Preprinted from Coastal Sediments '99
Proceedings of the 4th International Conference on
Coastal Engineering and Coastal Sediment Processes
American Society of Civil Engineers
June 20-24 1999, Long Island, NY

SCALES OF VARIABILITY ALONG THE COLUMBIA RIVER LITTORAL CELL

Peter Ruggiero[1], Jessica Côté[2], George Kaminsky[1], and Guy Gelfenbaum[3]

Abstract: This paper presents initial results from a beach morphology monitoring program designed to document short- to medium-term coastal variability (event-seasonal-interannual scale) along the high-energy dissipative beaches of the Columbia River littoral cell. In just the first 1.5 years of the study, this highly dynamic coastal system experienced both the strongest El Niño of the century and the largest single wave event on record in the US Pacific Northwest. Morphologic response to this forcing has been complex, with the El Niño signal evident over scales of tens of kilometers and the single major storm event causing relatively minor beach change. The role that temporal and spatial variability of nearshore bathymetry has in determining the sub-aerial beach response to such forcing events is being investigated. As a result, nearshore bathymetric measurements are being combined with sub-aerial beach topography in generating three-dimensional surface maps of the nearshore active zone between the +5 m to the –12 m contour (MSL). Distinct differences in beach slope, sand bar size, and cross-shore location are evident among the sub-cells of the region. These differences indicate potential regional scale variability in morphologic response to similar environmental forcing.

INTRODUCTION

The dynamic interaction of environmental forcing and coastal morphology occurs over at least five orders of magnitude in time and space, with temporal responses ranging from multiple wave cycles (tens of seconds) to interannual climatic variations (El Niño) and spatial variability ranging from ripples to large-scale coastal behaviour. This wide range of scale presents a difficult sampling problem that must be overcome in order to aggregate to scales relevant to coastal management. The *Southwest*

[1] Washington Department of Ecology, Coastal Monitoring & Analysis Program, PO Box 47600, Olympia, WA, 98504-7600, USA, tel 360.407.6230, fax 360.407.6535
[2] US Geological Survey, 384 Woods Hole Road, Woods Hole, MA 02543
[3] US Geological Survey, 345 Middlefield Road, MS999, Menlo Park, CA 94025

Washington Coastal Erosion Study (SWCES), sponsored by the US Geological Survey and the Washington Department of Ecology, employs a hierarchical scale approach in order to understand the regional sedimentary system of the Columbia River littoral cell (CRLC) in the Pacific Northwest of the United States. The primary goal of this multidisciplinary effort is to predict morphologic behaviour along the 165 km long CRLC, extending from Tillamook Head, Oregon to Point Grenville, Washington, (Figure 2) at a management scale of decades and tens of kilometers.

From the end-user (*eg*. coastal manager or home-owner) perspective, the evolution of the sub-aerial beach is of principle interest due to its proximity to valuable coastal properties and infrastructure. The most common reference point for long-term change on the sub-aerial beach is the shoreline, typically defined in relation to horizontal reference features on aerial photographs or topographic maps such as the Average High Water Line (AHWL). A time series of AHWL are often used to generate predictions of future shoreline positions (Kaminsky *et al.*, in press). However, this main morphological area of interest (MAI, see Figure 1) is also one of the most variable within the active coastal zone. Tens of meters of shoreline recession in a single storm event are not uncommon. Therefore, predicted future shorelines are of limited value without detailed understanding of the short-term variability of sub-aerial beach morphology. Fortunately, this portion of the active coastal zone is readily available for measurement (via aerial photography and beach profiles) and, as a result, most beach monitoring programs focus on measuring the temporal and spatial variability of the sub-aerial beach.

The sub-aerial beach, however, comprises only a small percentage of the active coastal zone. In order to develop reliable predictive capabilities of shoreline change, an understanding of the sub-aqueous beach profile variability is also necessary. In contrast to the sub-aerial portion of the profile, the large-scale behaviour of sand bars and nearshore morphology is just beginning to be understood. The few quality data sets presently available, including the Jarkus data set on Dutch coast, the CRAB data set of the US Army Corps of Engineers at the Field Research Facility in Duck, North Carolina, and the Argus video data sets now available over a range of morphologic beach types (Holman *et al.*, 1993), reveal increasingly more complex behaviour than originally thought to exist. For example, analyses of nearshore bathymetry have demonstrated that interannual change contributes significantly to the overall nearshore bathymetric variability (Plant, 1998). Although bars have been shown to respond to individual storm events, long-term fluctuations of 4-15 years have been documented (Wijnberg, 1996). This interannual morphologic variability cannot be described by state of the art models, which assume that changing wave conditions force beach morphology changes.

Since bars dissipate wave energy and provide a buffering capacity to protect the sub-aerial beach, both the temporal and alongshore variability of nearshore morphology (*i.e*. position, height and length of sand bars) may create regions (in time or space) of vulnerability or resilience along the coast. A Duck, NC study of kilometer-scale shoreline response to storms found that erosion occurred at random locations or "hot spots" (List and Farris, 1998). Alongshore gradients in offshore bar position and geometry may be responsible for this storm response variability along the shoreline. However, measuring nearshore bathymetry is more difficult and expensive than sampling the sub-aerial beach profile and the present lack of data over large enough spatial scales limits the understanding of these erosion patterns. Although the exact time and space scales associated with how bar variability affects shoreline position is not precisely known, this morphological link is suspected to act over longer time scales than shoreline fluctuation itself. Therefore, nearshore bathymetry should be considered a longer-term area of interest (LTAI, Figure 1) for coastal management.

This paper presents a nested sampling scheme for the CRLC which aims to resolve spatial scales ranging from hundreds of meters to tens of kilometers and temporal scales ranging from storm events to years. A combination of GPS technologies and remote sensing techniques has been employed to acquire baseline data of the coastal zone from approximately +5 m to –12 m elevation (MSL) at selected sites along this highly dynamic coast. The magnitudes of morphologic change associated with a variety of time and space scales are presented with examples from the different components of a beach morphology monitoring program.

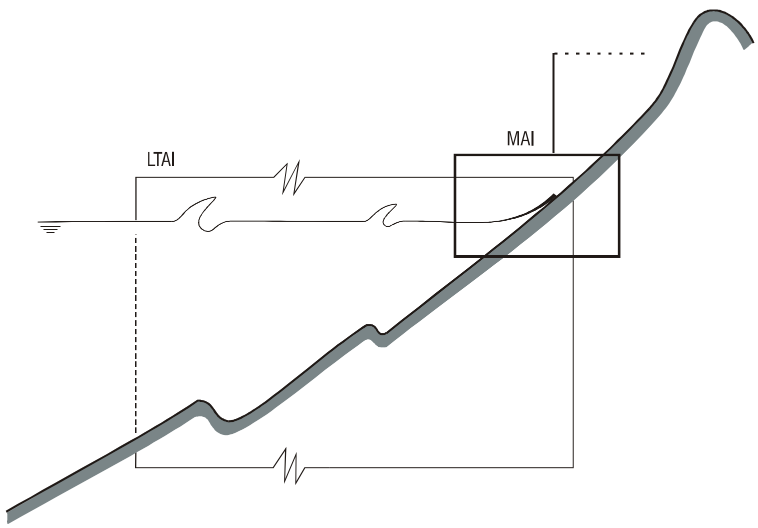

Figure 1. Beach profile schematic for the design of a nested scale beach morphology monitoring program (after J.A. Jiménez, personal communication). The shoreline is the main area of interest (MAI) from a coastal management perspective, however, nearshore bathymetry must also be considered. The open boxes, both in deep water and at sub-aerial elevations only rarely impacted by waves, suggest even long time scales of morphologic change.

BEACH MONITORING PROGRAM

A regional beach morphology monitoring program, designed to document short- to medium-term coastal variability (event - seasonal – annual scale), is being implemented along the high-energy dissipative beaches of CRLC (Ruggiero *et al.*, 1998). The CRLC contains three major estuaries, the Columbia River Estuary, Willapa Bay and Grays Harbor, sub-dividing the region into 4 distinct sub-cells (Figure 2). Following the installation of a dense geodetic control network, a nested sampling scheme of detailed three-dimensional surface mapping, cross-shore beach profiles (both sub-aerial and sub-aqueous) and shoreline change monitoring was initiated in the summer of 1997.

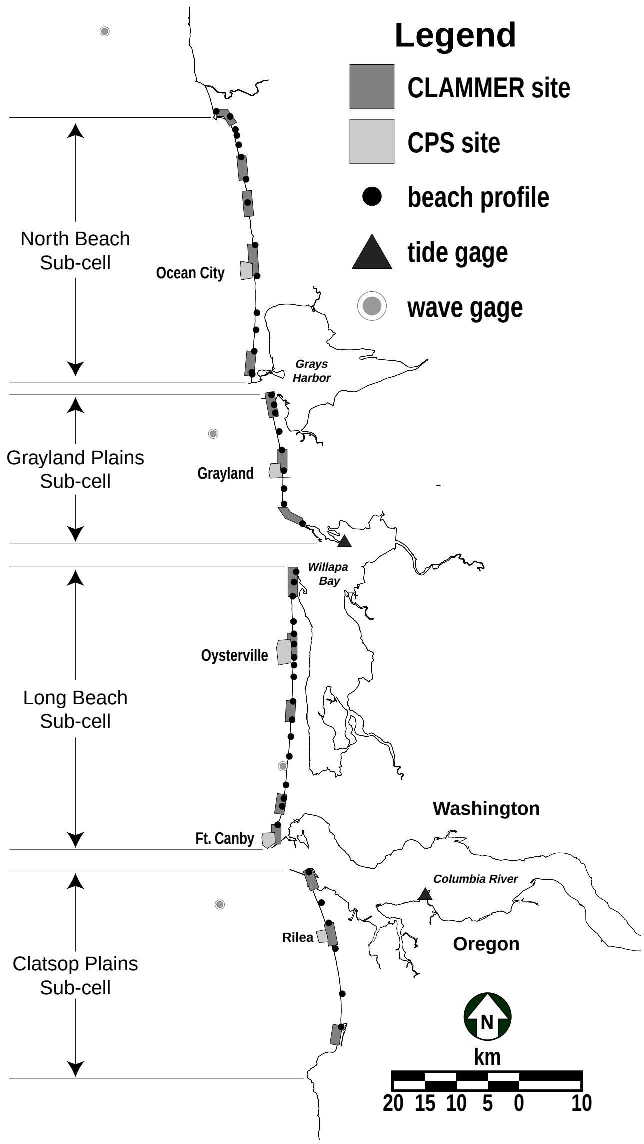

Figure 2. Nested beach morphology monitoring sampling scheme of the Columbia River littoral cell consisting of cross-shore beach profiles, 3-dimensional surface maps (CLAMMER) and nearshore bathymetry (CPS).

The beach morphology monitoring program employs RTK-DGPS surveying techniques. Topographic beach surfaces are generated biannually at 16 sites (Figure 2). Each surface map is nominally 4-km in length, and is obtained by collecting dense three-dimensional beach measurements with a DGPS antenna mounted to a six-wheel drive all-terrain vehicle called the CLAMMER (the CoastaL All-terrain Morphology Monitoring and Erosion Research vehicle). Cross-shore beach profiles are collected quarterly at 47 locations, spaced roughly 3-4 km along the coast, to examine two-dimensional beach change. Descriptions of these GPS surveying techniques are provided in Ruggiero *et al*. (1998). The Coastal Profiling System (CPS) developed by Beach *et al*. (1995) has been used to characterize nearshore bathymetry at selected sites beginning in 1998 (Figure 2). The system is comprised of a Yamaha Waverunner III equipped with RTK DGPS, an echo sounder to measure depth, and an onboard computer. In October 1997, extensive testing and ground-truthing of the system was performed at Duck, NC (Côté, 1999). Nearshore bathymetric surveys were measured simultaneously by the Coastal Research Amphibious Buggy (CRAB) and the CPS. Errors in the CPS data were found to be O(0.10 m) in the vertical. During July and August 1998, the system was evaluated as a tool for long-term morphology monitoring by the SWCES. Due to the energetic nearshore environment of the US Pacific Northwest, this effort represented the first attempt to collect nearshore bathymetry along the CRLC since surveys conducted by Willard Bascom and others during 1945-1947 (Kraus *et al*., 1996). Several remote sensing data sets have also been collected as part of the monitoring program and include airborne laser beach topographic mapping (Sallenger *et al*., in press), aerial video documentation of bar location (Worley *et al*., 1997), and Argus video techniques.

Figure 3 provides a regional inventory of two of the physical beach state parameters derived from the monitoring program. Both mean sediment diameter, sampled at MHW, and mean foreshore beach slope are presented for each of the 47 beach profile locations. A regional gradient in grain size exists along the CRLC with a fining of sediments with distance from the Columbia River. This trend is interrupted only near the mouth of Grays Harbor where a relic coarse sediment lag is evident. Mean foreshore beach slopes are obtained by averaging slopes from each of the three surveys, summer 1997, winter 1998 and summer 1998 between the 1.0 m and 3.0 m (NAVD 88) contours. Beach slopes are typically steeper near estuary entrances, lowering in slope with distance from the estuaries. The most dissipative beaches can be found in the North Beach sub-cell with slopes as mild as 1:100.

TIME SCALES OF MORPHOLOGIC CHANGE

In the following sections, examples from the variety of field techniques being applied in the beach morphology monitoring program illustrate the magnitude of morphologic change along the CRLC over a variety of time scales ranging from single storm events to net annual change computed between summer 1997 and summer 1998.

Event-Scale Change

The Pacific Northwest is well known for the severity of its wave climate (Tillotsen and Komar, 1997) with deep-water significant wave heights and periods averaging 3.0 m and 12 s respectively in the winter. Analyses of the region's extreme wave climate suggest that the 50 year wave height is O(10 m) (Ruggiero *et al*., 1997) and winter storm waves in excess of 6.0 m are not uncommon. For example, during the months of January and February 1998, data from the Grays Harbor wave buoy indicated 13 events with waves that reached or exceeded 6.0 m. Three of these events occurred between 21 January and 3 February 1998. Beach profile surveys were conducted at Ocean Shores, WA, the southern limit of the North Beach sub-cell, both before and after these events. These large wave heights were coupled with spring tide water levels

0.5 m above their predicted elevations associated with a major El Niño (Kaminsky *et al.*, 1998). During this period, the beach was locally lowered as much as 2.0 m while dune erosion of over 10 m was measured. Figure 4 shows beach profile change of approximately 110 m^3 m^{-1} at profile X-1 north (Figure 3). This dramatic morphologic change may be a result of a combination of the chronology of several successive large events coupled with the presence of a large rip-current embayment, centered on this profile during the storms.

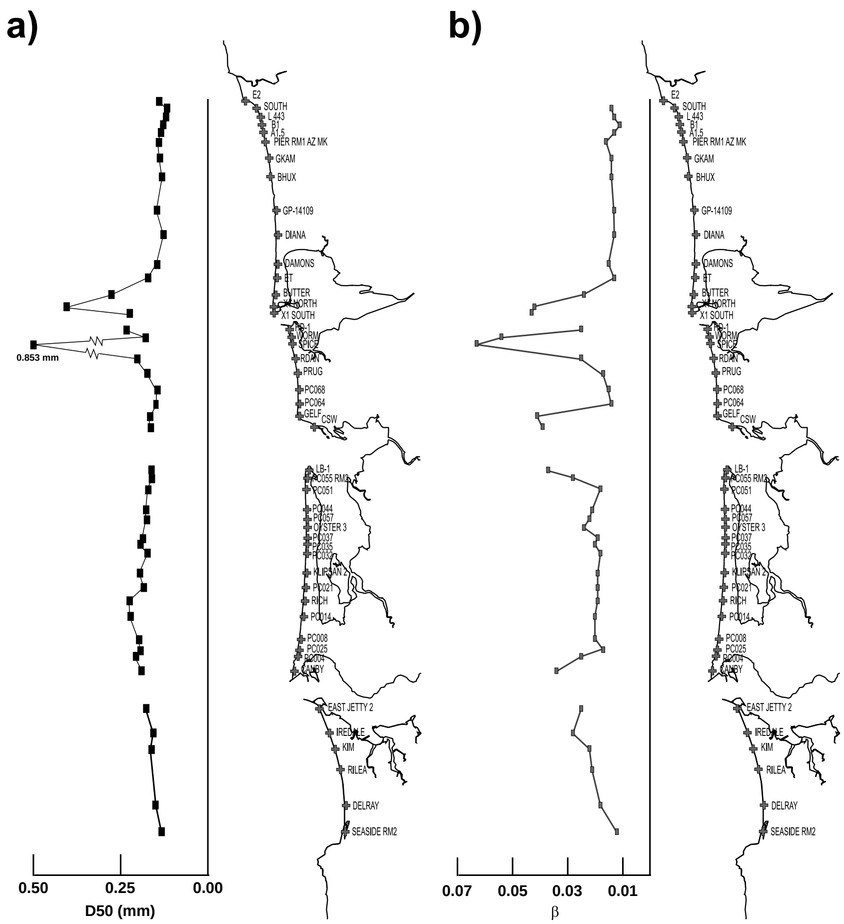

Figure 3. a) Median grain size, D_{50} (mm) and b) mean beach slopes, β (radians), at each of the 47 beach profile locations. Beach slopes are foreshore slopes, calculated between the 1.0 and 3.0 m contours (NAVD 88), and are averaged from 3 surveys, summer 1997, winter 1998 and summer 1998.

The largest storm recorded by the Grays Harbor buoy occurred on 3 March 1999. Deep-water wave heights exceeded 9.0 m for over 5 hours, peaking at 10.6 m and accompanied by a storm surge of 1.4 m forced by sustained 80 km/hr winds. Coastal flooding was widespread throughout the CRLC, particularly in Ocean Shores where several houses were damaged and a public rest room was destroyed. However, the sub-aerial beach at Ocean Shores responded only by flattening between the 1.0 and 4.0 m contours. Mean beach surface change measured by the CLAMMER between 1 March 1999 and 3 March 1999 was only 0.02 m over a 2 km alongshore distance. Dune recession of approximately 5 m did occur along a 200 m stretch of shoreline fronted by a small-scale rip current embayment, much smaller than the embayment present during the 1998 event. Unfortunately, no nearshore bathymetry is available for either event to test the hypothesis that alongshore variability in bar morphology may affect shoreline response during such a storm.

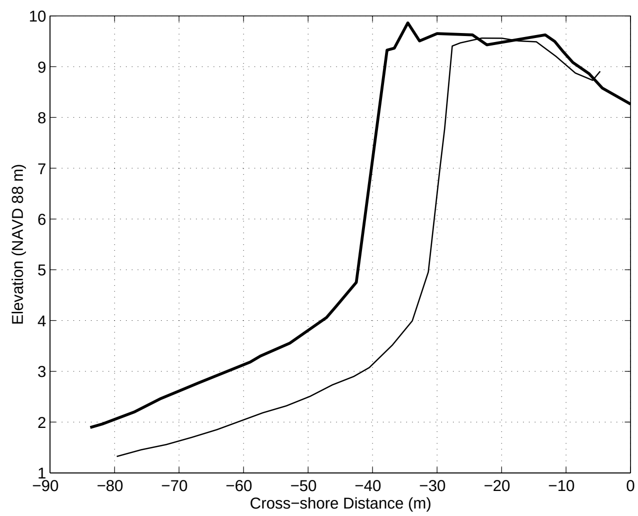

Figure 4. Beach profile change at Ocean Shores, WA between 21 January 1998 (thick line) and 3 February 1998 (thin line). Approximately 110 m^3 m^{-1} of beach erosion occurred during this period.

Seasonal Change

A three-dimensional sub-aerial beach surface map has been collected at Ocean Shores nominally on a montly basis since August 1997 in order to document the seasonal variability of the southern end of the North Beach sub-cell. This highly dynamic stretch of coast has historically accreted a few kilometers. Over the last decade, this accretion has slowed and eventually reversed towards a trend of erosion (Kaminsky *et al*., 1997).

Results from the 4 km-long surveys at Ocean Shores have been aggregated into bulk parameters and are presented in Figure 5. The top panel illustrates the mean beach surface elevation change over a 19 month period. Beach surface change is calculated from three-dimensional grids which have been generated from each of the data sets with the August 1997 survey serving as a baseline for subsequent comparison. A clear seasonal signal is evident in the data with up to 0.5 m of mean beach surface lowering during the winter of 1998. By October 1998 the beach had recovered slightly beyond its summer 1997 elevation and then began to lower again. This method of calculating beach surface elevation change, from subsequent surface grids, becomes problematic when surveys do not extend the same distance offshore, due to tide or wave conditions at the time of the survey, or when a coastline has a long term trend of either recession or progradation. Therefore, a more robust parameter used to quantify surface map change is contour line migration. Figure 5b also reveals the seasonal cycle at Ocean Shores through the patterns evident in the behaviour of the 1.0, 2.0 and 3.0 m contour lines (NAVD 88). The 2.0 m contour line is the approximate value of Mean High Water, although this tidal datum does vary spatially along the coast relative to the land-based

NAVD 88 datum, throughout the CRLC and serves as a reasonable proxy for shoreline change.

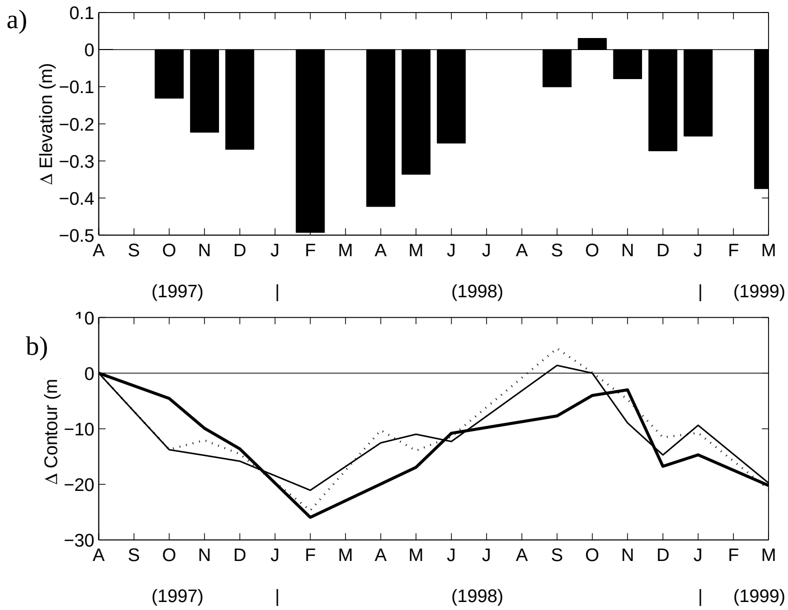

Figure 5. Monthly change at Ocean Shores, WA, represented as a) mean beach surface elevation change and b) mean change of the 1.0 m (thick line), 2.0 m (dashed line) and 3.0 m (thin line) contour lines (NAVD 88) from an August 1997 baseline. Values are averaged over a 4 km alongshore distance.

The three beach profiles shown in Figure 6, surveyed by the CPS and the CLAMMER at Ocean City, WA during April, July, and October 1998 also reveal seasonal morphologic variability. Poor resolution of the inner surf zone is due to high wave or wind conditions during the surveys. The well defined outer bar, O(2 m) in height, evident in the April survey lowered by July as the crest moved onshore with deposition in the trough. An inner bar in 3 m water depth is evident during the July survey. Even with the occurrence of a few minor storms in late September, the outer bar continued to decrease in amplitude with movement onshore between July and October and the trough became only weakly defined. No appreciable change in profiles is seen beyond the 6 m depth contour, however these surveys only span a short time period. Aerial video methods (Worley *et al.*, 1997) are also being employed to document seasonal sand bar migration patterns.

A third example of seasonal morphologic variability within the CRLC can be found in Figure 7b. The horizontal recession of the 2.0 m contour, averaged over each of the 4-km long surface map sites, is illustrated for the period between summer 1997 and winter 1998. This contour line averaged more than 30 m of recession over the 65 km of surface map data with a maximum recession of 132 m at North Cove and a minimum recession of only 0.6 m at Westport.

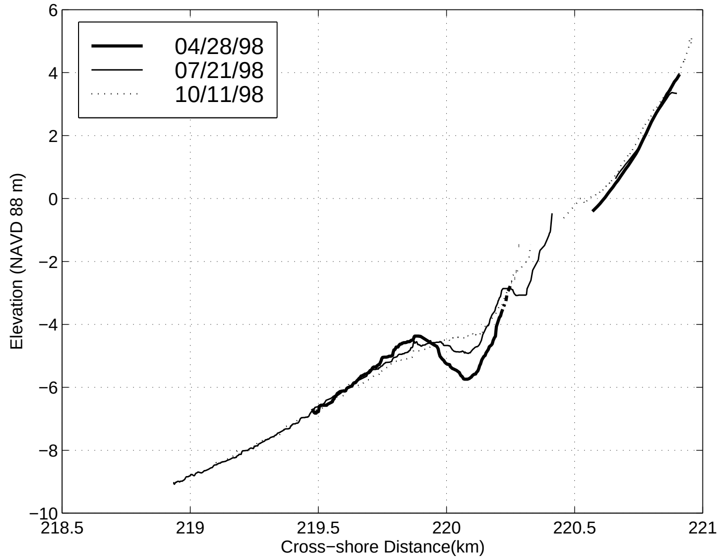

Figure 6. The seasonal comaprison of beach profiles surveyed at Ocean City, WA during April (dark line), July (light line), and October (dashed line) 1998 by the CPS and the CLAMMER. MLLW is approximately -0.5 m NAVD 88.

Annual Change

Annual morphologic change is considered for the sub-aerial beach profiles and surface map data. Between the summer 1997 and summer 1998 surveys, 25 of the beach profiles experienced a net loss of sediment while 22 profiles experienced a net gain (Figure 7a). For the year, 17 profiles featured less than 0.10 m of vertical change (averaged over the cross-shore distance between the location of the 1.0 m and 4.0 m contours during the summer 1997 surveys) and 9 profiles had less than 0.05 m of vertical change, the approximate limit of our ability to resolve beach change (Ruggiero *et al*., 1998). Therefore, 26 of the 47 beach profiles experienced only a minor net change for the year. However, many profiles exhibited larger trends with 7 profiles experiencing greater than 0.4 m of net elevation gain and 7 profiles experiencing greater than 0.4 m of net elevation loss.

Of the four sub-cells, only profiles along the Long Beach sub-cell experienced more net loss than net gain for the year, with 13 of the 17 profiles revealing net beach elevation lowering. Beach profile data for both this sub-cell and the northern portion of the North Beach sub-cell show evidence of re-alignment with the anomalous acute southerly wave angles that occurred during the 1997/1998 El Niño. Results from the surface mapping data illustrate this trend for each of the sub-cells. Figure 7b presents the net change of the 2.0 m contour line averaged over each 4-km long surface map. Each sub-cell shows maximum net erosion or minimum net accretion at the southern end of the sub-cell and maximum net accretion at the northern boundary of the cell. Kaminsky *et al.* (1998) discusses the processes and morphologic response to the 1997/1998 El Niño in more detail. The average net change, derived from the surface map data, was 3.9 m of recession, however much of this is associated with the North

Cove erosion "hot spot." Eliminating North Cove from the analysis reveals a mean net progradation of 3.5 m over 60 km of sampled beach surface.

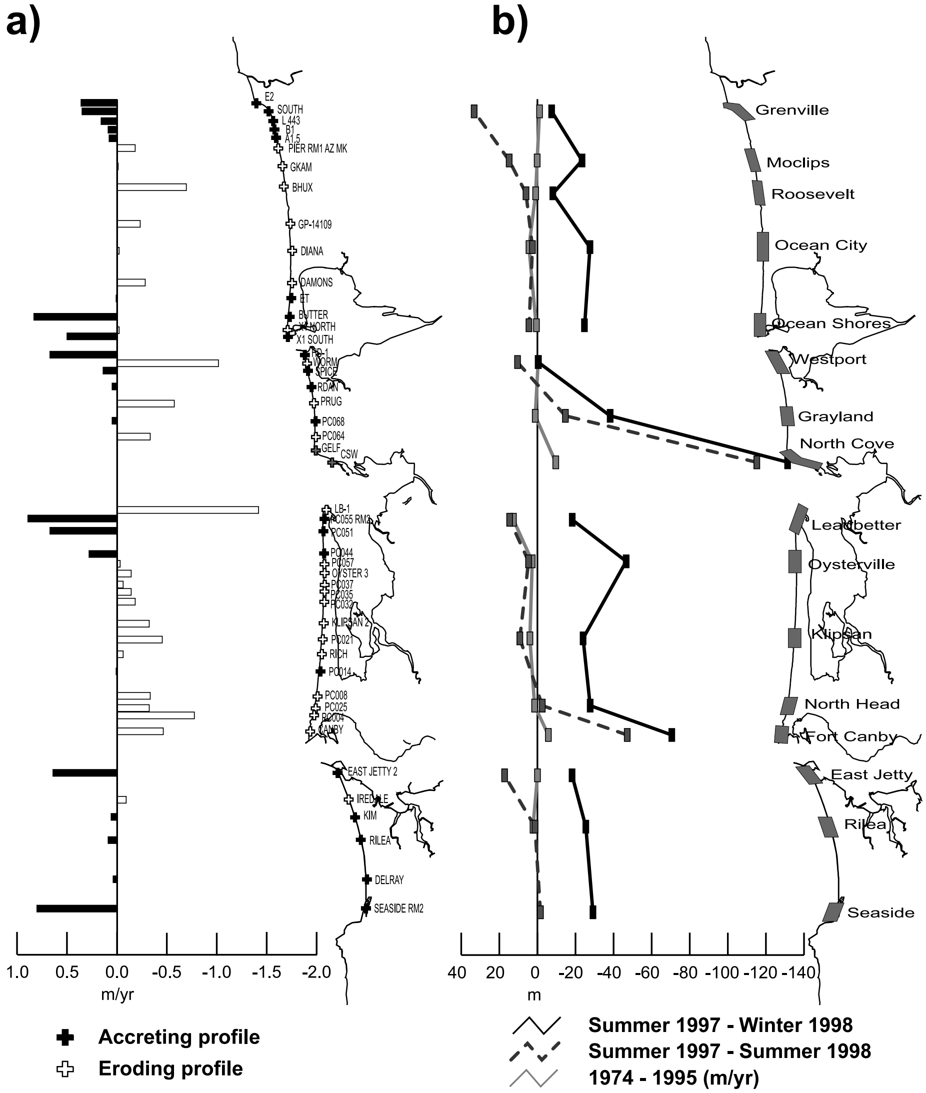

Figure 7. a) Mean beach profile lowering between the 1.0 m and 4.0 m contours at each of the 47 beach profiles from summer 1997 to summer 1998. b) Seasonal, summer 1997 to winter 1998, and annual, summer 1997 to summer 1998, variability of the 2.0 m contour as averaged over each of the 4.0 km long surface maps. Also shown is the alongshore averaged long-term shoreline change rates at each of the surface map locations as derived from 1974 and 1995 aerial photography.

SPATIAL VARIABILITY

The beach monitoring program was designed to quantify morphologic variability over a variety of spatial scales ranging from beach cusps and rip current embayments O(100 m) to sub-cell variability O(10 km). The monthly time series of three-dimensional surface maps at Ocean Shores, WA, reveals that the summer surface is characterized by multiple mega-cusps, typically associated with rip current embayments, with dominant alongshore length scales O(400 m). The winter beach mega-cusp field has dominant length scales of approximately 1000 m. The movement of this mega-cusp field was documented during the fall and winter of 1997 revealing that these features can maintain their form for several months while moving at rates of approximately 100-200 m/month (3 – 6 m/day).

Kilometer Scale Variability

In order to begin quantifying the kilometer scale variability of the complete active zone within the CRLC, nearshore bathymetric surveys were added to the monitoring program in 1998. Nearshore bathymetry is collected with the CPS at one representative site per sub-cell and Fort Canby (Figure 2). A 2 – 3 km region was surveyed at each site with cross-shore transects spaced at approximately 150 m intervals. To quantify gradients in alongshore morphology, the CLAMMER and the CPS data have been merged, resulting in three-dimensional surface maps of the nearshore zone from approximately the + 5 m contour to the – 12 m contour (NAVD 88).

Figure 8 illustrates the nearshore planform of the Oysterville site, located on the Long Beach Peninsula, as measured in August 1998. The data spans 2.5 km in the cross-shore and almost 4 km in the longshore (Figure 8a). Figure 8b reveals a distinctly linear outer bar in approximately 6.0 m water depth and a crescentic inner bar in 4.0 m of water with an alongshore wavelength O(1500 m). In shallower water, the alongshore wave length of swash bars decreases and morphologic complexity increases. Above the 1.0 m contour the morphology again resumes patterned behaviour with large-scale rhythmic mega-cusps.

Figure 9a features the merged topographic and nearshore bathymetric data collected at Fort Canby, a site bounded by the Columbia River North Jetty to the south and North Head to the north. After accreting over 1 km in the first half of this century, Fort Canby is currently experiencing rapid shoreline recession (Kaminsky *et al*., in press). This site has a steep foreshore slope O(1:50), but quickly flattens to 1:100. The North Jetty of the Columbia River lies approximately 250 m south of the southern end of the survey and the onshore limits of the ebb-tidal extend to the offshore limits of the survey data. The beach profile close to the jetty exhibits a concave shape, absent of bars or troughs. To the north, a longshore bar develops with its amplitude increasing with distance from the jetty. This bar eventually becomes similar in magnitude and length than the Oysterville site approximately 30 km to the north, but is located in shallower water. This kilometer scale gradient in bar morphology is almost certainly related to the proximity of the jetty, the ebb-tidal delta and the nearshore circulation associated with these boundary conditions. Shorelines derived from GPS measurements during the winters of 1998 and 1999 indicate that this site also experienced strong alongshore gradients in shoreline change rates during the past year (Figure 9b). The large gradients in sand bar position and height are thought to be of first order importance in driving these gradients in shoreline erosion.

Sub-cell Variability

In Figure 10, an alongshore-averaged beach profile from each of the survey sites illustrates the variability of bar size, bar position, and beach slope among sub-cells (Côté, 1999). The CPS nearshore profiles are merged with sub-aerial profiles and the origin of the coordinate system is horizontally adjusted to begin at the 1.0 m contour (NAVD 88), an elevation approximately equal to MSL. The resulting beach profiles were then averaged across a 1 km alongshore distance to produce a spatial mean profile at each of the five survey sites. The beach profiles are presented with extreme vertical exaggeration (1V:125H) to emphasize subtle variations in shoreface morphology. All sites are characterized by a multiple barred profile, however, poor resolution of the swash zone (+1 m to -1 m) as a result of high wave and/or wind conditions occasionally hindered the connection of nearshore profiles to sub-aerial beach profiles.

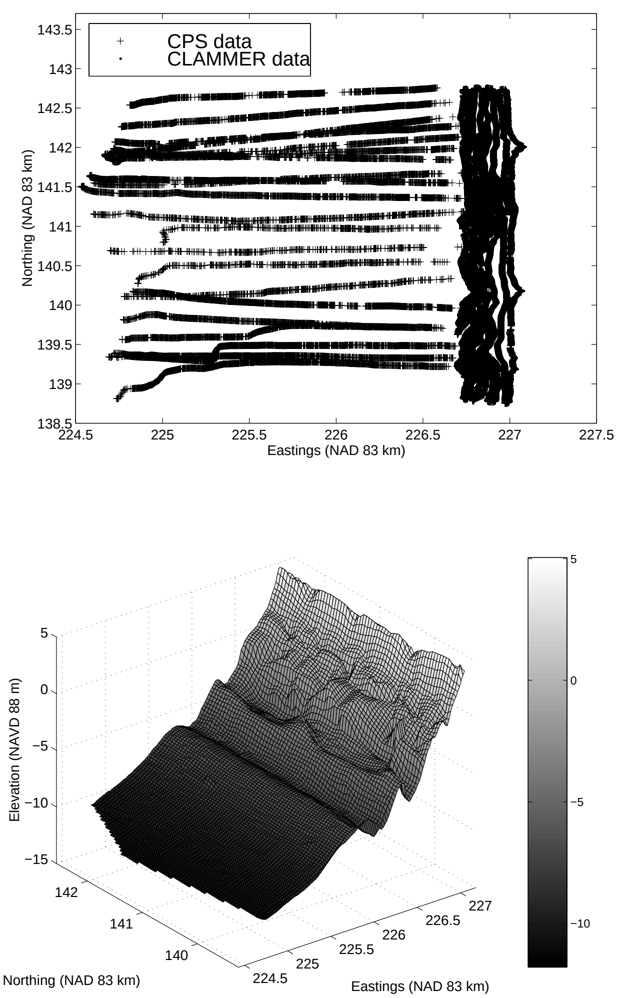

Figure 8. (a) A plan view of topographic, alongshore transects collected by the CLAMMER, and nearshore bathymetric data, cross-shore transects collected with the CPS, surveyed to produce the b) 3-dimensional surface map of the Oysterville, WA nearshore planform during August 1998 (Côté, 1999).

To represent the basic shape of the profile, the alongshore-averaged data were fit to an equilibrium profile. The shape factor, A, and the exponent, m, of the equilibrium profile were calculated through a least squares fit by the Gauss-Newton method and are given in Table 1. A beach slope, β (1.5 km), spanning from 0 m to -1500 m in the cross-shore has been calculated from the equilibrium mean profile. The Ocean City profile has the shallowest slope (0.0059) and Rilea the steepest (0.077). A foreshore slope, β (fs), calculated from the alongshore averaged profile, reveals Ocean City has the mildest sloping beach (0.013) but Fort Canby has the steepest foreshore slope (0.034).

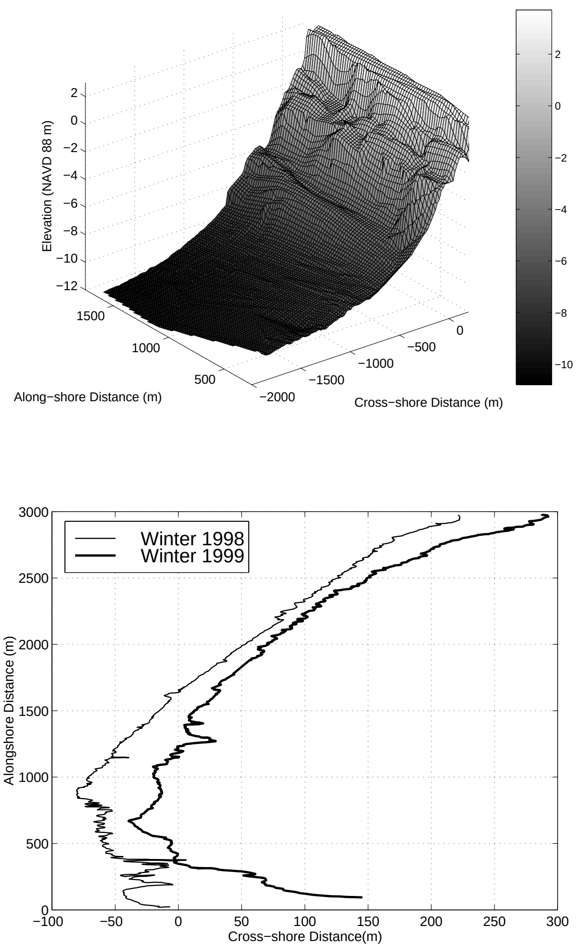

Figure 9. a) Merged topographic and nearshore bathymetric data at Fort Canby, WA and b) GPS derived shorelines at Fort Canby, Washington during the winter of 1998 and the winter of 1999.

Sand bars are identified based on deviations from the least squares fit equilibrium profile (Plant, 1998). The presence of a sand bar is indicated by a zero-down-crossing in the deviation profile, marking the change from a positive to negative anomaly, *ie.* the seaward flank of the bar. The position of the bar on the profile is identified as a local profile maximum, h_{bc} at the bar crest and measured relative to 0.0 m at the cross-shore position x_{bc}. Likewise, the trough occurs as a local minimum, h_{bt}, also determined from the local profile slope. With these parameters the height of the sand bar, H_b, and the length of the bar, L_b, are derived from the deviation profile. The volume of sediment contained in a bar, *V*, from the landward trough to the seaward trough is also calculated from the deviation profile.

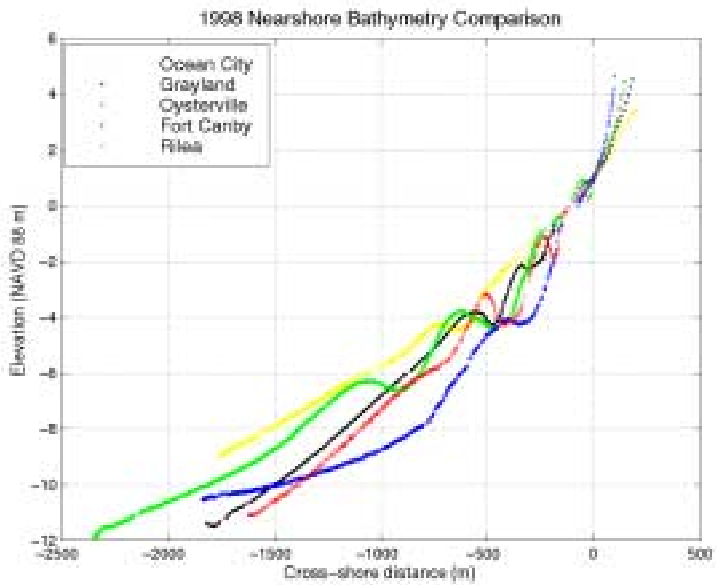

Figure 10. The five survey regions are represented by a 1 km alongshore-averaged profile. The coordinate system origin has been set to the 1.0 m contour NAVD 88. Differences in morphology and slope demonstrate the variability within the CRLC (Côté, 1999).

A minimum of two well-defined sand bars were present at all five survey sites. With the exception of Ocean City, there is a swash bar located between +0.76 and -0.74 m at 50 to 175 m from the origin. Four of the five survey sites exhibit both inner and outer bars. Fort Canby is anomalous with only two bars, a swash bar and an inner bar. At three of the five locations the outer bar is in approximately 6.5 m water depth. The sand bars range in height from 0.2 to almost 2 m, in length from 164 to 949 m and in volume from 48 to 535 m^3/m.

DISCUSSION AND CONCLUSIONS

The beach morphology monitoring program is revealing that the Columbia River littoral cell is a dynamic coastal system with interesting morphologic behaviour evident at a variety of time and space scales. For example, morphologic change due to single storm events has been shown to not linearly depend only on wave conditions, but rather on a combination of forcing and antecedent morphologic conditions. On the other hand, the 1997/1998 El Niño event, which by some measures was the largest of the last century, forced morphologic change over scales of tens of kilometers. The nested sampling scheme employed by this study appears to have resolved the realignment of each of the sub-cells with the acute southerly wave directions associated with the El Niño (Kaminsky *et al*., 1998).

Although over 30 m of contour line recession took place during the winter of 1997/1998, the 2.0 m contour experienced a net progradation of 3.5 m for the year over 60 km of sampled beach surface. Ironically, at a time when many CRLC beaches are experiencing unprecedented erosion, this mean progradation rate is twice that of the mean shoreline change rate between 1974 and 1995 (Kaminsky *et al*., this proceedings) averaged over the same spatial area as the surface map data from which contour change was derived. Comparing decadal scale shoreline change rates with one year of monitoring data is imprudent due to the marked difference in time scales as well as the fact that the 2.0 m contour has not yet been reliably shown to be comparable to a shoreline derived from aerial photography. However, in Figure 7b the decadal scale shoreline change rates for the entire littoral cell have been plotted. Remarkably, the majority of the 16 surface map sites show similar magnitudes and trends during 1997 – 1998 as during the 21-year period. The largest difference between rates occurs at North Cove and Fort Canby (erosion hot spots) and at the northern ends of the Clatsop Plains, Grayland Plains and North Beach sub-cells. These three sites show higher rates for the single year, probably due to the 1997/1998 El Niño. The effects of the several El Niños occurring between 1974 and 1995 would be filtered out over the longer shoreline change time period.

Table 1. Results of equilibrium profile fit and sand bar identification methods to quantify the variability between sub-cells (Côté, 1999).

Site	**Equilibrium profile**				**Sand bar statistics**					
	A	m	β(fs)	β(1.5km)	bar #	x_{bc}	h_{bc}	H_b	L_b	V_i
Ocean City	0.031	0.699	0.013	0.0059	1	-326	-1.36	0.731	596.7	423.4
					2	-750	-4.30	0.845	352.7	99.1
					3	-1215	-6.60	0.203	553.9	48.0
Grayland	0.027	0.789	0.015	0.0073	1	-50	0.76	0.566	232.7	130.0
					2	-342	-2.14	0.666	225.8	105.2
					3	-567	-3.81	1.145	949.1	534.9
Oysterville	0.037	0.660	0.024	0.0064	1	-175	-0.45	1.076	429.5	429.5
					2	-613	-3.79	1.602	359.0	359.0
					3	-1088	-6.32	1.249	409.0	409.0
Fort Canby	0.039	0.562	0.034	0.0075	1	-157	-0.74	1.417	217.3	217.3
					2	-426	-4.11	0.962	322.2	322.2
Rilea	0.030	0.780	0.021	0.077	1	-90	0.38	0.797	164.2	193.6
					2	-244	-1.12	1.132	184.2	126.4
					3	-516	-3.17	1.913	317.1	208.8
					4	-887	-6.46	0.412	647.4	141.1

The one remaining anomaly in this comparison of change rates occurs at the center of the Grayland Plains sub-cell. The long-term trend at this site is approximately 1.0 m yr $^{-1}$ of accretion while the net change for 1997/1998 was 14 m of erosion. A possible explanation for this dramatic change in shoreline change rates can be found in Figure 10 and Table 1. Grayland is the only CPS site, of the four representative sites from each sub-cell, that does not have an outer bar in approximately 6.5 m during the summer 1998 surveys. The lack of a buffering outer bar may be responsible for this anomalous shoreline change. The nearshore bathymetry surveys during the summer months of July and August of 1998 will serve as the baseline for future comparisons that will seek to answer such questions. Future work will attempt to determine relationships between the temporal and spatial variability of nearshore morphology and shoreline position at scales relevant to coastal management.

ACKNOWLEDGEMENTS

The Southwest Washington Coastal Erosion Study is jointly funded by the US Geological Survey and the Washington Department of Ecology. The authors would like to thank Brian Voigt for his help in figure preparation and the superb team of field scientists who collected the data presented in this paper under a variety of, well, interesting conditions.

REFERENCES

Beach, R.A., Holman, R.A. and Stanley, J., 1996. Measuring Nearshore bathymetry on high energy beaches., American Geophysical Union Fall Meeting, San Francisco, pp. F286.

Cote, J.M, 1999, The Measurement of Nearshore Bathymetry on Intermediate and Dissipative Beaches, Masters Thesis, Oregon State University, Corvallis, Oregon, 106 pp.

Holman, R., A. Sallenger, T. Lippmann, and J. Haines, The application of video image processing to the study of nearshore processes, Oceanography, 6, 78-85, 1993.

Kaminksy, G.**,** G. Gelfenbaum, M. Buijsman, P. Ruggiero, C.D. Peterson, H.M. Jol and A. Gibbs, these proceedings**,** Synthesizing geological observations and processes-response data for modeling coastal change at management scale, Coastal Sediments 99, *ASCE*, Long Island, NY.

Kaminsky, G., P. Ruggiero and G. Gelfenbaum, 1998, Monitoring coastal change in Southwest Washington and Northwest Oregon during the 1997/98 El Niño, Shore and Beach, 66 (3), pp. 42-51.

Kaminsky, G., Daniels, R., Huxford, B., McCandless, D. and Ruggiero, P., in press, Mapping erosion hazard areas in Pacific County, Washington, Journal of Coastal Research, 37 pp.

Kaminsky, G.M., P. Ruggiero, G. Gelfenbaum, and C. Peterson, 1997, Long Term Coastal Evolution and Regional Dynamics of a US Pacific Northwest Littoral Cell, Coastal Dynamics ‘97, pp. 614-623.

Kraus, Nicholas C., R.L. Weigel, and W.N. Bascom, 1996, Beach profile surveys along the U.S. Pacific Coast 1945-1947, Proceedings of the 25th ICCE, *ASCE*, pp. 3020-3033.

List, J.H. and Ferris, A.S., 1998. Regional-scale Shoreline response to Storms, American Geophysical Union Fall Meeting. Supplement to EOS Transactions, San Francisco, pp. F445.

Plant, N.G., 1998. The role of morphologic feedback in surf zone sand bar response. PhD Thesis, Oregon State University, Corvallis, Oregon, 167 pp.

Ruggiero, P., Kaminsky, G. and Plant, N.G., 1998, Coastal Morphologic Variability of High Energy Dissipative Beaches, 26^{th} International Conference on Coastal Engineering, Copenhagen, DK, 14 pp.

Ruggiero, P., G.M. Kaminsky, P.D. Komar, and W.G. McDougal, 1997, Extreme waves and coastal erosion in the Pacific Northwest, Ocean Wave Measurement and Analysis, Proceedings of the 3^{rd} International Symposium, Waves ’97, pp. 947-961.

Sallenger, A.H., Krabil, W., Brock, J., Swift, R., Jansen, M., Manizade, S., Richmond, B., Hampton, M. and Eslinger, D., (in press), EOS, American Geophysical Union.

Tillotsen, K.J. and P.D. Komar, 1997, The wave climate of the Pacific Northwest (Oregon and Washington): A comparison of data sources, Journal of Coastal Research, 13, pp. 440-452.

Wijnberg, K.M., 1995. Morphologic Behavior of a Barred Coast over a period of Decades. Doctoral Thesis, University of Utrecht, Netherlands, 245 pp.

Worley, C.R., Lippman, T.C., Haines, J.W. and Sallenger, A.H., 1997. An aerial video system for rapidly measuring sand bar morphology. In: E.B. Thorton (Editor), Coastal Dynamics '97. ASCE, Plymouth, U.K., pp. 346-354.