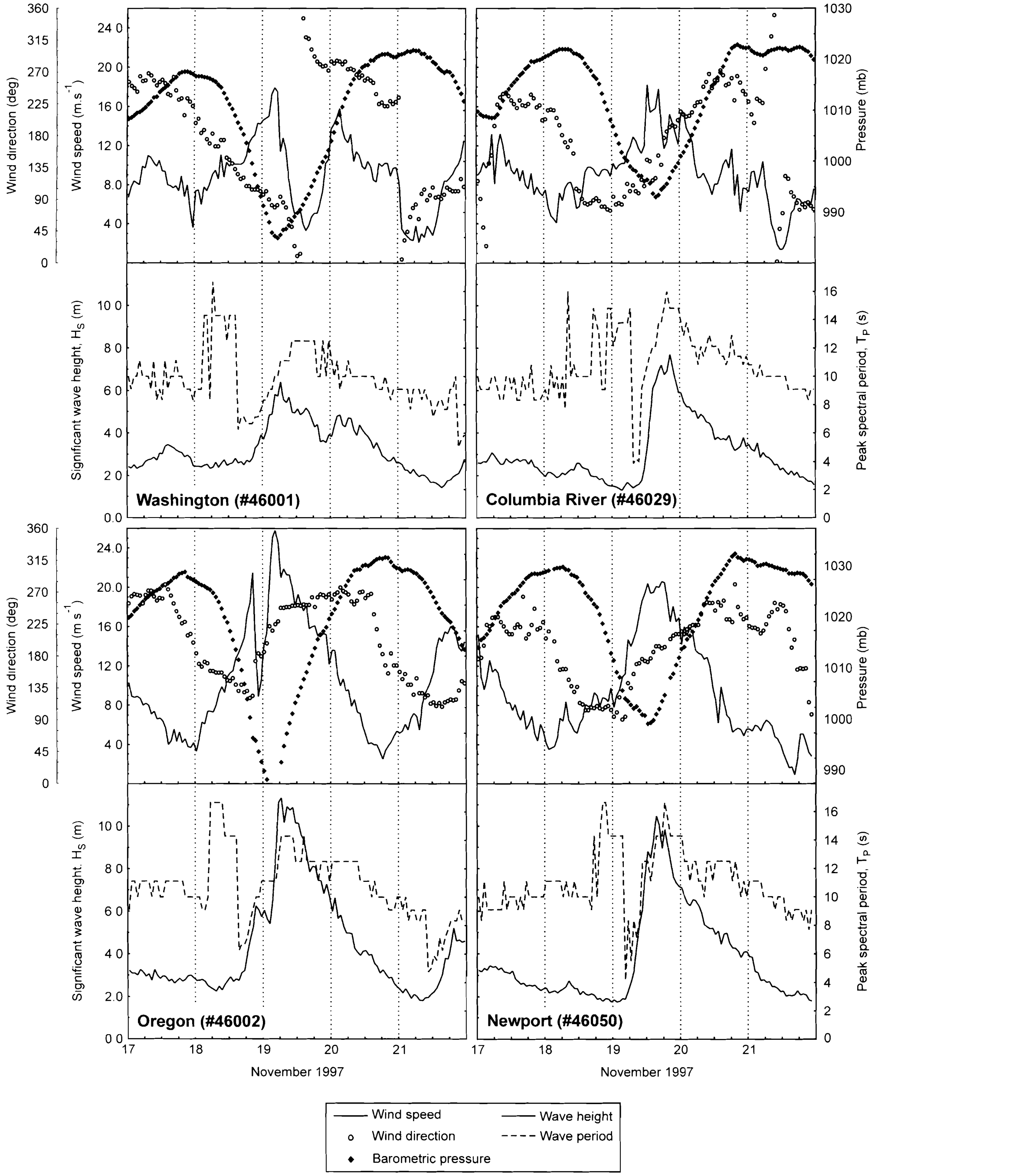

Figure 3. Measurements of atmospheric pressures and wind speeds, and wave heights and periods, derived from the four NDBC buoys during the 17–20 November 1997 storm.

speeds began to increase on 17 November. Buoys to the south (#46002) and east (#46029 and #46050) did not show an increase in wind speeds until the early hours of 18 November. Wind directions were initially from the east due to the presence of a large high-pressure system that was located over the North American continent. As the storm approached from the southeast, winds progressively swung round to the south and southwest. At each of the buoys, the change in wind speeds and directions occurred approximately simultaneously with a drop in the atmospheric pressure, Figure 3.

The significant wave heights measured at the four buoy sites during the duration of the storm are also graphed in Figure 3. Wave conditions prior to the onset of the storm were characterized by low wave heights (H_s = 2–3 m) and long

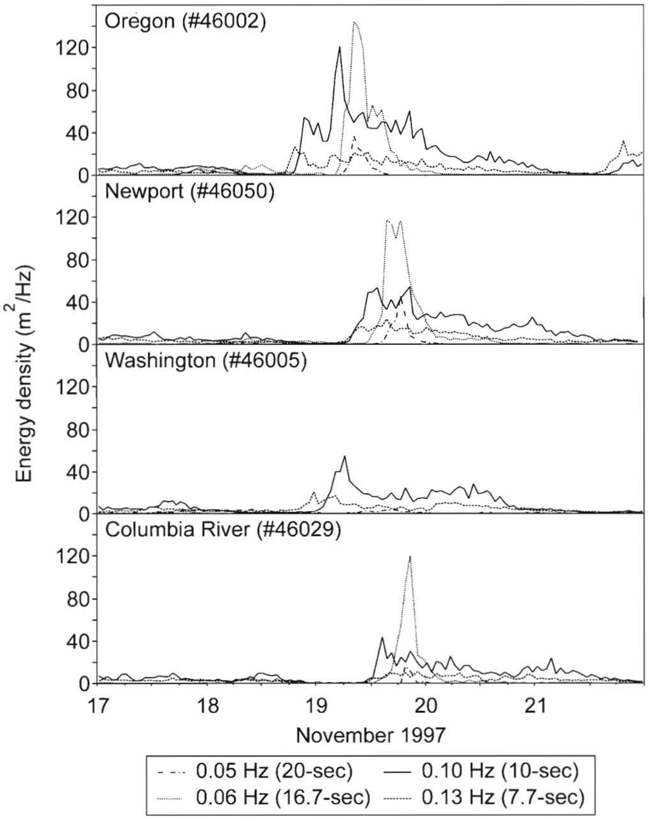

Figure 4. Spectral energies of waves at four frequencies, generated by the 17–20 November 1997 storm.

periods (T_p = 16.7 sec). However, as the storm approached from the southwest, the buoys reveal a sudden decrease in the wave periods to around 6 sec between 12–18h on 18 November, prior to the development of large waves. Figure 4 shows the resulting variations in spectral energy densities for four frequency bands, 0.05, 0.06, 0.10 and 0.13 Hz (corresponding to periods of 20, 16.7, 10 and 8 sec respectively), derived from each of the buoys. The figure reveals a small amount of energy at low frequencies (0.05 and 0.06 Hz) early on 18 November, associated with long period swell waves. At the Oregon buoy (#46002), located farthest offshore and therefore closest to the approaching storm, the increase in the 0.13 Hz highest frequency waves at about 18h on 18 November, Figure 4, reflects a change from the pre-storm swell state to the first arrival of waves generated by the approaching storm. These changes occurred about 4 hours later at the offshore Washington buoy (#46005), and several hours later at the Newport and Columbia River buoys. By 18h on November 18, the central pressure of the storm system was 986 mb, and was centered approximately 750 km to the southwest of Oregon.

As a result of a high-pressure system to the south and east of the developing storm, Figure 2, the storm briefly moved toward the north between 18–00h on 18–19 November. However, by 06h GMT on 19 November the system had swung

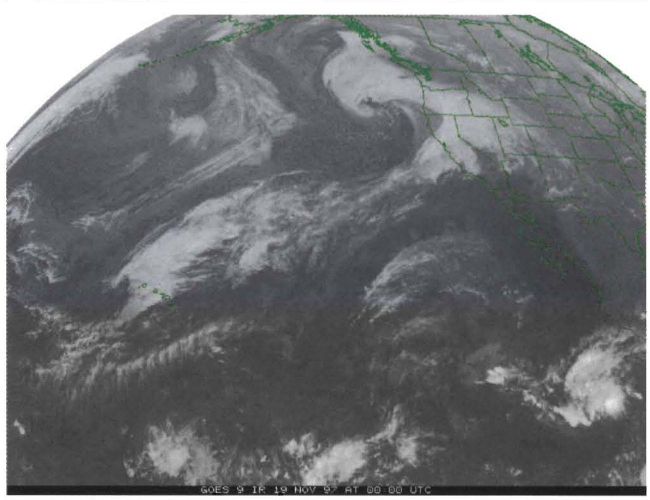

Figure 5. The GOES infrared satellite image at 00h on 19 November 1997, at the peak of the storm.

back toward the Oregon coast, Figure 2, passing between the offshore Oregon and Washington buoys. This passage is indicated in Figure 3 by the sudden drop in wind speeds measured first at the Oregon buoy, and more dramatically at the Washington buoy, indicating that the eye of the storm passed close to the Washington buoy; this passage is also indicated by a full 360° change in wind directions measured by the Washington buoy.

By 06h on 19 November, the storm had reached its peak with a maximum central pressure of 972 mb. The infrared GOES satellite image taken at 00h GMT, close to the storm's peak, Figure 5, shows the pronounced development of the cyclonic system offshore from the PNW. At the storm's peak, fetch distances over which the wind speed and direction were relatively constant were on the order of 400 km, indicating considerable potential for the generation of high waves. This fetch was located to the south of the storm center, Figure 2, and was orientated west-southwest so that the generated waves were directed toward the PNW coast, primarily sweeping along the northern Oregon coast and progressively onto the Washington coast.

As can be seen in Figure 3, wind speeds increased rapidly throughout 19 November, reaching a maximum hourly average speed of 50 knots at the Oregon buoy, and over 40 knots at the Newport buoy. These peak wind speeds coincided approximately with the times at which the lowest atmospheric pressures were recorded at each of the buoys. In response to the strong winds and relatively large fetches to the southwest, wave growth occurred rapidly at the Oregon, Newport, and Columbia River buoys (Figure 3). For example, wave heights at the Newport buoy were around 2.7 m at 06h on 19 November, and reached a maximum significant wave height of 10.5 m by 15h. Thus, about ten hours were required to form the maximum significant wave height, with the largest waves occurring during a 6-hour period between 12–18h GMT, coinciding with the strongest winds. This is further reinforced in the wave energy spectra plot, which shows that the highest energy levels were achieved during a period of about 9 to 14 hours (Figure 4).

The above findings are supported to some degree by wave hindcasts we have made using the ACES package of analysis programs developed by the U.S. Army Corps of Engineers. Based on an average wind speed of 35 knots (average wind for 19 November), duration of 18 hours, and a straight-line fetch of 400 km, the maximum significant wave height was found in the hindcast to be on the order of 9.3 m. This is comparable to the maximum significant wave height measured by the Newport wave buoy (within about 13%). However, the modeling suggests that a slightly longer time frame is required for the waves to fully develop.

Large waves were also recorded at the Oregon buoy (11.3 m), while the Columbia River and Washington buoys recorded smaller waves (7.7 and 6.4 m respectively). It is likely that these smaller wave heights are a function of the lower wind speeds and considerably shorter fetches to the north of the storm's eye. Due to the close proximity of the Oregon buoy to the storm center, peak wave periods at the height of the storm reached 14 sec, while the Newport and Columbia River buoys were characterized by slightly longer wave periods, 16.7 and 16 sec respectively. Differences here relate to the greater distances the Newport and Columbia River buoys were from the storm, so that wave dispersion during travel resulted in the development of spectra dominated by longer-period waves, apparent in Figure 4.

Although peak wind speeds occurred late on November 19, the cyclonic system had begun to "fill" earlier in the day, with an increase of pressure within the storm's eye. Nevertheless, the deep-water significant wave heights remained above 6 m at the Oregon and Newport buoys until early on 20 November, Figure 3. The storm progressively weakened as it moved toward the Washington coast, Figure 2, eventually crossing the coast at 06h GMT on 20 November.

The 1998–99 La Niña Storms

As discussed earlier, during a La Niña the jet stream crosses directly over the PNW, so one might expect a higher incidence of large magnitude storms than during an El Niño. This certainly was the case during the 1998–99 La Niña. It is likely that the strongly positive EP index was a contributing factor, since there were exceptionally high wave conditions along the entire West Coast, not just in the PNW (ALLAN and KOMAR, 2000, in review).

Associated with a strongly positive EP, the 1998–99 La Niña was characterized by a deeper than normal Aleutian Low, although spatially its coverage was considerably less than during the 1997–98 El Niño winter. The Hawaiian High shifted eastward so that it covered much of the eastern Pacific, and was again characterized by higher than normal surface pressures. The jet stream was again well developed, with a strong zonal flow dominating the area between Japan and the PNW (BANCROFT, 1999). As a result of the development of a series of strong upper lows over central Siberia late in 1998, which moved east to include the Kamchatka Peninsula, storm development initially occurred to the east of Japan. These early storms were carried in a northeasterly direction toward the Gulf of Alaska. In January 1999, a very strong upper low developed over the Gulf of Alaska that directed the jet stream southward over the PNW (BANCROFT, 1999). This resulted in the passage of a number of severe extratropical storms across the PNW, producing widespread coastal erosion. Although there were four major storms during the 1998–99 La Niña when deep-water significant wave heights reached or exceeded 10 m, all of which have been analyzed, here we will examine only the 2–3 March 1999 storm that generated waves having a 14.1-m deep-water significant wave height.

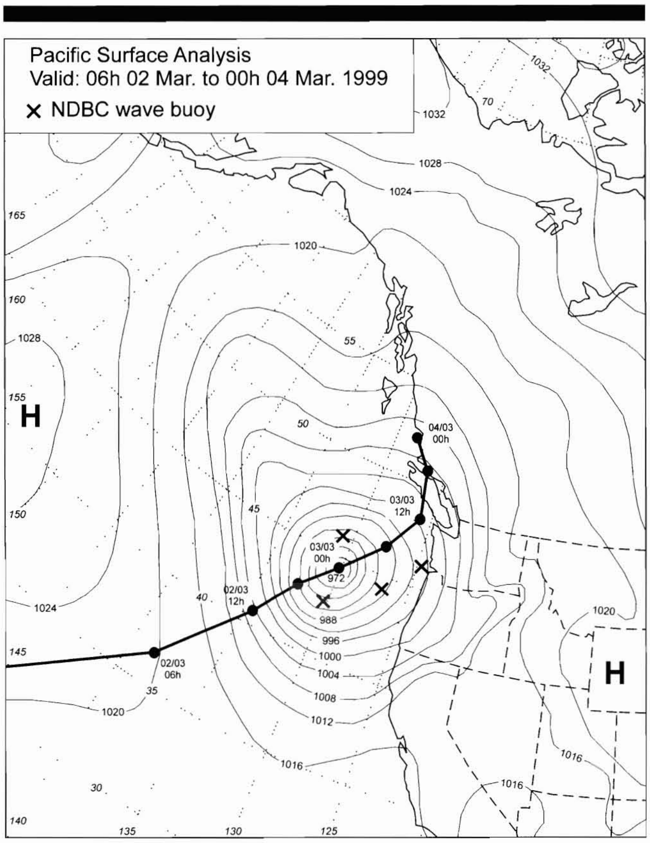

Figure 6. The track of the 2–4 March 1999 La Niña storm, with the pattern of atmospheric pressures at the time of the storm's peak.

The March 1999 storm was one of the most severe extratropical cyclonic systems to hit the PNW coast since the 12 October 1962 "Columbus Day" storm. This particular storm recorded a central pressure that was close to the Columbus Day storm, while the wave heights were the highest in memory (BANCROFT, 1999). The storm developed near 30°N and 150°W around 00h on 2 March, and was a classic "bomb", forming rapidly with a pressure drop of 43 mb in 24 hours. Figure 6 shows the storm track and surface analysis near the peak of the storm, while Figure 7 is a GOES visible image of the storm taken at 1830h on 2 March. As seen in Figure 7, the storm was characterized by a very well defined center, with bands of clouds spiraling inward.

The March storm began with a central pressure of 1003 mb. As it rapidly intensified, the system moved in a north-

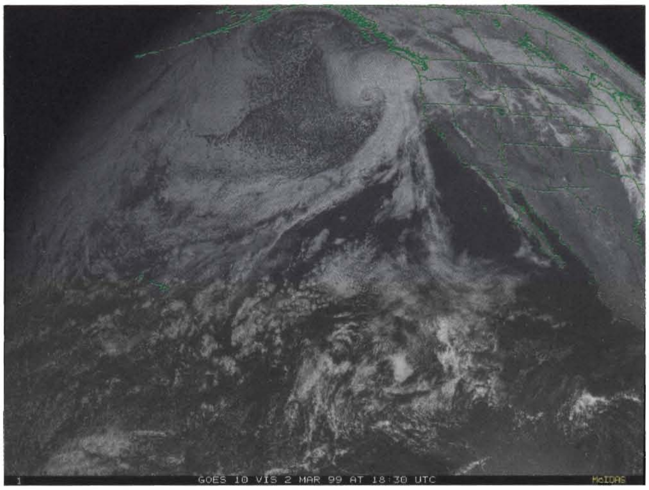

Figure 7. The GOES infrared satellite image at 1830h GMT on 2 March 1999.

easterly direction toward the Washington coast (Figure 6). By 12h on 2 March, the storm's central pressure had dropped to 989 mb, with wind circulation occurring around a well defined low-pressure center. Twelve hours later, the system had deepened to 960 mb. This process of development was strongly aided by an upper-level trough that formed west of British Columbia, which had migrated southeastward toward the PNW (BANCROFT, 1999). Due to the strong jet stream and the formation of the upper level trough close to the developing storm system, conditions were ideal for cyclogenesis, and the development of a major storm system. Fetch distances at 18h on 2 March were about 1,000 km, decreasing to about 700 km by 00h on 3 March.

Figure 8 presents the meteorological conditions and wave characteristics as measured by the wave buoys located offshore from the PNW. Wind speed and direction data were not available for the Washington buoy, while the Oregon buoy was not operational at all. Effects from the approaching storm are highlighted by the dramatic drop in pressure measured by each of the functioning buoys (Figure 8). Between 06h and 00h GMT on 1–2 March, wind speeds initially decreased, reaching lows around 00–06h on 2 March. However, soon thereafter the wind speeds increased rapidly at each of the buoys, Figure 8, peaking at over 45 knots by 06h on 3 March. As can be seen for the Columbia River and Newport buoys, Figure 8, the rise in wind speeds coincided with the fall in atmospheric pressure, with the highest wind speeds occurring at the same times as the lowest pressures were measured at the buoys.

As a result of the strong winds and substantial fetches to the south of the storm center, wave heights began to increase around 00h on 3 March, approximately 20 hours after winds had begun to increase in strength. This early phase of wave development was characterized by generally short wave periods, with peak periods of around 6 sec (Figure 8). This is further emphasized by the spectral-energy density plot in Figure 9 for each of the buoys, again for the four frequency bands 0.05, 0.06, 0.10, and 0.13 Hz (periods of 20, 16.7, 10 and 8 sec, respectively). Due to the close proximity of the Washington buoy to the storm's center, the effects of the approaching storm were felt there first. As revealed by Figure 9, the generated waves were dominated by short period (high frequency) waves during the early hours of March 3. However, as the wave field developed, there is a pronounced shift in the wave energy spectra from 0.1 to 0.06 Hz between 06h and 12h on March 3 (Figure 9). More significant is the relatively large amount of energy (greater than that observed during the major El Niño storm) contained in the 0.05 Hz bandwidth. Thus, as the wave heights increased, so did the wave periods, with the longest wave periods coinciding with the peak significant wave heights.

The most notable feature of Figure 8 is the rapidity at which the significant wave heights increased, with the largest wave heights occurring in about 8 hours at the Columbia River buoy, and 3 hours later at the Newport buoy. Highest wave heights occurred some 30 hours after wind speeds had begun to build. The significant wave heights eventually reached over 14 m at the Newport buoy, Figure 8, with 12.8 m waves recorded at the Columbia River buoy. Further to the west, the Washington buoy recorded a maximum significant wave height of only 8.7 m. These smaller waves are due largely to the much shorter fetch lengths to the east, a function of the storm's position and track.

The storm continued to move in a northeasterly direction, toward the Washington coast. However, after 00h GMT on 3 March the storm filled rapidly, and by 06h on 3 March the storm's central pressure had risen to around 980 mb. The storm eventually crossed into British Columbia late on 3 March.

Hindcasts were also performed for this storm, utilizing the ACES package of the U.S. Army Corps of Engineers. However, unlike the relatively good wave hindcast achieved for the November 1997 storm, wave hindcasting for the March 2 storm yielded a maximum significant wave height of 11 m, much lower than the 14.1-m measured heights. This analysis is based on a fetch of 700 km, 40 knot wind speeds and a duration of 18 hours, the latter variables having been determined from the Oregon (#46002) NDBC wave buoy. Adjusting the duration time to 30 hours and increasing the fetch to 1000 km was found to make little difference in the hindcast wave height, which increased only slightly to 12.4 m. It is likely that the above difference between predicted and measured waves simply reflects the difficulty in accounting for the wind conditions along the fetch. For example, subtle variations in the wind speed can produce large changes in the estimated hindcast wave heights, a problem that is shared by nearly all wave modeling studies (EARLE *et al.*, 1984). Perhaps more significant is that the hindcasting model requires a much longer generation time for the waves to develop. This finding may reflect a limitation of the ACES hindcasting model to adequately account for the growth of large waves associated with a rapidly moving storm system.

Summary

Table 2 summarizes the peak storm wave statistics associated with each of the major extratropical storms that oc-

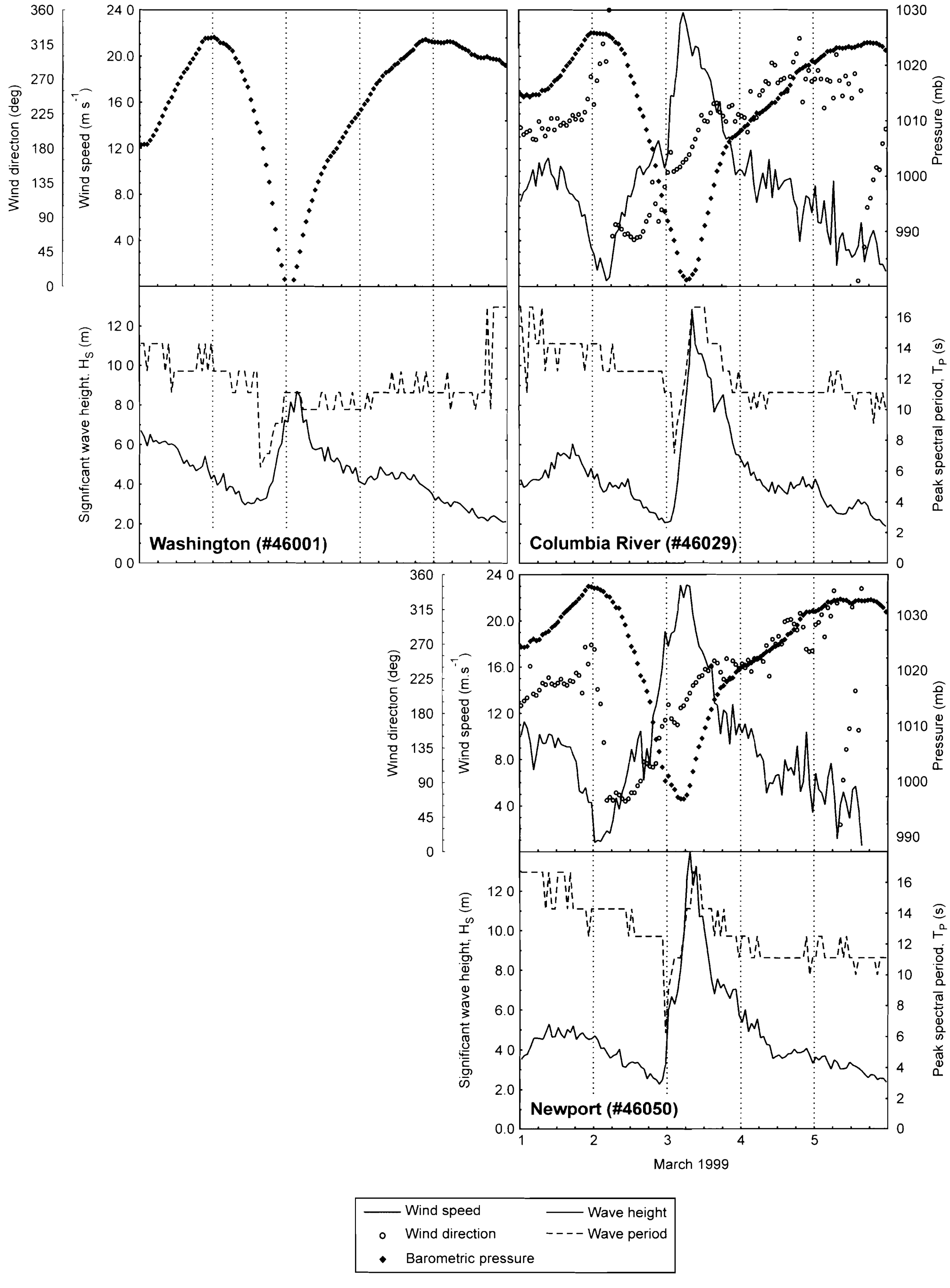

Figure 8. Measurements of meteorological and wave conditions derived from the three operating NDBC buoys during the 2–3 March 1999 storm.

curred during the 1997–98 El Niño and 1998–99 La Niña events, as well as a large wave event that occurred in January 2000. As indicated in Table 2, the maximum significant wave heights associated with the six storms ranged from 10 to over 14 m in height, with periods in the range of 12 to 20 seconds. Maximum wave breaker heights are also included in Table 2, calculated using the formula of KOMAR and GAUGHAN (1972) from the measured deep-water wave heights and periods. The breaker heights are estimated to range from 10.8 to 15.8 m, with the largest breaker heights associated with the 2–3 March 1999 storm, while the large breaker heights estimated for the 16–17 February 1999 storm is a function of the storm's unusually long wave period, 20 sec.

An interesting feature of Table 2 is the much longer peak wave period of 20 sec experienced during the 16–17 February 1999 storm, compared with the other storms. These long pe-

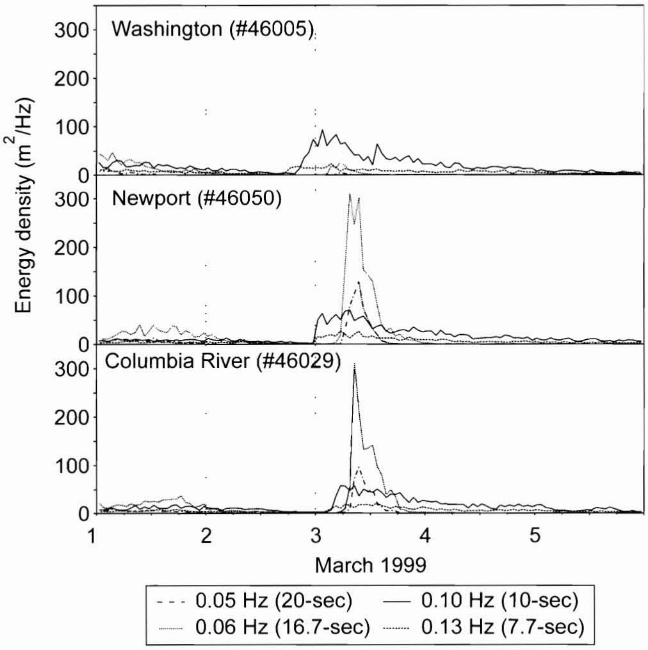

Figure 9. Spectral energies of waves at four frequencies, generated by the 2–4 March 1999 storm.

Table 2. *Peak storm wave statistics derived from the Newport buoy (#46050) for the major 1997–98 El Niño and 1998–1999 La Niña storms.*

#46050	Date	Significant Wave Height (m)	Wave Period (m)	Breaker Height (m)
El Niño	19–20 Nov, 1997	10.5	14.3	11.8
La Niña	25–26 Nov, 1998	10.8	12.5	11.3
	6–7 Feb, 1999	10.1	12.5	10.8
	16–17 Feb, 1999	10.0	20.0	12.9
	2–3 Mar, 1999	14.1	16.7	15.0
2000	16–17 Jan	12.1	14.2	13.1

riods are probably a function of the storm's position, which was located a considerable distance offshore from the PNW coast at the time of the storm's peak. As a result of the large fetches, wave dispersion enabled the development of high swell waves that contained considerable energy. In a similar study of North Pacific storms that occurred during the 1982–83 El Niño, EARLE *et al.* (1984) described a storm in which the wave energy spectra was characterized by substantial wave energy at the unusually long wave periods of 20 to 25 sec. These long period waves developed well out in the North Pacific, and propagated toward the California coast as high swell, causing extensive damage when they reached the coast. EARLE *et al.* noted that such long wave periods were unusual and had been seldom measured during high sea states by NOAA wave buoys. Unlike the extremely long wave generation fetches that typified the 1982–83 El Niño storms, the 1997–98 El Niño and 1998–99 La Niña storms were generally characterized by much shorter fetches, while the rapid development and speed of storm propagation likely precluded the development of wave energy spectra dominated by very long periods.

The major storms of the 1997–98 El Niño and 1998–99 La Niña were clearly unusual due to the rapidity of storm development, and the high waves that were generated along the PNW coast. Furthermore, the occurrence of six major storm events in such a short period is unusual in the eastern North Pacific based on a 25-year record of wave measurements, raising questions about the frequency of such storms during the past.

DANIELSEN *et al.* (1957) provided an early examination of the frequency of severe storms in the North Pacific between 1922 and 1952 (excluding World War II years). Although they noted a large amount of variability in the intensities of the storms, they observed that the years with very severe storms tended to be grouped together, with the bad winters separated by years with relatively few major storms. Almost half of the major storms occurred during the winters of 1932–33 and 1951–52. Interestingly, both of these winters coincided with moderate El Niño climate events.

ALLAN and KOMAR (2000) carried out similar analyses of the frequency of storms for the period 1976 to 1999. Their results revealed that the incidence of major storms in the North Pacific since at least the mid-1970s was characterized by a distinctive cyclical pattern. For example, the frequency of storms increased throughout the late 1970s and reached a peak of 10–12 storms during the early to mid-1980s; it decreased in the early 1990s, and then storm frequency rose considerably, reaching a peak of 20–23 storms between 1997 and 1999. More recent evidence of the unusual nature of the latest period of severe North Pacific winter storms has come from the work of GRAHAM and DIAZ (2001). Their comprehensive examination of North Pacific storm climatology indicated a long-term increase in both the frequency and magnitude of storms in the North Pacific since the early 1940s. Their results also substantiate the earlier work of DANIELSEN *et al.* (1957) concerning the severity of the winter of 1952–53. The more vigorous cyclone activity is apparently a function of an increase in upper tropospheric winds and vertical wind shear over the central North Pacific. GRAHAM and DIAZ (2001) identified increasing sea surface temperatures in the western tropical Pacific as a plausible cause of the observed changes in North Pacific storm frequency and intensity. This raises the obvious question of what might be expected in the next 25 years, with the apparent on-going trend of global warming.

ELEVATED MEAN WATER LEVELS

Important to the erosion caused by the storms were the elevated levels of the tides, with the measured tides having been 10s of centimeters higher than predicted. Although the high water levels experienced during the 1997–98 winter can be partially attributed to the occurrence of an El Niño, the high water levels experienced during the 1998–99 winter season were predominantly caused by the strong onshore winds and low barometric storm pressures which produced significant storm surges along the PNW coast. This section presents a detailed analysis of the monthly-mean water elevations ex-

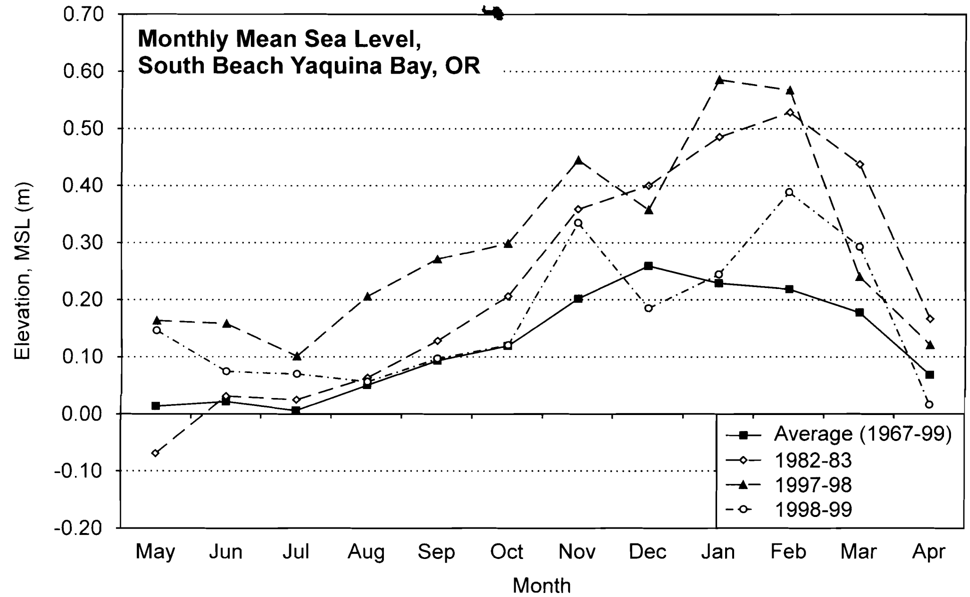

Figure 10. Monthly mean water levels derived from analyses of tide-gauge measurements in Yaquina Bay, Oregon. Included is the 1967–99 long-term averages (excluding El Niño years), and results for the 1982–83 and 1997–98 El Niño years and the 1998–99 La Niña year.

perienced along the PNW coast between 1997 and 1999. Furthermore, it examines the hourly measured water levels observed during the major storms, and presents new information on the magnitudes of storm surges along the PNW coast.

Monthly-Mean Water Levels

Apparent during an El Niño are the unusual heights of tides, with measured tides typically being some 0.5 m higher than predicted. These elevated tides persist throughout the winter, and raise water levels at all tidal stages. Therefore, it must represent processes that affect the mean level of the sea all along the coast, processes that continue for several months. They can be documented by calculations of monthly-mean water levels, determined by averaging the measured tides over the span of a month. Such analyses have been conducted by FLICK (1998) for tide-gauge data from California, and by HUYER *et al.* (1983) and KOMAR *et al.* (2000) for the Oregon coast. These studies demonstrated that unusually high water levels occurred during the 1982–83 and 1997–98 El Niños, much higher than occur during "normal" or La Niña years.

Such an analysis is presented in Figure 10, based on tide-gauge data from Yaquina Bay (Newport), on the mid-Oregon coast (Figure 1). Although not shown here, related analyses of data from the Toke Point tide gauge in Willapa Bay, Washington, yielded closely similar results. The curve for the complete 33-year Yaquina Bay record (excluding those years in which El Niños occurred) shows that water levels tend to be lowest during the summer, a result of coastal upwelling that produces cold, dense water in the summer, depressing the mean level of the sea along the coast (HUYER, 1983). In the winter the water is warmer due to the absence of upwelling, and its thermal expansion contributes to the elevated water levels. Coastal currents also play a role, the northward direction of the current affecting the cross-current geostrophic slope of the water's surface, raising water levels to the right of the current along the PNW coast; the stronger the current, the greater the rise in the water level (HUYER, 1983).

Included in Figure 10 are monthly averages for the 1982–83 and 1997–98 El Niños, with the results demonstrating the occurrence of unusually high monthly-mean water levels that reached 0.53 m and 0.59 m respectively. These high monthly averages are some 0.26 and 0.33 m higher than the 33-year Yaquina Bay monthly averages, and can be attributed to the offshore water being abnormally warm, and the geostrophic effects of stronger northward flowing currents, both being characteristic of El Niño winters along the U.S. West Coast (HUYER *et al.*, 1983; KOMAR, 1986). Also contributing to the rise in water levels may be the passage of a sea-level "wave" generated at the equator by the cessation of the Trade Winds during an El Niño (WYRTKI, 1977, 1984), which then travels northward along the Pacific coasts of Central and North America (ENFIELD and ALLEN, 1980). In contrast, the results in Figure 10 for the 1998–99 La Niña show that mean water levels returned to nearly their long-term averages. The somewhat higher water levels in November 1997 and again in February and March 1999 were produced by storm surges of the extreme La Niña storms, rather than by the longer-term processes associated with El Niños.

Storm Surges

Storm surges are the product of several processes (PUGH, 1987). With strong winds, a horizontal force is exerted on the water's surface, which induces a surface current approximately in the direction of the wind. When the shoreward transport of water encounters shallow water, it is slowed in response to a change in the water depth. As further shoaling occurs there is a convergence of water near the shore, which causes the mean water level to be elevated along the coast (CERC, 1984; HSU, 1988). Essential to the development of a high storm surge is the presence of strong winds and a wide, shallow continental shelf (PUGH, 1987; FLATHER, 1994). The rise in water level is further enhanced by the low atmospheric pressure of the cyclonic storm system, through the inverse barometer effect (CHELTON and DAVIS, 1982). In general, the sea surface is raised by 1 cm for each millibar (mb) of decreased atmospheric pressure. Thus, during the passage of an intense low-pressure system over the ocean, the sea surface can be raised by tens of centimeters due to the inverse barometer effect alone. CHELTON and DAVIS (1982) established that along the PNW coast, about 50 to 60% of the sea-level variability reflects the simple inverse barometric response to the local atmospheric pressure.

The role of storm surges along the PNW coast has been largely ignored in analyses of coastal hazards, primarily because the surge elevations were assumed to be small. For example, analyses by RUGGIERO *et al.* (1996) of daily mean water levels at Newport, Oregon, revealed that the surges are typically only on the order of 0.10 to 0.15 m. This is probably a function of the large water depths that exist across the steeply sloping continental shelf offshore from the PNW, which causes the levels of storm surges to be significantly reduced. Furthermore, the absence of significant surges along the PNW coast may in part be related to the more southwesterly winds that blow at strongly oblique angles to the coast during major storms, rather than being directed onshore. Despite this, PETERSON and DARIENZO (1996) reported the occurrence of a storm surge on the Oregon coast in November 1981 that ranged from 0.5 to 1.2 m, indicating that under the right circumstances significant surges can develop. Given the intensities of the storms during the 1997–98 and 1998–99 winters, it is of interest to examine the magnitudes of the surges associated with those storms.

Analyses of the mean water levels along the PNW coast have been based on the Newport, Oregon, and Toke Point, Washington, tide gauges (Figure 1). The hourly water level data were obtained from the National Ocean Service (NOS), while the predicted tidal elevations were estimated using the computer program WXTIDE32. This program uses the same algorithm as the one used by the NOS for predicting tidal elevations. The predicted tidal elevations were subtracted from the measured tides, the standard definition and analysis approach of a storm surge (PUGH, 1987; KOMAR, 1998b). The results are given in Figures 11 and 12, presenting the hourly variations of the measured tides minus the predicted tides, respectively for the major 19–20 November 1997 El Niño storm and the 2–4 March 1999 La Niña storm. Included in the figures are hourly changes in the barometric pressure, which document the storm's approach and in part account for the magnitudes of the resulting surges.

A feature of the 19–20 November 1997 El Niño storm, Figure 11, was the already elevated mean water levels of about 34–40 cm at both tide gauges, prior to the arrival of the storm. Nearly all of the 34–40 cm variation can be attributed to the seasonal increase in mean water levels due to the El Niño processes (Figure 10). With the storm's approach, the barometric pressure began to fall around 12h on 18 November. However, the mean water levels did not begin to rise until 00h on 19 November at the Newport gauge, and about 10 hours later at Toke Point (Figure 11). Thus, Figure 11 indicates that the increase in water levels lag the rising wind speeds and decrease in atmospheric pressures, a function of the storms proximity to the tide gauges and the speed with which the storm developed. A peak water level of 0.81 m was reached at the Newport gauge at 17h on 19 November, while a maximum water level of 0.98 m was experienced at Toke Point some five hours later. This difference in the maximum water levels on the Oregon and Washington coasts is probably related to the storm's greater westerly position offshore from Oregon at 09h on 19 November, Figure 2, compared with its position several hours later closer inshore to the Washington coast. The storm surge caused by the 19–20 November 1997 storm is estimated to have been between 0.4 to 0.6 m, once the monthly average water level is subtracted from the total water level. Of the 0.4 to 0.6 m storm surge, approximately 30–40% of the surge height reflects a simple inverse barometer effect, with the remainder having been produced by the wind stress and by setup caused by wave breaking along the shore.

Unlike the 1997–98 El Niño, mean monthly water levels during the 1998–99 La Niña were generally closer to the long-term average curve, Figure 10, except for the deviations produced by the effects of the storm surges on the monthly means. During March 1999 the average monthly water levels ranged from 0.28 m at Newport to 0.17 m at Toke Point. As shown in Figure 12, the approach of the storm was characterized by a dramatic decrease in barometric pressure measured at the tide gauges during the early hours of 2 March. Similar to the 19–20 November 1997 storm, the rise in water levels lags the fall in barometric pressure and increase in winds by some 12 to 18 hours. At the Newport gauge, the maximum water level of 0.76 m occurred twice; the first peak occurred at 07h on 3 March, while the second peak took place five hours later (Figure 12). Further north at Toke Point, a more dramatic picture emerges with the highest water levels having reached 1.76 m above the predicted tide (Figure 12). This occurred some 5 hours after the first high water level peak was measured at Newport, and took place about two hours after high tide. However, unlike the Newport gauge there is no second peak at Toke Point. Perhaps more important for coastal erosion is the fact that the water levels remained high (above 0.6 m) for about 10 hours at Newport, and 18 hours at Toke Point. Similar to the 19–20 November 1997 El Niño storm, the highest water levels were observed about six hours after the lowest barometric pressure, peak winds, and highest wave heights. Removing the monthly average water levels from the maximum water levels measured by the respective tide gauges yields a storm surge of about 0.5 m at Newport and 1.6 m at Toke Point. In contrast to the El Niño storm, our analyses reveal that the inverse barometer effect was small, accounting for only about 20 to 35% of the storm surge. This suggests that other factors such as the wind and wave set-up components, the product of the intense

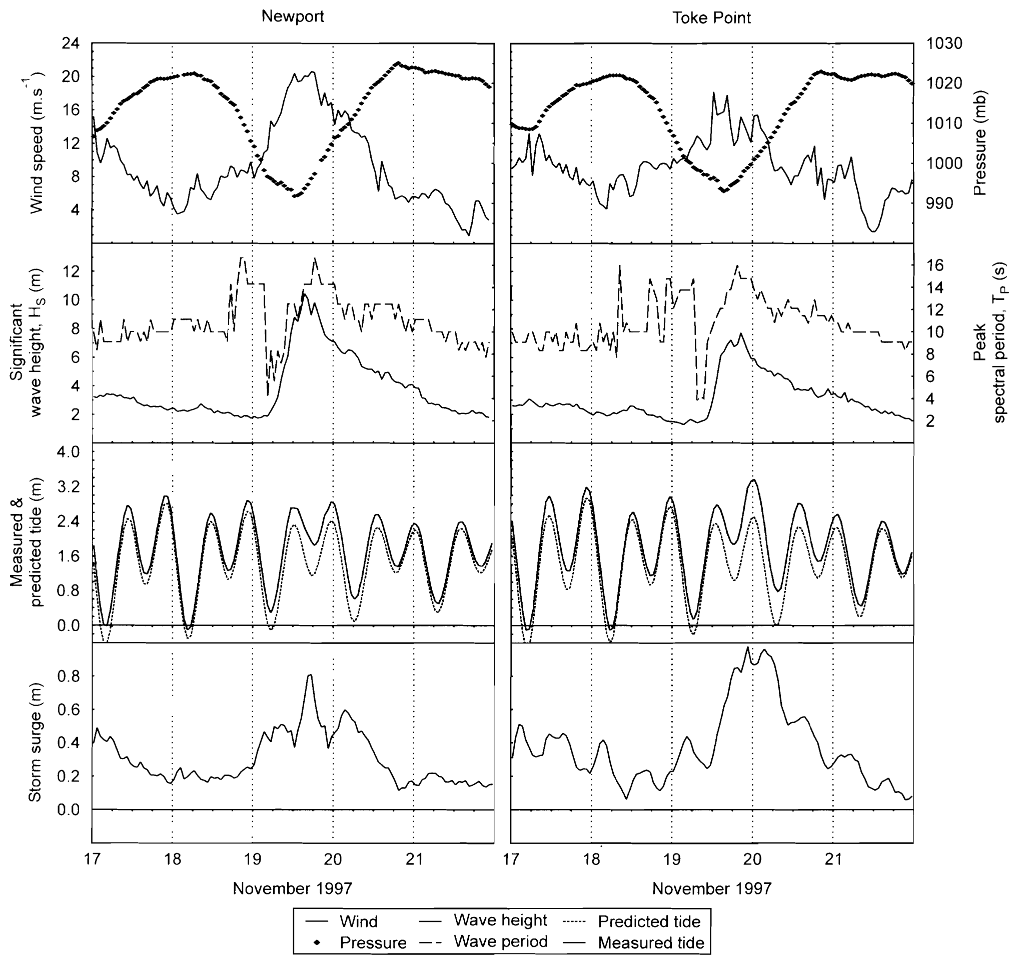

Figure 11. Analyses of the storm surges generated by the 17–20 November 1997 El Niño storm as measured by the Newport, Oregon, and Toke Point, Washington, tide gauges. Shown are the local atmospheric pressures, and the storm surge as determined by subtracting the predicted tide from the measured tide.

nature of this storm, were considerably more important during the 2–3 March La Niña storm.

All of the major storms during the 1997–98 El Niño and 1998–99 La Niña were analyzed as above to evaluate the associated storm surges (KOMAR and ALLAN, 2000). Table 3 presents a breakdown of the water-level components, including an assessment of the mean monthly water level and the amount of water level increase due to the inverse barometer effect. In deriving an approximate estimate of the mean monthly water level, we have ignored those hourly water levels that coincided with an hourly wind speed greater than 6.6 $m.s^{-1}$ (equivalent to a Force 4 breeze on the Beaufort wind scale), and a barometric pressure less than 1013 mb. Although approximate, this approach essentially eliminates those periods characterized by significant storm surges, enabling a better evaluation of the mean monthly water level, and hence the actual storm surge above that level.

One of the features of Table 3 is that the Washington coast appears to have experienced generally higher surges compared with the Oregon coast. Certainly, part of this difference can be explained in terms of the paths of the storms, which generally tracked closer to the Washington coast. This is highlighted in Figures 2 and 6, which show that both the major El Niño and La Niña storms had northeast tracks, so the storms crossed close to or directly over the Washington coast. As a result, part of the difference in the storm surges can be attributed to the inverse barometer effects associated with the lower atmospheric pressures measured at the Toke Point gauge, Table 3, compared with the Newport tide gauge. It is also probable that due to the northeast storm tracks, the longer fetches directed toward the Washington coast resulted in greater wind-stress and wave set-up components in the storm surge, contributing to the higher total-water elevations.

SHIPPING AND EROSION IMPACTS

The storms documented here produced major impacts along the PNW coast, both to shipping and in the form of large-scale beach and property erosion. On 4 February 1999

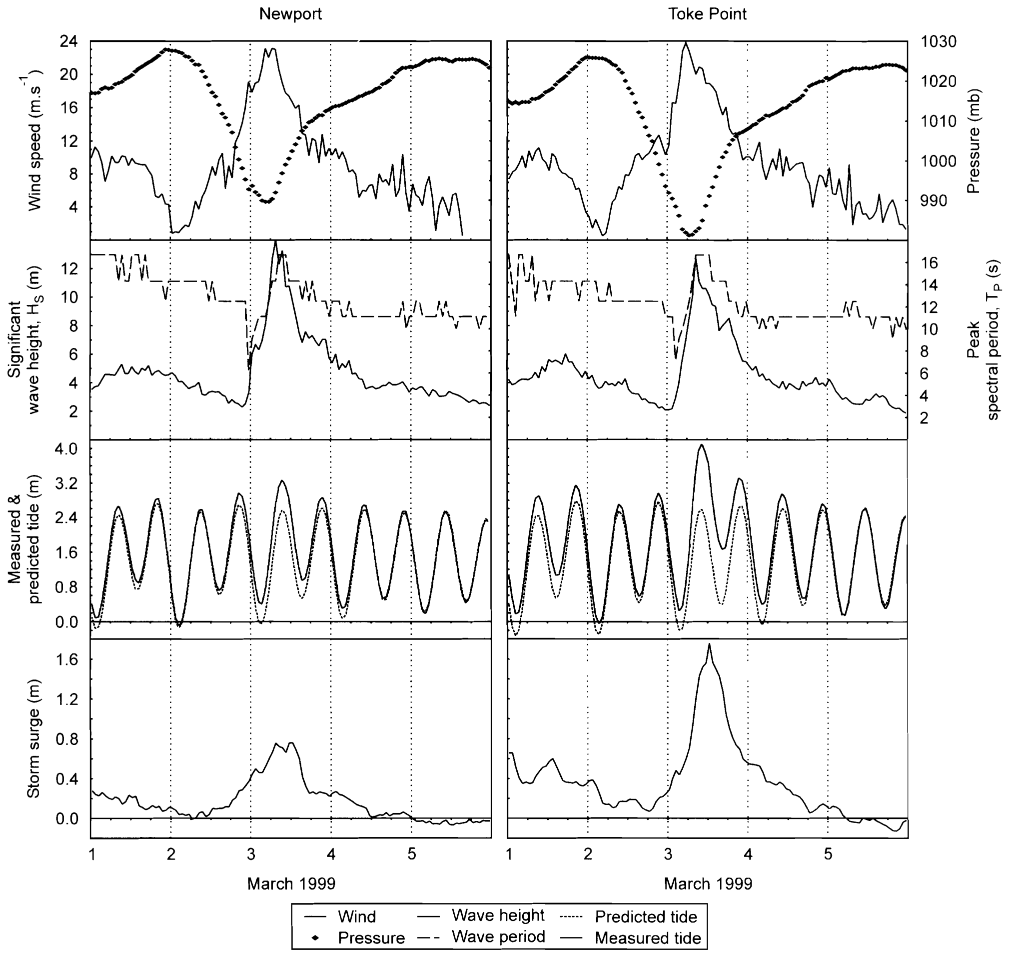

Figure 12. Storm surge analyses as undertaken in Figure 11, but for the 2–4 March 1999 La Niña storm.

the *M/V New Carrisa,* a 195-m long bulk freighter, grounded on the beach just to the north of the Coos Bay harbor entrance on the southern Oregon coast (HALL, 1999). At the time, winds were locally reported as having reached 39 knots, with seas having a significant wave height of 8 m. This was the early stage of one of the major storms analyzed in this study, when the storm reached the northern Oregon and Washington coast at which time the deep-water significant wave height exceeded 10 m. Of concern in the grounding of the *New Carrisa* was the 400,000 gallons of fuel oil it con-

Table 3. *Storm surge and water level characteristics associated with the major storms in 1997–98 and 1998–99.*

	Date	Barometric Pressure (mb)	Total Water Level (m)	Monthly Average (m)	Surge (m)	Inverse Barometer Effect (m)	Inverse Barometer Effect (%)
Newport							
El Niño	19–20 Nov, 1997	997	0.81	0.40	0.41	0.16	39%
La Niña	25–26 Nov, 1998	999	0.82	0.21	0.61	0.14	23%
	6–7 Feb, 1999	989	0.66	0.31	0.35	0.24	69%
	16–17 Feb, 1999	1006	0.46	0.31	0.15	0.07	47%
	2–3 Mar, 1999	996	0.76	0.28	0.48	0.17	35%
Toke Point							
El Niño	19–20 Nov, 1997	993	0.98	0.34	0.64	0.20	31%
La Niña	25–26 Nov, 1998	995	1.15	0.24	0.91	0.18	20%
	6–7 Feb, 1999	979	0.95	0.31	0.64	0.34	53%
	16–17 Feb, 1999	999	0.82	0.31	0.51	0.14	27%
	2–3 Mar, 1999	981	1.76	0.17	1.59	0.32	20%

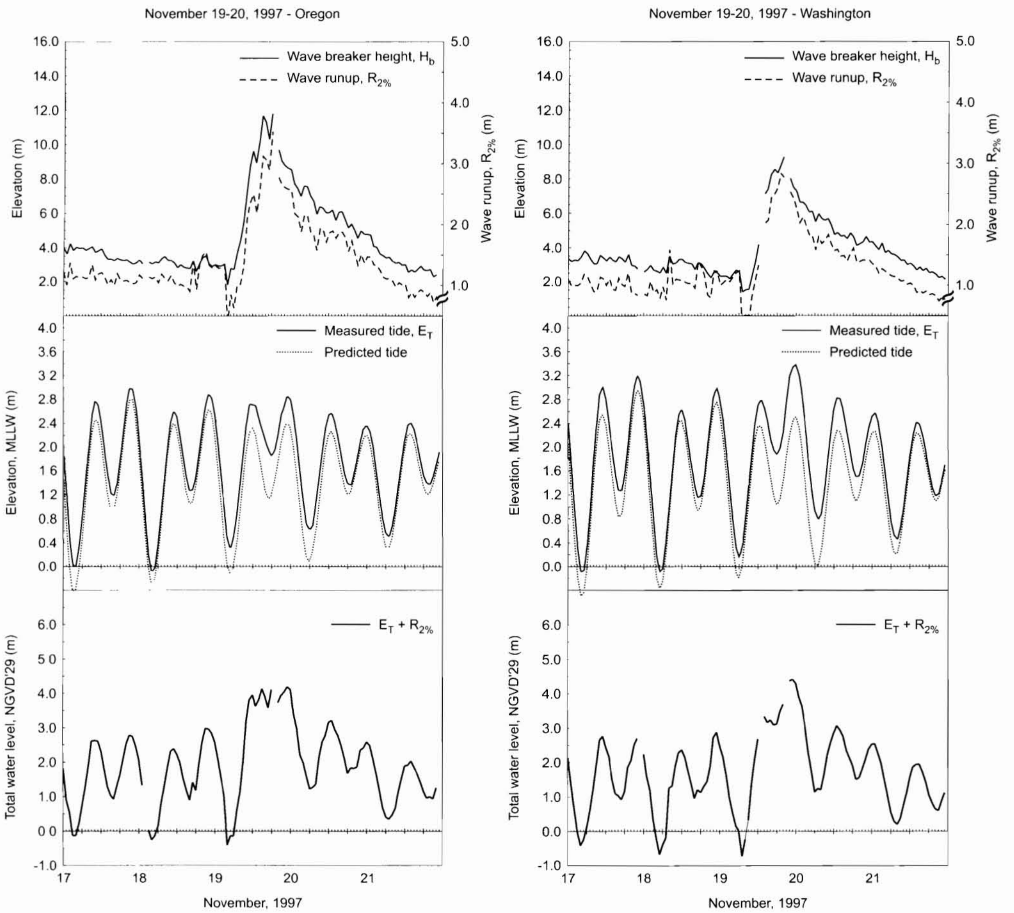

Figure 13. Analyses of wave-breaker heights and $R_{2\%}$ runup levels at the shore, predicted and measured tides (R_T), and total water levels ($R_T + R_{2\%}$) on PNW beaches, for the period centered on the 19–20 November 1997 El Niño storm. The results for Washington and Oregon are compared.

tained. During the subsequent weeks, some of this oil was spilled and contaminated the adjacent beaches, with the loss of a large number of shore birds; however, much of the oil was pumped out of the ship or burned, limiting the extent of environmental damage. It eventually was decided to tow the ship offshore into deep water and sink it, but with profound bad luck this was attempted during the strong 2–4 March 1999 La Niña storm. A wind gauge on the tug reported winds up to 65 knots, which is hurricane strength on the Beaufort wind scale, at which point the wind sheared off the gauge. After having towed the ship about 50 miles offshore, the 2.25-inch wire rope parted, and the *New Carrisa* washed back onshore, further to the north, polluting another stretch of beach.

Under the combined effects of the El Niño and La Niña storms, beach and property erosion occurred along much of the Oregon and Washington coasts, to a greater extent than had occurred in many years (KOMAR *et al.*, 2000). Significant to the resulting erosion was the superposition of high measured tides, produced by the elevated monthly-mean water levels and by storm surges during specific events, plus the runup of the storm waves when they reached the beaches. This can be estimated using the model developed by RUGGIERO *et al.* (1996, 2001), where the measured tide is added to the runup level calculated with the relationship

$$R_{2\%} = 0.27(SL_\infty H_\infty)^{1/2} \tag{1}$$

where S is the beach slope, H_∞ is the deep-water significant wave height, and L_∞ is the deep-water wave length calculated with $L_\infty = (g/2\pi)T^2$ where T is the wave period. The vertical runup level, $R_{2\%}$, is the 2% exceedence value, which is slightly lower than the maximum runup but involves a number of swash events so can be expected to be meaningful in assessments of sea cliff or dune erosion. Equation (1) is based on runup measurements under a range of conditions on Oregon beaches, together with the data of HOLMAN (1986) obtained at the Field Research Facility in Duck, North Carolina.

Detailed analyses of the November 1997 El Niño storm and March 1999 La Niña storm are presented respectively in Figures 13 and 14. In each case analyses are undertaken for the Oregon coast using tide measurements from Newport, Figure 1, together with wave data from the inshore Newport buoy, and for the Washington coast with tide data from Toke Point, Willapa Bay, and wave data from the nearby Columbia River

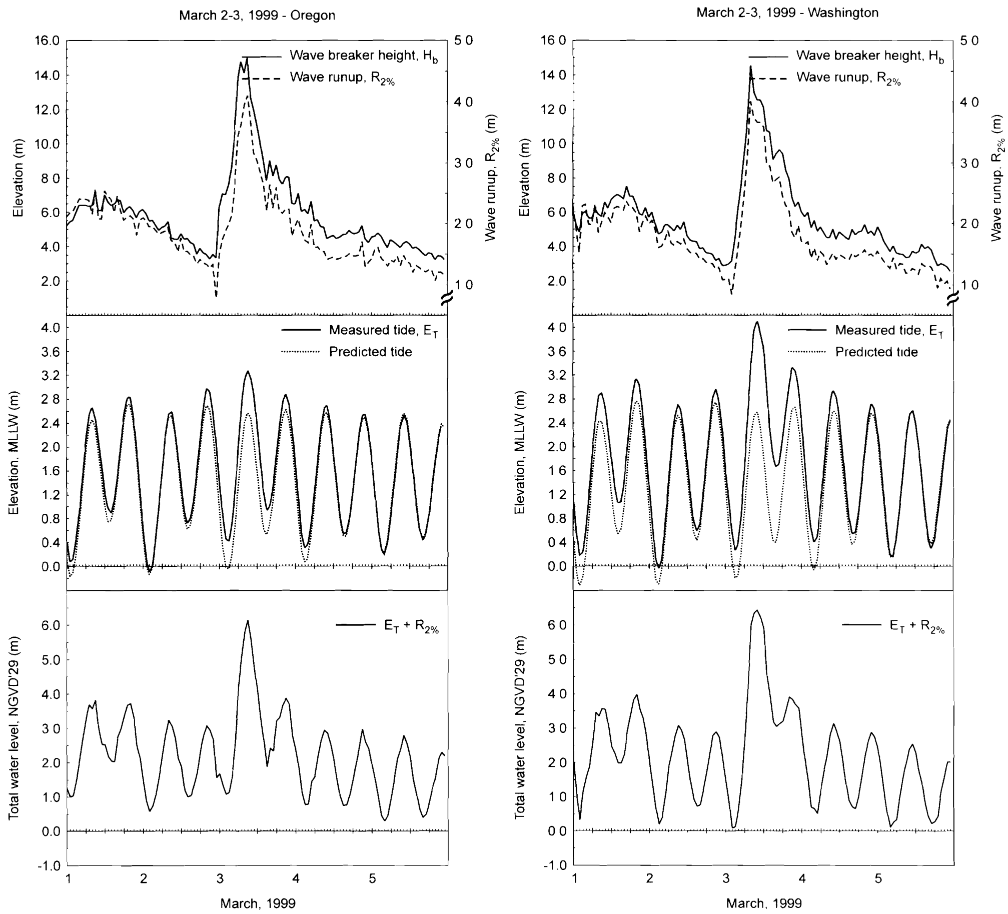

Figure 14. Analyses like those in Figure 13, but undertaken for the 2–4 March 1999 La Niña storm.

buoy. Each analysis graphs the significant wave breaker heights in the nearshore, calculated with the formula of KOMAR and GAUGHAN (1972) where the breaker height depends on the measured deep-water wave height and period, together with the runup level calculated using equation (1) where the beach slope is taken as $S = 0.04$, representative of PNW beaches. Also graphed in Figures 13 and 14 are elevations of the predicted and measured tides, with the difference reflecting the effects of monthly-mean water levels and the storm surge. Finally, the analyses present the total water elevations at the shore, $E_T + R_{2\%}$, the sum of the measured tidal elevation (E_T) and the wave runup. While the predicted and measured tides graphed in Figures 13 and 14 are referenced to Mean Lower Low Water (MLLW), in the final calculation the total water level is referenced to the NGVD'29 datum, which is used in land surveys and in defining the beach-zone line for the State of Oregon. This shift in the datum from MLLW to NGVD'29 represents a subtraction of the water-level elevations by 1.25 m for the Yaquina Bay tide gauge, and 1.34 m for the Toke Point gauge.

In Figure 13 the analysis of the 19–20 November 1997 El Niño storm shows that the breaking wave heights increased dramatically as the storm approached the coast, reached a maximum, and then slowly decreased following the storm. The curve for the calculated runup closely follows the curve for the breaker heights, with slight differences due to variations in wave periods. In comparing the results for the southern Washington and central Oregon coasts, it is seen that the breaker heights and runup levels were greater for Oregon. The values at the peak of the storm impacts, derived from Figure 13, are listed in Table 4. Offsetting the higher runup on the Oregon coast is that it occurred at a time of lower tides, whereas the highest runup on the Washington coast corresponded to high tides. A detailed examination of the curves in Figure 13 for the predicted and measured tides reveals the effects of the monthly-mean water level rise, largely attributable to the El Niño processes (warmer water temperatures, *etc.*); this difference is best seen prior to the occurrence of the storm. With the arrival of the storm, there is a much greater difference between predicted and measured tides, and this is due to the addition of the storm surge, which was substantially higher on the Washington coast. Ultimately, the total water levels, the measured tides plus the runup, reached slightly higher elevations on the Washington coast, 4.4 m NGVD'29, versus 4.2 m NGVD'29 on the Oregon coast (Table 4).

Table 4. *Breaker heights, estimated wave runup elevations, and total water level ($E_T + R_{2\%}$) characteristics associated with the major storms in 1997–98 and 1998–99. Note: the total water level elevation is relative to the NGVD 1929 vertical datum; ND denotes No Data.*

	Date	Breaker Height, H_b (m)	Wave Runup, $R_{2\%}$ (m)	Total Water Level, $E_T + R_{2\%}$ (m)
Newport				
El Niño	19–20 Nov, 1997	11.8	3.5	4.2
La Niña	25–26 Nov, 1998	11.3	3.5	4.5
	6–7 Feb, 1999	10.8	3.0	4.3
	16–17 Feb, 1999	12.9	4.3	6.2
	2–3 Mar, 1999	15.0	4.1	6.1
2000	16–17 Jan	13.1	3.4	4.5
Toke Point				
El Niño	19–20 Nov, 1997	9.3	2.8	4.4
La Niña	25–26 Nov, 1998	10.8	3.1	4.5
	6–7 Feb, 1999	9.3	2.6	4.4
	16–17 Feb, 1999	12.7	4.2	5.6
	2–3 Mar, 1999	14.6	4.0	6.4
2000	16–17 Jan	ND	ND	ND

In Figure 14 the March 1999 La Niña storm again illustrates the addition of processes that control total water levels along the shore, but in a more dramatic fashion due to the larger wave heights and generated storm surge of this extreme event. Again, the highest total water level was achieved on the Washington coast, due mainly to the substantially higher storm surge. The maximum elevation there reached 6.4 m NGVD'29 (Table 4).

Table 4 includes the tabulated results for the five major storms during the 1997–98 El Niño and 1998–99 La Niña, plus another storm that occurred during the following winter on 14–18 January 2000, when the deep-water wave height exceeded 12 m. Within this set of six storms we see that the predicted $R_{2\%}$ runup values ranged approximately from 2.6 to 4.3 m, while the measured tides ranged on the order of 2.4 m to slightly more that 4 m NGVD'29; both components are therefore important contributors to the total water elevations, $E_T + R_{2\%}$, which ranged from about 4.2 m to 6.4 m NGVD'29.

The large wave heights and moderately long wave periods generated during the 1997–98 El Niño and 1998–99 La Niña were an important contributing factor to major erosion problems experienced along much of the Oregon and Washington coasts (KOMAR *et al.*, 2000; ALLAN and PRIEST, 2001). As demonstrated in Figures 13 and 14, of special interest are the total water levels reached during the storms since they determine whether the water reaches up to the elevations of sea cliffs and causes erosion, or in the case of foredunes backing the beaches, are capable of eroding back the dunes or possibly producing overwash events (RUGGIERO *et al.*, 1996, 2001; SALLENGER *et al.*, 1999). Under the onslaught of the storms along the PNW coast, there was appreciable beach and property erosion, most apparent in areas where the beaches are backed by dunes, which commonly retreated by 10s of meters. The erosion was cumulative, with the initial cut back of the beaches and dunes having occurred during the 1997–98 El Niño winter. However, the erosion during an El Niño is not uniform along the PNW coast, but instead occurs mainly in "hot-spot" areas north of headlands and jetties, due to the northward displacement of beach sand within the littoral cells, caused by the dominant approach of waves from the southwest, with the storms mainly crossing the coast of California (KOMAR, 1986, 1998b; PETERSON *et al.*, 1990; REVELL *et al.*, in press). There was little recovery of the beaches in the following summer, so that additional erosion immediately occurred during the 1998–99 La Niña. In that the La Niña storms passed more directly over the PNW coast, the resulting erosion was more widespread, not being limited to "hot spot" areas as during the El Niño (KOMAR *et al.*, 2000).

Apparent in Table 4 for the successive total water levels produced by the series of storms was the importance of the two major La Niña storms in February 1999, as well as two smaller storms that month, followed by the March 1999 storm that was the strongest of all, yielding the highest total water elevations in this two-year period. Coming at the end of two winters with cumulative erosion, the March 1999 storm attacked an already weakened coast, resulting in the most dramatic retreat of foredunes. Of interest, surveys of beaches and dunes following that storm showed reasonable agreement between elevations of the bases of the eroded dune-scarps and the calculated maximum runup level achieved during the March 1999 storm at those specific locations, providing confirmation of the results of the model calculations as presented in Figures 13 and 14, and in Table 4 (KOMAR *et al.*, 1999, 2000).

CONCLUSIONS AND DISCUSSION

Beginning with the winter of 1997–98, the Pacific Northwest (PNW) coast experienced a series of unusually severe storms that affected shipping and produced considerable beach and property erosion. The objective of this paper has been to document the meteorological conditions and wave generation of these extratropical storms, and the occurrences of associated storm surges that elevated measured tides well above predicted levels. The findings and conclusions of this study include the following:

- The storms evolved rapidly as they approached the coast, sometimes abruptly changing directions, and generally exhibited decreasing atmospheric pressures and increasing winds, at times with a rapidity wherein meteorologists characterize the storm as being a "bomb";
- The generated waves likewise increased rapidly in heights and periods as the storms approached the coast;
- Applications of wave-generation analysis techniques, based on storm fetches and wind velocities, showed reasonably good agreement with the measured waves, but with a tendency to under-predict significant wave heights;
- Monthly-mean water levels derived from analyses of tide-gauge records were elevated by an additional 0.26–0.33 m above the normal seasonal cycle during the 1997–98 El Niño winter due to ocean conditions related to that climate event. In contrast, the monthly-mean water levels were much closer to normal levels at both tide gauges during the 1998–99 La Niña;
- The highest storm surge, experienced during the 2–4

March 1999 storm, increased the measured tide by 1.76 m above the predicted tide on the Washington coast, but part of this increase was produced by the elevated monthly mean water level not associated with the storm, leading to an estimate of 1.6 m rise as having been generated by the low atmospheric pressures and high wind speeds of the storm itself;

- Due to the oblique approach of the storm systems toward the coast, during which time they continued to develop, substantial along-coast variations in generated waves and storm surges were experienced on the PNW shores;
- The major storms observed during the 1997–98 El Niño and 1998–99 La Niña winters where the largest seen during the past 25 years (ALLAN and KOMAR, 2000), and appear to follow a pattern of a progressive increase in the magnitude and frequency of storms in the North Pacific (GRAHAM and DIAZ, 2001).

Of significance to the occurrence of beach and property erosion are the total water levels achieved at the shore during the storms, the sum of the monthly mean water level, the enhanced elevation produced by a storm surge, and the runup of the waves on the beaches, governed by the heights and periods of the generated waves. As expected, the relative contributions of these processes differed between the 1997–98 El Niño and 1998–99 La Niña. During the El Niño winter, the unusually high monthly mean water levels contributed significantly to the total water levels and thus to erosion occurrences. On the other hand, it was expected that the El Niño would result in reduced storm conditions and lower wave heights along the PNW coast, due to the more southerly tracks of the storms (SEYMOUR, 1996). In that respect, the occurrence of the major storm during November 1997 was unexpected, an event that produced high waves and a storm surge, contributing to the elevated water initiated by the monthly-mean water level. The 1998–99 La Niña brought increased numbers of storms, with higher wave conditions and more significant storm surges than previously experienced. While increased numbers of storms in the PNW are expected during a La Niña, their extreme nature with unusually high generated waves and storm surges is likely to have been caused mainly by a strongly positive EP index, governed by atmospheric pressure differences between the Aleutian Low and Hawaiian High (ALLAN and KOMAR, 2000, in review). Further research is needed to establish whether there are aspects of La Niñas that are conducive to the occurrence of intensified storms and the generation of higher waves.

The occurrences of major storms in recent years resulted in reassessments of the extreme-wave projections, the 25- through 100-year deep-water significant wave heights, with the 100-year event having been increased from 10 m as projected in 1996, to 16 m (KOMAR and ALLAN, 2000). This 16-m projection was made using standard extreme-value analysis techniques, and did not include a projection of the long-term trend of increasing wave heights into the future found by ALLAN and KOMAR (2000, in review), since we have been unable to determine the climate controls and therefore whether they will continue. But as seen in the analyses presented here, an extreme erosion event involves more that just the storm-wave heights, and includes the multiple atmospheric and oceanic processes that elevate mean water levels so that measured tides are substantially higher than predicted. Therefore, the evaluation of a potentially extreme event depends on several processes, some of which are independent in their occurrence, while others—like storm waves and a storm surge—occur at the same time. This has complicated assessments of the most extreme conditions that might be expected along the PNW coast, important to the design of jetties or required in management applications such as the establishment of set-back distances for safe development along the coast. In the latter application KOMAR and ALLAN (2000) and KOMAR *et al.* (2000) have taken the approach of providing separate analyses of El Niño and La Niña conditions, with projections of expected erosion patterns and dune retreat distances. The recent storms were important in providing tests of the techniques that were used, including attempts to project the expected dune erosion impacts. Thanks to the test provided by these recent storms, we feel that we can now more confidently make projections of set-back distances required to keep developments safe from even more extreme events.

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