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An Application of LIDAR to Analyses of El Niño Erosion in the Netarts Littoral Cell, Oregon

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ABSTRACT

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El Niño produces coastal and beach erosion along the West Coast of the USA by elevating mean water levels so that tides are significantly higher than predicted, and by altering the paths of storms that generate large waves. In the past it has been difficult to adequately document the erosion impacts since they are so widespread. This difficulty has been solved through the application of LIDAR, which uses a scanning laser mounted in a small aircraft to rapidly and accurately survey beach elevations. This study uses LIDAR to document the beach changes and shoreline erosion that occurred during the 1997–98 El Niño within the Netarts Littoral Cell on the Oregon coast, a 14-km long "pocket beach" between large rocky headlands. The LIDAR surveys demonstrate that sand generally migrated northward within the cell due to the southwest approach of the El Niño storm waves, but there was a complex pattern of beach-elevation change due to the superposition of eroded rip-current embayments. The greatest beach erosion occurred near the south end of the cell, where it impacted Cape Lookout State Park, and to the north of the inlet to Netarts Bay where it threatened The Capes, a development of condominiums located on a high bluff. In both cases the LIDAR data proved to be extremely useful in quantifying the erosion, and in providing a better understanding of the erosion processes that occur during an El Niño.

ADDITIONAL INDEX WORDS: *Coastal erosion, large-scale coastal behavior, El Niño, LIDAR, Oregon.*

INTRODUCTION

The occurrence of a major El Niño is significant in producing beach and property erosion along the West Coast of the United States. Erosion during the strong El Niño winters of 1982–83 and 1997–98 reached near catastrophic levels, documented by a number of publications (GRIGGS and BROWN, 1998; HAMPTON *et al.,* 1999; KAMINSKY *et al.,* 1998; KOMAR, 1986, 1998; SALLENGER *et al.,* 1999; STORLAZZI and GRIGGS, 1998; USGS *et al.* 1998).

While the erosion processes related to El Niños have been analyzed with measurements of tides and waves, it has been difficult to quantify the coastal impacts since they are so widespread. Analyses of erosion along the Oregon coast during the 1982–83 El Niño were limited to descriptions of the general patterns of large-scale coastal change, and lacked any before and after profiles of beaches, dunes and sea cliffs that would have quantified the impacts. Fortunately, such data are available for the 1997–98 El Niño, in the form of LIDAR surveys that cover large portions of the West Coast, including the northern Oregon coast where the erosion was particularly severe. LIDAR makes use of a scanning laser mounted in a small aircraft that can rapidly and accurately survey land elevations (SALLENGER *et al.,* 1999). In anticipation of the arrival of the 1997–98 El Niño, LIDAR surveys were made during October 1997 along much of the West Coast, and then repeated in April 1998.

The objective of this paper is to utilize the LIDAR data to document the erosion within the Netarts Littoral Cell on the Oregon coast, where impacts were particularly severe at Cape Lookout State Park on Netarts Spit and at The Capes development. LIDAR provides the ability to test our concepts of how El Niño processes account for the large scale patterns of beach and shoreline erosion, and provides a good example of the use of LIDAR to analyze specific "hot spot" erosion problems.

EL NIÑO EROSION PROCESSES

El Niño affects both mean water levels and wave intensities along the West Coast of the United States, and in this way influences the extent of coastal erosion. During an El Niño the daily and monthly mean water levels are significantly higher than normal, so that measured tides exceed the predicted levels, allowing the runup of storm waves superimposed on elevated high tides to reach foredunes and sea cliffs backing beaches.

The increased levels of measured tides during an El Niño are caused by several factors including higher water temperatures and the accompanying thermal expansion of the water's volume, variations in the directions and magnitudes of coastal currents, and the existence of sea-level "waves" that

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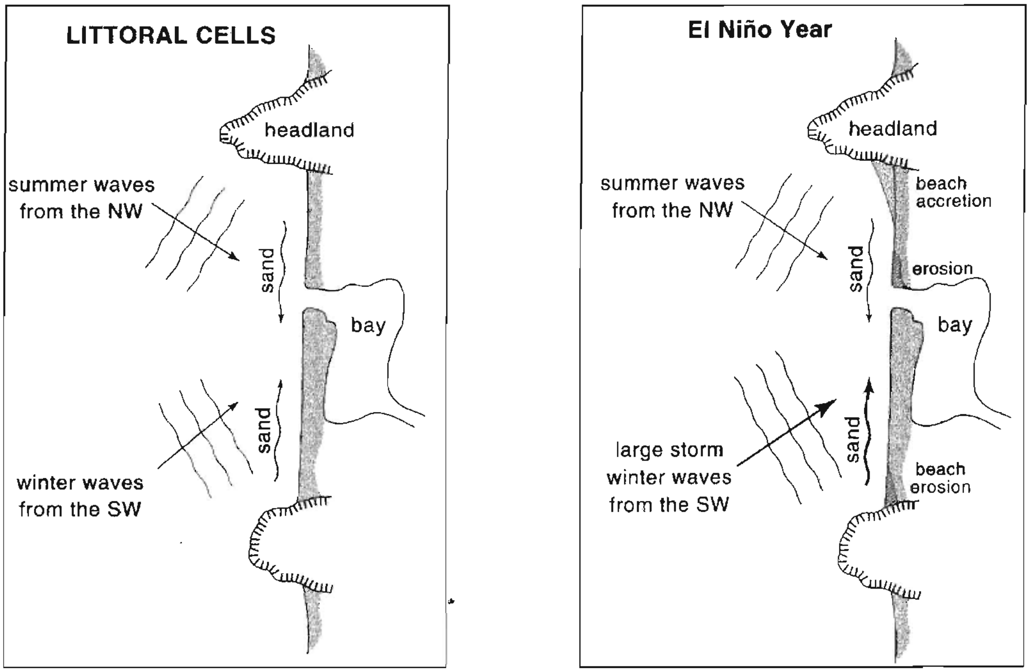

Figure 1. Schematic diagram of the longshore movement of sand within Oregon littoral cells during normal years (left) and during an El Niño (right).

emanate from the equatorial Pacific when the trade winds decrease (Wyrtki, 1984). These combined processes typically raise mean water levels along the West Coast of the United States by tens of centimeters. Based on analyses of tide-gauge records from La Jolla and San Francisco, California, for both the 1982–83 and 1997–98 El Niños, Flick (1998) found monthly-averaged sea levels elevated by up to 35 cm. Analyses of tide gauge records from the Oregon coast during the 1982–83 El Niño demonstrated that monthly mean sea levels reached a maximum during February 1983, nearly 60 cm higher than the mean water surface in May 1982, nine months earlier (Huyer *et al.,* 1983; Komar, 1986). Similar analyses have been undertaken for the 1997–98 El Niño (Komar *et al.,* 2000). The highest water elevations were reached in January and February 1998, when monthly-averaged levels were raised by 60 to 70 cm.

The tracks and intensities of storms, important to wave generation, are also altered during an El Niño. Of particular importance, the subtropical jet stream crosses California, bringing storms and high waves to the coast (Seymour, 1998). Due to this diversion to the south, away from the Pacific Northwest, Seymour suggested that fewer storms reach the Oregon and Washington coasts during an El Niño than in average years. However, analyses of the Northwest wave conditions during the 1997–98 El Niño showed that high wave conditions persisted (Komar *et al.,* 2000; Allan and Komar, 2000, in press). In particular, major storms occurred on 19–20 November 1997 and 17–18 January 1998, with the November storm generating deep-water significant wave heights of 10 m, approximately equal to what had been projected for the 100-year storm, based on 30 years of wave data through 1996 (Ruggiero *et al.,* 1996). Based on the occurrence of that storm plus four storms that also exceed this prediction during the 1998–99 La Niña, the 100-year storm wave projection has been revised to 15 km (Komar and Allan, 2001). That aside, it is clear that the high wave-energy levels typical of the Northwest coast persisted during the 1997–98 El Niño, even though the storm systems predominantly crossed the coast further to the south.

The southward displacement of the storm tracks during an El Niño is one of the most important factors in producing erosion along the Oregon coast (Komar, 1986, 1998). The significance is that waves approach the beaches more from the southwest, resulting in the transport of sand from south to north along the beaches. The stretches of beach on the Oregon coast are interrupted by rocky headlands, forming a series of "pocket beach" littoral cells (Komar, 1997). As illustrated in Figure 1 (left), during normal years there tends to be a near balance between the southward longshore movement of sand during the summer, versus the northward movement in the winter. In contrast, during an El Niño winter (Figure 1, right), the large storm waves arrive from a still more southwesterly direction, moving unusually large quantities of sand to the north. This systematically shifts sand from the south ends of littoral cells, where extreme beach erosion may occur, to the north ends where the beach may even accrete. This northward sand movement can also deflect tidal inlets to the north, producing erosion along the north bank of the inlet. This pattern of longshore sand displace-

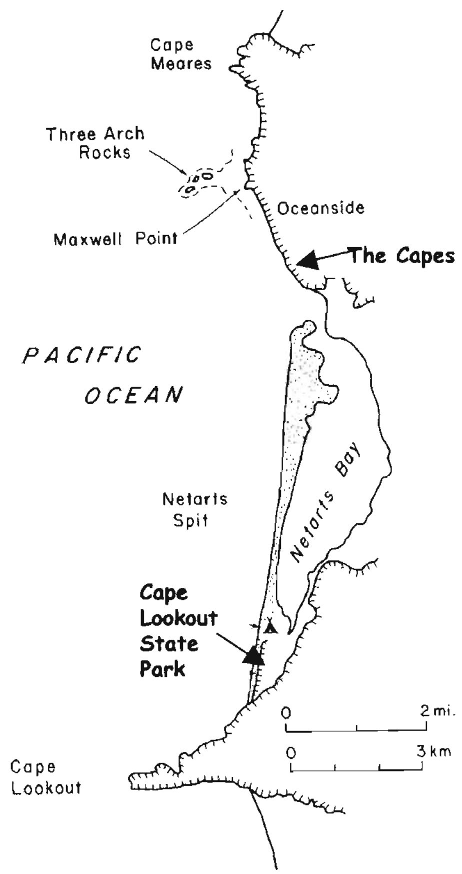

Figure 2. The Netarts Littoral Cell, with the maximum El Niño erosion having occurred at Cape Lookout State Park and at The Capes development.

ment during an El Niño accounts for localized erosional "hot spots", indicated in Figure 1 (right) (Komar, 1986, 1998).

The erosion that occurred along the Oregon coast during the 1982–83 and 1997–98 El Niños was in response to these combined processes (Komar, 1986, 1997, 1998; Komar *et al.,* 2000). The storm waves that struck the coast arrived at the same time as sea level was approaching a maximum, so that wave runup superimposed on elevated mean water levels combined to produce extreme water levels that reached the base of foredunes and sea cliffs, resulting in severe shoreline erosion. However, the erosion tended to be greatest in the "hot spot" areas diagrammed in Figure 1 (right), caused by the northward movement of sand within the littoral cells.

EL NIÑO EROSION WITHIN THE NETARTS LITTORAL CELL

Particularly severe erosion occurred during both the 1982–83 and 1997–98 El Niños within the Netarts Littoral Cell, Figure 2, on the northern Oregon coast (Komar *et al.,* 1988; Komar, 1998; Revell, 2000). This is one of Oregon's smallest littoral cells, having a 14-km longshore length from Cape Meares in the north to Cape Lookout in the south. Maxwell Point, together with the offshore Three Arch Rocks, separate the littoral cell into two sub-cells within which the longshore movement of sand is somewhat restricted; the pocket beach to the north is composed mainly of cobbles, with some subtidal sand, while the beach to the south is nearly all sand. The Netarts Littoral Cell is an excellent example of the "hot-spot" erosion impacts depicted in Figure 1 (right), with erosion north of Cape Lookout affecting a state park, while the northward migration of the inlet to Netarts Bay caused sea-cliff erosion and landsliding that threatened The Capes condominium development.

Cape Lookout State Park, which contains a campground and day-use facilities, is located at the south end of Netarts Spit. Erosion during the 1982–83 El Niño was attributed mainly to the northward transport of sand by the approach of waves from the southwest (Komar *et al.,* 1988). Much of the sand on the beach disappeared, reducing its buffering protection for the park. Another factor was the presence of a large rip current and its erosional embayment centered on the campground. During the 1982–83 event, erosion partially destroyed an old log seawall, and then began to erode the high ridge of dunes that sheltered the campground (Komar *et al.,* 1988).

Erosion of the park during the 1997–98 El Niño essentially continued where the 1982–83 event left off (Komar, 1998). Additional dune erosion occurred, and the public bathroom in the campground was in danger of being undermined by waves until riprap was placed for protection, Figure 3. High water elevations combined with storm wave runup washed into the park, depositing large volumes of beach sand in the campground. Dramatic erosion also occurred at The Capes, Figure 4, a development of expensive condominiums built in 1994–96 on the high bluff to the immediate north of the inlet to Netarts Bay. The northward migration of the inlet during the 1997–98 El Niño eroded the fronting beach and created deepened water directly offshore. The runup of storm waves combined with the elevated mean water levels associated with the El Niño reached the toe of the high bluff below The Capes. The development is located atop an ancient landslide, with the underlying portion consisting of a layer of clay that is weak and extremely mobile, while the overlying material within the bluff is relict dune sand. As sand was scoured from the fronting beach during the 1997–98 El Niño, the clay layer was exposed to wave action and the landslide was reactivated (Revell, 2000). Thus, while there were pre-existing hazardous conditions for The Capes development, the present instability and movement of the landslide can be attributed to the erosion impacts of the 1997–98 El Niño.

LIDAR SURVEYS

LIDAR is an acronym for *L*ight *D*etecting *A*nd *R*anging (analogous to RADAR), and employs a scanning laser mounted in a small aircraft to rapidly and accurately survey land elevations. The basic system was developed by NASA for use in investigations related to climate change, specifically for annual surveys of the Greenland Ice Sheet (Krabill *et al.,* 1995). In recent years it has seen increasing application to document large-scale coastal change and storm impacts (Sallenger *et al.,* 1999; Hampton *et al.,* 1999).

Figure 3. Erosion in Cape Lookout State Park during the 1997–98 El Niño. Remnants of the log seawall can be seen in the background, together with the eroding high dunes. The bathrooms were threatened, and had to be protected by a line of riprap (*Photo: Komar*).

A major asset of LIDAR is the high spatial density of data collection, with ground elevations measured every two meters over hundreds of kilometers of coast. When compared with ground surveys of beaches, LIDAR has been found to have a RMS vertical error of about 15 cm (SALLENGER *et al.*, in press), which is sufficient resolution to quantitatively evaluate beach erosion during major storms. When used in the present study on the Oregon coast to define profiles across the beach, it was found that the LIDAR surveys typically provide 20 to 25 surveyed elevations within a 50-m profile length. Therefore, LIDAR can resolve changes in elevations across a profile, or large-scale longshore variations in beach topography. There are difficulties in using the LIDAR data. This particular LIDAR system records the first reflected return from the laser. As well as reflecting off the sandy beach, the laser reflects off vegetation, water, and even birds. It is not always easy to distinguish between the sand on the beach and the water surface of the swash, or to determine whether vegetation is affecting the apparent elevations of dunes. A few spurious data points (birds?) were edited out prior to the profile analysis because they were obvious outliers along the surveyed portion of the dry beach. Simultaneous with the measurement of ground elevations, aerial videography was collected that can be helpful in interpreting the survey results.

In anticipation of the 1997–98 El Niño, a LIDAR flight was made during October 1997 along extended reaches of the West Coast, and then repeated in April 1998 to document the changes that had occurred. This was a cooperative effort between NASA, NOAA and the USGS. SALLENGER *et al.* (1999) and HAMPTON *et al.* (1999) have demonstrated the usefulness of the LIDAR data in documenting the beach morphology changes and erosion on the coast of central California.

The analyses presented here extend the application to the Netarts Littoral Cell on the Oregon coast. Flights over the area occurred on 15 and 17 October 1997, but the data collected on the 15th were determined to be faulty, and have not been used in the analyses. The surveys were repeated on 26 and 28 April 1998, about six months later, to document the beach-morphology changes that had occurred during the El Niño winter. The coverage of interest in this study extends from Cape Lookout in the south to Maxwell Point in the north (Figure 2). The LIDAR surveys did not satisfactorily cover the short pocket beach between Maxwell Point and Cape Meares so changes there cannot be analyzed. That pocket beach is composed mainly of cobbles, but of potential interest

Figure 4. The Capes development north of the Netarts Bay inlet. Erosion cut away the toe of the cliff, re-activating a large landslide upon which the development had been placed *(Photo: Komar)*.

might have been whether sand bypassed Maxwell Point during the El Niño winter, entering that pocket beach.

The tide levels at the times when the LIDAR surveys passed over the Netarts Littoral Cell are given in Table 1. An average higher-high tide on the Oregon coast is approximately 2.75 m MLLW, equivalent to a land elevation of 1.50 m NGVD29, which is the datum used in this study for surveyed land elevations. It is seen in Table 1 that the 17 October 1997 survey was made at mid-tide, which somewhat reduced the area of beach covered by the survey. However, in October the Oregon beaches retain most of their broad summer width, so this LIDAR survey documented the elevations of an expansive area of dry beach. More significant is that the surveys of 26 and 28 April 1998 occurred at times of exceptionally low tides, important in that the beaches still tend to be narrow following the winter.

Table 1. *Tide levels at the times of the LIDAR surveys of the Netarts Littoral Cell (values in meters).*

Tide Datum	17 Oct. 1997	26 April 1998	28 April 1998
MLLW	1.74	−0.58	−0.46
NGVD29	0.49	−1.83	−1.71

PATTERNS OF LONGSHORE SAND DISPLACEMENT

The northward displacement of beach sand within Oregon littoral cells during the 1982–83 El Niño was detected by the accumulation of sand south of headlands, versus erosion to the north (KOMAR, 1986). Such general observations led to the development of the "hot-spot" erosion model diagrammed in Figure 1. A primary objective of the present investigation is to utilize the LIDAR surveys to more fully document the northward displacement of beach sand within the Netarts Littoral Cell.

The actual response of the beach to El Niño processes is more complex than simply a northward transport of sand, yielding erosion at the south end of the cell and beach accretion at its north end. It is important to note that the six months between flights spanned the winter and therefore captured two erosion phenomena, the normal seasonal cycle of profile change plus the effects of the El Niño. The high waves of any winter act to erode the beach berm, transferring sand to offshore bars. This cell-wide beach erosion due to the offshore transport of sand is modified during an El Niño by the simultaneous northward longshore movement of sand, cutting back still further the beach at the south end of the

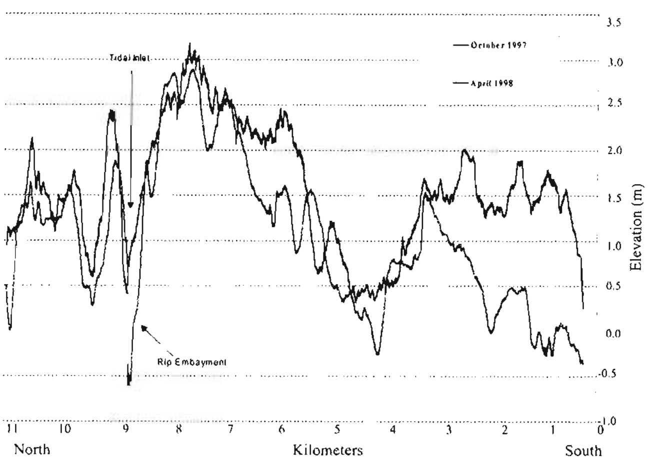

Figure 5. LIDAR profiles extending along the length of the beach within the Netarts Littoral Cell, showing beach elevations on 17 October 1997 and 26 April 1998. The profiles represent moving 25-m averages.

cell, generating the "hot-spot" zone of maximum erosion. At the north end of the cell, while beach sand is transported offshore during the winter, there should be some gain from the northward longshore transport. Assuming that Maxwell Point acts to block most of this transport, the erosion there should be less than the normal offshore transport, and it is even possible that the beach could accrete during the El Niño winter if the northward transport exceeds the offshore sand loss.

The LIDAR data are versatile in that profiles of beach elevations can be constructed having any desired orientation. This is illustrated in Figure 5 by the pre- and post-El Niño profiles oriented along the length of the beach, extending from Cape Lookout to Maxwell Point, interrupted only by the inlet into Netarts Bay. The profiles are positioned at about mid-beach, approximately 30 m out from the edges of the dunes and sea cliffs. Even with this simple pair of longshore profiles it can be seen that the greatest extent of beach-elevation reduction occurred toward the south end of the littoral cell. Farther to the north, erosion still prevailed, but by a smaller amount. The individual profiles also illustrate the considerable longshore variability in the elevations of the beach, and there is a tendency for those irregularities to be retained as the beach erodes during the winter. Overall, the beach elevations ranged between 0 and 3 m NGVD29, with the changes occurring over hundreds to thousands of meters in the longshore distance, so the slopes are actually small and would be difficult to recognize by an individual on the beach. Indeed, in viewing the videos obtained during the October 1997 surveys, the beach appeared to be very regular, with a wide berm as expected toward the end of the summer months. In contrast, the videos obtained during the April 1998 surveys, at times of lower tides, revealed the dramatic effects of rip currents on the beach topography, including the presence of large embayments eroded by the rips and systems of channels and bars. The observed irregularities seen in the longshore profiles were for the most part produced by embayments eroded by rip currents, even in the October survey. In most places these embayments deepened and were cut farther landward during the El Niño winter, making them more apparent in the April video.

In order to provide quantitative assessments of beach sand movements during the 1997–98 El Niño, analyses were undertaken to measure incremental sand volume changes along the length of the cell's shoreline. This was accomplished by dividing the length of the beach into 100-m segments, and generating standard cross-shore profiles to determine the position of the back of the beach where it meets the dunes or sea cliffs. Based on the profile inspections, it was decided that the analyses would be limited to a 40-m wide stretch of backshore profile, this being representative of the erosion of the dry part of the beach during the El Niño winter. The offshore limit taken is somewhat arbitrary, but it was desirable to exclude the irregularities of bars and troughs that would introduce scatter in the results. In order to include more LIDAR survey data than a single profile line, the evaluations of the beach-elevation changes centered on the 40 m dry sand cross-shore section between the 100 m spaced longshore profiles, each section forming a rectangle covering 4,000 m^2 area of beach. Of interest was the calculation of the average beach-level change, so the differences were calculated between the beach elevations from the 17 October 1997 and April 1998 LIDAR surveys, and the results were averaged over the rectangular areas. The results in Figure 6 again show a considerable degree of irregularity along the length of the littoral cell. Overall, most areas of the beach eroded, with the greatest degree of erosion occurring toward the south end and in the area immediately south of the tidal inlet to Netarts Bay. Both regions experienced average beach elevation reductions greater than -1.5 m. While nearly the entire beach suffered erosion, three localized areas on Netarts Spit experienced accretion, a rise in the average beach level by about $+0.5$ m. It is apparent in Figure 6 that these zones of accretion are part of a rhythmic pattern of beach-level change along the entire length of the littoral cell. It appears that they were produced by the northward migration of rip-current embayments between the October 1997 and April 1998 surveys, with the zones of accretion in Figure 6 corresponding to areas where embayments had been filled with sand as the adjacent giant horn to the south migrated northward. There is also some indication of this in the longshore profiles in Figure 5.

As discussed earlier and diagrammed in Figure 1, the northward migration of an inlet during an El Niño is expected to produce "hot spot" erosion of its north shore. This is not particularly well documented by the LIDAR surveys across the inlet to Netarts Bay. Some inlet migration had already occurred prior to the first LIDAR survey in October 1997. The video taken at that time, as well as ground photos, show that the inlet mouth curved northward, having already partially cut back the beach in front of The Capes development. This particular LIDAR system does not capture underwater topography, so most of the inlet channel shift was missed. The results in Figure 6 demonstrate that between the October 1997 and April 1998 surveys, beach elevations increased to the immediate north and south of the inlet. On the south side of the inlet, the north end of the spit changed its configura-

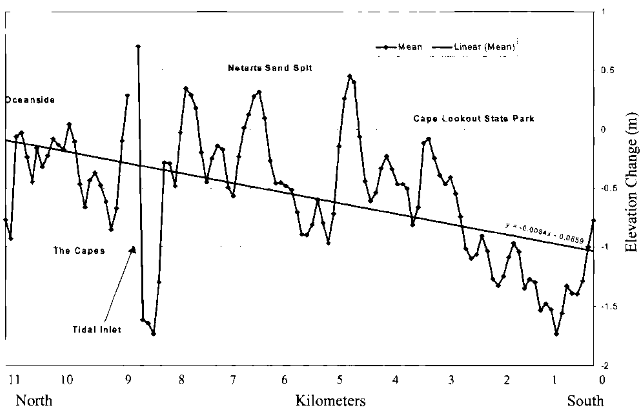

Figure 6. The LIDAR analysis of beach-elevation changes experienced along the length of the Netarts littoral cell during the El Niño winter, derived from taking the difference between surveyed elevations on 17 October 1997 and 26 April 2000. Each mean value represents a 4,000 m^2 area of beach, extending 100 m in the longshore direction and 40 m across the stretch of mid beach.

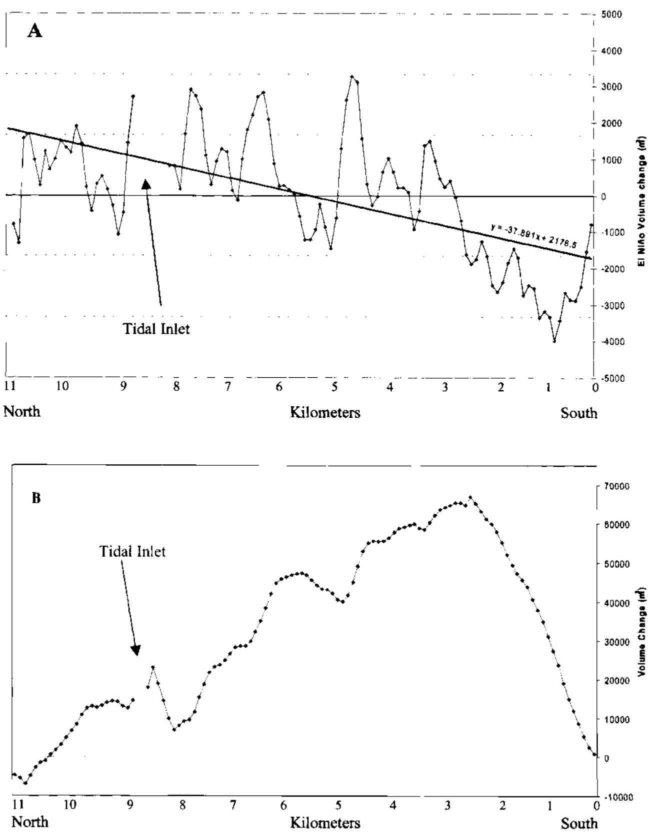

Figure 7. (**A**) The longshore variation in beach-elevation change, as in Figure 6, but where the mean value of erosion has been removed, which is assumed to represent sand eroded from the beach and transported offshore, so that the elevation changes diagrammed here reflect the south-to-north longshore sand movement during the El Niño winter. (**B**) A south-to-north summation of the volumes of sand eroded or accreted in the 40 by 100-m rectangular segments of beach, representing the variation in the quantities of sand transported to the north during the El Niño winter.

tion with the formation of a hook that extended into Netarts Bay, also seen during other El Niño years (REVELL, 2000). The high degree of localized erosion further to the south of the inlet, Figure 6, is believed to have been part of this reconfiguration, although the presence of a rip current may also have been important. On the north shore of the inlet, the LIDAR surveys show a smaller amount of accretion (Figure 6), produced by sand that was swept into the inlet from erosion of the beach and bluff directly in front of The Capes development.

The analysis in Figure 6 also shows a south-to-north overall decrease in the degree of elevation change, one that reflects the northward movement of sand expected during an El Niño. A regression line has been fitted to the variations, Figure 6, ranging from a −1.1 m elevation change adjacent to Cape Lookout, to about −0.1 m of beach erosion at Maxwell Point. However, it is seen that the maximum beach erosion did not occur adjacent to Cape Lookout, but was displaced about 500 m to the north. This is likely due to the sheltering effect of Cape Lookout to the southwesterly storm waves (Figure 2), providing a zone of wave refraction and diffraction that reduced wave-energy levels. Furthermore, as seen in Figure 6, there was a zone of enhanced erosion immediately south of Maxwell Point, rather than this location being the area of minimum erosion. This localized erosion was caused by a rip current that formed adjacent to Maxwell Point, likely due to the offshore deflection of northward-flowing longshore currents generated by the southwest storm waves.

Keeping in mind that the two LIDAR surveys captured both the seasonal and El Niño erosion patterns and the fact that nearly all areas of shoreline were eroded, the results in Figure 6 imply that substantial quantities of sand removed from the berm were transported to offshore bars. Without subaerial profile data, the total volume of this offshore bar component cannot be evaluated. Based on our understanding of the seasonal cycle of cross-shore transport, we can approximate that offshore transport by quantifying the cell-wide average erosion of the beach berm, an average of the data graphed in Figure 6. This average has been calculated as −0.57 m, and represents an average of 2,280 m^3 of sand eroded from the 40 by 100-m shoreline segments, or 22.8 m^3 per meter of shoreline length. The total volume of sand moved offshore along the full 11-km length of the littoral cell from Maxwell Point to Cape Lookout was 2.5 × 10^5 m^3. In that this quantity represents only a 40-m long cross-shore portion of the eroding inner profile, the actual quantities of sand transported from the berm to offshore bars must have been substantially greater.

If this average rate of erosion used as an estimate for offshore transport (−0.57 m) is subtracted from the values of beach-elevation change, a value is obtained representing the elevation change that reflects the south-to-north longshore transport of sand. This is graphed in Figure 7A, where the average beach-elevation changes have been multiplied by

4,000 m² to determine the equivalent volumes of sand eroded or deposited within the 40-by-100 m segments. Assuming that the erosion of the beach at the south end of the cell contributed to the longshore transport northward, the values graphed in Figure 7A can be summed in sequence from south to north, added to the volume of sand being transported if erosion occurred within a particular segment, or subtracted if accretion occurred. The result of such an analysis is graphed in Figure 7B. It is seen that beginning in the south at Cape Lookout, where it is assumed that the initial longshore transport was zero, the volume of sand transported to the north progressively increased, reaching a maximum value of just over 70,000 m³, and with increasing distance to the north the longshore transport of sand progressively decreased since accretion occurred in most of the remaining segments. The volumes of sand graphed in Figure 7B represent the cumulative transport during the six months between LIDAR surveys. Realistically the transport would have occurred mainly between November 1997 and February 1998, the months of strongest storms. Assuming that the maximum value, 70,000 m³, did occur during those months, the average daily rate of transport to the north would have been only 580 m³/day. Again, this represents the 40-m stretch of inner beach width, with the total quantities of longshore transport across the entire beach width having been somewhat greater. Even then, the results indicate that the south-to-north displacement of sand within the Netarts Littoral Cell during the 1997–98 El Niño did not require substantial magnitudes of longshore sand transport.

AREAS OF HOT-SPOT EROSION

As discussed earlier, there were two areas of concentrated erosion within the Netarts Littoral Cell during the 1997–98 El Niño—Cape Lookout State Park and the bluff fronting The Capes development. Those sites conform with the "hot spot" locations of maximum erosion expected during an El Niño (Figure 1), and the above analyses using LIDAR surveys substantiated that the northward movement of beach sand was an important factor in impacting properties within the Netarts Littoral Cell. The objective of this section is to utilize the LIDAR surveys in more detailed examinations of these erosion sites.

Cape Lookout State Park

The erosion of Cape Lookout State Park during the 1982–83 El Niño was attributed to the northward movement of beach sand, enhanced by the presence of a rip current embayment directly offshore from the campground where the erosion was greatest (Komar *et al.*, 1988). Erosion of the park persisted for several years after that El Niño, caused by the continued deficit of sand along the fronting beach, making the park vulnerable to renewed erosion during subsequent winters. The persistent deficit of sand likely resulted because it required several years of summer wave conditions to return the sand from the north end of the cell where it had accumulated during the El Niño. It is also possible that some of the beach sand was carried into Netarts Bay during the El Niño as it was being transported to the north, perhaps having been permanently lost from the littoral system.

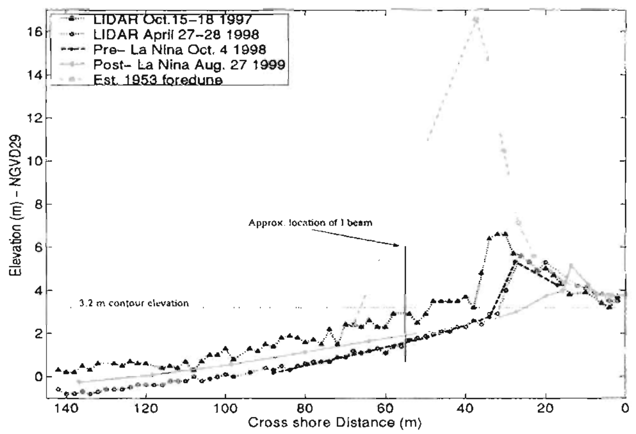

Figure 8. An approximate survey in 1953 of the former high dunes along Cape Lookout State Park, and the more recent LIDAR and ground surveys along the same line.

The LIDAR data are useful in more detailed analyses of the erosion that occurred at Cape Lookout State Park by providing beach profiles needed in assessments of storm-wave runup levels on the beach, and in documenting the total amount of erosion that occurred. Figure 8 shows a compilation of profiles across the beach and dunes in the area of the campground where the erosion was greatest. The earliest profile is from 1953, reconstructed from State Parks' blueprints and a topographic survey in 1953, so the profile is only approximate (Revell, 2000). Of interest was the presence of a high dune (~15 m) covered by large trees, which sheltered the campground along its entire length. A seawall consisting of horizontal logs supported by vertical I-beams was constructed in 1966 in an effort to focus public access between the campground and beach, minimizing traffic over the dunes. The approximate location of the seawall and I-beams is shown in Figure 8, and represents the base of the dunes throughout the 1960s and 70s. Wave attack during the 1982–83 El Niño resulted in the failure of the seawall along its southern half, followed by the rapid erosion of the high dune ridge (Komar *et al.*, 1988). The LIDAR survey obtained on 17 October 1997, Figure 8, indicates the degree of change with the disappearance of the high dune, leaving only a small remnant dune at the back of the beach. The post-El Niño LIDAR survey in April 1998 shows the extent of change produced during the second major El Niño event. The elevation of the beach was lowered by about 1 m, and the small residual dune was lost. Of interest, a ground survey was obtained on 4 October 1998, about five months later, which shows a close congruence with the LIDAR survey, verifying the LIDAR data and also demonstrating that little sand had returned to this part of the beach during the summer months. This set the stage for renewed erosion during the following winter, which turned out to be a La Niña when a series of unusually severe storms occurred during February and March 1999, producing overwash events into the State Park (Komar *et al.*, 1999,

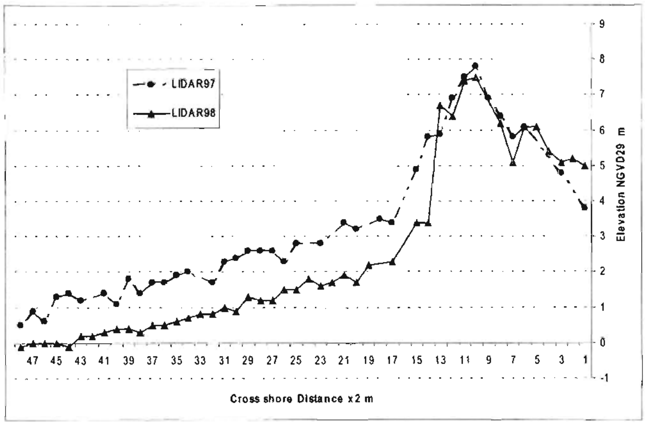

Figure 9. LIDAR surveys in the area of Cape Lookout State Park that suffered particularly severe erosion during the 1997–98 El Niño.

2000; REVELL, 2000; ALLAN and KOMAR, in press). A post-La Niña ground survey is included in Figure 8, showing the extent of elevation changes.

A pair of profile lines derived from the LIDAR surveys are given in Figure 9, positioned respectively at the north end of the campground where the high dunes remained but were eroded during the 1997–98 El Niño, and to the south where the dunes had been nearly eliminated during the 1982–83 El Niño, the area that received the greatest impact during the 1997–98 El Niño and 1998–99 La Niña. The northern-most profile (A) demonstrates that considerable toe erosion occurred along the base of the high dunes. Calculations of wave runup on Oregon beaches, added to measured tides to obtain the total levels achieved by the water during the El Niño storms, indicate that the maximum elevations achieved by wave swash were on the order of 5 m NGVD29 (KOMAR *et al.,* 1999, 2000). The LIDAR profile indicates that at this 5-m elevation, the profile retreated by about 11 m. This had the effect of removing a large volume of sand at the back of the beach, extending up to an elevation of 13 m NGVD29, together with a retreat of the face of the high dune by some 2 to 3 m. An assessment of the response of the highest parts of the dune is complicated by the fact that the LIDAR elevations include tall trees as well as the dune.

Profile B in Figure 9 is located 100 m to the south of profile A. The high dunes had been eroded during the 1982–83 El Niño, leaving only a small remnant dune. It is seen that during the 1997–98 El Niño, the elevation of the beach was lowered by about 1 m, leaving a level surface at an elevation of 4 m NGVD29 behind the beach. Some overwash into the State Park occurred in this area during storms of the 1997–98 El Niño, but became the central area of severe overwash during the 1998–99 La Niña, a time of even stronger storms with the occurrence of a significant storm surge.

Sea Cliff Erosion at The Capes Development

Two LIDAR-derived profiles across the beach and bluff fronting The Cape development are given in Figure 10, documenting the extent of change during the 1997–98 El Niño. In this area the head of the slide extends farther inland and was missed by the 1997 LIDAR so the profiles show only the lower half of the slide. The main changes between the two LIDAR surveys are seen on the surface of the lower landslide, between the 8 and 15 m elevations. Profile (A), Figure 10, is in an area of The Capes where there was general landsliding of the loose dune sand and shows the bluff retreat of the landslide some 15 m of horizontal retreat at the 5 m elevation. There was not an accumulation of sand at the base of the landslide since it was carried away by the waves. Retreat of the toe of the landslide, at the beach/dune junction, amounted to about 10 m. Profile (B) to the north also captures the area affected by landsliding during the 1997–98 El Niño. For the most part this area decreased in elevation by 1 to 3 m between the LIDAR surveys, likely caused by settlement as the toe of the slide eroded away. At the base of the steep slope the elevation increased by 3 to 4 m between surveys, produced by the accumulation of the loose sand that slid down the upper face. The toe of the landslide at the back of the beach shows little or no change between October 1997 and April 1998, in spite of the fact that it is known that the

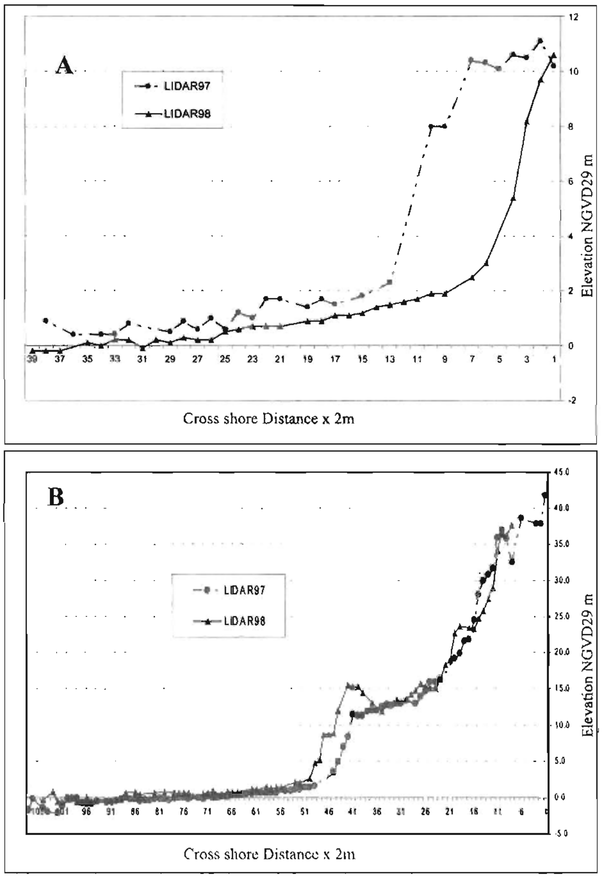

Figure 10. Profiles derived from the LIDAR in the area of The Capes development and landslide. (A) Profile shows the retreat of the loose sand bluff. (B) In the area of the Figure 4. LIDAR collected in this area it shows the accumulation of slide debris about the middle of the slope.

toe of the slide tended to push forward across the beach. The explanation is that strong toe erosion by waves at times of high tides continued to cut back the toe of the slide, maintaining its horizontal position with an elevation of the beach/toe junction at about 3 m, corresponding approximately to the 4 to 5 m NGVD29 level of the calculated extreme runup during the major El Niño storms (KOMAR *et al.*, 1999).

CONCLUSIONS

The LIDAR surveys during October 1997 and in April 1998 spanned the 1997–98 El Niño winter, permitting detailed analyses of changes in beach elevations and assessments of cross-shore and longshore sand movements. This study has concentrated on analyses within the Netarts Littoral Cell, an ideal location to examine beach responses and associated erosion impacts to El Niño processes.

LIDAR-derived profiles of beach elevations along the length of the littoral cell and calculations of average elevation changes generally demonstrated the expected patterns related to El Niño processes, with the greatest amount of beach erosion occurring near the south end of the littoral cell and significantly less erosion at the north end. The entire length of the beach experienced offshore transport of sand as part of the normal seasonal cycle of beach profile change, with sand eroded from the inner beach transported to offshore bars during the winter. Within the dry part of the beach covered by the LIDAR surveys, the average beach elevation change over the entire length of the cell amounted to −0.57 m, representing 320,000 m^3 of sand volume that must have been transported offshore (with perhaps a small amount having entered Netarts Bay). At the same time the LIDAR analysis showed a fairly regular pattern of northward longshore sand transport, increasing linearly northward from Cape Lookout to a maximum volume transport of about 70,000 m^3 of sand having moved northward during the El Niño winter. Further to the north, the transport volume progressively decreased as sand was added to the beach, reducing the amount of erosion at the north end of the cell from that produced by the offshore transport. This northward displacement of sand within the littoral cell can be attributed to the more southwesterly approach of storm waves during the El Niño as suggested by KOMAR (1986).

In addition to this general pattern of offshore and longshore transport of beach sand within the Netarts Littoral Cell during the 1997–98 El Niño, there were pronounced variations documented by the LIDAR surveys, due to the presence of rip currents which locally eroded embayments into the beach. Thus, the areas of greatest erosion within the littoral cell corresponded to locations where rip-current embayments enhanced the "hot spot" erosion patterns attributable to El Niño processes. This accounts for the severe erosion within Cape Lookout State Park and at The Capes development. The present study has demonstrated that as well as permitting the documentation of large-scale coastal behavior, the LIDAR surveys can be extremely useful in detailed analyses of localized erosion problems.

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