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Conservation and Development

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ANALYSES OF EXTREME WAVES AND WATER LEVELS ON THE PACIFIC NORTHWEST COAST

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SUMMARY

Homes and other properties backing beaches are threatened by erosion during extreme events, when the runup of large storm waves on the beach is superimposed on exceptionally high tides. The objective of this report is to examine the potentially extreme waves and tides that can be expected along the Pacific Northwest coast, ranging over time spans of 25 to 100 years. Reassessments of these processes are needed in that during recent winters the Northwest coast has experienced both extreme waves and tides. In particular, during the 1998-99 La Niña, four storms generated deep-water significant wave heights that exceeded 10 meters, what had been projected in 1996 to represent the 100-year extreme event. During a storm on 2-4 March 1999, significant wave heights reached 14 meters, and measured tides were 1.75 m higher than predicted, mainly due to the associated storm surge.

This report begins with a re-analysis of the Northwest wave climate, the objective being to provide up-dated projections of the most extreme storm wave heights and periods. Analyses of wave data derived from four ocean buoys off the Northwest coast, installed by the National Data Buoy Center of NOAA, indicate that the revised 100-year deep-water significant wave height should be on the order of 16 meters. However, the projection of future extreme-wave conditions is uncertain due to the discovery that during the past 25 years of buoy measurements, wave heights off the Northwest coast have progressively increased; for example, the buoy offshore from Washington documents a rate of increase of 0.168 m/yr for the largest storm waves of the year, representing an increase in wave heights by 4.2 meters in 25 years. In that the climate factors which produced this increase have not been clearly identified, it is not possible at present to predict whether this increase will continue and thereby affect the projections of the 25- through 100-year extreme wave heights.

Improvements in the predictions of extreme tides also have been accomplished through analyses of measured water levels that occurred during the major storms of the 1997-98 El Niño and 1998-99 La Niña. As in previous El Niños, it was found that the monthly mean water levels were raised by 50 to 60 cm due to warmer ocean water temperatures and strong ocean currents. Analyses of individual storms demonstrated that the accompanying storm surges commonly elevated water levels by an additional 50 to 70 cm during the one to two days duration of the storm, while the extreme March 1999 storm generated a storm surge of 150 cm, which raised the measured tide about 175 cm above the predicted tide due to the superposition of the storm surge above the monthly-mean water level.

This report ends with a discussion of how these multiple processes can be combined in applications to evaluate potential water levels on beaches, to obtain predictions of the 25- to 100-year maximum levels achieved by the water due to the superposition of the runup of storm waves on top of exceptionally high tides. This is explored through analyses of three scenarios: (1) A normal (non El Niño) winter, with the occurrence of a 100-year storm; (2) An El Niño winter characterized by high monthly-mean water levels that enhance the tides, but with the probability of reduced storms; and (3) A "worst case" situation when a major storm occurs during an El Niño when there are elevated tides. Scenario #1 predicts a total water level of 7.3 meters NGVD29, mainly due to the high wave runup of the 100-year storm and the generation of a 1.75-meter storm surge. In contrast, the El Niño scenario #2 yields a total water elevation of 5.9 meters NGVD29, less than scenario #1 because the elevated monthly mean water levels and measured tides of an El Niño are not as great as the wave runup and storm surge contributions of a 100-year storm in scenario #1. This contrast demonstrates that beach and property erosion during an El Niño are not particularly caused by extreme total water levels, but are due to "hot spot" erosion north of headlands and tidal inlets caused by the northward transport of beach sand within the littoral cells. Although the occurrence of a near 100-year storm is less likely during an El Niño year due to the southerly tracks of the storm systems, such an event cannot be entirely ruled out, and the "worst case" scenario #3 represents that condition. However, the total water level of scenario #3 is only about 30 cm higher than scenario #1. In spite of that small difference, management planning for scenarios #1 and #3 differ in that #3 includes the hot-spot erosion impacts associated with an El Niño as well as the extreme wave runup and storm surge of a major storm, the factors important to scenario #1. All three scenarios predict the potential of significantly greater erosion impacts along

the Northwest coast than were assessed in 1996, prior to the major 1997-98 El Niño and 1998-99 La Niña winters.

In order to improve predictions of extreme events on the Northwest coast that may lead to major erosion impacts, a better understanding is required of how the climate regime over the North Pacific controls the strengths of storms and the waves they generate. Only with such an understanding can we predict whether the increases in wave heights and periods that have occurred during the past 25 years will increase during the next 25 to 100 years, and fully establish how factors such as the occurrence of an El Niño or La Niña govern the wave conditions during any particular year.

INTRODUCTION

The most hazardous conditions occur in the coastal zone during extreme events, when large storm waves are superimposed on exceptionally high tides. This is particularly true for homes and other properties backing beaches, where the elevated tide places the mean shoreline high up on the beach, and the runup of the storm waves above that shore position reaches and erodes coastal dunes and sea cliffs, undermining the homes. Such a model for the analysis of coastal erosion has been developed by Ruggiero et al. (1996, in press), with the primary focus being on applications along the Pacific Northwest coast (PNW), Oregon and Washington. Analyses of extreme waves and tides are important in other applications, such as in the engineering design of harbor jetties and shore-protection structures.

The objective of this report is to examine the potentially extreme waves and tides that can be expected along the PNW coast, ranging over times spans of 25 to 100 years. Reassessments of these processes are needed in that during recent winters the PNW coast has experienced both extreme waves and tides. Those occurrences came during the El Niño winter of 1997-98 and La Niña winter of 1998-99, suggesting that the severe storms may have been related to those global climate events. The need for revised estimates of extreme wave conditions is apparent in that based on wave measurements up through 1996, we had projected that the 100-year storm would generate a deep-water significant wave height of about 10 meters. That height was exceeded by one storm during the 1997-98 El Niño, while four 100-year storms occurred during the 1998-99 La Niña, with one storm on 2-4 March 1999 having generated deep-water significant wave heights of 14 to 15 meters.

This report begins with a re-analysis of the PNW wave climate, with the objective being to provide up-dated projections of the most extreme storm wave heights and periods. The report then turns to analyses of extreme tidal elevations, a complex problem in that this depends on multiple atmospheric and oceanic processes that cause measured tides to reach substantially higher than the predicted tides. For example, the highest monthly mean water levels are known to occur during El Niños, due to multiple causes including warmer offshore water temperatures and stronger northward-flowing currents along the coast. But superimposed on the elevated monthly-mean water level is the storm surge associated with an individual storm event, which may last for only one to two days. When one considers the several combined processes, it is difficult to predict the expected extreme 25- to 100-year tidal elevations. This report ends with a discussion of how these multiple processes can be combined in applications to evaluate potential water levels on beaches, the 25- to 100-year maximum levels achieved by the water due the superposition of the runup of storm waves on top of exceptionally high tides.

THE PACIFIC NORTHWEST WAVE CLIMATE

Wave data for the PNW are available for nearly 45 years, if one includes the hindcast assessments undertaken by the Wave Information Study of the U.S. Army Corps of Engineers, which covered the years 1956 through 1975 (Hemsley and Brooks, 1989). However, in a comparison with direct measurements of wave heights and periods that overlapped with the last few years of WIS hindcasts, Tillotson and Komar (1997) found that the WIS values were systematically higher than the measured values, by 30 to 60%, so it was recommended that the WIS data not be used in applications.

The earliest source of direct measurements of waves along the Northwest coast was the microseismometer system of Oregon State University, which has been in operation since 1971 at the Marine Science Center in Newport. That system is based on the theoretical analysis of Longuet-Higgins (1950), which relates the generation of microseisms to the pressure field on the ocean floor produced by standing waves that result from the interaction of incident waves and their reflection from the coast. Based on this theory of microseism generation where the amplitudes and periods of the microseisms are related to the heights and periods of the ocean waves, the Newport microseismometer was placed in operation in May 1971 to monitor the ocean wave conditions on a daily basis (Zopf et al., 1976). This required that the microseismometer record be calibrated against the actual ocean waves, which was accomplished initially using visual observations of wave heights and periods, and then with records from a pressure sensor located in 20-meters water depth offshore from Newport. The resulting calibrated wave heights derived from the microseismometer showed good agreement with the heights measured visually and with the pressure sensor, yielding a correlation coefficient R^2 = 0.76 and a standard error of 0.49 meters (Zopf et al., 1976). In a more extensive comparison, made possible by the installation of offshore buoys, Tillotson and Komar (1997) confirmed that the Newport microseismometer provides good assessments of significant wave heights, but poor results for wave periods.

The first buoys installed off the PNW coast to obtain long-term measurements of wave conditions were placed by the National Data Buoy Center (NDBC) of NOAA in 1975 and 1976, respectively westward from the Oregon and Washington coasts. Those buoys are located in the deep-ocean basin, about 500 to 600 km offshore, and provide the longest record of measurements derived from buoys of PNW wave conditions. Beginning in the 1980s, buoys were also installed closer to the coast, over the continental shelf, in deep to intermediate water depths. In 1981 buoys were placed offshore from Bandon on the south coast of Oregon, and offshore from Grays Harbor, Washington, by the Coastal Data Information Program (CDIP) of the Scripps Institution of Oceanography (Seymour et al., 1985). In 1983, CDIP also installed directional arrays in shallow water (11-meters depth) off the Oregon and Washington coasts, to provide inshore data and directions of wave approach to the shore. Additional buoys were placed by NDBC over the continental shelf, beginning in 1987, to the west of Newport and offshore from the Columbia River.

The several NDBC and CDIP buoys located over the continental shelf have been analyzed by previous investigations (Tillotson and Komar, 1997; Ruggiero et al., 1996, in press; Komar et al., 1999). However, it is difficult to define the Northwest wave climate based on data from the inshore NDBC buoys, due in part to the short lengths of the records (13 years), but in particular because there are numerous gaps of missing data. The CDIP buoys, installed in 1981, were withdrawn from service after 15 years of data collection, unfortunately just prior to the recent major El Niño and La Niña winters when the wave conditions were exceptional. Because of such limitations in the data from buoys on the continental shelf closer to the coast, our analyses presented here have had to rely almost entirely on the NDBC buoys #46005 (Washington) and #46002 (Oregon), Figure 1, located further offshore in the deep-ocean basin. We will only utilize data from the inshore buoys to confirm the evaluated extreme-wave conditions, the 10- through 100-year events, and then mainly to resolve apparent discrepancies between our results and those presented earlier by Tillotson and Komar (1997) and Ruggiero et al. (1996).

Allan and Komar (2000, in press) have analyzed the two NDBC buoys offshore from the Washington and Oregon coasts, along with buoys off the coasts of California and Alaska, Figure 1, in order to fully define the wave climate of the eastern North Pacific. Figure 2A gives the monthly mean significant wave heights and periods derived from the buoys, showing that on average the wave heights are comparable off the PNW to those in the Gulf of Alaska, and are on average about 1 meter higher than those off the coast of California. In the north the monthly-averaged significant wave heights reach their highest levels in November through January, on the order of 3.6 to 3.8 meters. It is seen in Figure 2B that the wave periods are longest in the south, reaching on average to nearly 14 sec at the Point Arguello buoy, decreasing progressively to the north so that on average they reach to only 11 sec in the Gulf of Alaska; in the Pacific Northwest the wave periods during the winter average just over 12 sec.

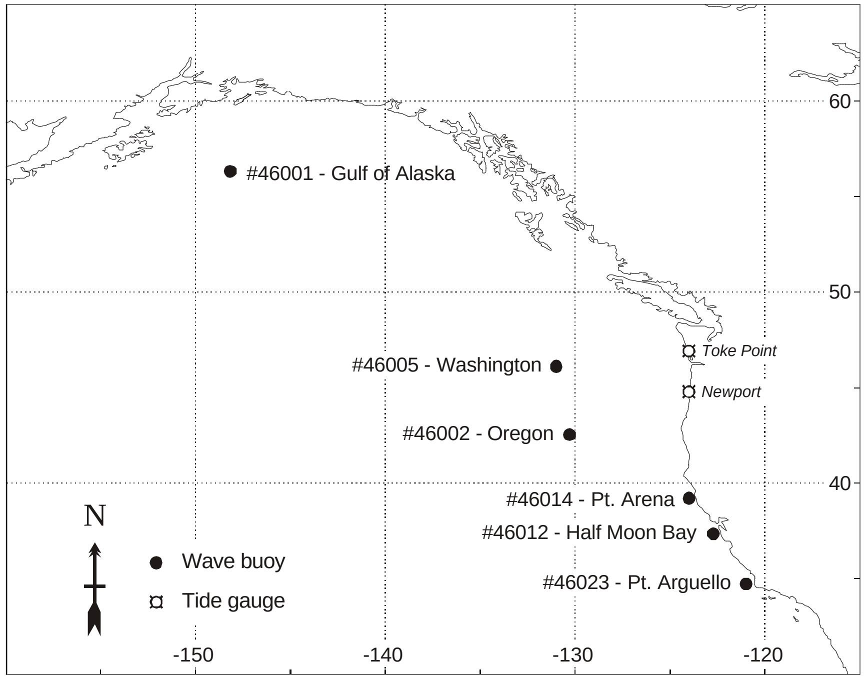

Figure 1 Locations of the NDBC wave buoys in the North Pacific, analyzed by Allan and Komar (2000) to determine the wave climate.

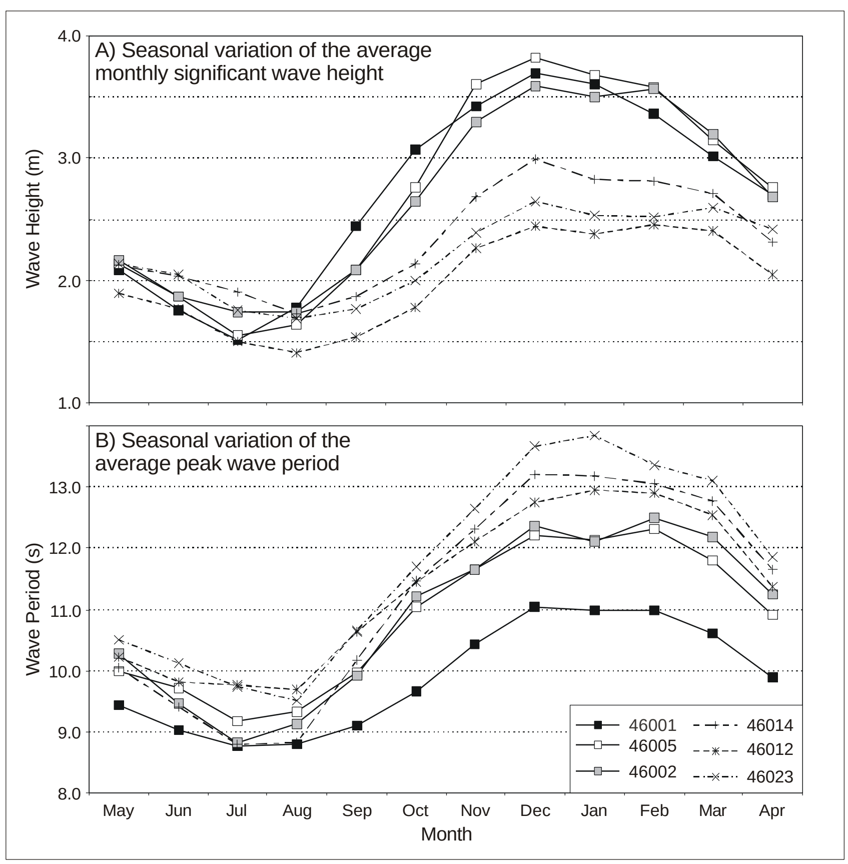

Figure 2 Seasonal variability of monthly-averaged wave heights and periods for the six buoys shown in Figure 1.

Of special interest are the heights of the largest storm waves, graphed in Figure 3 for the series of buoys, arranged by latitude. In that the strongest storms and highest waves occur during the winter months, the results presented in Figure 3 focus on the wave conditions during October through March. The lower curve (open squares) gives averages of the largest annual waves measured by the buoys, averaged over the span of operation of each buoy. The upper curve (dark triangles) gives the maximum significant wave heights found within the entire record of the buoy. This latter graph shows that off the PNW coast and in the Gulf of Alaska, the largest waves measured by the buoys since they began to operate in the early to mid-1970s reached 14 to 15-meters deep-water significant wave heights. This provides an initial assessment of the most extreme wave conditions expected along the Northwest coast.

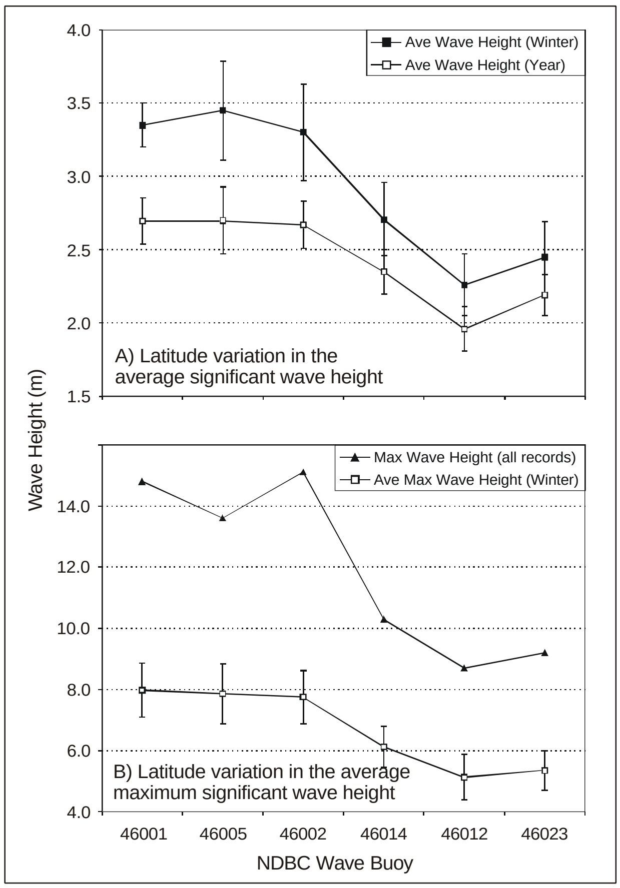

Figure 3 Latitude variations in winter wave heights measured by the six NDBC buoys, Figure 1, evaluated as averages of the highest waves experienced each month during the winter (October through March), and as the largest waves measured during the operational life time of the buoy.

It has been found that wave heights off the PNW coast have been progressively increasing during the 25-year records provided by the NDBC buoys (Allan and Komar, 2000, in press). This increase is shown in Figure 4 for the Washington (#46005) and Oregon (#46002) buoys, plots of the annual averages of the highest wave heights measured during each of the winter months, again defined as October through March, and as the individual largest significant wave height generated by a storm during that particular year. Upward trends are apparent in all of the graphs, the steeper the line the greater the increase in wave heights during the 25-years of wave records. Although the records from the buoys on the continental shelf are shorter and more fragmentary due to missing data, they substantiate these trends of increasing wave heights documented by the offshore buoys.

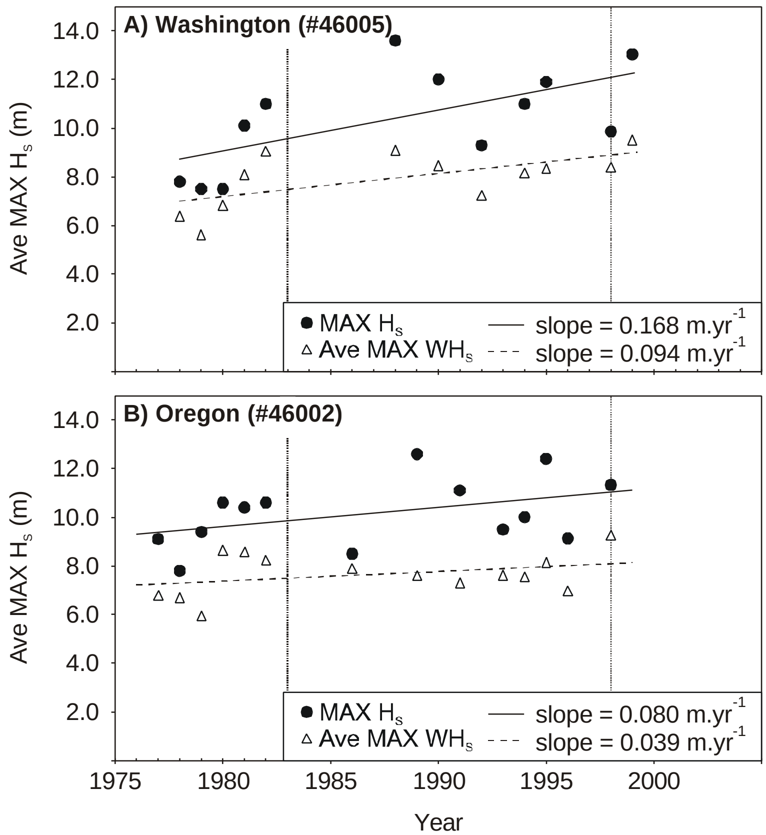

Figure 4 Annual values of the largest measured significant wave heights, and of averages of the largest monthly values measured during the winter, October through March.

It is seen in Figure 4 that the Washington buoy (#46005) yields the stronger trends of increasing wave heights. The least-squares regression for the average winter maximum wave heights yields a rate of increase of 0.094 m/yr, which amounts to an increase in average storm-wave heights by 2.4 meters over a 25-year time span. The rate of increase for Oregon, 0.039 m/yr, represents an increase in wave heights by about 1 meter in 25 years. The increase in the largest storm-wave heights of the year, graphed in Figure 4 for the Washington buoy, is even more impressive; a rate of 0.168 m/yr, an increase in the storm-wave heights by 4.2 meters in 25 years. The rate for the Oregon buoy is lower, 0.080 m/yr, but in this case the regression is not statistically significant.

Of the six NDBC buoys analyzed in our investigation (Allan and Komar, 2000, in press), those shown in Figure 1, the increase in wave heights were found to have been greatest for the Washington buoy, slightly less offshore from Oregon, still smaller for the Point Arena buoy in northern California, and negligible for the Half Moon Bay and Point Arguello buoys in central to southern California, and also for the buoy in the Gulf of Alaska. Thus, a systematic latitude dependence exists in the documented increases in wave heights during the past 25 years in the North Pacific. It is noteworthy that the PNW represents the zone of coastline over which the winter storm systems generally pass, and it is the increasing intensities of these storms that must account for the wave-height increases. There must be some underlying climate control, and our continuing research is focusing on identifying the climate factors. For example, we have attempted to relate the increasing wave heights to the East Pacific (EP) Teleconnection Pattern, the difference in atmospheric pressures between the Aleutian Low and Hawaiian High, expected to be important to the intensities of North Pacific storm systems. While the EP index did not account for the long-term, progressive increase in PNW wave conditions, this index does in part account for the variability in wave heights above and below the long-term trend, and so is important to the year-to-year changes in wave heights. That variability is also in part accounted for by cycles between El Niños and La Niñas, related to the Southern Oscillation Index and other similar indices that have been devised to measure intensities of El Niños and La Niñas. Important in this climate cycle are changes in the paths of the storms, wherein during an El Niño the storm systems follow more southerly courses and cross the coast of central California, bringing high wave conditions to central and southern California (Seymour et al., 1984; Seymour, 1998; Komar, 1986; Komar et al., 1999). With the storms following a more southerly course, it was expected that wave conditions in the PNW would be reduced somewhat during an El Niño, but this did not prove to be the case during the 1997-98 El Niño when we experienced unusually intense storms and high wave conditions. The intensities of the storms and heights of waves reached unprecedented levels during the 1998-99 La Niña, during which four storms generated deep-water significant wave heights equal to or greater than 10 meters, with the March 1999 storm generating 14-meter significant wave heights. During a La Niña the storm systems are again crossing over the Pacific Northwest, so one would expect higher waves than experienced during an El Niño, but the climate factors important to the occurrence of extreme waves during the 1998-99 La Niña have not been positively identified. The unusually large waves and numbers of storms in recent years must in part be the result of the long-term increase documented in Figure 4, but the underlying cause still remains to be determined.

Analyses have been undertaken, using standard techniques, to project the 10- through 100-year extreme values for the deep-water significant wave heights, based on measurements by the Washington and Oregon NDBC buoys (#46005 and #46002), and also for the NDBC buoys inshore over the continental shelf, in order to substantiate the offshore results and confirm their applicability to the Northwest coast. The data entered into the analyses are the largest wave heights measured each year, those graphed in Figure 4. We have used the ACES package of analysis programs developed by the U.S. Army Corps of Engineers, which includes several theoretical extreme-value equations, the objective being to find the curve that provides the best fit to the data. The resulting graphs are given in Figure 5, and the derived values for the 10- through 100-year projected extreme deep-water significant wave heights are listed in Table 1. For such a projection to be statistically valid, it generally is considered that the measured record must be at least one-third the time span of the projected extreme value; for example, to project the 100-year storm-wave conditions, it is necessary to have at least 33 years of wave measurements. The two NDBC buoys relied upon in the present analysis have been in operation since 1975-76, 25 years, which means that the 75-year projected significant wave heights listed in Table 1 are statistically valid, but the 100-year projections are uncertain.

Table 1 Extreme-wave projections (meters) based on data from NDBC buoys.

Projection (years)	*Oregon (#46002)*	*Washington (#46005)*	*Newport (#46050)*	*Columbia River (#46029)*
10	12.9	12.4	12.7	10.3
25	14.2	13.6	14.4	11.7
50	15.2	14.3	15.6	12.9
75	15.7	14.5	16.3	13.6
100	16.1	15.0	16.8	14.1

The projected extreme wave heights found here from the offshore NDBC buoys are substantially greater than determined by Tillotson and Komar (1997) and Ruggiero et al. (1996) in similar analyses. Those studies respectively projected 100-year significant wave heights of 8.2 and about 9.1 meters. In both cases they utilized data from the CDIP buoy offshore from Bandon, Oregon, which at that time had been in operation for only 15 years, so the projection of a 100-year event was not statistically valid. That problem aside, Tillotson and Komar (1997) found that there was a systematic difference between wave heights measured by the CDIP and NDBC buoys, with the NDBC measurements on average being 13% higher. Therefore, their results derived from the CDIP data are equivalent to projections of 9.3 and 10.4 meters in terms of NDBC measurements for the 100-year projection. As noted in the Introduction, one storm exceeded 10-meters significant wave heights during the 1997-98 El Niño winter, and four storms exceeded that height during the 1998-99 La Niña, with one storm reaching 14-meter significant wave heights. It appears that our projections prior to these recent winters were seriously in error, but at the time seemed well founded in that the microseismometer, with data back to 1971, and the CDIP and NDBC buoys over the continental shelf, had recorded significant wave heights at maximum in the 7 to 8-meter range. We have up-dated the extreme-wave analyses using the inshore NDBC buoys so as to include the severe 1997-98 El Niño and 1998-99 La Niña winters, and the results are listed in Table 1. The projected 100-year wave heights now range from 14.1 meters for the Columbia River buoy, to 16.8 meters for the buoy offshore from Newport. Although these results for the 100-year projection are statistically invalid due to the shortness of the records, they agree with those given in Table 1 for the NDBC buoys #46005 and #46002 located further offshore. There is also basic agreement for the 10- through 75-year projected values.

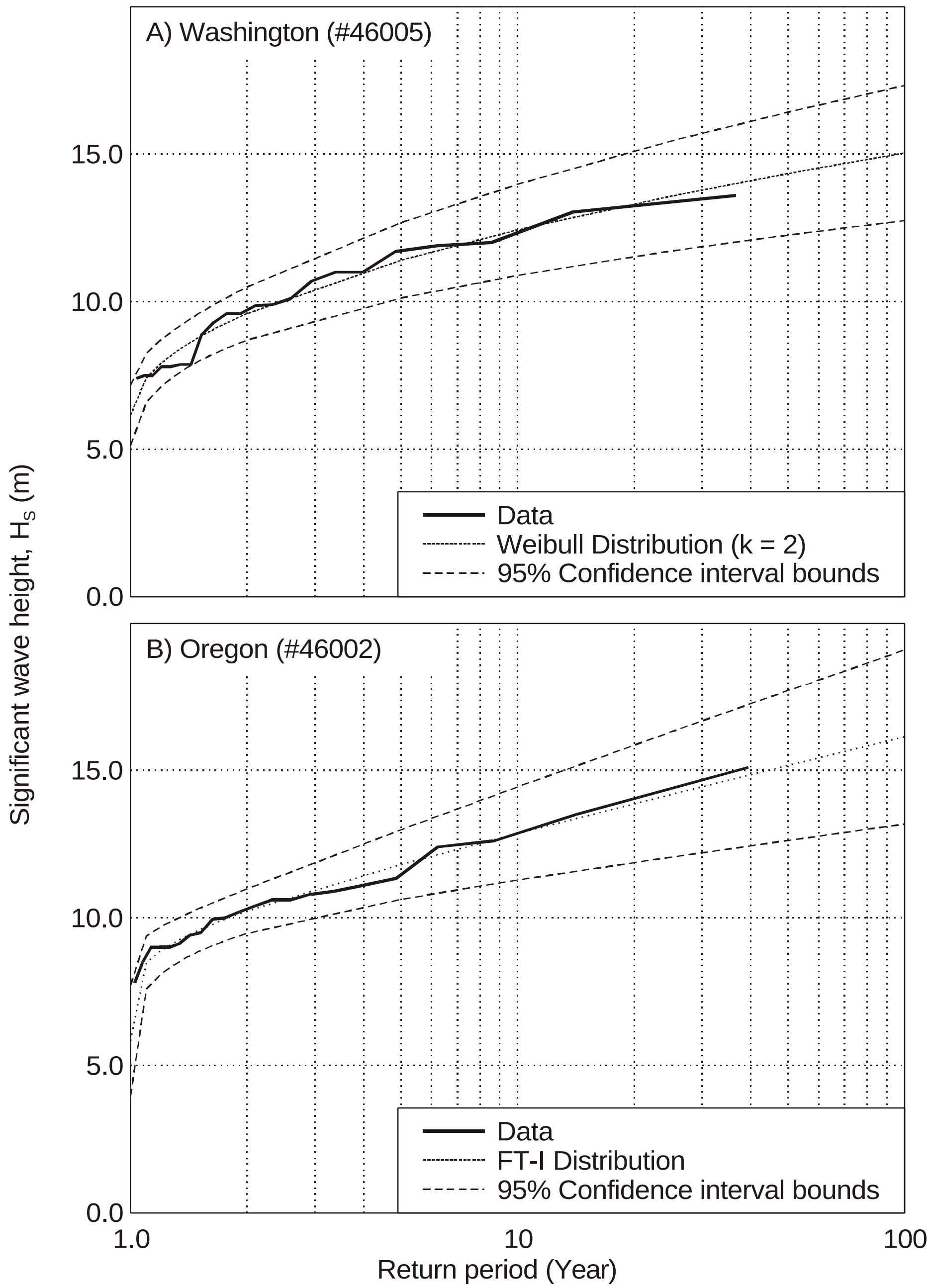

Figure 5 Extreme-value distributions fitted to annual measurements of the largest storm-wave heights by the Washington and Oregon buoys.

This approximate agreement between the data collected by the several buoys off the Northwest coast, both in the deep-ocean basin and over the continental shelf, suggests that the extreme-value significant wave heights listed in Table 1 can be used in applications. However, this traditional approach does not account for the long-term trends of increasing wave heights, documented in Figure 4. If those trends continue for another 100 years, they predict that the largest storms off the PNW coast would generate significant wave heights on the order of 25 to 30 meters! While possible, such an increase seems unlikely. If we knew for certain the climate factors that had caused the increase during the past 25 years, we would be in a better position to predict what might happen in the future. At present the values listed in Table 1 can serve as a guide in applications, with perhaps the addition of 1 to 2 meters onto the 25- to 100-year projected heights, which would account for another 25-years of increasing wave heights at the present rates.

Some applications require values of wave periods as well as heights; this is the case for wave runup on beaches, the application considered later in this report. Tillotson and Komar (1997) developed joint-frequency graphs of significant wave heights versus spectral-peak periods for data derived from the CDIP-Bandon buoy and for the NDBC buoy located over the continental shelf offshore from Newport. Figure 6 shows the joint-frequency graph developed in the present study, based on buoy #46005 in Figure 1, located offshore from Washington. The diagrams from both studies indicate that the largest wave heights are centered mainly at a period of about 15 seconds, but Figure 6 indicates that the periods could reach 20 seconds. A list of the annual storms having the largest wave heights, those used in the extreme-value analyses in Figure 5, shows that the periods of those major storms ranged between 12.5 and 20 seconds, with periods of 15 to 17 seconds having been predominant. Figure 6 shows that occasionally waves have periods up to 25 seconds, but they are associated with lower wave heights, less than 4 meters, apparently representing long-period swell from a distant source rather than having been generated by local storms.

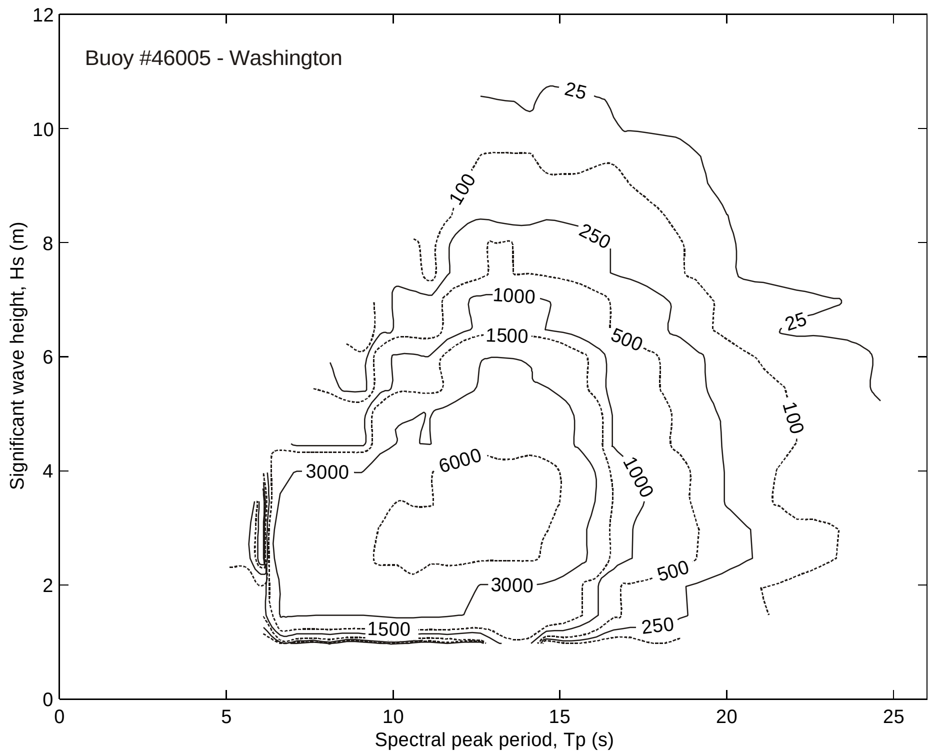

Figure 6 Joint-frequency graph of significant wave heights versus periods, based on data from NDBC buoy #46005 positioned seaward from Washington (Fig. 1).

TIDES AND EXTREME WATER LEVELS

The level of the tide at the time of a storm is important in determining the degree of the resulting beach and property erosion. The actual level of the measured tide can be considerably higher than the predicted level given in Tide Tables, thereby contributing to the erosion. The predicted tide depends solely on the astronomical forces of the Moon and Sun, while a number of atmospheric and oceanic processes can alter the water level and measured tide. These latter processes may include a storm surge created by the strong winds and low atmospheric pressures during the few hours of the storm's duration, to longer-term processes such as offshore water temperatures and ocean currents that affect monthly-averaged mean water levels, to changes in the relative mean sea level that spans decades to centuries. Many of these water-level factors are connected to climate cycles such as the occurrences of El Niños and La Niñas, and therefore are difficult to predict. This is particular true if one is attempting to evaluate potentially extreme water levels during the 10- to 100-year time frame, since the highest water levels on the PNW coast are likely to occur during an El Niño which elevates the monthly-mean water levels, together with the addition of a storm surge that raises the water still further for a day or two. These various water-level factors result from processes that are largely independent, each having its own probability of occurrence, so the development of an extreme water level involves the joint probabilities of their occurrence.

Measurements of tides on the Oregon coast are available from gauges located in Yaquina Bay (Newport) and in the Columbia River (Astoria). The long-term record from Crescent City, California, is also useful in analyses of tides on the southern Oregon coast. On the ocean coast of Washington, the longest record of tides is available from the gauge in Neah Bay at the entrance to the Juan de Fuca Strait, and a shorter record is available from the gauge at Toke Point in Willapa Bay. The analyses presented here are derived from the Newport gauge, as it is central to the Oregon coast and is located within the estuary close to the Bay's mouth. In our past research of the processes important to coastal erosion, we have relied mainly on tide measurements from that gauge.

Hamilton (1973) compiled the statistics of the tidal elevations for the Newport gauge, with his results for both predicted and measured tides being diagrammed in Figure 7. Of significance, the highest predicted tide is 10.3 ft (3.14 m) MLLW, which would occur during a perigean Spring tide when the astronomical tidal forces are strongest. However, as of 1973 when Hamilton completed this analysis, the highest measured tide had been 12.63 feet (3.85 m) MLLW, presumably having occurred during a storm when the surge (and possibly other processes) raised the water and measured tide along the coast. Figure 7 also marks an "extreme high tide" at 14.5 feet (4.42 m) MLLW, assumed to be a projected extreme water level assessed by Hamilton, which might occur under a combination of processes.

Figure 7 demonstrates that the highest measured tides can reach substantially higher elevations than the predicted tides. As noted above, this difference is due to the influence of a number of atmospheric and oceanic processes such as variations in atmospheric pressures, effects of ocean currents and changing water temperatures, and the occurrence of climate events such as an El Niño that can affect many of these processes. Tides tend to be enhanced during the winter months due to warmer water temperatures and the presence of northward flowing ocean currents that raise water levels along the shore. This effect can be seen in monthly averaged water levels, Figure 8, derived from the Yaquina Bay tide gauge, but where the averaging process has removed the water-level variations of the tides, yielding a mean water level for the entire month. Based on 33 years of data, the results in Figure 8 show that on average monthly-mean water levels during the winter are nearly 30 cm higher than in the summer. Water levels are most extreme during El Niño events, due to an intensification of the processes. This occurred particularly during the unusually strong 1982-83 and 1997-98 El Niños; as seen in Figure 8, water levels during those climate events were 50 to 60 cm higher in the winter than during the preceding summer. The importance of this is that all tides would be elevated by that amount, low tides as well as high tides. According to Figure 7, a mean higher-high tide on the central Oregon coast averages 8.38 ft (2.55 m) MLLW, but this would be raised to 3.15 m MLLW during an El Niño due to the 60-cm increase in the mean water level, bring it closer to the highest measured tide, 3.85 m MLLW. It has been documented that such elevated tide levels during an El Niño have contributed significantly to coastal erosion problems along the PNW coast (Komar, 1986, 1997, 1998a; Kaminsky et al., 1998).

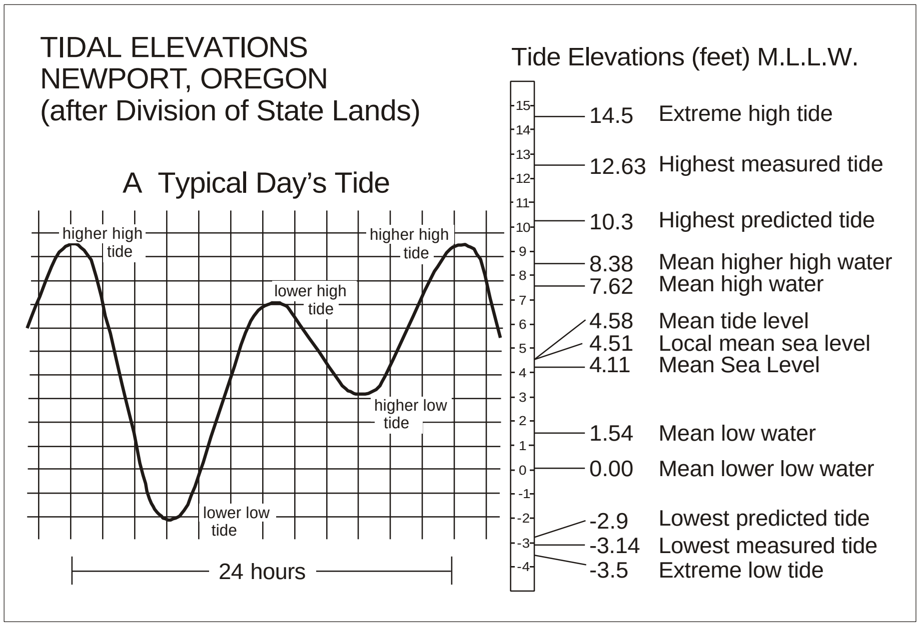

Figure 7 Daily tidal elevations predicted and measured in Yaquina Bay. [*after* Hamilton (1973)]

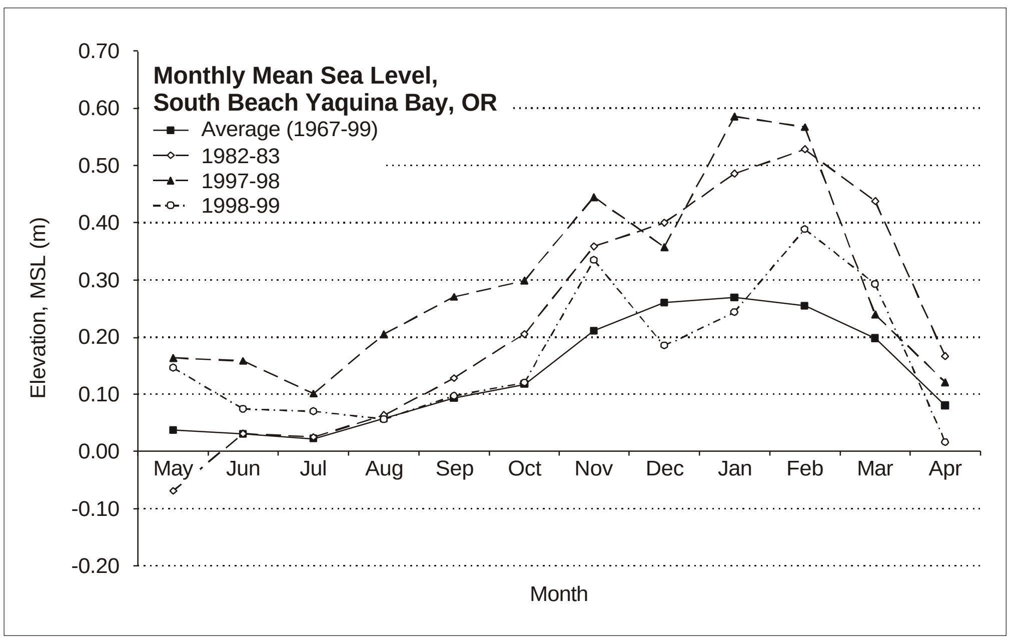

Figure 8 Monthly mean water levels derived from the Yaquina Bay tide gauge, for the entire 33-year period of measurement, and specifically for the 1982-83 and 1997-98 El Niño years and 1998-99 La Niña.

During a storm, water levels can be elevated still further by the occurrence of a storm surge, produced by the onshore winds and low atmospheric pressures associated with the storm. In comparison with the high storm surge elevations produced by hurricanes on the East and Gulf coasts, which can amount to 5 to 10 meters, storm surges on the Northwest coast have been generally small. Analyses of daily mean water levels by Ruggiero et al. (1996), measured by the Yaquina Bay tide gauge, indicated that storm surges typically elevate water levels by 10 to 15 cm. However, our analyses undertaken as part of the present investigation, which focused on the particularly severe storms of the 1997-98 El Niño and 1998-99 La Niña, have yielded much higher storm surge elevations. Our analyses have been undertaken on a monthly basis, from October through March, for the recent El Niño and La Niña winters. The results for October 1997 and February 1998, during the El Niño, are given in Figure 9, while Figure 10 shows the results for February and March 1999 during the La Niña. The bold arrows represent times of storms when the deep-water significant wave heights exceeded 6 m for a duration of 9 hours or longer. Each graph includes a curve for the measured atmospheric pressures, and it is apparent that the storms correspond to drops in the pressure, as expected. The other curve in each graph is the difference between the measured tide and predicted tide, the standard definition and analysis approach of a storm surge (Komar, 1998b).

It is seen in Figure 9 that during the El Niño, four storms occurred in October 1997, while in February 1998 there was a close succession of nine storms. The inverse response between the atmospheric pressure and storm-surge water level is apparent, especially in October 1997, the reduction in atmospheric pressure at the time of the storm being important to the generation of the storm surge through the inverse-barometer effect. Of interest here are the levels of water-surface rise associated with the storm surges. Two events in October 1997 raised the water level by 65 to 70 cm, while the third event at the end of the month produced a storm surge of about 50 cm. In February 1998, one surge event reached 80 cm, and two others were in the 60 to 70-cm range. Similar magnitudes of storm-surge elevations were experienced during the other winter months of the 1997-98 El Niño.

As discussed above and graphed in Figure 8, an El Niño winter is characterized by elevated monthly-mean water levels, which are largely due to warmer water temperatures and ocean currents. According to that graph, in October 1997 the monthly mean water level was elevated by 35 cm, and that elevation would be incorporated into the storm-surge measurement for that month in Figure 9, since we based its calculation on the measured tide minus the predicted tide. This suggests that of the 50 to 70-cm increases in water levels attributed to storm surges in October 1997, Figure 9, on the order of 35 cm of that elevation was contributed by the El Niño processes, with the balance, 15 to 35 cm, actually having been produced by the storm processes that spanned 2 to 3 days. However, the division is not so simple. In February 1998, Figure 9, so many storm surges occurred that they would have had a significant effect on the monthly-averaged mean water level, which was calculated as having been between 60 to 70 cm (Fig. 7). In that case it is not easy to separate the effects of the El Niño processes on the monthly water level versus the storm surge associated with the specific storm event.

This problem is even more apparent during the La Niña, when monthly-mean water levels are expected to have returned to the normal seasonal cycle with water levels being about 30 cm higher in the winter compared with the summer. But in Figure 7 it is seen that in February 1999, during the recent La Niña, the monthly mean water level increased by over 50 cm. Here there is a clear association between the monthly-averaged water level and the extraordinary number of storms, which occurred that month, Figure 10, and their generated storm surges. The highest storm surge reached 65 cm on February 6-7, while most other events were within the range 30 to 50 cm. Of special interest is the storm on 2-4 March 1999, the unusually strong event that generated deep-water significant wave heights of 14 meters. It is seen in Figure 10 that there was an abrupt drop in the atmospheric pressure as the low-pressure center of the storm crossed the coast, and this reduction in pressure combined with the strong winds to generate a storm surge that reached a height of about 72 cm as measured by the Yaquina Bay gauge. It is probable that on the order of 40 to 50 cm of this elevation was directly associated with the storm, with 20 to 30 cm contributed by the monthly-averaged water level. Due to its northward track, that particular storm had its greatest impact on the Oregon coast north of Newport, and particularly on the Washington coast. An analysis of the storm surge measured in Willapa Bay by the Toke Point gauge revealed that within this more central zone of the storm, the surge reached an elevation of 1.76 meters. This occurrence provides a better assessment of the potentially extreme surge generated by a major storm along the Northwest coast. Again, 20 to 30 cm of the elevation may have been contributed by the monthly-mean water level, so the actual surge associated with the storm would have been 1.46 to 1.56 m. Due to the extreme nature of this 2-4 March 1999 storm, both in the generation of waves and a storm surge, more detailed analyses of that event are underway, which may better define the storm surge heights and how they varied along the coast.

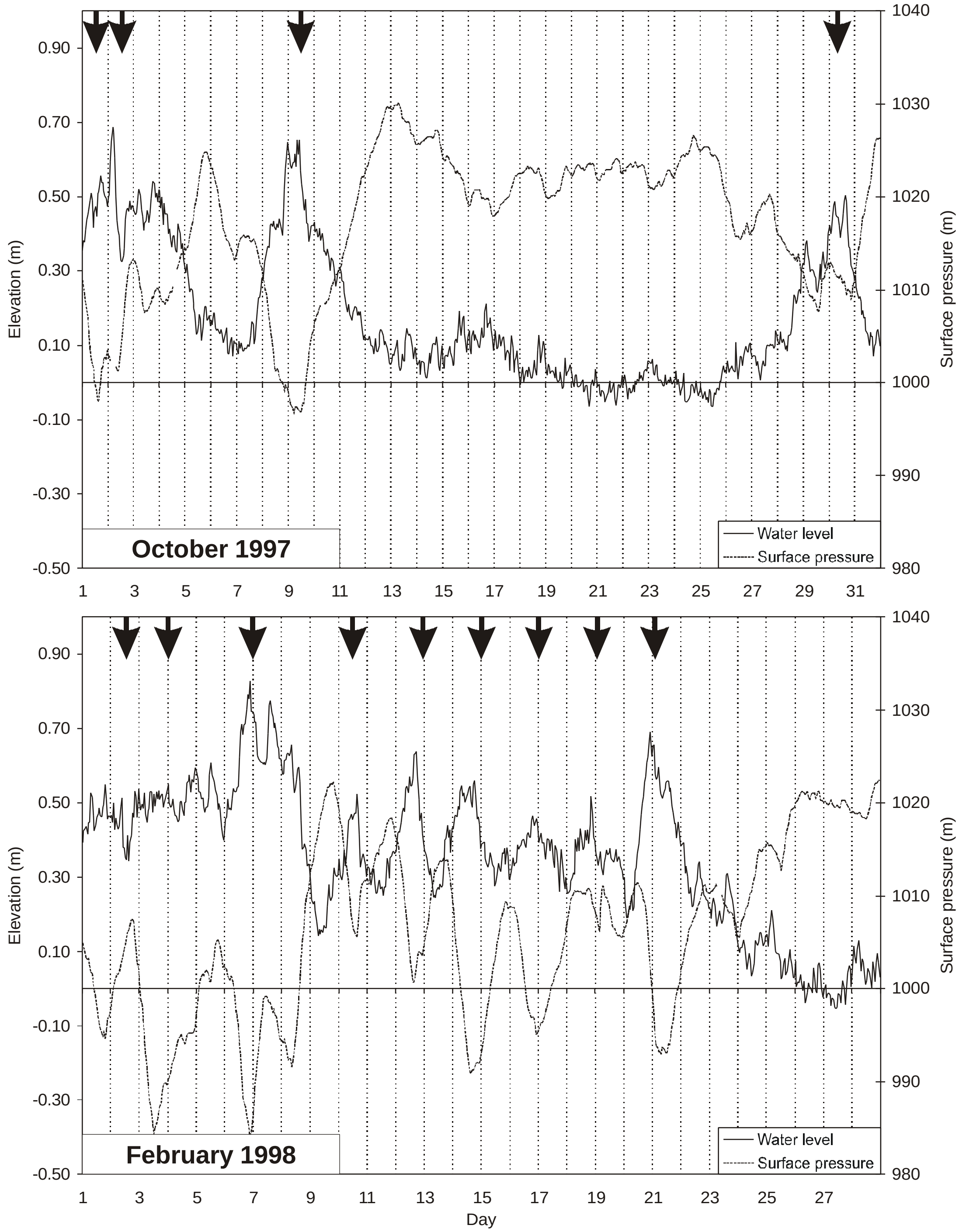

Figure 9 Analyses of storm-surge water elevations and atmospheric pressures in October 1997 and February 1998, during the 1997-98 El Niño winter. The arrows indicate times of storms when the deep-water significant wave height exceeded 6 meters for 9 hours or longer.

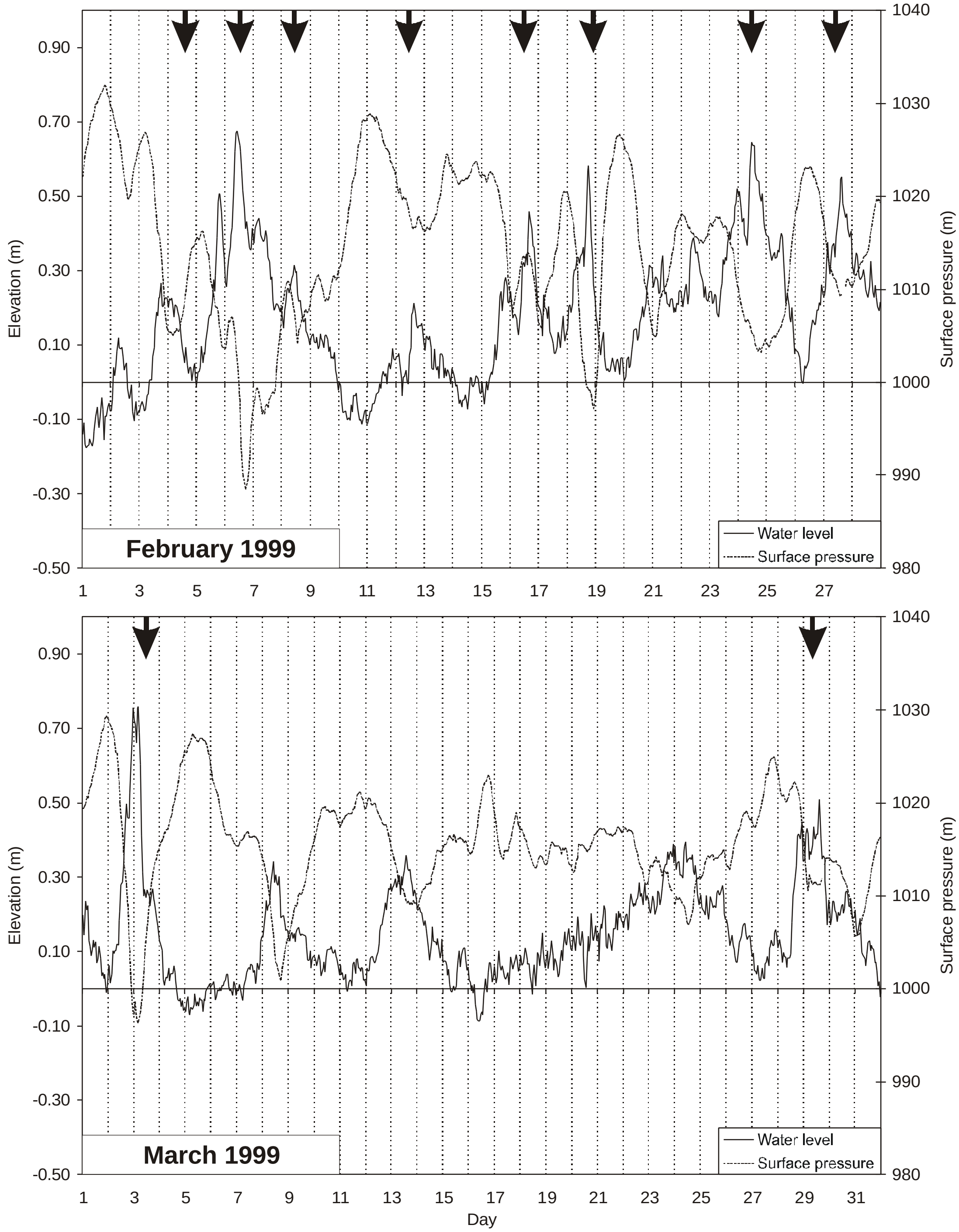

Figure 10 Analyses of storm-surge water elevations and atmospheric pressures in February and March 1999, during the 1998-99 La Niña winter. The arrows indicate times of storms.

Measured levels of tides can be analyzed for their potentially extreme occurrences, their 10- through 100-year levels, much like wave heights were analyzed above, or more analogous, how floods in a river are analyzed to predict their 100-year extreme levels. Such an analysis of tides is based on the record of their measured annual extremes, without consideration of the cause, whether it occurred during an El Niño or was produced by a major storm event, a storm surge. Such an analysis was completed by Shih et al. (1994), and the results are given in Figure 11. Both the predicted and measured tides were analyzed, and as expected, the results for the measured tides are substantially higher than the predicted. Values for the series of extreme tides derived from this graph are listed in Table 2, first in reference to mean sea level (MSL) as given in Figure 11, and then referenced to the MLLW tidal datum, the conversion being based on the tide statistics for the Yaquina Bay (Newport) tide gauge given in Figure 7. It is seen that there is almost no difference in the 10 versus 100-year predicted tides, due to the relative constancy of the tide-generating forces during the 33-year operation of the Yaquina Bay gauge; the difference between the 10 and 100-year projected extreme measured tides is only 17 cm.

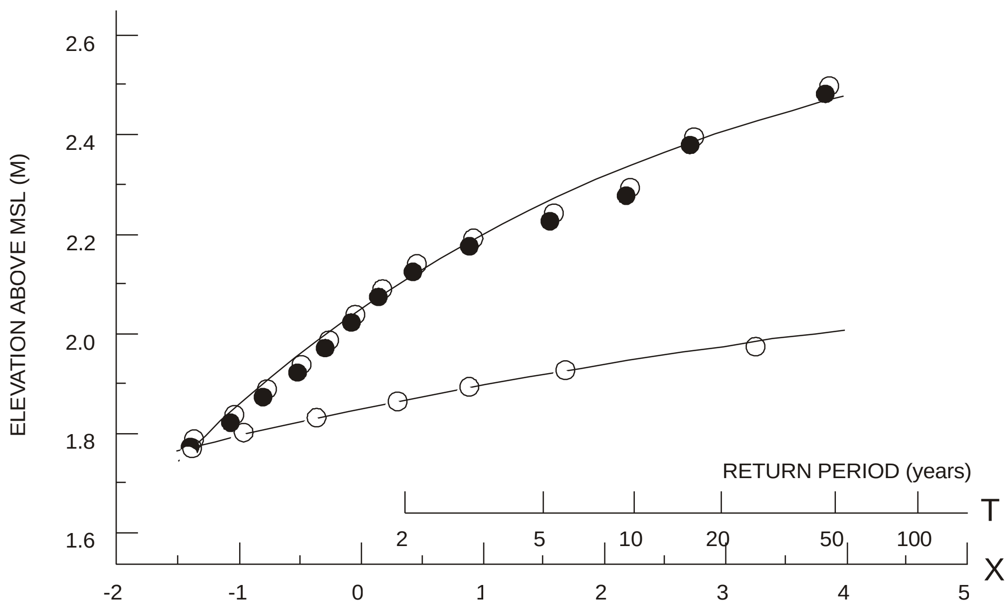

Figure 11 Extreme-value analyses of predicted and measured tides in Yaquina Bay. [*from* Shih et al. (1994)]

Table 2 Extreme annual tides derived from Figure 11.

Projection (years)	*Predicted (m)*		*Predicted (m)*	
	*MSL**	*MLLW*	*MSL**	*MLLW*
10	1.95	3.32	2.33	3.67
25	1.97	3.34	2.41	3.78
50	1.99	3.36	2.46	3.83
75	2.00	3.37	2.48	3.85
100	2.01	3.38	2.50	3.87

*MSL is equivalent to the NGVD29 datum

The analyses discussed thus far relate to the short-term effects of processes that determine daily to monthly variations in mean water levels, those that do not permanently alter the mean level of the sea. In the longer term, however, a net rise in global (eustatic) sea level has occurred, spanning thousands of years, associated with the melting of glaciers and the return of water to the oceans, and also with a thermal expansion of the ocean's water as it warms. This rise during the past century is generally placed at 1 to 2 mm/yr, 10 to 20 cm/century, estimated from tide-gauge records throughout the world (Komar, 1998b).

The pattern of sea-level rise along the Northwest coast is made complex by on-going changes in the level of the land. Of importance to coastal erosion is the change in "relative sea level", that is, how the global level of the sea has increased relative to the level of the land. This is what is measured by a tide gauge when it's record is averaged for an entire year to determine "mean sea level" for that year, and then is repeated over many years to see if the level has progressively changed. Since the gauge is mounted on the land, it is apparent that the resulting assessment will reflect both the global rise in sea level and the local change in elevation of the land.

Such a determination of the progressive long-term change in relative sea level can be obtained from the 33-year record of measured water levels obtained by the Yaquina Bay tide gauge. The result is graphed in Figure 12, a plot of the mean water level each year. It is seen that there has been large fluctuations from year to year, with particularly high water levels associated with the El Niño events in 1982-83 and 1997-98. However, within those annual variations a long-term progressive rise in sea level is apparent, one that is on the order of 3.1 mm/yr (31 cm per century). The slightly higher value for the Yaquina Bay tide gauge, compared with the estimate of 1 to 2 mm/yr for the global rise in sea level, might suggest that this stretch of the Oregon coast is subsiding. However, the reality is that this 3.1 mm/yr estimate for Newport is uncertain due to the large effects of El Niños on the water levels, and the short duration of this record.

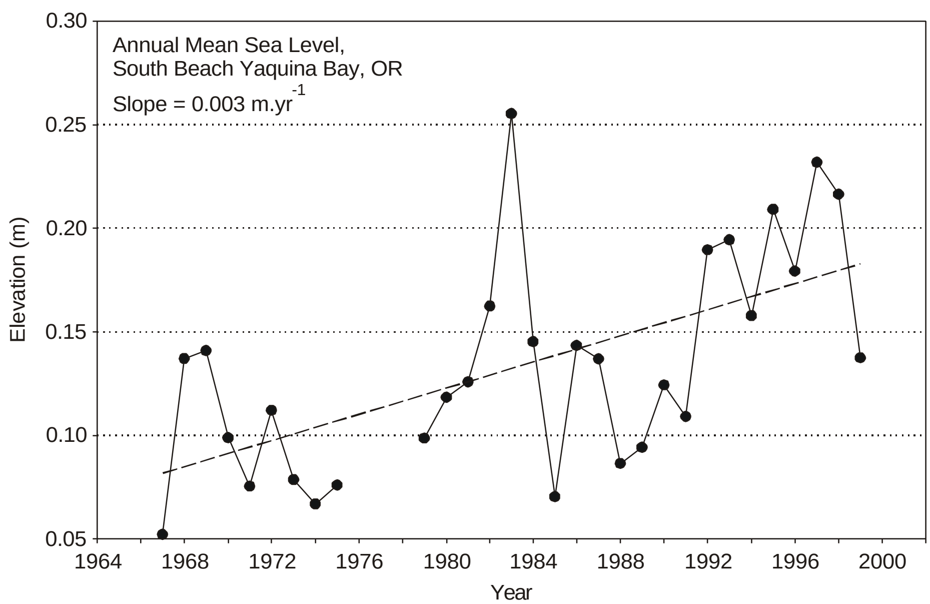

Figure 12 Annual values of mean sea level determined from the Yaquina Bay tide gauge, demonstrating that temporary high water levels occurred during the 1982-83 and 1997-98 El Niños, but that there is also a progressive rise in the sea relative to the land at an average rate of 3.1 mm/yr.

This estimate for the relative sea-level rise at Newport is not representative of the entire Northwest coast in that there are substantial spatial variations in the rates of tectonic change in the level of the land along the Oregon and Washington coasts (Komar, 1997). This pattern of changing levels of the land has been documented by government surveys of geodetic benchmarks used in surveying, monuments that give the precise location and elevation. By resurveying these bench marks every few years, the results document changes in elevations of one benchmark relative to another. Such an analysis has been undertaken by Vincent (1989) for the benchmarks along the length of the Oregon coast, and the results are graphed in Figure 13. The data have been further analyzed by linking the benchmark elevation changes with the tide-gauge records at Crescent City and Astoria, positioned at the ends of the survey line, so the results in Figure 13 reflect the change in relative sea level. A distinct pattern emerges, with the southern Oregon coast — roughly south of Florence — tectonically rising at a faster rate than the global rise in sea level, while most of the northern Oregon coast is being slowly submerged by the rising level of the sea.

The rates of sea-level rise relative to the land, Figures 12 and 13, are not large but over the span of 100 years could amount to 10 to 20 cm change in mean sea level relative to the land. In terms of potential effects on coastal erosion, the rapid tectonic rise of the southern Oregon coast could result in a decrease in the total water levels and potential erosion; however, the results in Figure 13 indicate that this reduction in water level would amount to only about 10 cm, a small amount that is within the uncertainties of assessments of the other water-level processes discussed here. On the northern Oregon coast the water is rising relative to the land, and could amount to 20 to 30 cm in 100 years, sufficiently large that it should be included in long-range assessments of potential erosion.

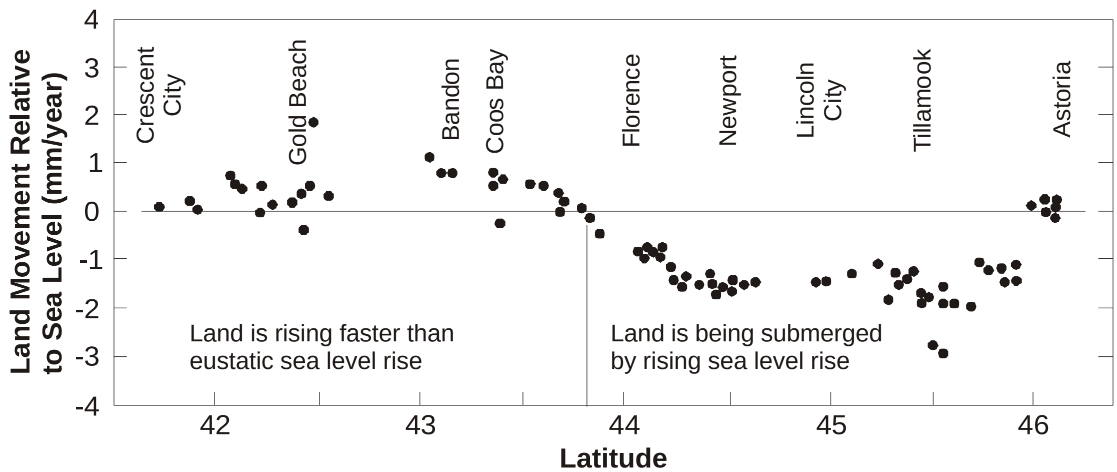

Figure 13 Elevation changes along the Oregon coast, measured by geodetic surveys (Vincent, 1989). The elevation changes are relative to the global increase in sea level, with positive values representing a rise in the land at a higher rate than the increase in sea level, while negative values represent the progressive submergence of the land. [*from* Komar (1997)]

JOINT OCCURRENCES OF EXTREME WAVES AND WATER LEVELS

In the preceding sections analyses were undertaken to predict extreme storm waves and tides, respectively their 10- through 100-year magnitudes. But it is a combination of high waves and water levels that results in beach and property erosion. The challenge is to evaluate the joint occurrences of these processes and their potential erosion impacts. This addition of processes is not a simple task, and there is no direct established path to evaluate 10- through 100-year joint occurrences, of the "worst case" erosion event that might impact the Northwest coast.

The uncertainty involves whether or not the respective processes act independently from one another, that is, whether they can be expected to occur at the same time or if their joint occurrence is random chance. For example, the generation of extreme waves by a major storm can be expected to coincide with a storm surge that elevates the mean water level. On the other hand, it has been established that the highest monthly-mean water levels are associated with El Niño events, the elevated water being caused in large part by warmer water temperatures and stronger ocean currents, factors that are independent of wind-generated waves. It was thought that an El Niño year would represent a time of reduced waves in the Northwest, due to the southward displacement of the storm tracks so they cross the coast of California rather than the PNW coast (Seymour, 1996). However, during the 1997-98 El Niño a major storm generated deep-water significant wave heights of 10 meters along the Northwest coast, previously thought to be the 100-year condition. In spite of that storm occurrence, it remains unlikely that the revised 100-year storm with a deep-water significant wave height of 16 meters (Table 1) will strike the coast during an El Niño, it being more likely that it will occur during a normal or La Niña periods when the storm tracks mainly cross the Northwest. Hence, there is still some validity in separately considering the climate regimes in analyses of severe ocean conditions that might produce major erosion impacts. That approach will be taken here through analyses of three possible scenarios: (1) An El Niño winter when the tides are elevated to unprecedented levels, while only moderate storms occur; (2) A normal or La Niña winter when monthly mean water levels and tides are average, but with the occurrence of a major storm that generates the 100-year wave conditions together with a significant storm surge; and (3) A "worst case" scenario when something close to a 100-year storm occurs during an El Niño winter that has elevated mean water levels.

The model that serves as the foundation for assessments of these scenarios is diagrammed in Figure 14. Of interest is the total water level produced by the combined processes, compared with the elevation of the beach/dune junction; the comparison could also be made with the elevation of the toe of a sea cliff, though the subsequent erosional responses of a dune and cliff are clearly different. For the waves to erode the dunes, the elevation of the measured tide (E_T) plus the runup of the waves (R) must reach or exceed the elevation of the beach/dune junction (E_J). Here our interest focuses on analyses of the extreme occurrences of total water levels, the measured tides plus the wave runup ($E_T + R$); clearly, the more extreme the total water level, the greater the resulting erosion of dunes and sea cliffs.

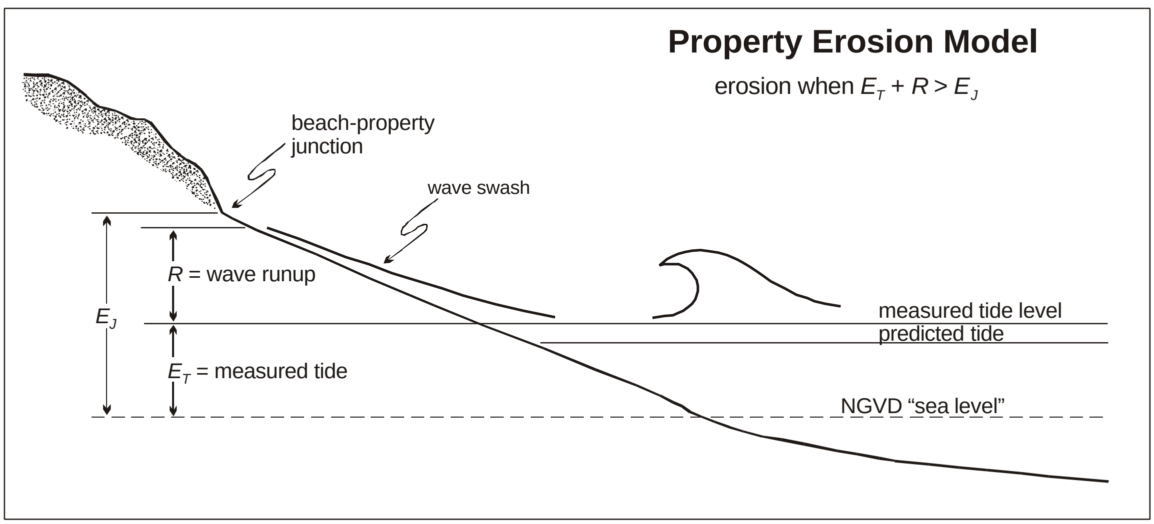

Figure 14 Model for the quantitative assessment of foredune erosion, where the elevation of the measured tide (E_T) plus the runup of the waves (R) must reach or exceed the elevation of the beach/dune junction (E_J) for erosion to occur.

From our earlier discussion it is recognized that the measured tide is governed by the predicted tide, produced by astronomical forces, plus the effects of a number of atmospheric and oceanographic processes. In the present analysis we will take

Measured Tidal Elevation (E_T) = Predicted Tide (E_{PT})
+ Monthly Mean Increase (MM)
+ Storm Surge (SS)

and these three components of the measured tides will be separately evaluated. We will also assume that they act as independent processes, which is true except that our measurements of monthly-mean sea levels, Figure 2, are affected somewhat by occurrences of storm surges during that particular month. In the evaluations of extreme events undertaken here, some attempt will be made to account for this tendency toward duplication.

Important to the application of the model is the runup elevation R of the storm waves on the beach. Part of our research has been directed toward obtaining measurements of runup under a range of deep-water wave conditions and beach slopes (Ruggiero *et al.*, 1996, in press). Measurements on the Oregon coast over a wide range of conditions, combined with those obtained by Holman (1986) at the Field Research Facility, Duck, North Carolina, yield the relationship

$$R = 0.27\,(S\,H_{SO}\;L_O)^{1/2} \tag{1}$$

for the runup elevation (the 2% exceedence elevation), where S is the slope of the beach, H_{SO} is the deep-water significant wave height, and L_O is the deep-water wave length given by $L_O = (g\,/\,2p\,)T^{\,2}$ where T is the wave period, and g is acceleration due to gravity (9.81 m/s). The calculations of R in the scenarios developed below therefore depend on values of wave heights and periods established in our analyses of the Northwest wave climate, specifically on the values for the 10- through 100-year deep-water significant wave heights.

The estimated tide factors and wave runup for the three scenarios are listed in Table 3. The first entry for each scenario is the predicted tide, E_{PT}, which depends on the astronomical forces of the Moon and Sun, and goes through a monthly cycle between Neap and Spring Tides, the latter achieving the highest levels. From Figure 7, a value of 8.38 ft (2.55 m) MLLW is used, as it represents the average of the higher-high predicted tides. That tide level is referenced to the Mean Lower-Low Water tidal datum, whereas in assessments of potential coastal erosion it is preferable to have the elevations referenced to a survey datum such as the National Geodetic Vertical Datum of 1929 (NGVD29). According to Figure 7, the difference between the datums is 4.11 ft (1.25 m), so that the 2.55 m MLLW tide level becomes 1.30 m NGVD29. This is the value that is entered into Table 3. When the other water-level components are added to this predicted tide, in effect converting it to an expected measured tide, the resulting water levels will continue to be relative to NGVD29. And finally when the wave runup is added, the resulting total water level will be relative to NGVD29, which is convenient since land survey elevations are related to that datum, including the foredunes and sea cliffs backing the beach.

Scenario #1 in Table 3 represents a normal or La Niña year, that is, the opposite to El Niño conditions. It is seen in Figure 8 that under normal conditions, during the winter the monthly mean water levels are about 0.40 meter higher than the predicted tides, and this value has been entered for MM in Table 3. Most important to scenario #1 is the potential occurrence of a major storm that will generate a storm surge and high waves. The best guide we have to such an occurrence is the 2-4 March 1999 storm, which produced a storm surge on the order of 1.5 meters on the Washington coast. In terms of wave heights, the 14-meter significant wave heights generated by that storm now rank as approximately the 50-year event (Table 2), while the projected 100-year event has a deep-water wave height of 16 to 17 meters. Presumably, the storm surge would also be enhanced during the 100-year storm, being higher than during 2-4 March 1999. Accordingly, in Table 3 the storm surge entry, SS, is set at 1.75 meters, 25 cm higher than during the March 1999 event. This estimate assumes an extreme low-pressure storm of approximately 960 mb (about 20 mb below the 2-4 March 1999 storm when it crosses the coast), coincident with strong west to southwest winds. Finally, the runup R has been calculated with equation (1) using the 100-year storm-wave height H_{SO} = 16.5 meters, period T = 20 seconds, and with a beach slope S = 0.02, which is fairly representative of PNW beaches. With a calculated runup of R = 3.88 m and an accompanying storm surge of SS = 1.75 meters, it is apparent that in scenario #1, it is the occurrence of processes related to an individual major storm that are important in controlling the total water level and hence the erosion impacts, with the level of the tides being a smaller factor. The last entry in Table 3 for scenario #1 is the total water level, 7.33 m NGVD29, the sum of the process components (E_{PT} + MM + SS + R). This is equivalent to the water-level diagrammed in Figure 14, E_T + R.

Scenario #2 in Table 3 represents a major El Niño event, during which monthly-mean water levels will be elevated, but the storms might be expected to be reduced somewhat along the PNW coast due to the more southerly tracks of the storm systems. The predicted tide level is again set at 1.30 m NGVD29, but the level of the measured tide is enhanced by the monthly-mean rise, MM, which in Table 3 is taken as 0.70 meters, seen in Figure 8 as a level that occurred during the 1982-83 and 1997-98 El Niños. The value of the superimposed storm surge, SS, is taken as 0.50 meters. Adding these water-level factors (E_{PT} + MM + SS) yields 2.50 m NGVD29 for the measured tide, a level that corresponds to the 100-year projected level in Table 2. During the 1997-98 El Niño, one storm generated deep-water significant wave heights of 10 meters. At that time this was the projected wave height of the 100-year storm, but due to the occurrence of several storms in recent years, the projected extreme wave heights listed in Table 1 are much higher. In the analysis of scenario #2, we have used an approximate 10-year wave event, a deep-water significant wave height of 12.5 meters and wave period of 20 seconds, and the calculated wave runup is R = 3.37 meters. This value is not that much lower than the runup of the 100-year storm analyzed for scenario #1, due to the fact that according to equation (1) the runup depends more on the value of the wave period than the wave height, and in both scenarios we have taken T = 20 seconds in order to maximize the potential wave runup. As can be seen in Table 1, the combined processes components sum to yield a total water level of 5.87 m.

Table 3 Analyses of total water levels due to measured tides plus the runup of waves, as diagrammed in Figure 14.

Scenario #1: Normal (non-El Niño) winter with the occurrence of a 100-year storm.

Scenario #2: El Niño winter characterized by high measured tides, but with a probability of reduced storms.

Scenario #3: A "worst case" situation when a major storm does occur during an El Niño when there are elevated measured tides.

Factor	*Scenario*		
	#1	*#2*	*#3*
Predicted Tide, E_{PT}	1.30	1.30	1.30
Monthly Mean Water Level, MM	0.40	0.70	0.70
Storm Surge, SS	1.75	0.50	1.75
Wave Runup, R	3.88	3.37	3.88
Total Water Level	7.33	5.87	7.63

In analyzing scenario #2 for an El Niño climate event, it was assumed that the occurrence of a major storm is unlikely due to the predominance of southern paths followed by the storms so they cross the coast of California rather than the PNW. Scenario #3 is based on a combination of processes that might occur if this assumption of paths is incorrect. This scenario represents something of a "worst case" event, when the 100-year storm occurs during an El Niño year. In such a situation, the El Niño contributes to the erosion by producing an elevated monthly-mean water level, MM = 0.70 meters, while the 100-year storm contributes a storm surge SS = 1.75

meters to the measured tide, while the generated waves add a runup R = 3.88 meters, giving a calculated total water level of 7.63 meters (Table 3).

DISCUSSION OF RESULTS AND POTENTIAL EROSION

The analyses of the three scenarios presented in Table 3 differ considerably from the results, had similar analyses been undertaken in 1996. At that time the 100-year projected extreme deep-water wave height was about 10 meters. There was a high level of uncertainty in that projection due to the shortness of records of wave measurements. But the largest change in the 10- through 100-year wave projections has resulted from the unprecedented number of major storms during the winters of 1997-98 and 1998-99, with a total of five storms having exceeded the earlier projection of 10 meters for the 100-year event. Analyses presented here, Table 1, indicate that the 100-year storm should generate deep-water significant wave heights on the order of 16 to 17 meters, with the further projection that we can routinely expect 10-meter waves, approximately every 5 years. It is uncertain what change in climate has brought about this recent increase in storm-wave heights. It is clear that for the past 25 years there has been a progressive increase in wave heights and periods along the PNW coast (Allan and Komar, 2000, in press). The climate factors responsible for this progressive increase have not been determined, and without such an identification it is not possible to predict whether this trend will continue in the future. If it does, the extreme waves in the future will be even greater that the projected values given in Table 1, the result of an analysis procedure that assumes the wave climate is static, with no long-term trend.

The other major change in Table 3, compared with similar estimates made in the past, involves the level of enhancement of the tide by the occurrence of a storm surge. As of 1996, analyses of storm surges had indicated they would typically raise the water level by 15 to 30 cm, and during a severe storm might raise it by 50 cm. This view changed when the storm of 2-4 March 1999 raised the measured tide above the predicted tide by about 1.75 meters as measured by the Toke Point tide gauge in Willapa Bay. In the analyses presented in this report, it is suggested that about 1.5 meters of this actually represented the storm surge, the balance in the water-level increase having been produced by the monthly-mean water level. This occurrence is 1-meter higher than the 50-cm elevation previously projected for an extreme storm surge.

In that both the increased wave heights and storm surge elevations are associated with the occurrence of major storm events, the revisions in Table 3 compared with estimates in 1996 clearly reflect the increased storm intensities that have occurred in recent years. Scenarios #1 and #2 clearly reflect that experience. Scenario #1 is basically for the occurrence of what is now projected to be the 100-year storm event. In calculating the component factors, we have adopted something of a "worst case" situation wherein the storm and its generated waves and surge strike the coast at a time of high tides. However, in all scenarios we used an average for the predicted higher-high tides, rather than using the greater elevation of a Spring Tide. So in that sense the scenarios do not represent worst-case events. The monthly-mean water levels (MM) entered into scenarios #1 and #2 have been well documented by measurements, Figure 2, and do not represent particularly extreme values based on past experience. The wave runup (R) is a reasonable estimate except that its calculation is based on a wave period T = 20 seconds. An examination of the largest storms, those that were used to project the extreme wave heights, demonstrated that a number of them had periods up to 20 seconds, whereas others had periods as low as 12 seconds. In that the calculation of R, equation (1), is very sensitive to the wave period, being directly proportional to T, whether the storm has a period of 20 or 12 seconds will result in a substantial difference in the level of the wave runup. In that we used a value of 20 seconds in developing the scenarios in Table 3, we again have based the assessment on a worst-case condition.

The results for the total water levels in Table 3 suggest that in terms of the resulting coastal erosion, an El Niño climate event should have less impact on the coast than a "normal" or La Niña winter. This finding appears to conflict with our experience that significant erosion occurs along the coasts of Oregon and Washington during an El Niño (Komar, 1986, 1997, 1998a; Kaminsky et al., 1998). However, most of the El Niño related erosion is not necessarily the result of extreme storms and water levels, the factors analyzed in Table 3, but is due instead to the shift in the wave directions to a more southwesterly quadrant, producing a northward movement of beach sand within the littoral cells between headlands. During both the 1982-83 and 1997-98 El Niños, it was observed that the most severe beach and property erosion occurred in "hot spot" zones north of headlands and north of migrating tidal inlets, produced by the northward movement of beach sand. Those occurrences of erosion demonstrate the fact that there are other factors and processes important to the problem that it is not simply due to extreme levels of tides and wave runup as analyzed in Table 3. However, during a normal or La Niña winter, when the storms come more directly across the Northwest coast, the northward movement of sand as occurs during an El Niño is not an important factors in the erosion, so the total water level of scenario #1, governed mainly by the occurrence of a major storm, is likely to dominate the resulting erosion, which will also tend to develop along the full length of the littoral cell, rather than being localized in "hot spot" areas as during an El Niño. This coast-wide pattern of erosion was illustrated by that which occurred along the Northwest during the 2-4 March 1999 storm, even though the calculated maximum total water levels reached to only 4 to 5 meters NGVD29, because the storm struck the coast at a time of relatively modest predicted tides (Komar et al., 1999).

Normally one attempts to quantitatively estimate the probability of the occurrence of a natural event; in the present application, the probabilities of the calculated total water levels for the three scenarios in Table 3. It should be recognized that although we tend to express the probability, for example, as the "100-year event", that event actually represents the 1-in-100 probability of occurrence during any one year (in other words, a 1% chance of occurrence in any given year). It is difficult evaluate this probability when one is considering the joint occurrences of multiple processes, each of which has its own probability of occurrence. To make such an analysis, we might separate the processes that control the mean water levels — measured tides — from the runup of the storm waves. If these two components were completely independent in their occurrences, then one might couple the 2-year water level with the 50-year wave runup occurrence to arrive at a 100-year combined event (alternately, we could use 10-year combinations). But as we have seen, an important part of the measured tide is the storm surge, which occurs at the time of the enhanced wave generation and runup, so a division between measured tides and wave generation cannot be considered as independent processes. A more rational division is between the predicted tides plus the monthly-mean water levels as affected by water temperatures and offshore currents, versus the storm-occurrence processes of wave generation (runup) and the storm surge. To a degree such a division was made in scenarios #1 and #2, where #1 represents the 100-year storm while the combination of predicted tide and monthly mean water level is a 1-year assessment. In the opposite direction, scenario #2 represents an El Niño winter when the water levels are close to a 100-year occurrence, while the storm wave heights are more moderate and of frequent occurrence.

The selections of conditions for scenarios #1 and #2 were based on the desire to have the combined results sum to a total water level that has an approximate 1-in-100 probability of occurrence. However, in that those specific climate regimes do not occur every year, the probabilities are lower. In that most years are "normal", those years combined with the occurrences of La Niñas to give scenario #1 have close to a 1-in-1 probability, so the total water level calculated in Table 3 for scenario #1 can be taken as having close to a 1-in-100 probability. In that strong El Niños are infrequent, the projected water level in Table 3 for scenario #2 has a low probability, much less than 1-in-100, but this is perhaps irrelevant since most of the erosion during an El Niño has the "hot spot" pattern associated with the northward movement of beach sand within the littoral cells, rather than being caused by total water levels.

The greatest potential impact to the Northwest coast would come from scenario #3 in Table 3, which in effect combines the major impacts of an El Niño (including the northward movement of beach sand), and the occurrence of a 100-year storm as analyzed for scenario #1. Although storm systems do tend to be displaced toward the south during an El Niño, so we might expect some reduction in wave-energy levels as hypothesized by Seymour (1996), the possibility cannot be ruled out entirely that sometime in the future we will experience a 100-year storm event during an El Niño year. Considering the degree to which our ideas and assessments of the processes have changed during the past few years due to the occurrence of much stronger storms, we should hesitate to rule out the possibility of scenario #3.

In terms of total water levels, Table 3, the difference between scenarios #1 and #3 only amount to 30 cm. However, management planning for scenarios #1 and #3 is different in that #3 includes the hot-spot erosion impacts as well as the most extreme wave runup and total water levels. Thus, there would be the coast-wide erosion inherent in the major storm scenario #1, with a localized hot-spot erosion produced by the northward transport of sediment within the littoral cells, characteristic of an El Niño. To a degree, the erosion experienced during the winter of 1998-99 demonstrates the potential impacts in that the Northwest beaches had not fully recovered from the 1997-98 El Niño, when they were further eroded by the series of major storms of the 1998-99 La Niña. However, the potential impacts of scenario #3 would be still greater than that recent experience, due to the significantly higher total water level of scenario #3 than occurred during the winters of 1997-98 and 1998-99.

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