Coastal Morphologic Variability of High Energy Dissipative Beaches

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Abstract

A beach morphology monitoring program was initiated in the Columbia River littoral cell along the coasts of Oregon and Washington, USA, during the summer of 1997. The field program is designed to document short- to medium-term morphologic variability of the high-energy dissipative beaches within the littoral cell over a variety of spatial scales. Following the installation of a dense network of geodetic control monuments, a nested sampling scheme of cross-shore beach profiling, 3-dimensional beach surface mapping and shoreline reference feature surveying was devised. Monitoring is being conducted using RTK DGPS survey methods that combine both high accuracy and speed of measurement. Sampling methods resolve alongshore length scales of O(100 m) to O(100 km) and cross-shore length scales of O(1 m) to O(1 km). Long-term beach profile evolution, estimated via a comparison with surveys collected in the 1940s, feature regional variability. Some beach profiles revealed remarkably little change over the last 50 years. Although this study is in its infancy, large signals in both forcing and response have yielded exciting results. During the 1997/1998 winter, the littoral cell was influenced by one of the most significant El Niño events on record. Steeper than typical southerly wave angles forced alongshore sediment transport gradients that were evident in seasonal morphology on a regional scale. The morphologic data from the monitoring program are being integrated with other geophysical data sets to develop a conceptual model of the region and to begin shoreline change modeling to predict coastal evolution at a management scale (*ie.*, decades and tens of kilometers). The magnitudes of both the environmental forcing and morphologic variability of the beaches along the Columbia River littoral cell are greater than the better understood, lower energy and more reflective beaches of, for example, Duck, North Carolina and the central Dutch coast (Holland). These differences in scale raise questions regarding the validity of directly applying morphologic change models developed from these coasts to the Columbia River littoral cell.

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Introduction

A regional study of long-term coastal evolution and shoreline response has been initiated for a 160 km long littoral cell in the Pacific Northwest of the United States extending from Tillamook Head, Oregon to Point Grenville, Washington (Kaminsky *et al.*, 1997). The Columbia River littoral cell (CRLC) is characterized by wide dissipative beaches of fine sand, ranging between 0.13 and 0.23 mm in mean diameter, typically backed by broad dune fields or sea cliffs. Beaches in the region have 3-dimensional multiple bar systems with infragravity energy dominating the inner surf zone. Four sub-cells exist within the region separated by three large estuaries, the Columbia River, Willapa Bay and Grays Harbor. Although this region is well known for the severity of its wave climate, most of the littoral cell has historically been accretionary. Recently, however, episodes of severe erosion throughout the cell (Figure 1) have resulted in lost or damaged infrastructure, threatening local economies. To date, millions of Federal and State dollars have been spent on erosion mitigation efforts. In many areas the long-term accretion appears to have slowed or even reversed, indicating a regional trend of erosion. Both anthropogenic influence and variability in large-scale environmental forcing may be causing these changes in morphologic behaviour.

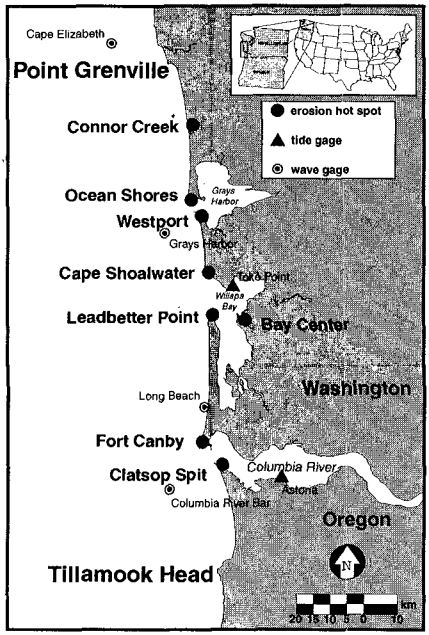

Figure 1. The Columbia River littoral cell with erosion hot spots and the locations of long-term wave and tide measurements.

This paper discusses the variety of survey techniques being applied to and the initial results from a regional beach morphology monitoring program designed to quantify morphologic variability within the CRLC at a variety of spatial and temporal scales. The objectives of the monitoring program include: the quantification of short- to medium-term (event-seasonal-interannual) morphologic variability; development of data sets for beach profile modeling; shoreline change and coastal flooding predictions; and the comparison of variability scales with other coastlines. These objectives are aligned with a primary goal of the Southwest Washington Coastal Erosion Study, predicting coastal behaviour of the CRLC at a management scale. Several existing long-term monitoring programs, specifically the beach profiling done at the US Army Corps of Engineers Field Research Facility (FRF) in Duck, North Carolina and the Jarkus data base of the Dutch Department of Public Works (Rijkswaterstaat), provide guidance for designing sampling schemes. Since 1981, bi-monthly beach surveys have been collected at the FRF over a 1 km alongshore reach with the Coastal Research Amphibious Buggy (CRAB). Utilizing this dense data set, many researchers have examined long-term beach profile evolution and sand bar migration patterns to develop valuable engineering models of coastal morphology (*eg.*, Larson and Kraus, 1994 and Plant, 1998). The Jarkus data set, which consists of 30 years of annual profiles spaced every 250 meters along the Dutch coast, has also led to advances in understanding temporal profile evolution and the spatial variability in morphologic behaviour. Components of these programs, particularly observations of meso- to large-scale fluctuations and alongshore inhomegenity, were considered in the design of the CRLC beach morphology monitoring program. The program has been established to acquire regional coverage of the littoral cell that is dense enough to resolve short-term change of kilometer scale evolution of the coastal planform. Results from this study are being used to develop a conceptual model of coastal morphologic variability on high-energy dissipative beaches.

Monitoring Program Components

Beach morphology monitoring is being conducted using Real Time Kinematic Differential Global Positioning System (RTK DGPS) surveying techniques, widely accepted as an accurate and efficient means to collect coastal morphology data (Morton *et al.*, 1993). The following sections describe the techniques associated with each component of the monitoring program.

Geodetic Control

In order to reference all monitoring program data to consistent horizontal and vertical datums, a dense network of 77 geodetic control monuments was established during the summer of 1997 (Figure 2a). After an inventory of existing monuments within the littoral cell, 13 additional monuments were installed to ensure consistent spacing of 3 to 4 km along the coast. A two-week field campaign was then conducted using 8 dual-frequency full-wavelength GPS receivers to establish a 2 cm-level vertical control network in accordance with the most recent guidelines provided by the National Geodetic Survey. The network has been referenced to the Washington State Plane (South) North American Datum of 1983 (NAD 83) and the land-based North American Vertical Datum of 1988 (NAVD 88).

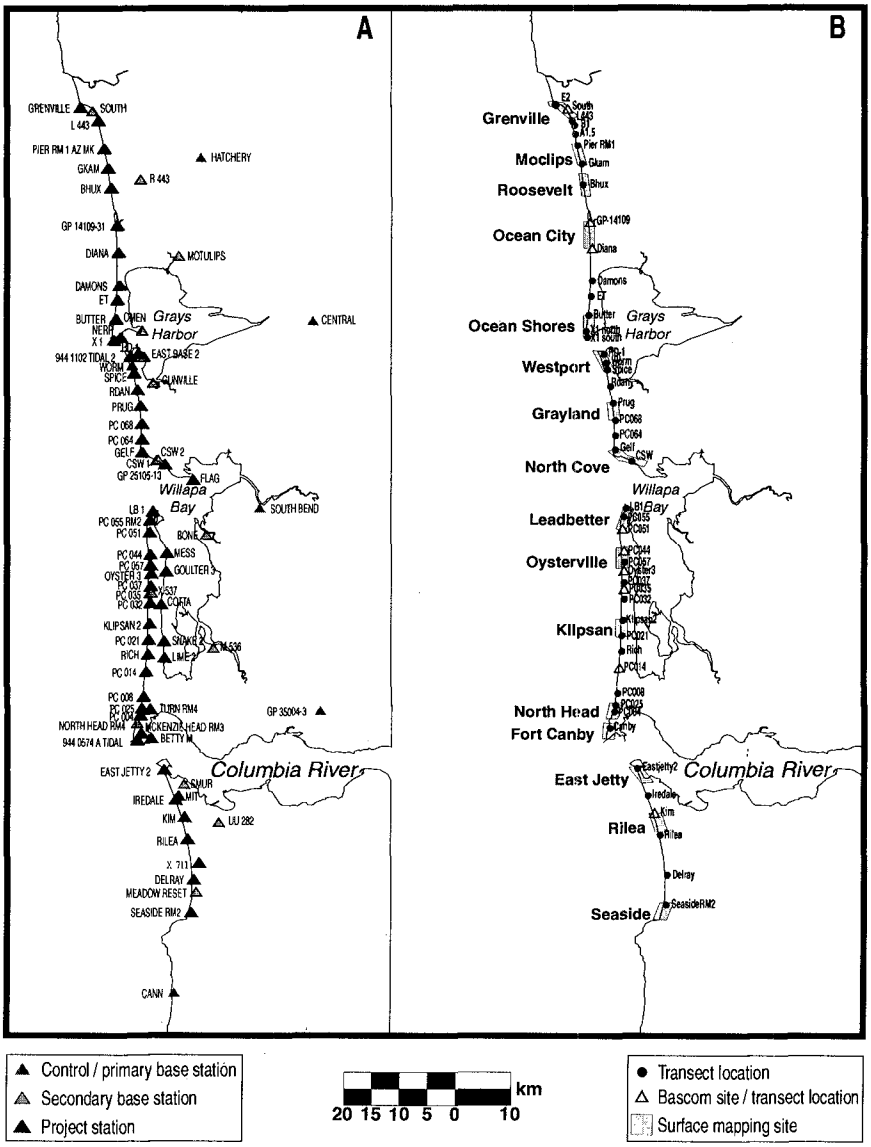

Figure 2. a) Locations of geodetic control monuments and b) locations of beach profiles and 3 dimensional surface maps.

Cross-shore beach profiles

The high-energy dissipative beaches of the Pacific Northwest have been studied less intensely than the lower energy, more reflective beaches typical of the US East Coast. Initial attempts at creating a regional database (Peterson *et al.*, 1994) and scattered work by resource management agencies, comprised the only beach morphology data for the Columbia River littoral cell before the onset of the Southwest Washington Coastal Erosion Study (Kaminsky *et al.*, 1997). The first comprehensive regional morphology monitoring program began in the summer of 1997. In an effort to quantify seasonal morphologic change, cross-shore beach profiles are being collected bi-annually at 47 locations, spaced approximately 3-4 km throughout the littoral cell (Figure 2b). Profile locations are typically coincident with the locations of control network survey monuments. The beach profiles are obtained by walking from the landward edge of the primary dune to wading depth at spring low tides with a GPS receiver and antenna mounted to a backpack. Although the manufacturer's reported 3-dimensional error of the RTK GPS receiver is less than 2 cm, the vertical RMS error of this technique compared to surveying with a leveled pole and bipod is typically 4 cm. While not as accurate as standard terrestrial surveying, this technique is justified by both the reduction in survey time and the large morphologic change signals observed on these beaches. A field experiment scheduled to begin in spring 1999 will begin to examine beach profile evolution on even shorter (processes) time scales via bi-weekly surveys at a number of locations.

Due to the difficulty of surveying in the Pacific Northwest's dissipative, yet energetic nearshore environment (mean annual significant wave height is 2.0 m), most beach profiles do not extend beyond the inner surf zone. Willard Bascom and associates, in conjunction with the Wave Project of the University of California at Berkeley, collected the only set of nearshore bathymetric surveys in the region prior to the onset of this study (Komar, 1978 and Kraus *et al*, 1996). In an attempt to document long-term morphologic change, these profiles are now being re-occupied utilizing a new technique, the Coastal Profiling System (CPS), developed at Oregon State University (Beach *et al.*, 1996, Cote *et al.*, in press). The system consists of a Yamaha Waverunner III equipped with an RTK GPS receiver, an echo sounder and onboard data storage capabilities. The system was extensively tested during the SandyDuck field experiment at the FRF in the fall of 1997 with results indicating an RMS error ranging from 10 to 20 cm. A reconnaissance level, nearshore bathymetric survey campaign was initiated in the CRLC in April 1998. Beach profiles, spaced at 150 m over 2-3 km long sections, from the beach to the 12 m depth contour, have been collected in the approximate center of each of the four sub-cells. These study sites were chosen to overlap with beach surface mapping sites (described in the next section) and include Ocean City, Grayland, Oysterville, Rilea, and Fort Canby (Figure 2b). A series of seasonal surveys in April, July, and October 1998 is underway at the northern most site, Ocean City, WA, in an attempt to document seasonal bar migration patterns.

Beach Surface Maps

Although analysis of beach profiles can reveal both cross-shore variability in beach elevation and volumetric change over an individual profile, little information about the

longshore component of morphologic change can be obtained. In lieu of multiple closely-spaced cross-shore transects, three-dimensional surface maps are being generated by mapping the beach surface with a GPS antenna mounted to a six-wheel drive amphibious all-terrain vehicle called the CLAMMER (CoastaL All-terrain Morphology Monitoring and Erosion Research vehicle). Alongshore reaches, approximately 4 km in length, are being mapped between the toe of the primary dune and the swash zone (typically 100's of meters in the cross-shore direction due to mild sloping beaches). To determine both the alongshore and cross-shore morphologic variability at a variety of spatial scales, 16 sites (Figure 2b), totaling more than 60 km of alongshore distance, are being surveyed bi-annually.

Individual measurements are densely spaced in the alongshore direction, O(5-10 m), to resolve relatively small-scale features such as beach cusps, and are over long enough distances to resolve larger scale, potentially migrating features such as mega-cusps, rip-current embayments, sand waves and regional gradients. The cross-shore distance between alongshore transects is typically 20 - 30 m but is determined in the field based on cross-shore breaks in beach slope such as at swash bar crests and troughs. The non-uniformly spaced raw data (typically 5,000 to 10,000 points) is mapped onto a surface via triangle-based, weighted linear interpolation. The model surface is then interpolated on a uniform 2-dimensional grid for comparing subsequent data sets. Although individual model elevations feature sub-decimeter accuracy, the RMS error of the interpolated surface compared to detailed surveying using a leveled pole is typically 5 cm. Surface maps are collected bi-annually at all 16 sites to determine seasonal fluctuations, however, in areas that are eroding rapidly, survey frequency has been increased in an attempt to determine shorter scale temporal changes, *eg.* mega-cusp migration.

Other Monitoring Components

Four surface sediment samples are collected at each beach profile location, within the dune, at the dune toe, at mid-beach and within the swash zone at low tide. Sand grain size distributions are being determined by using ASTM approved dry sieves at quarter phi intervals following current EPA protocols for sediment analysis in the state of Washington. Modern shorelines are being mapped on rapidly eroding beaches by walking erosion reference features, such as scarps or driftlines, with a GPS backpack. This shoreline position data is being used to complement the historical shoreline change analyses being conducted by digitizing historical NOS topographic sheets and aerial photography (Kaminsky *et al.*, in press, a). Shoreline change reference features also serve to expand the regional coverage between cross-shore profiles and provide a definite shoreline boundary to the beach surface maps. Several remote sensing techniques have also been applied within the CRLC as part of the Southwest Washington Coastal Erosion Study including airborne laser mapping and remote video technology. Lidar coverage, as part of a NASA/NOAA/USGS cooperative, will be used to create a high resolution Digital Elevation Model of the littoral cell. A video station (Argus camera) has been installed at Cape Shoalwater and a second station is scheduled for deployment at Ocean Shores in October 1998 for processes scale (*e.g.*, mega-cusp migration) studies.

Waves and Water Levels

Coupled with the beach monitoring program is the long-term analysis of environmental data, *eg.*, waves and water levels. The locations of long-term wave (both NOAA and CDIP gages) and tide measurements are shown in Figure 1. Mean annual significant wave height along the CRLC is approximately 2.0 m with a peak period of 10 s with winter storms generating waves greater than 8.0 m with 20 s periods (Ruggiero *et al.*, 1997). There is a distinct seasonality in wave height, period and direction with increased wave heights and periods propagating from the south in the winter and lower waves and periods arriving from the north in the summer. The littoral cell is meso-tidal with a 2.0 to 4.0 m range and winter water levels as much as 0.3 m higher than the summer water levels. Figure 3 illustrates the seasonality of both the water levels measured at Toke Point, WA, and the wave parameters taken from the Grays Harbor directional waverider buoy.

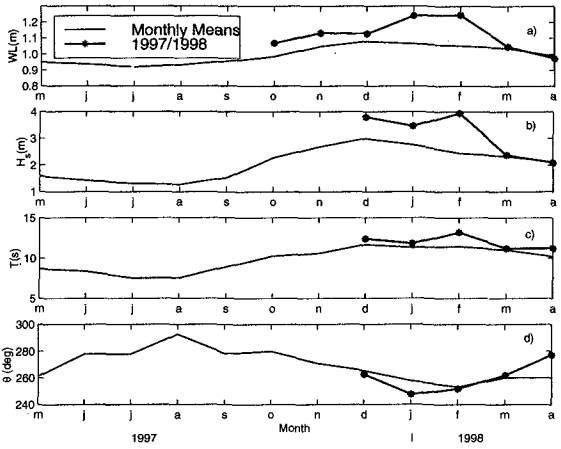

Figure 3. Monthly mean a) water levels, WL, for the Toke Point tide gage (NAVD 88), b) significant wave heights, H_s, c) periods, T, and d) direction, θ, from the Grays Harbor buoy. Values from the 1997/1998 El Niño event are shown with darker lines and asterisks.

1997/98 El Niño

The winter of 1997/1998, the first winter of the monitoring program, coincided with one of the largest El Niño events of the 20th century. In the Pacific Northwest, strong El Niños are decadal scale forcing anomalies featuring increased frequency of extreme waves from the south-southwest and higher than normal sea levels (Komar and Good, 1989). During the previous major El Niño, 1982/1983, large wave heights and acute wave angles forced excessive offshore and northerly sand transport, causing severe beach erosion and shoreline orientation change that persisted for several years (Peterson *et al.*, 1990). The 1997/1998 El Niño fit this pattern by generating some of the highest water levels on record in the Pacific Northwest (Figure 3a). Monthly mean water levels were

typically 10-15 cm higher than usual for much of 1997 with the main increase in elevation occurring in January and February 1998.

Wave conditions were also more intense than typical during the 1997/1998 winter. Figures 3b and 3c show the increase in monthly mean values for both significant wave height and period. The most intense month, February, featured wave heights on average of 1 m higher than normal with wave periods over 2 s greater than normal. During the months of January and February 1998 there were 13 storm events in which the significant wave height reached or exceeded 6 m, approximately the 1 year event (Ruggiero *et al.*, 1997). Figure 3c shows that in January 1998 waves approached the coast from a more acute southerly angle than typical, as derived from monthly mean calculations since 1993, when the gage became directional.

Initial Results

Like any long-term monitoring program, the data collected as part of this study will increase in value over time. Although limited to one year of data at the time of this publication, the monitoring program is beginning to reveal scales of morphologic change within the littoral cell for comparison with lower energy reflective beaches. Results from other monitoring components, *ie.* Argus remote sensing techniques and shoreline change analyses will be provided in subsequent publications.

Cross-Shore Beach Profiles

The 47 beach profiles in the monitoring program provide a regional inventory of the variability of beach slope, elevation and volume change during the seasonal exchange from summer (calm or berm profile) to winter (storm or barred profile). In order to extract comparable quantitative statistics from beach profiles ranging over the 160 km long littoral cell, standard methods need to be adopted. Many predictive runup models depend on foreshore beach slopes, (Ruggiero *et al.*, 1996). Therefore, slopes have been computed for each of the profiles between the 1.0 m and 3.0 m contour elevations. This definition of beach slope coincides with the Bascom (1951) definition of a "reference point" for comparison of profiles taken at a variety of locations, *i.e.*, the "part of the beach face subject to wave action at mid-tide elevation." The elevation of MSL varies along the length of the cell between approximately 0.9 and 1.4 m NAVD 88. Foreshore beach slopes vary between 1:100 and 1:10 while a mean slope for this dissipative cell is approximately 1:75.

Volume change between subsequent profiles has been calculated between the 1.0 m and 4.0 m contour elevations. Although many of the summer profiles extend to lower contours, the winter profiles were taken during periods of high wave conditions when both wave setup and swash limited the depth to which profiles could be safely obtained. The volume calculations have been further standardized, reducing the effect of beach slope variability, by normalizing by the cross-shore length between contours. Regional scale volume change is thus presented as an average vertical change across subsequent profiles between the 1.0 m and 4.0 m contours for each of the 47 profiles in Figure 4a. As anticipated, the southern ends of sub-cells, Ft. Canby, Cape Shoalwater and Ocean

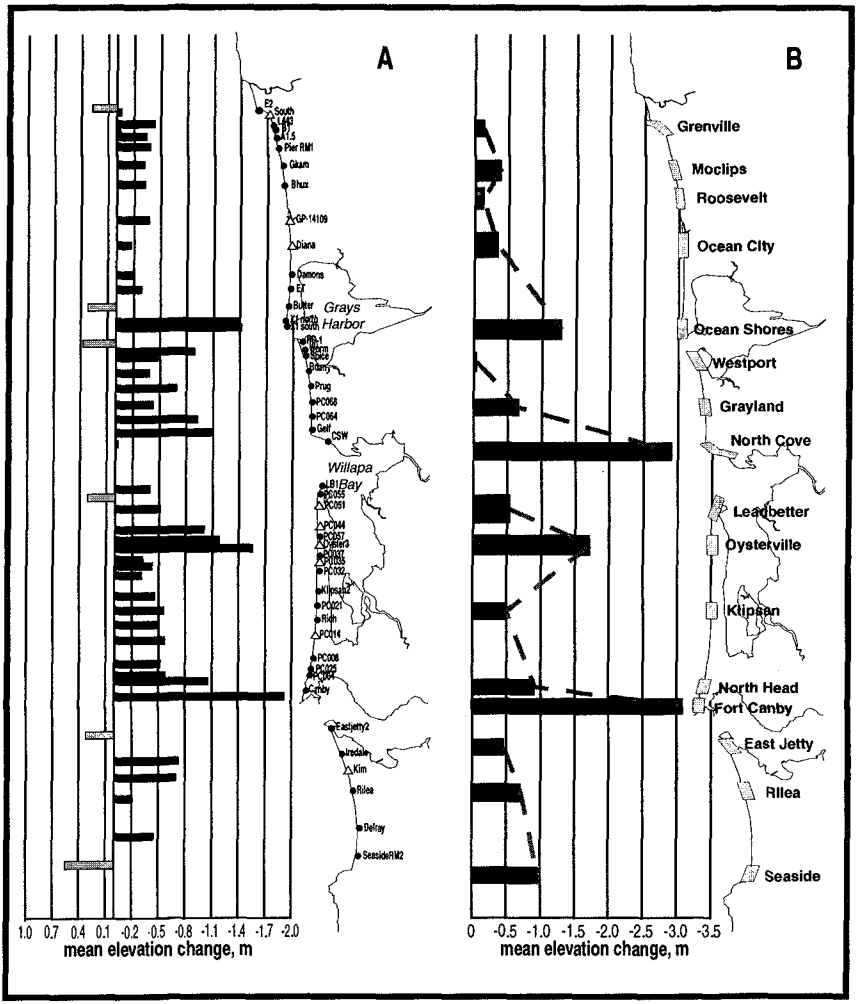

Figure 4. Beach elevation change calculated from a) beach profiles and b) surface maps.

Shores, experienced high levels of erosion during the El Niño winter of 1997/1998. The accretion at Tillamook Head (profile Seaside RM2) is associated with the northerly migration of a small creek, consistent with the expected pattern of El Niño influenced sediment transport. Remarkably, erosion hotspots at the northern ends of sub-cells, Clatsop Spit and Westport, showed net accretion during the winter. The three northern most sub-cells each reveal a trend of decreasing erosion from south to north, however erosion volumes are not balanced between erosion and accretion indicating substantial

offshore sediment transport. A detailed description of other El Niño related observations can be found in Kaminsky *et al.* (in press, b). Initial analyses of profile data from the summer of 1998 reveal a surprisingly rapid recovery of many of the beaches within the cell. More data will be necessary to identify anomalous morphologic change signals in response to this decadal scale forcing event.

The Coastal Profiling System was utilized to extend the cross-shore beach profiles and surface maps beyond the swash zone at 5 locations during summer 1998, including 3 of the 9 Bascom profiles. A simple Hallemeir-type calculation based on the 1-year return wave height and period gives an estimated profile closure depth of 12 m. It was not always possible to survey to this depth during the field campaign due to high waves and fog. Figure 5 provides sample profiles, Ocean City (a) and Oysterville (b), in which CLAMMER and CPS data have been merged and compared to Bascom's data collected in the 1940s. The large gap in the Ocean City profile (approximately 300 m) is due to the CPS not resolving the bathymetry in the surf zone under relatively high wave conditions (approximately 3 m in April 1998). The origin of the coordinate system has been set at the cross-shore position of the 4.0 m NAVD 88 contour in the 1945 profile. The Bascom data was originally collected and reported in MLLW and has been adjusted to the land based vertical datum. Corrections for the horizontal offset between subsequent profiles were determined via historical aerial photographs and shoreline change rates.

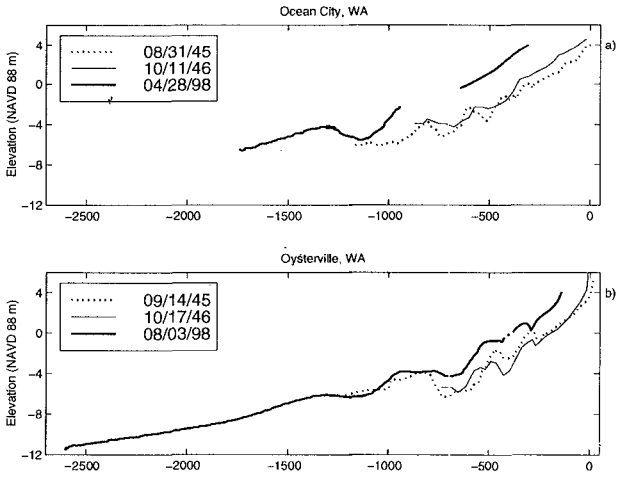

Figure 5. Beach profiles at a) Ocean City and b) Oysterville comparing data collected by Bascom and associates in the 1940s with modern profiles collected with the Coastal Profiling System and the CLAMMER.

The example profiles illustrated in Figure 5 suggest that recent beach slopes are similar to those of Bascom's profiles collected over a half century ago. However, dramatic shoreline change has occurred during this period, with approximately 2 m of beach

elevation gain along most of the profile. The earlier surveys show substantial short-term fluctuations of the upper beach profile associated with either seasonal variability or alongshore sediment transport gradients. The modern Ocean City profile is different than the Bascom data in that the sand bar is broader and contains more sediment volume. The Oysterville data is remarkable, as the form of the profiles, separated by over 50 years, is almost identical with 3 distinguishable bars of similar magnitudes in the same cross-shore position. All sites where nearshore bathymetry has been collected are characterized by multiple barred profiles with varying levels of 3-dimensionality. Two offshore sand bars can be identified at each survey site between the 2.0 m and 7.0 m depth contours with vertical relief O(2 m). An additional bar in the swash zone at the 0.0 m contour was resolved in some cross-shore profiles. Sand bar formation and migration patterns will be determined from the series of quarterly surveys at Ocean City, WA.

Beach Surface Maps

Surface maps have been collected at 16 sites throughout the littoral cell in order to resolve 3-dimensional morphologic features and changes and to eliminate the alongshore aliasing problem of single cross-shore beach profiles. Figure 6 shows the difference between surface maps collected at Ocean Shores, WA, on 18 August 1997 and 27 February 1998. The patterns of alternating accretion and erosion represent the migration of morphologic features such as megacusps and rip current embayments. A series of monthly surface maps has been collected at this site since summer 1997 generating a 1-year time series of morphodynamic change. Superimposed on the map are the 1.0 m, 2.0 m and 3.0 m contour elevations over the 4 km stretch of beach. The average horizontal retreat of these contours has been calculated for each of the 16 surface maps. Flatter beaches will experience greater contour recession than steeper beaches for a similar forcing. For inter-comparison, the horizontal retreat has been normalized by multiplying by the average beach slope along the length of the mapped region. This calculation gives a proxy for the average vertical change between the position of the elevation contours. Figure 4b illustrates this quantity for the 2.0 m contour between the summer 1997 and winter 1998 surface maps. These results show the regional gradient in erosion from south to north along each of the sub-cells. The southern boundaries at each sub-cell, Seaside, Fort Canby, North Cove and Ocean Shores, exhibited severe erosion, while the northern sub-cell boundaries all showed nearly the minimum elevation change for the sub-cell. Most of these areas are erosion hot spots, therefore it will be important for future monitoring to distinguish the El Niño signal from typical seasonal changes and long term trends.

Engineering Applications of Morphology Data

Beach morphology monitoring data is being directly applied to a variety of existing coastal processes models with the ultimate goal of predicting shoreline evolution. The Dutch model UNIBEST (Delft Hydraulics, 1995) is currently being applied to the northern sub-cell to model decadal scale shoreline evolution. Nearshore bathymetric surveys will be used in attempts to determine closure depths within the cell, a critical parameter in one-line shoreline change models such as UNIBEST. Engineering profiles such as the Dean equilibrium profile (Dean, 1977) and exponential profiles (Komar and McDougal, 1994) are being fitted to the measured cross-shore bathymetry for input into

these processes models. The tuning parameters for each model have been determined by minimizing the RMS error between the measured profile and the modeled profile in a least squares sense. The Dean profile typically has a slightly lower RMS error which better models the inner-surf zone, while the exponential profile performs better in deeper water.

Beach slopes and intersection elevations of the beach face and backing dune are being used in a probabilistic model (Ruggiero *et al.*, 1996), developed specifically for high-energy dissipative beaches. The model evaluates the relative susceptibility of coastal properties to flooding and erosion based on extreme water levels and wave conditions. Model results will be used to enable coastal planners to make informed, long-term coastal management decisions. Surface mapping data, coupled with nearshore bathymetric surveys, are being used to quantify seasonal and long-term adjustments of the entire nearshore planform. Following a spring 1999 experiment, event driven cross-shore beach profile response will be correlated with environmental forcing data in efforts to calibrate cross-shore beach and dune erosion models for Pacific Northwest beaches.

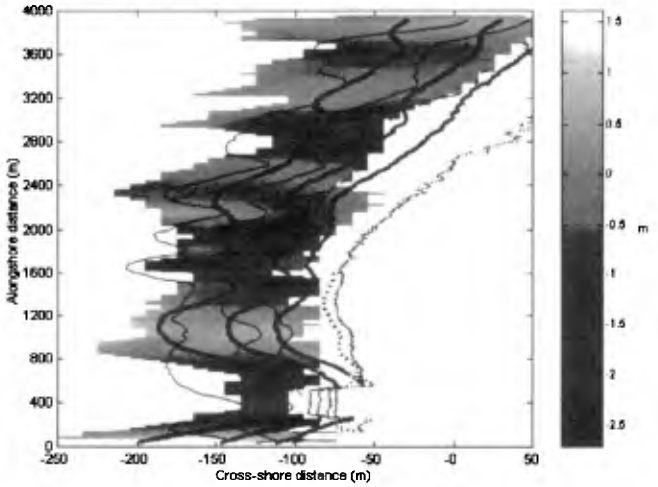

Figure 6. Surface difference map for Ocean Shores, WA from 18 August 1997 to 27 February 1998. The grayscale bar to the right of the figure represents the vertical change over the mapped area with darker shades indicating erosion and lighter shades indicating accretion. The 1.0 m, 2.0 m and 3.0 m contour positions are shown for both the summer 1997 data, light lines, and the winter 1998 data, darker lines. Also shown in the diagram is horizontal retreat of the erosion scarp backing this site, dashed to solid line, and the location of a rock revetment (solid lines show the stepped revetment at the 400 m alongshore distance) designed to slow this shoreline retreat at one location.

Conclusions

A morphology monitoring program has been initiated in the CRLC, consisting of 47 cross-shore beach profiles and over 60 km of beach surface topography, documenting short- to medium-term morphologic variability. This program is beginning to provide regional scale quantitative data on high-energy dissipative beaches for the first time in the Pacific Northwest. The 1997/1998 seasonal response was very large, in part due to a major El Niño event. Gradients in sediment transport are evident in the regional morphologic response to this decadal-scale forcing event.

High quality long-term data sets exist in other locations, with two of the most comprehensive collected at Duck, NC and the Dutch coast. Much has been learned about morphologic behaviour at these sites and many models have been formulated from the data. In order to determine the applicability of these morphodynamic models to the CRLC, the scales of environmental forcing and morphologic response need to be compared. Table 1 lists several parameters and gives ranges and mean values from the CRLC as well as typical values for Duck and the central Dutch coast (Plant, 1998; Wijnberg, 1995). The CRLC features higher energy than the other two coastlines and the morphology is more dissipative with finer sediment sizes and lower beach slopes, β, both on the foreshore and within the surf zone (from the +1 m contour to 750 m seaward). At least for the winter of 1997/1998, the seasonal morphologic variability (average change in elevation across a profile, ΔZ, and the average 2.0 m contour recession, ΔX) appears to be greater in the CRLC than at Duck or in Holland. Future work will include the collection of data to improve the temporal resolution of morphologic variability and existing models will continue to be tested, identifying modifications necessary for application to the CRLC.

Table 1. Scales of environmental forcing and morphologic change.

Parameter	Range (CRLC)	Mean (CRLC)	Duck, NC	Holland
H_s (m)	1.0 – 8.0+	2.0	1.1	1.2
T (s)	5.0 – 20.0	11.0	8.4	5.0
Tide (m)	2.0 – 4.0	3.0	1.5	1.6
β (foreshore)	0.01 – 0.095	0.02	0.10	0.03
β (surf zone)	0.0067 – 0.0095	0.008	0.01	0.0065 – 0.017
D_{50} (mm)	0.13 – 0.23	0.18	0.50	0.26
ξ_o (surf similarity)	0.10 – 0.75	0.19	0.5 – 2.5	0.20
Bar Height (m)	1.0 – 2.8	2.0	0.9	2.0
Δ Z (m)	-1.92 – 0.55	-0.45	-0.3 – -0.1	-0.3
Δ X (2.0 m)	-109.0 – -0.6	-33.0	-15.0 – -10.0	-15.0 – -10.0

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