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Regional Scale Sandbar Variability:

Observations from the U.S. Pacific Northwest

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Abstract

Understanding sandbar dynamics and variability is integral to developing a predictive capacity for nearshore flows, sediment transport, morphological change, and ultimately for determining coastline exposure to damaging storm waves. Here we report on a nearshore bathymetric data set from the U.S. Pacific Northwest (PNW) that stretches from Point Grenville, Washington to Cascade Head, Oregon, over approximately 260 km in the alongshore and includes 8 distinct littoral cells. We describe and quantify the morphological variability of sandbars on a regional scale, using 560 individual cross-shore transects, as well as attempt to explain the inter-littoral cell variability via relationships to various environmental parameters. The cross-shore extent of the bar zone extends over 1km from the shoreline in the northern part of the study area, but only to about 600m from the shoreline in the southern part. Maximum bar crest depths are typically 7m below MLLW. Bar heights range from a step in the cross-shore profile to over 3m from crest to trough. The northernmost littoral cells typically have two or more subtidal sandbars per cross-shore profile whereas the littoral cells in the southern part of our study area have only one bar. The mean depths of the bars, however, are much more consistent across littoral cells even while the upper shoreface slope significantly increases from north to south, requiring that the maximum bar distance from the shoreline decreases from north to south. Results from a limited study of the temporal variability suggest that while data collected over large spatial scales captures significant amounts of overall sandbar variability, it does not completely characterize the variability over the entirety of the net offshore migration cycle.

1 Introduction

Nearshore sandbars are found in the active zone of sandy coastlines worldwide, often contain substantial volumes of sand, and are important expressions of nearshore sediment transport. An understanding of sandbar dynamics is important for coastal hazard and change prediction. Because these features can often dominate nearshore morphological variability, taking a large scale approach, by examining long duration and large-scale bathymetric data sets, can yield important insight into their characteristics and behavior (*eg.*, Birkemeier, 1984; Lippmann et al., 1993; List and Terwindt, 1995; Grunnet and Hoekstra, 2004). Unfortunately, in-situ measurements of nearshore bars have historically been relatively scarce due to the difficulty and expense of collecting such measurements. Few studies are continued over long time scales and even fewer encompass large spatial scales (*e.g.* Plant et al., 1999b; Wijnberg and Terwindt, 1995; Ruessink et al., 2003; Grunnet and Hoekstra, 2004b; Pape et al., 2010).

Given the difficulties of collecting this type of data, it is not surprising that large scale spatial and temporal sandbar variability is still relatively poorly understood. Previous efforts have, in general, focused either on the net offshore migration (NOM) of sandbars or on classification systems for spatio-temporal variability. NOM has particularly intrigued the coastal community (Lippmann and Holman, 1990; Plant et al., 1999; Ruessink and Terwindt, 2000; Ruessink et al., 2003; Grunnet and Hoekstra, 2004; Ruessink et al., 2007; Pape et al., 2010; Kuriyama, 2012; Walstra et al., 2012; Wijnberg, 2002); studies have described and characterized the cycle of bar generation near the shoreline, offshore migration, and bar degeneration well seaward of the shoreline. Timescales and patterns of NOM have been documented at several coasts worldwide (*e.g.* Lippmann et al., 1993; Grunnet and Hoekstra, 2004, Ruessink et al., 2003). Recent efforts have focused on modeling the processes responsible for interannual to decadal-scale bar behavior (*e.g.* Ruessink et al., 2007; Pape et al., 2010; Kuriyama, 2012; Walstra et al., 2012). Larger scale studies have documented alongshore differences in the NOM behavior of bar systems along different coastlines and have attempted to correlate the variability to environmental variables (Wijnberg and Terwindt, 1995a; Wijnberg, 2002; Ruessink et al., 2003). However, truly satisfactory explanations of the underlying causes of differing bar behavior are still lacking.

Studies focused on spatial variability have used classification systems to characterize the longshore variability of sandbar planforms, typically using categories such as linear, rhythmic, and non rhythmic (Wright and Short, 1984; Lippmann and Holman, 1990; van Enckevort and Ruessink, 2003a; Van Enckevort and Ruessink, 2003b). These efforts have primarily focused on the variability of a continuous outer or inner bar as a response to varying hydrodynamic conditions, over scales on the order of a kilometer (Lippmann and Holman, 1990; van Enckevort and Ruessink, 2003b). Sandbar behavior at this scale is influenced by both wave conditions and self organization (Coco and Murray, 2007).

Here we report on over 260 km of nearshore bathymetry data measured between 2010 and 2012 in the U.S. Pacific Northwest (PNW). Sandbars dominate the variance of the nearshore active zone of the PNW coast (Ruggiero et al., 2005), and this data provides an opportunity for characterizing the variability of sandbars on a regional scale. The PNW region broadly shares the same Quaternary geologic history and present-day environmental forcing. However, smaller scale, local variations in the geologic and depositional history dictate the location of headlands and barrier spits as well as the amount and type of sediment available in the nearshore. The geology of the region organizes the coast into littoral cells which share sediment sources and depositional history. Likewise, while the large-scale wave climate varies little at the regional scale, within the region there will be local alongshore variability in wave shoaling, refraction, and diffraction patterns over a heterogeneous bathymetry (García-Medina et al., 2013, García-Medina et al., 2014). Here we investigate whether the alongshore variability of underlying geology and environmental forcing is expressed as differences in nearshore bar morphology at the regional scale.

The primary goal of this work is to describe and understand spatial sandbar morphological variability at the regional scale. More specifically, our objectives are to (1) quantify the spatial variation of sandbars over approximately 260 km of the southwest Washington and northwest Oregon coastline, (2) consider environmental variables that might cause or contribute to the variation observed in (1), and (3) contextualize the observed spatial variability in terms of temporal bar variation. We concentrate on large, inter-littoral scale variability and trends.

Below, we first describe the study area and data set in detail. Next we elaborate on the methods used to extract sandbar morphometrics from cross-shore beach profiles. The remainder of the paper describes how the observed variability in nearshore morphology links to variability in a suite of environmental parameters.

2 Study Area and Data Set

2.1 Study Area

Data collection for this research was conducted along a 260 km long section of the U.S. PNW coast in southwest Washington and northwest Oregon (Figure 1). The southwest Washington coast is characterized by broad, low-lying accreted barrier beach plains (Peterson et al., 2010b; Vanderburgh et al., 2010), while much of the northern Oregon coast is characterized by pocket beaches separated by more erosion resistant headlands. Our study area encompasses 9 littoral cells, including the four sub-cells of the Columbia River littoral cell (CRLC) as well as the Cannon Beach, Rockaway, Netarts, Neskowin, and Sand Lake littoral cells in northern Oregon (Figure 1). These littoral cells are delineated by natural features such as headlands and estuary mouths, and the sediment within them has been isolated from neighboring littoral cells within the late Holocene (Clemens and Komar, 1988). The lack of bypassing of beach sands between littoral cells results in distinct characteristics of the individual pocket beaches. For these reasons littoral cells serve as a natural spatial scale in this study for assessing sandbar variability. The CRLC is the largest littoral cell in the study region and spans approximately 165 kilometers from Point Grenville, WA to Tillamook Head, OR. The CRLC is divided into the sub-cells of North Beach, Grayland Plains, Long Beach, and Clatsop Plains by large estuary mouths at the Columbia River, Willapa Bay, and Grays Harbor (Figure 1). Each of the sub-cells shares the Columbia River as their sediment source. During the late Holocene, Long Beach and Clatsop Plains received large amounts of Columbia River sediment beginning 4.7-5 ka. After more than 50 km of longshore transport, Columbia River sediment reached Grayland Plains (2.5-2.8 ka) and North Beach (2.8-3.2 ka) (Peterson et al., 2010a). Gelfenbaum et al., (1999) and Kaminsky et al. (2010) document a significant reduction of Columbia River sediment supply over the 20th century due to anthropogenic influences such as flood control and hydropower.

Five additional littoral cells are examined in northwest Oregon: Cannon Beach, Rockaway, Netarts, Neskowin, and Sand Lake (Figure 1). Many of the large Oregon headlands are highly effective at restricting sediment transport along the shoreline and so delineate these littoral cells. The Cannon Beach cell extends ~20 km south from Tillamook Head, Oregon to Cape Falcon, Oregon. The Rockaway cell starts south of Cape Falcon and stretches 32 km to Cape Mears. The Netarts cell is the smallest littoral cell in our study area (~17 km), and is located between Cape Mears and Cape Lookout. The Sand Lake and Neskowin littoral cells are separated by Cape Kiwanda, a relatively minor headland that is substantially smaller than either Cape Lookout to the north or Cascade Head to the south and does not necessarily restrict sediment transport. We therefore combine these two small littoral cells (~15 km each) into a single analysis region, the coastline between Cape Lookout and Cascade Head, referred to hereafter as the Neskowin cell.

Sediments in the PNW overlie an erosional, geomorphic ravinement surface created by wave action during Holocene sea level transgression (Peterson et al., 2010; Vanderburgh et al., 2010). This surface slopes shallowly seaward (Vanderburgh et al., 2010); thus the upper shoreface slope is influenced not only by present day sediment characteristics, but also by the underlying geology. The ravinement surface is expected to exist throughout the PNW region, but has not been mapped in detail south of Tillamook Head. While sediment exchange along the PNW coastline is presently limited by large headlands, during lower stands of sea level sediments traveled freely throughout the region. Tillamook Head represents a strong break in present-day sediment characteristics. North of the headland the CRLC beaches and nearshore are dominated by Columbia River sediments while south of the headland sediment mineralogies indicate multiple sources including the Umpqua River, the Coast Range, the Klamath Mountains, and the Columbia River (Clemens and Komar, 1988).

The PNW coast is exposed to a highly energetic wave climate with winter storm significant wave heights reaching 10 m approximately once per year (Allan and Komar, 2002). Average summer wave heights are between 1 and 2 m and average winter wave heights are between 3 and 4 m (Ruggiero et al., 2005). The mean wave direction also has a seasonal cycle, with winter waves approaching the coastline from a more southerly direction than summer waves

(Ruggiero et al., 2005). Here we consider May through September as summer, and October through April as winter, based on the frequency of storm events (Ruggiero et al., 2005).

The mesotidal tides in the PNW are mixed semidiurnal. The mean tide range for the study area is between 2 and 4 m (Komar, 1998). While storm surge in the PNW is relatively small (on the order of 1 m during the largest events, due to the narrow continental shelf), large winter storm waves combined with high tides cause episodic erosion and flooding in the region (Ruggiero et al., 2001).

2.2 Data Set

In this study we utilize data from two separate beach monitoring programs in the PNW. Annual nearshore bathymetry surveys in the CRLC began in 1998 as part of the Southwest Washington Coastal Erosion Study (Ruggiero et al., 2005; Ruggiero et al., 2007; Gelfenbaum and Kaminsky, 2010). More recently, a similar nearshore bathymetric data collection campaign has been initiated in several littoral cells in Oregon. Combining data from these two field campaigns allows us to analyze sandbar variability over a large spatial extent.

Between 2010 and 2012, 560 individual cross-shore profiles were collected along the 260 km study area, representing over 1000 km of cross-shore surveys. The majority of the transects (over 80%) were surveyed in summer 2011. To achieve continuous coverage of the study area, we include additional data from 2010 and 2012, representing approximately 15% and 4% of the total data coverage respectively (Table 1; Figure 1). The only gap in coverage between Point Grenville, WA and Cascade Head, OR is ~ 3 km north and ~11 km south of Willapa Bay. Because the inlet to Willapa Bay is the largest natural inlet on the U.S West Coast, not only is data collection in this area very hazardous, but the nearshore morphology is profoundly influenced by the ebb tidal delta and is not characteristic of the open coast dynamics that predominate in the rest of the study area. In addition, some of the study region is characterized by rocky backshore environments. Only beach profiles fronting sandy beaches, 465 profiles along approximately 210 km of coastline, are discussed in detail below.

3 Methods

Here we discuss the collection and processing of the profile data, the methods of extracting sandbar morphometrics from the data, and the sources and resolution of available environmental variable data.

3.1 Data Collection

The nearshore bathymetry data used in this study was collected using the Coastal Profiling System (CPS) which consists of a personal watercraft equipped with an onboard computer, monitor, Real Time Kinematic – Differential Global Positioning System (RTK-DGPS), and a single beam echosounder (Ruggiero et al., 2007; Stevens et al. 2012). CPS operators use Hypack® survey software to track their position with respect to predefined (repeatable) transects. Experienced operators can maintain their position ‘on line’ to within about 2 m, and generally not more than 10 m, along an approximately 2 km long transect extending from ~12 to 25 m depth to about 1 m of water. Topographic surveys, collected with RTK-DGPS mounted on a backpack or ATV, accompany the bathymetric surveys and extend the profiles across the beachface over the foredune or to the base of coastal bluffs or shore protection structures. Operators are typically able to stay within 1 m of the predefined topographic survey lines. The cross-shore profiles are spaced between 200 m and 1 km in the alongshore. The 1 km spaced transects efficiently cover large sections of coast, while still effectively capturing the large-scale sandbar morphology. The 200 m spacing captures greater detail of the often threedimensional morphology. Data collection at the regional scale requires some sacrifice of finer intra-littoral scale resolution for larger spatial coverage.

High levels of accuracy are possible through the use of RTK-DGPS. For these surveys, base stations are set up over a geodetic survey monument, the position of which is known to within centimeters (e.g., Daniels et al., 1999). Manufacturer reported GPS uncertainties are approximately 1 cm in the horizontal and approximately 2 cm in the vertical, with an additional 1 cm of uncertainty for every 1 km between the base station and the rover unit (Ruggiero et al., 2007). Mean vertical offsets between transects repeated on the same day are consistently less than 10 cm, and usually 5 cm or less (Stevens et al, 2012).

GPS drift caused by satellite geometry, satellite obstructions, and atmospheric conditions can be up to 10 cm (Sallenger et al., 2003). Local site calibrations are performed for the topography surveys to reduce these uncertainties to about 4 cm by occupying 2-5 geodetic monuments with the survey equipment and using a 3 parameter least squares fit to fix all data points within the survey network. Repeat topography surveys of a single line in a single day suggest additional repeatability uncertainties of 4 cm (Ruggiero and Voigt, 2000). Typical baseline distances of 5 km yield a GPS uncertainty of 6 cm. Combining the calibration uncertainty (~4 cm), repeatability uncertainty (~4 cm), and GPS uncertainty (~6 cm) in quadrature (assuming that they are random and independent) yields a total vertical uncertainty of approximately 0.08 m for the topography surveys (Ruggiero et al., 2007).

Water temperature and salinity variability can lead to significant differences between the speed of sound at the time of the survey and the speed of sound employed by the echosounder in the depth calculation (typically 1500 m/s), introducing additional uncertainty into bathymetry surveys (MacMahan, 2001). We do not consistently measure salinity or water temperature profiles, and thus cannot completely correct for their variability. Adding the GPS drift uncertainty (up to10 cm), the manufacturer reported GPS uncertainty (~6 cm), and the repeatability uncertainty (up to 10 cm) and the speed of sound uncertainty (up to 10 cm) in quadrature yields an estimate of between 0.15 to 0.18 cm for total vertical measurement uncertainty (Ruggiero et al., 2007). High sampling rates for the GPS (20 Hz) and echosounder (up to 20 Hz) make it possible to accurately resolve the bathymetry despite surveying through waves and evolving tidal stage. All surveys are referenced to the North American Datum of 1983 (NAD 83) in the horizontal and to the North American Vertical Datum of 1988 (NAVD 88) in the vertical.

3.2 Data Processing

The raw echosounder returns are initially digitized by the internal signal processing algorithm of the echosounder, and then post-processed in order to (1) eliminate digitization gaps, and (2) mitigate the effects of boat pitch and roll. Digitization gaps can be eliminated by using the echosounder full waveform returns to recover bottom soundings not automatically recognized by the algorithm. The effects of boat pitch and roll are reduced by identifying and removing sharp changes in the depth soundings. Along sandy coasts changes in the bathymetry are relatively smooth, and sharp changes in the bottom can be attributed to boat motion. Along rocky coastal areas sharp changes in the bathymetry are often real morphological features; data processing in these areas requires careful consideration of the raw echosounder returns. The final processing step smoothes the data using a standard deviation filter, followed by a running average filter on groups of 5-10 points which represent approximately 1-2 m of the transect, depending on water depth. Short gaps, less than 25 m, are typically filled by linear interpolation.

Processing is accomplished using a custom Matlab Graphical User Interface (GUI) (Andrew Stevens, personal communication).

3.3 Bar Extraction

In order to systematically quantify nearshore morphological variability, it is necessary to define specific features of sandbars that can be reliably, consistently, and, ideally, automatically extracted. Here we use three morphometric parameters to characterize sandbar morphology: bar crest position from the shoreline, bar crest depth, and bar height (Figure 2). The distance from the shoreline is defined as the along-transect distance from the 2.1 m (NAVD88) contour to the bar crest. This shoreline elevation is a LiDAR derived operational mean high water (MHW) datum originally developed by the USGS for shoreline change studies (Weber et al., 2005). For transects with a corresponding topography survey, the 2.1 m contour is extracted from the topographic data. In relatively few cases (~ 15% of analyzed transects) there is no complimentary topography survey, and surrounding topography is used to interpolate the shoreline position. The bar depth is defined as the depth below 0 m NAVD88, a vertical datum which is typically within a decimeter above or below mean lower low water (MLLW) in the study area. Bar height is defined as the difference between the depth of the bar crest and the depth of the bar trough immediately landward of the bar crest (Figure 2).

An established method for extracting sandbar morphometrics is by subtracting the mean profile over many years from the profile of interest to obtain a perturbation profile (Ruessink and Kroon, 1994; Plant et al., 1999; Grunnet and Hoekstra, 2004). Because mean profiles in the CRLC do not entirely eliminate bar-like features, we further smooth the mean profile with a loess smoother to remove features with cross-shore wavelengths less than 500 m (Plant et al., 2002). Bars are identified as maximums and minimums in the perturbation profile (Figure

3). Based upon estimated measurement uncertainties, the minimum perturbation we are able to confidently identify is approximately 0.2 m. Due to differences in sandbar shape, the location of maximums in the perturbation profile is not always precisely at the local maximum of the bar. Because we consider the local maxima and minima of the bars to be the important morphological characteristic, we adjust the initial crest and trough picks to the local maxima and minima of the actual profile (Figure 3). Bar picks are extracted automatically; however an analyst must approve, or change, the picks on each profile before the parameters are stored. This method is used on all CRLC profiles where there is over a decade of data and a mean profile can be computed. For profiles with only one year of data (much of the northern Oregon data) a mean profile cannot be defined and bar crests and troughs are picked as local maxima and minima directly from the profiles.

Nearshore terraces, or steps in the profile, are a relatively common characteristic of the nearshore bathymetry in the region. We distinguish between sandbars, which have a distinct crest and trough, and nearshore terraces, which are characterized by inflections in the profile without a clear trough. A terrace crest is defined not as a local maximum, but as the point where the profile flattens into a step, or the point of maximum curvature (Figure 3). Terrace crests appear in the perturbation profile in the same way as a bar crest does, making automatic extraction possible when we are able to compute a mean profile (

Figure 3). However, automatic terrace extraction is not always successful in the CRLC because terrace crests are less distinct features of the profile than bar crests; for many cases in the CRLC and for all profiles with only one year of data, terraces were extracted manually by visually estimating the point where the profile flattens. While terraces and bars are defined differently in the extraction process by necessity, they are not distinct features. Any one sandbar may vary in the alongshore and exist as both a bar and a terrace at the same time but in different locations and may also cycle in and out of a ‘terrace phase’ during its temporal lifecycle. Terraces are distinguished from bars by having a height equal to zero.

Sandbar morphometrics were further refined to improve data quality for subsequent analysis. Since survey operator safety often necessitates uneven coverage of the lower intertidal zone (approximately -1.5 m to 1 m), only subtidal bars (crest depth less than -1.5 m) are considered. Additionally, only transects intersecting sandy beaches are analyzed. Therefore, 465 out of the 560 profiles collected and 552 out of a total of 874 bar picks were used for the spatial analyses described below.

3.4 Environmental Variable Data

We examine the alongshore variability of several environmental variables (wave climate, tide range, sediment grain size, and upper shoreface slope) (Wijnberg, 2002) to improve our understanding of longshore variability in bar morphology. The wave climate was characterized using a 6-year hindcast obtained using Wave Watch III v3.14 and Simulating WAves Nearshore (SWAN) v40.81 (Garcia-Medina et al., 2013). The hindcast provides significant wave height, mean wave period, and mean wave direction for every hour of every day of the record at a model resolution of about 5 km in the alongshore. Wave characteristics were extracted at a depth of 50m and reverse shoaled using linear wave theory to obtain an equivalent deepwater wave height. Extracting the wave characteristics at 50m allows for wave shoaling on a variable bathymetry, important for determining alongshore variability in mean wave direction. We estimate breaking wave height using the method of Komar and Gaughan (1976),

$$H_b = 0.39g^{1/5} (T H_0^2)^{2/5},$$

where g is the acceleration due to gravity, T is the wave period, and H_0 is the deep water wave height. The alongshore varying wave climate is characterized by six-year averages of each wave variable. Tidal range variability was characterized using tide predictions from 2011 for four NOAA operated tide gauge stations in the study area (Garibaldi, OR, Hammond, OR, Toke Point, WA, and Westport, WA) located as close as possible to the open coast. Grain size data for the study area was obtained from Peterson et al. (1994), and includes the mean diameter and the standard deviation of the intermediate grain axis of mid-beach samples, at a spacing of approximately 5 km. The upper shoreface slope is defined between the position of the 2.1 m (shoreline) and the -10 m contours. Due to the extremely flat slope of northern North Beach, our data did not extend seaward enough to reach this contour. Thus the upper shoreface slope at the -10 m contour had to be extrapolated.. We first computed the slope at the -7 m contour and the -10 m contour for southern North Beach and found the mean difference between the two slopes (0.0016). Then we calculated the slope at the -7 m contour, the deepest contour available at every transect, for northern North Beach and subtracted the mean difference to obtain an estimate of the slope at the -10 m contour.

Similar to Ruessink et al. (2003), we investigate whether the above simple bulk statistics of environmental variables are associated with observations of variability in bar statistics through linear regression analysis.

4 Results

In this section we present regional, inter-littoral cell trends and variability in sandbar morphometrics and environmental variables.

4.1 Morphometric Parameters

There is considerable alongshore variability in the bar position from the shoreline, bar crest depth, and bar height, both within and among littoral cells (Figure 4). From north to south, the maximum and mean bar positions show a regional trend of decreasing distance from the shoreline (Figure 5; Table 2). Bars in the CRLC and the Cannon Beach littoral cell are more widely distributed over the nearshore zone than in Rockaway, Netarts, and Neskowin. Bar positions range from 200 m to 1000 m from the shoreline in the most northerly five littoral cells (the CRLC and Cannon Beach), while in the three most southerly littoral cells (Rockaway, Netarts, and Neskowin) the bars exist primarily between 200 m and 600 m from the shoreline (Figure 5; Table 2).

We define the maximum range of bar position for the entirety of a littoral cell as the effective bar zone. Bars in the CRLC and Cannon Beach have a wider effective bar zone than in Rockaway, Netarts, or Neskowin (Figure 4; Figure 5; Table 2). The width of the effective bar zone decreases from over 800 m in the CRLC to less than 400 m in Rockaway and Netarts.

In contrast to the longshore variability in bar position, bar depths are more consistent in the alongshore (Figure 4). The depth limit across the study area is approximately 7 m (Figure 8; Table 3). Only 3% of bar crests in the study area are deeper than 7 m, and the majority of the bars in every littoral cell (except Cannon Beach) are shallower than 5 m. There is no clear regional longshore trend in the maximum bar depth or depth range of the effective bar zone. Maximum depths within each of the littoral cells range from 5.8 m to 7.2 m. Cannon Beach has the deepest mean depth (Figure 8; Table 3); this is due to a higher occurrence of bars in the deeper part of the depth range rather than due to Cannon Beach exhibiting a larger depth range. Distributions of the bar depths for each littoral cell show similar results to the position distributions, in that there is a tendency for profiles to have multiple bars in the CRLC and Cannon Beach and a single bar in Rockaway, Netarts, and Neskowin (Figure 7).

It is helpful to explicitly discuss the relationship between the effective bar zone, the depth range, and upper shoreface slope. The effective bar zone narrows as we move south in the study area, but the depth range and maximum bar depth do not change significantly. It will be shown in the next section that the upper shoreface slope increases as we move south in the study area. Because the slope is increasing, the maximum depth at which bars are found occurs closer to the shoreline. In addition, there is a limit to how close to the shoreline a bar can get before it can no longer be considered a subtidal bar. Therefore, the effective bar zone must narrow, independent of other considerations.

An intriguing consequence of a narrower effective bar zone appears to be a transition from a multiple barred system in the CRLC and Cannon Beach to a single barred system in Rockaway, Netarts, and Neskowin (Figure 4). Individual transects in the CRLC and Cannon Beach are much more likely to contain two or more subtidal bars than transects further south. This tendency can most easily be seen in Long Beach, Clatsop Plains, and Cannon Beach (Figure 4). Frequency distributions of bar positions in each littoral cell illustrate variability in bar position and the number of subtidal bars (Figure 6). The CRLC and Cannon Beach have multiple peaked distributions for bar position, clearly displaying a tendency towards multiple barred systems. While Figure 4 and Figure 7 suggest that Long Beach displays a triple bar system, the rest of the CRLC and Cannon Beach show a double barred system. The bar position distributions for Rockaway, Netarts, and Neskowin have a single peak which is consistent with a single barred system. Ninety percent of the bars in the study area are less than 2 m in height and 65% are less than 1 m in height. Terraces make up 28% of the extracted bars (Table 4). Although maximum bar height does not exhibit any regional longshore trends, there is some alongshore grouping in the frequency of terrace occurrence (Figure 4; Figure 10; Table 4Table 2). The CRLC has an overall higher frequency of smaller bars compared with Cannon Beach, Rockaway, Netarts, and Neskowin (Figure 9). Rockaway has the largest mean bar height in the region, followed by Neskowin and Cannon Beach which do not differ significantly in mean bar height. Each sub-cell of the CRLC has a higher percentage of terraces than the study area as a whole, while each of the other littoral cells has a lower terrace percentage than the data set as a whole. For instance, 46 % of the bars in Rockaway are greater than 2 m in height, and only 16% are terraces. In contrast, in Grayland Plains there are not any bars greater than 2 m in height and 49% of the bars are terraces. The percent of terraces in each littoral cell clearly distinguishes the CRLC from the rest of the study area (Table 4Table 2), with terraces characterizing 38% of the CRLC bars.

4.2 Environmental Variables

The following section discusses the variability of the upper shoreface slope, wave climate, grain size, and tide range throughout the study region.

4.2.1 Upper shoreface slope

A striking regional trend in upper shoreface slope exists through the study area (Figure 11). The slope ranges from 0.0053 (~1:200), in North Beach, to 0.0205 (~1:50), in Neskowin, a change of almost a factor of 5 over approximately 260 km. The north to south steepening trend shows an abrupt shift towards a higher slope at Tillamook Head, partitioning the CRLC from Cannon Beach, Rockaway, Netarts, and Neskowin.

Within the regional trend, there are also smaller intra-littoral cell scale trends within the CRLC. The upper shoreface slope steepens towards Grays Harbor and the Columbia River

Mouth (MCR), both jettied estuary mouths. No similar trend is evident near Willapa Bay's ebb tidal delta because of the data gap due to hazardous conditions. Similar intra-littoral cell scale trends are not readily observed south of the CRLC.

4.2.2 Grain size

Throughout the study area the beaches are composed of very fine to medium sand (Figure 11). The majority of the sediment is fine sand in the range of 0.125 mm to 0.25 mm. The range of sediment sizes, represented by the standard deviation about the mean, is small, indicating well sorted sands (Figure 11). The degree of sorting within each sample is highest at the far north end of the study area and lowest at the far south end; however there is no trend in sorting through the middle of the study area. North Beach shows a high amount of longshore variability in the grain size at these mid-beach locations. The bar zone is not expected to show the same variability.

Within the CRLC, sediment fines away from the Columbia River (Figure 11) (Ruggiero et al., 2005). Mean grain sizes within Long Beach and Clatsop are 0.24 mm and 0.20 mm, respectively, while mean grain sizes in Grayland and North Beach are 0.18 mm and 0.16 mm, respectively. Grain size also generally coarsens south of Tillamook Head. The mean grain sizes for Cannon Beach, Rockaway, Netarts and Neskowin are 0.17 mm, 0.19 mm, 0.17 mm, and 0.32 mm, respectively.

4.2.3 Wave climate

Wave height, wave period, and wave power vary in the alongshore as a response to local wave transformations over the variable bathymetry, but a regional trend is not apparent (Figure 12). Mean wave direction (MWD) shows a clear longshore trend in the study area (Figure 12). The MWD ranges from an average of 267° (azimuth coordinate system), to an average of 279°, indicating a shift from a southwesterly approach to a northwesterly approach. There is also a substantial difference between the MWD of summer waves and winter waves. The average difference in the region is 8.3°. Individual bars often survive for multiple years and therefore, their characteristics are influenced by the cumulative effects of the wave and current conditions over a multi-year timescale. Considering this, from here on, we represent the wave climate variables with annual average conditions.

Cumulative longshore wave power was computed by summing the longshore component of wave power at each output point of the wave hindcast record. In order to examine regional and intra-littoral cell variability, we averaged the longshore wave power at 5 km intervals within each littoral cell. Net northward power is more common overall in the study area, but despite the longshore trend in MWD, the longshore component of wave power does not exhibit a regional trend. As the MWD transitions from south-westerly to westerly and then to north-westerly, the shoreline orientation mirrors the changing MWD. The lack of a regional trend in the longshore wave power stems from the changing shoreline orientation.

4.2.4 Tides

The tidal range in the study area shows very low variability (not shown). The highest mean spring tide range within the study area is 3.3 m, found in North Beach and Grayland Plains, and the lowest is 3.1 m, found in Rockaway. The highest mean neap tide range is 0.9 m, found in North Beach and the lowest is 0.7 m, found in Rockaway.

4.3 Relationships between sandbars and environmental characteristics

As the upper shoreface slope increases southward through the study area (Figure 11) there are noteworthy changes in the bar position characteristics. The mean bar position decreases, the maximum bar position decreases, and the width of the effective bar zone decreases as the upper shoreface slope increases. Along with these changes, the predominance of multiple bars per profile also transitions to a single bar per profile. In addition to the visually recognizable trends, the linear regression analysis indicates that the upper shoreface slope is significantly correlated (at the 95% confidence level) with the maximum and mean bar position (Table 5) as well as the position of the outer bar (Figure 13). In contrast, the range of depths through which bars are observed does not vary with the upper shoreface slope (Figure 13). Instead, there is a regional limit to bar depth at approximately -7 m. While the mean bar depth is not significantly correlated with any of the tested environmental variables, the depth range is significantly correlated with breaking wave height and wavelength (Table 5).

5 Discussion

We have thus far documented the presence and absence of regional trends in bar morphometrics as well as several environmental characteristic variables that have been suggested to affect morphodynamic variability in the literature. In the following section we consider the importance and significance of those trends for regional-scale bar morphology. We first consider the relationships between environmental characteristic variables and bar morphometric parameters. We then examine the spatial variability of the CRLC data in the context of its temporal variability.

5.1 Relating variability in bar morphometrics to environmental characteristics

The statistically significant correlations between upper shoreface slope and sandbar position and between breaking wave height and sandbar depth range suggest that the position and width of the bar zone are influenced by the zone of breaking waves. The nearshore of the CRLC is exceptionally low sloping and dissipative, with wide zones of breaking waves. As upper shoreface slope increases from north to south, but breaking wave height remains essentially the same, the nearshore zone becomes less dissipative and the zone of breaking waves narrows. Waves, wave induced currents, and especially, breaking waves are responsible for much of the sediment movement and sediment transport gradients in the nearshore zone. Thus we should expect that the width and location of the bar zone is influenced by the width and location of the breaker zone.

A clear physical explanation for the relationship between the upper shoreface slope and the number of bars per transect is not evident. Our observations show that the number of bars per profile decreases with increasing upper shoreface slope. Dolan and Dean (1985) and Short and Aagaard (1993) both present data that agree with these observations. Data from Dolan and Dean (1985) suggest that bar spacing increases with bar height; however we find no relationship between bar height and the distance between bar crests or between bar height and any of the environmental variables.

Ruessink et al. (2003) investigated the relationships between bar morphometrics and environmental characteristics using data from Duck, North Carolina, Hasaki, Japan, and four sites from the Dutch coast, focusing on intersite differences in NOM behavior. Linear regression analysis of bar morphometric parameters with bulk environmental variables suggested that the bar depth range tended to increase with the breaking wave heights of storms. However, because the statistical significance of several correlations was dependent upon which of the six sites was included in the analysis, the results were not deemed reliable enough to demonstrate conclusive relationships. Linear regression analysis between environmental variables and bar morphometric paramters from this study of the PNW also indicates that the bar depth range is influenced by breaking wave height (Table 5). While Ruessink et al. (2003) found considerable intersite differences in mean bar depth, we find that depth and depth range are the most spatially consistent morphometric parameter in the PNW. While Ruessink et al.'s (2003) specific definition of mean bar depth differs from the definition used in this study, the parameters are nevertheless related.

The Cannon Beach littoral cell is similar to the CRLC in some aspects of nearshore morphology and similar to Rockaway, Netarts, and Neskowin in others. Cannon Beach shares similar maximum and mean bar position statistics with the CRLC and also displays a two bar system; however in terms of sediment characteristics, slope trends, and percentage of terraces, Cannon Beach is more similar to Rockaway, Netarts, and Neskowin. The mixed characteristics of Cannon Beach suggest that no single environmental variable can explain all of the variability seen through the study area. Sandbar morphology, and the variability of that morphology, results from the interaction of multiple environmental factors.

To further investigate possible relationships between bar morphology and groupings of external environmental forcing parameters, we calculate the alongshore variability of three non-dimensional parameters, the Iribarren number, the dimensionless fall velocity, and the Relative Tide Range, and regress these against the bar characteristics. Non-dimensional quantities are often used to examine the collective influence of multiple processes on morphology, and are useful for comparing the influence of environmental variables on areas with disparate characteristics. The Iribarren number,

$$\xi_b = \frac{S}{\left(\frac{H_b}{L_0}\right)^{\frac{1}{2}}} \qquad (2)$$

combines slope with wave steepness, where S is here taken as the upper shoreface slope, H_b is breaking wave height, and L_0 is deep water wavelength. The Iribarren number is traditionally calculated using the deep water wave height and the foreshore beach slope. Here we use breaking wave height and the upper shoreface slope to emphasize the importance of shoaling and surf zone processes on sandbar morphology. The dimensionless fall velocity (Ω), also known as the Dean Parameter, (Masselink and Short, 1993) combines wave steepness and sediment size,

$$\Omega = \frac{H_b}{w_s T} \qquad (3)$$

where w_s is settling velocity, and T is wave period. The Dean parameter compares how often a sediment particle is lifted off the bed by waves with the time it takes for the sediment particle to settle out of the water column and has been used as an indicator of whether offshore or onshore sediment transport will dominate on a nearshore profile (where Ω greater than 2 suggests the dominance of offshore sediment transport) (Masselink and Hughes, 2003). Finally, the relative tide range (RTR) expresses the relative importance of shoaling, surf zone, and swash processes in the nearshore.

$$RTR = \frac{mean\ spring\ tide\ range}{H_b} \qquad (4)$$

The RTR influences the location of the surf zone with respect to the profile. As RTR increases, more of the profile is subject to shoaling processes over a tidal cycle, increasing the probability that beach morphology is influenced by shoaling processes (Masselink and Short, 1993).

Similar to many of the environmental characteristic variables, the non-dimensional environmental parameters do not display obvious alongshore trends in the study area (Figure 14). However, a few significant correlations exist between these parameters and the bar variables (Table 5). The Iribarren number varies between 0.033 and 0.12. A north-south increasing trend is driven by the upper shoreface slope trend, and despite the change in magnitude, the range of values indicates relatively similar surf zone conditions. The dimensionless fall velocity (Ω) displays more alongshore variability, ranging from 5.6 to 48; however, the highest values of this range are due to large changes in the mid-beach grain size in North Beach. The high alongshore variability of the mid-beach grain size is not expected to be perfectly representative of the bar zone. Unfortunately, due to the high-energy nature of the PNW, nearshore grain size information for the bar zone is very limited. Since the dimensionless fall velocity is strongly influenced by the mid-beach grain size changes, it cannot be used here to predict bar characteristics. The RTR displays relatively low variability, with a difference of only approximately 0.1 between the maximum and minimum values (Figure 14), however a statistically significant correlation does exist between RTR and maximum bar position (Table 5), suggesting that as RTR increases bars are found further from the shoreline.

5.2 Temporal Variability

In order to put the spatial variability of our regional scale sandbar morphology data set in context of temporal variability, we extracted sandbars in 1km long sections of coastline for the four CRLC littoral sub-cells for which we have at least 13 years of data (Figure 1). These data allow us to consider how well a regional scale snapshot of sandbar morphology represents the full range of morphology seen over timescales characteristic of NOM cycles. The NOM cycle in the PNW is thought to be on the order of 2 to 4 years (Cohn et al., 2014), but definitively determining this cycle is beyond the scope of this paper.

We consider 6 profiles (spaced at 200 m in the alongshore, covering 1 km) in each of North Beach, Grayland Plains, Long Beach, and Clatsop Plains. The locations of the chosen profiles maximize record length and avoid the influence of jetties and headlands on nearshore morphology. The profiles in North Beach and Long Beach have 15 years of data covering 1998 to 2012. The Clatsop Plains profiles cover the same time period, but are missing 2004 and 2012. The profiles in Grayland Plains have 14 years of data between 1999 and 2012. These data have the same quality restrictions as used with the regional scale data and are characterized by the same morphological parameters. From 354 profiles, 554 subtidal sandbars were extracted.

The temporally varying data reveal similar statistics of morphometric parameters when compared to the regionally varying spatial data. The mean values for each morphometric parameter are relatively consistent across data sets, while the maximums and minimums are more variable (Figure 5; Figure 8; Figure 10; Table 6). Bar crest depth was the most consistent morphometric parameter in both time and space (Figure 8; Table 6). The depth range of the effective bar zone is also similar in time and space. Mean bar heights in North Beach, Grayland Plains, and Long Beach from the temporal data set are consistent with those from the spatial data set (Table 6; Figure 10), but are more variable.

One of the more striking spatial changes noted through the study region is a transition from transects that predominantly have multiple subtidal bars per profile to transects that predominantly have a single bar per profile. Because the number of bars per profile might change through the NOM cycle, we compare the number of years for which each littoral cell displays a multiple bar system to the number of years for which it displays a single bar system. To be classified as a multiple bar system at least half of the profiles (3) must show at least 2 bars. Along the focus section within each littoral cell, North Beach and Grayland Plains display a single bar system about as often as a multiple bar system. Long Beach and Clatsop Plains display a multiple bar system about twice as often as a single bar system. Based on these results, the observed spatial trends, though capturing significant amounts of sandbar variability, should not be considered to be a complete characterization of the variability over the entirety of the NOM cycle.

Without several more years of nearshore bathymetric data in the non-CRLC littoral cells we will not unequivocally know how well the spatial statistics represent bar morphometrics through time. However, since the results from the CRLC suggest that the range of bar depth, position, and height seen in time are well represented by the spatial data it is reasonable to assume that the correlations between bar morphometrics and environmental variables would hold. Since the number of bars per profile over the bar cycle are not as well represented by the spatial data, inferences about this characteristic are less reliable.

6 Conclusions

A regional scale data set of nearshore bathymetry is used to describe and quantify the spatial variability of sandbar morphology and explore environmental variables that may influence the observed sandbar variability. From north to south along an approximately 260 km stretch of U.S. Pacific Northwest coast: the upper shoreface slope increases, the width of the effective bar zone decreases, the mean bar position decreases, and the maximum bar position decreases. Higher upper shoreface slopes are associated with a transition from transects with predominantly multiple bars per profile to transects with a single bar per profile. Sandbar depths are spatially consistent, with a regional limit of approximately -7 m MLLW. The mean sandbar crest depths for most of the littoral cells examined are not statistically distinct. Of the environmental characteristic variables investigated here, the most substantial regional scale trend observed was the north to south steepening trend in upper shoreface slope. Correlation analyses between environmental variables and bar morphometrics show significant correlations between slope and bar position and also between breaking wave height and depth range and wavelength and depth range. Steepening of the upper shoreface slope is associated with decreasing bar positions from the shoreline. Higher breaking wave height and wavelength are linked to greater depth ranges. No significant correlations between bar morphometrics and tide range, grain size, wave direction, wave power, or dimensionless fall velocity were found. While data collected over large spatial scales captures significant amounts of overall sandbar morphometric variability, it does not completely characterize the variability over the entirety of the net offshore migration cycle.

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9 Figures

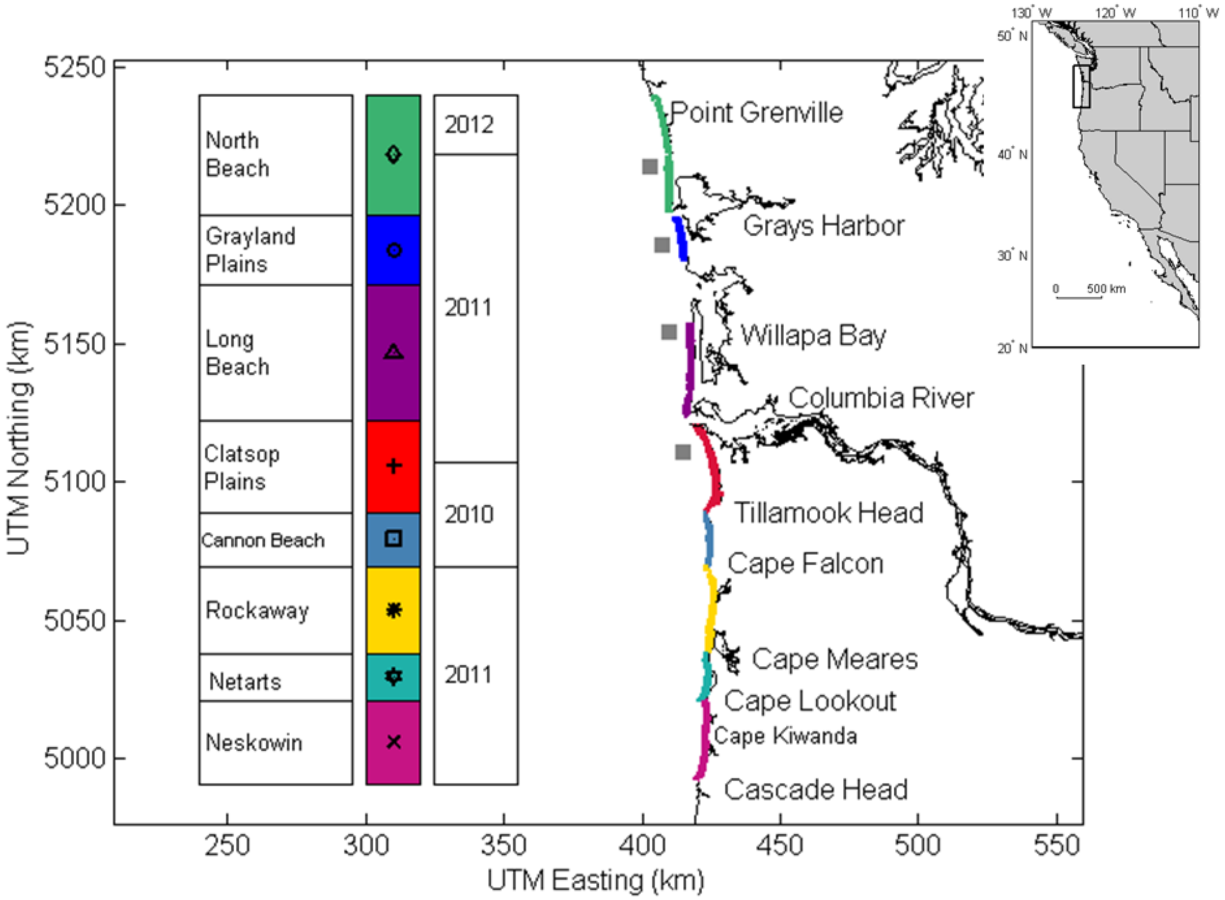

Figure 1. Map of the study area. Vertical bars show the year of data collection for each area, color and symbol assigned to each littoral cell, and name of each littoral cell. Each cross-shore transect is plotted along the coast using the respective color of each littoral cell. Gray squares represent the location of the transects used for the temporal study.

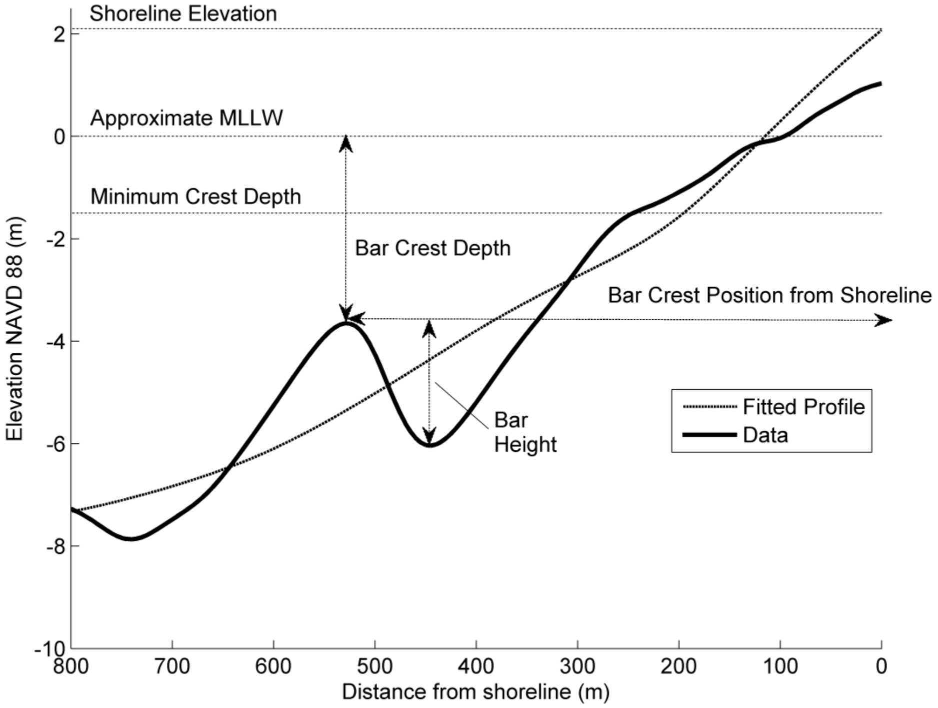

Figure 2. Definition sketch of sandbar morphometric parameters. Minimum crest depth refers to the inclusion of subtidal bars only.

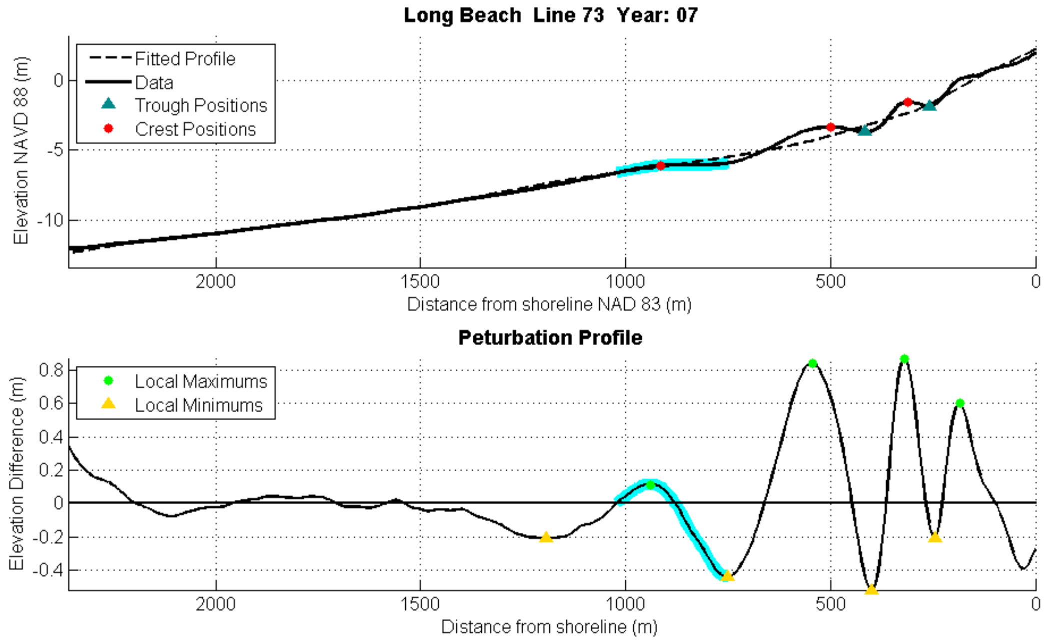

Figure 3. Top: Perturbations from the mean profile greater than 0.2m are shown on the smoothed data. The terrace location is highlighted in blue. Bottom: Perturbations greater than 0.2m from the mean profile are identified.

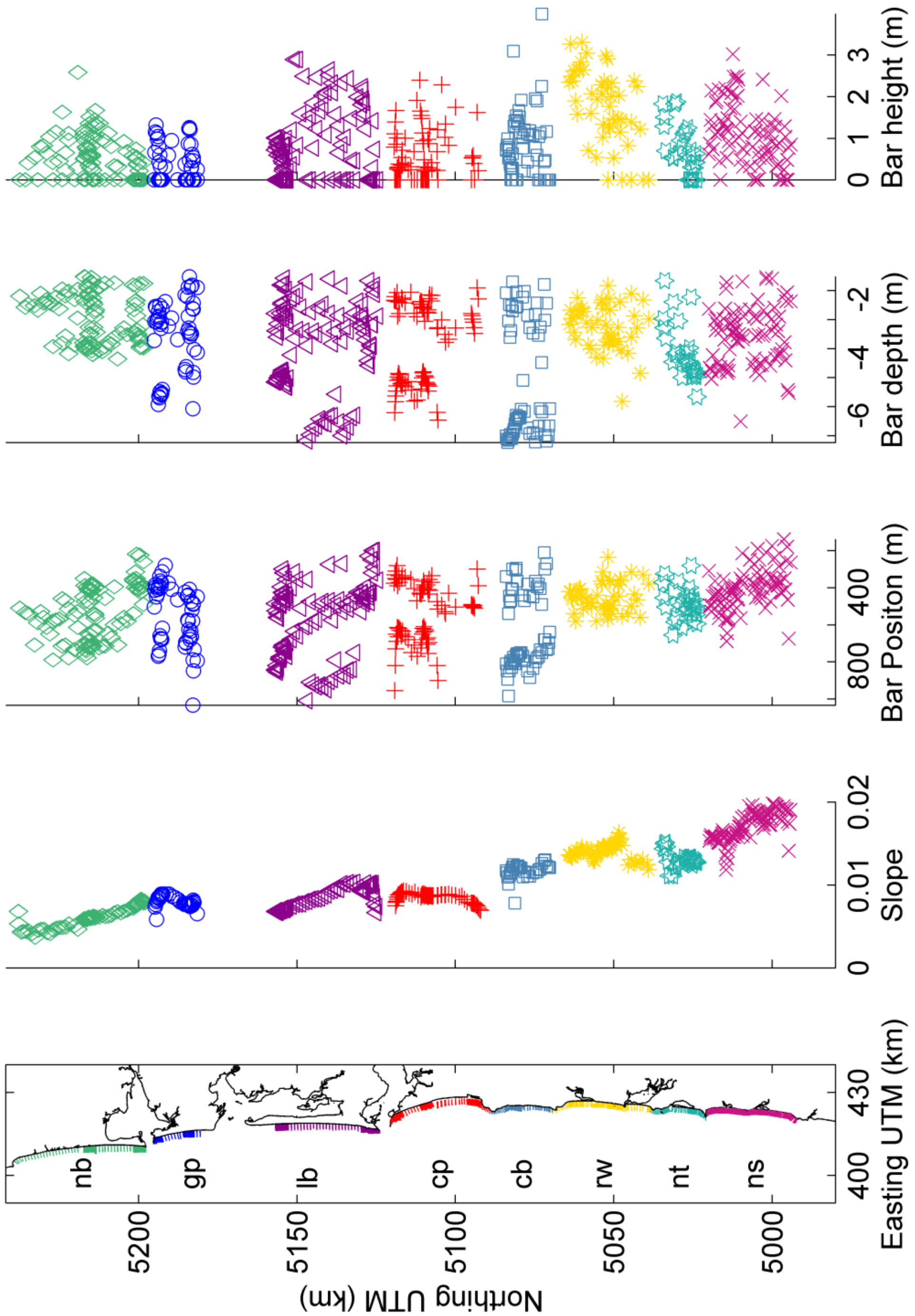

Figure 4. Summary of bar morphometric parameters separated by littoral cell. Each transect is plotted along the shoreline in panel 1. Littoral cells are labeled with their assigned abbreviation. Panels 2 through 4 show the variability bar position, bar depth, and bar height, respectively. Each littoral cell is represented by the color and symbol indicated in Figure 1.

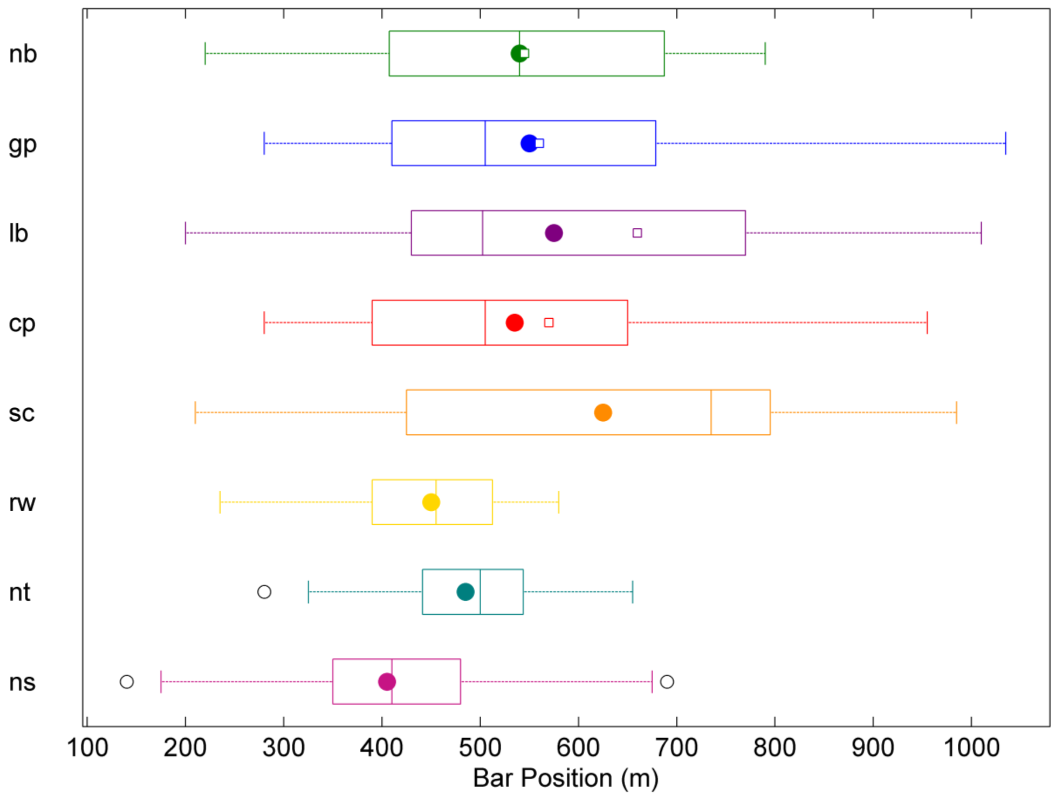

Figure 5. Boxplot of the bar position statistic. Black open circles represent outliers. Solid circles represent means of the spatial data. Open squares represent means of the temporal data. Some of the temporal means plot directly on top of the spatial means.

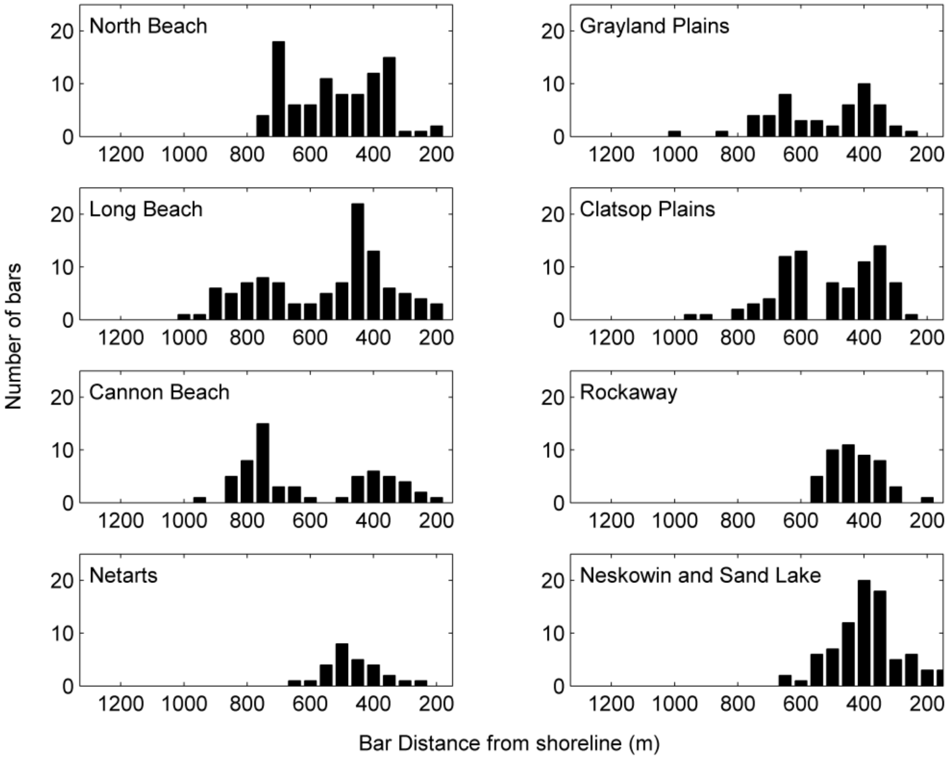

Figure 6. Histograms of bar position relative to the shoreline within each littoral cell documenting the transition from multiple barred systems to single barred systems. Bins are 50m wide.

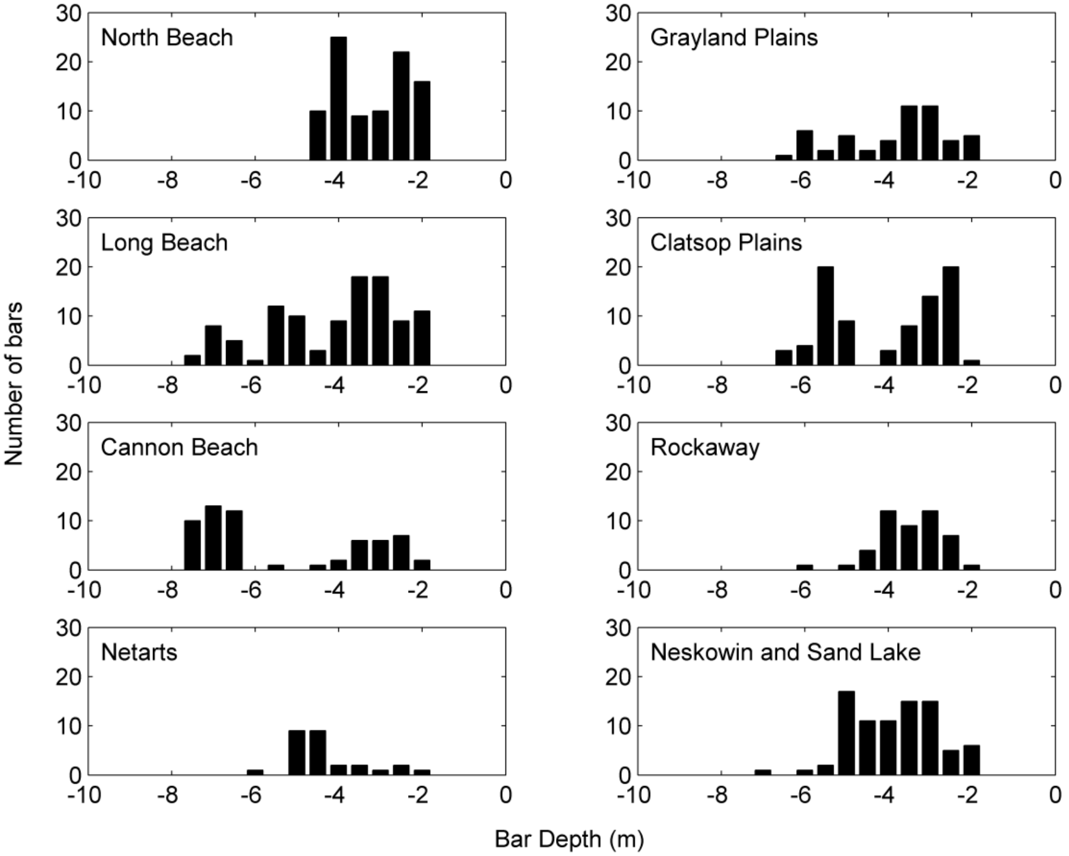

Figure 7. Histograms of bar depth for each littoral cell document the transition from multiple bars per profile to a single bar per profile. All littoral cells share a similar maximum depth. Bin widths are 0.5m.

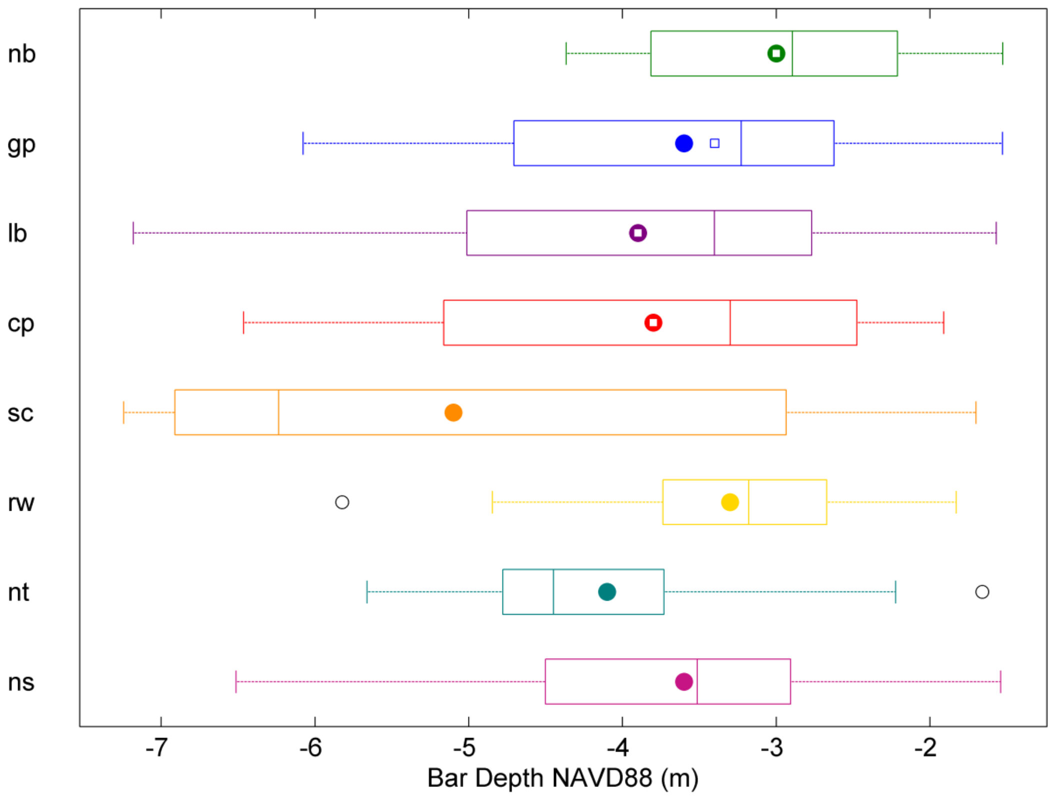

Figure 8. Boxplot of the bar depth statistic. Black, open circles represent outliers. Solid circles represent means of the spatial data. Open squares represent means of the temporal data. Some of the temporal means plot directly on top of the spatial means.

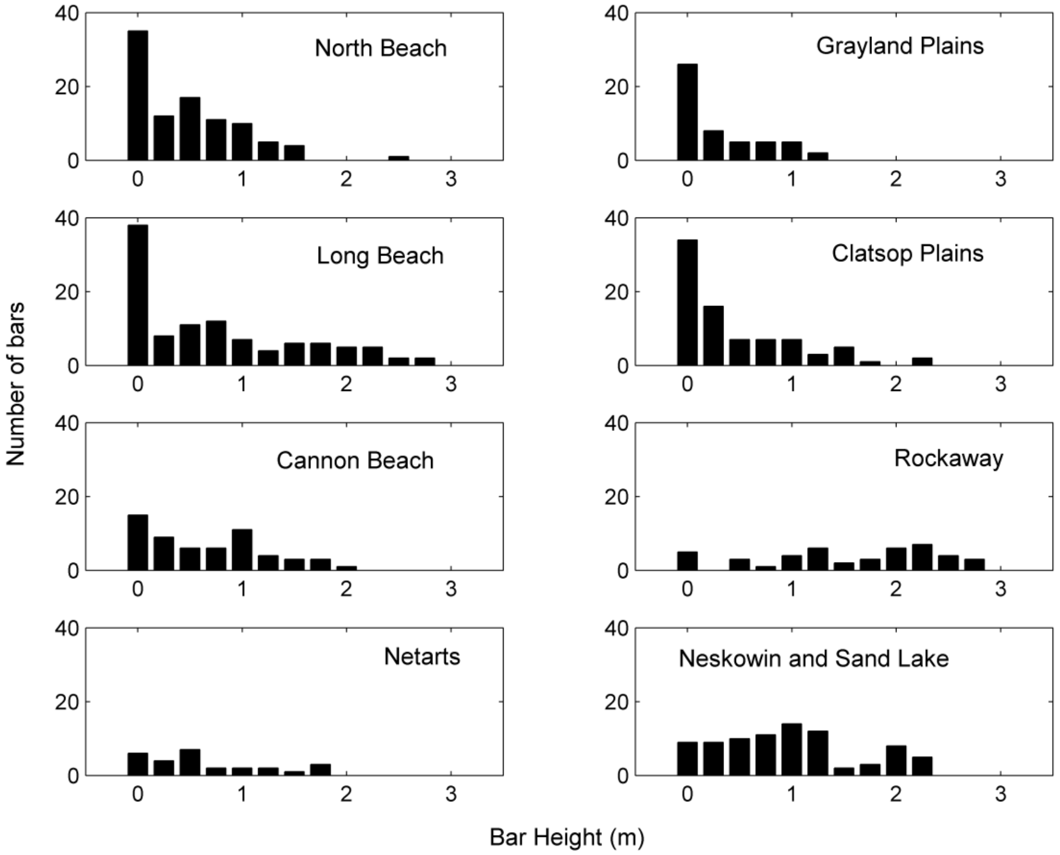

Figure 9. Histograms of bar height for each littoral cell. Bin widths are 0.25m.

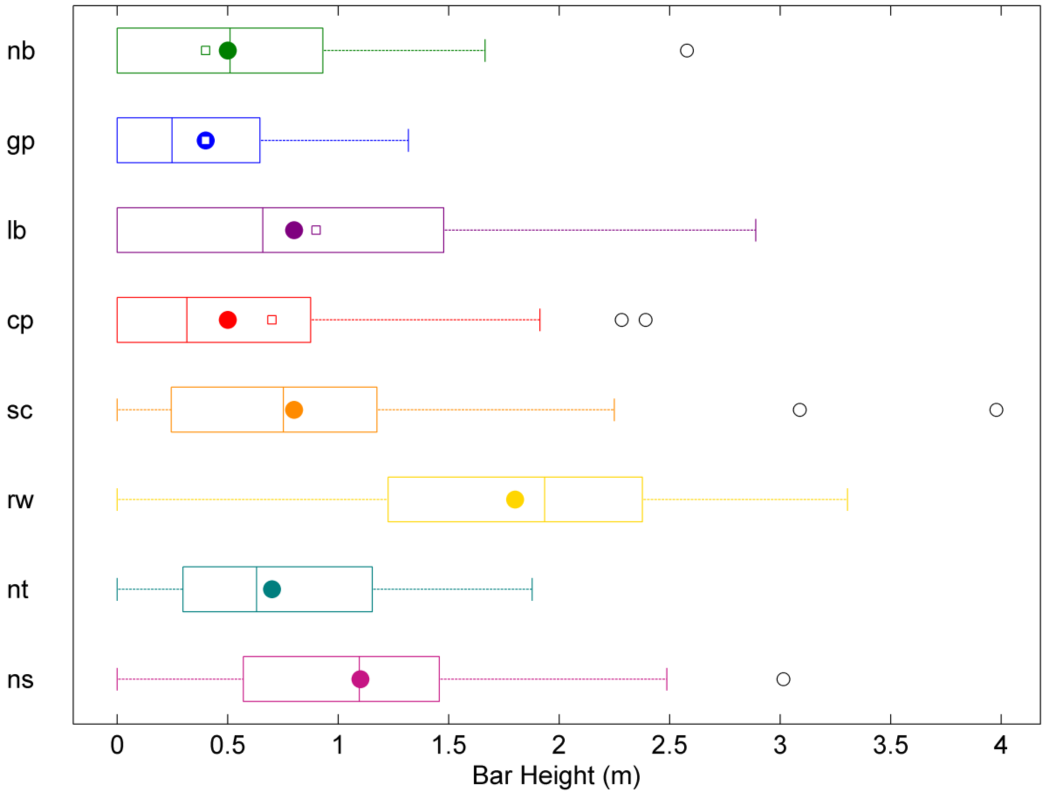

Figure 10. Boxplot of the bar height statistic. Black, open circles represent outliers. Solid circles represent means of the spatial data. Open squares represent means of the temporal data. The temporal mean of Grayland plots directly on the spatial mean.

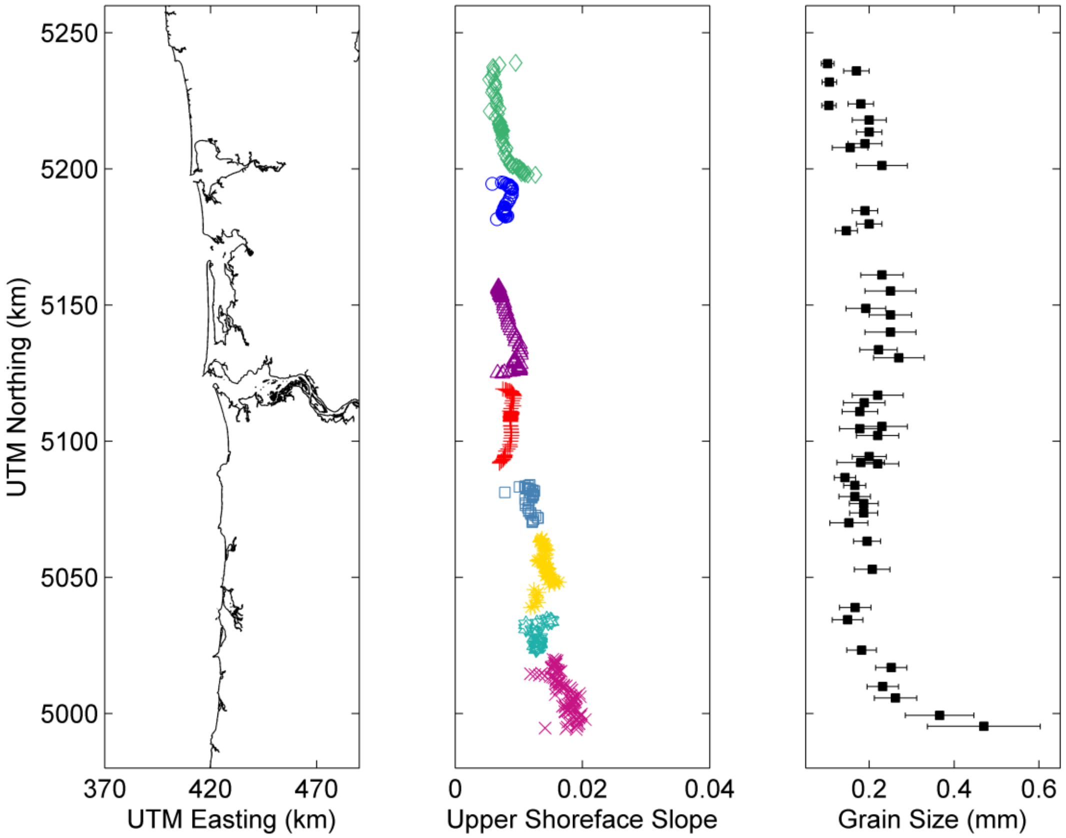

Figure 11. Regional variations in slope and mean grain size. The slope along each transect is represented by the color and symbol assigned to each littoral cell as indicated in Figure 1. The mean grain size is shown with error bars illustrating sorting using the standard deviation about the mean.

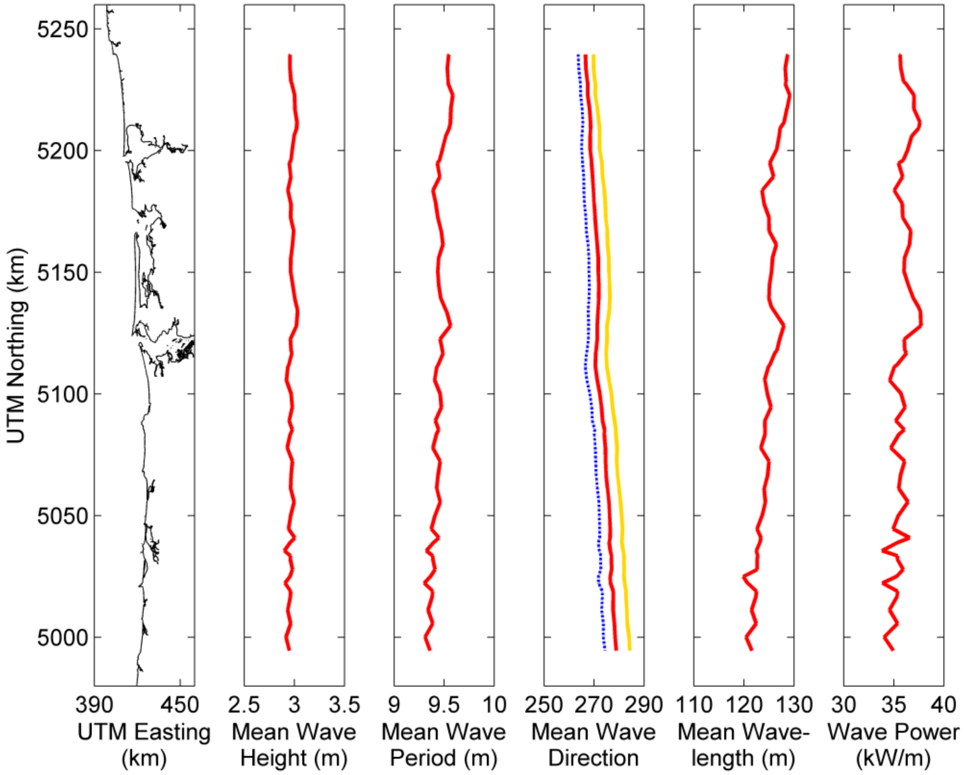

Figure 12. Longshore variability in mean breaking wave height (H_b), mean wave period (T), mean wave direction (MWD), mean wavelength (L_0), and wave power (P) as computed from the hindcast. Means are computed over the entirety of the data record and for breaking wave conditions unless otherwise specified. Mean wave direction is shown for summer (yellow), winter (blue dashed), and entire record (red). Mean wave direction is in an azimuthal coordinate system with waves at 270 arriving from due west. Mean wave direction is shown 50m depth.

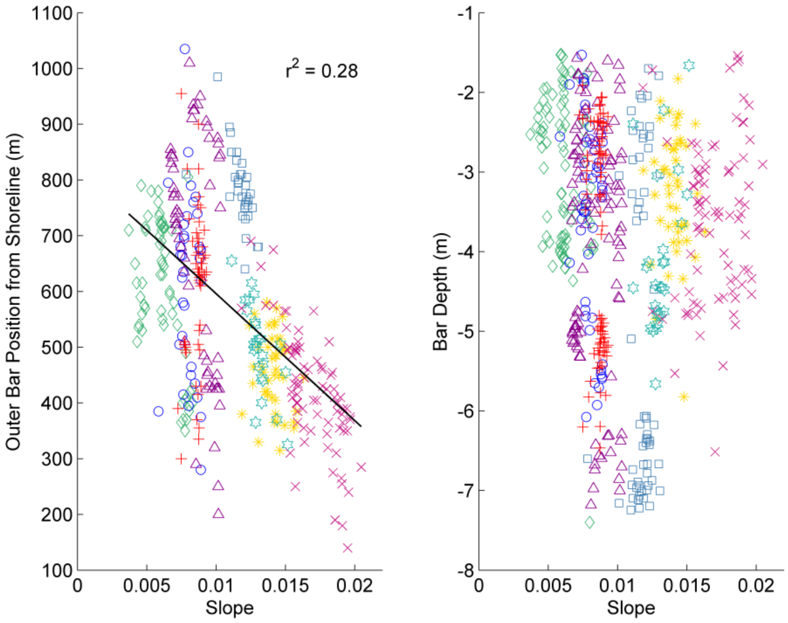

Figure 13. Relationship between upper shoreface slope and outer bar position and depth with all littoral cells represented by their respective colors and symbols indicated in Figure 1. The relationship between slope and outer bar position is significant at the 95% confidence level.

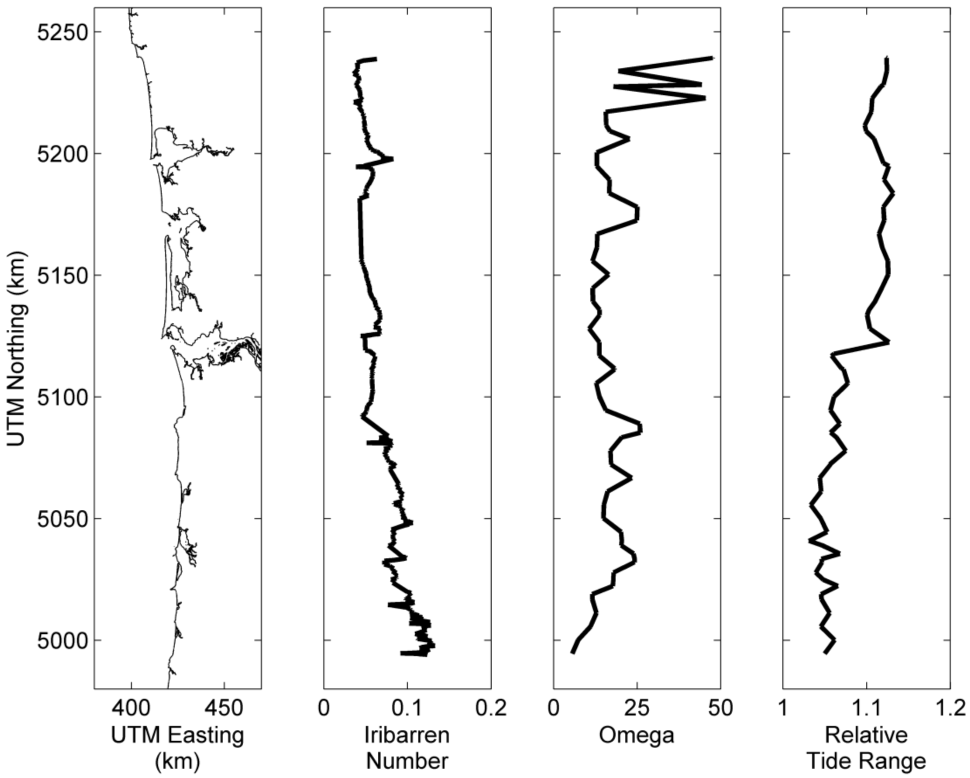

Figure 14. Regional variability in Iribarren number, dimensionless fall velocity (omega), and relative tide range.

10 Tables

Table 1. Characteristics of the regional nearshore bathymetric data set. The amount of data for each littoral cell varies according to its length and the density of the transect spacing. Sandy coastline refers to the length of coastline not including headlands and estuaries.

Littoral Cell	Length of sandy coastline (km)	Number of transects analyzed	Number of bars extracted	Year data collected (All years of data)
North Beach	43	73	95	2011, '12 (1998-2012)
Grayland Plains	18	40	51	2011 (1998-2012)
Long Beach	42	68	106	2011 (1998-2012)
Clatsop Plains	29	65	82	2011 (1998-2012)
Cannon Beach	15	36	60	2010 (2010)
Rockaway	26	57	47	2011 (2008-09, ‘11)
Netarts	11	28	27	2011 (2011)
Neskowin	26	98	84	2011 (2011)
Total	**210**	**465**	**552**	**-**

Table 2. Bar Position Statistics

Littoral Cell	Minimum distance from shoreline (m)	Maximum distance from shoreline (m)	Width of effective bar zone (m)	Mean distance from shoreline (m) (Std)
North Beach	220	805	585	540 (150)
Grayland Plains	280	1035	755	550 (165)
Long Beach	200	1010	810	575 (205)
Clatsop Plains	280	955	670	535 (160)
Cannon Beach	210	985	766	625 (210)
Rockaway	235	580	345	450 (80)
Netarts	280	655	375	485 (90)
Neskowin	140	690	550	405 (110)

Table 3. Bar Depth Statistics

Littoral Cell	Maximum bar depth (m)	Minimum bar depth (m)	Depth range of effective bar zone (m)	Mean bar depth (m) (Std)
North Beach	4.4	1.5	5.9	3.0 (1.0)
Grayland Plains	6.1	1.5	4.6	3.6 (1.3)
Long Beach	7.2	1.6	5.6	3.9 (1.5)
Clatsop Plains	6.5	1.9	4.6	3.8 (1.4)
Cannon Beach	7.2	1.7	5.5	5.1 (2.0)
Rockaway	5.8	1.8	4.0	3.3 (0.8)
Netarts	6.8	1.7	5.1	4.1 (1.0)
Neskowin	6.5	1.5	5.0	3.6 (1.0)

Table 4. Bar Height Statistics. Mean bar heights in parentheses represent the mean taken without the zero heights associated with nearshore terraces.

Littoral Cell	Maximum bar height (m)	Mean bar height (m)	Std of mean (m)	Percent terraces
North Beach	2.6	0.5 (0.8)	0.5	34
Grayland Plains	1.3	0.4 (0.7)	0.4	49
Long Beach	2.9	0.8 (1.3)	0.8	34
Clatsop Plains	2.4	0.5 (0.8)	0.6	33
Cannon Beach	4.0	0.8 (1.1)	0.8	22
Rockaway	3.3	1.8 (1.9)	0.9	11
Netarts	1.9	0.7 (0.9)	0.6	22
Neskowin	3.0	1.1 (1.2)	0.7	10

Table 5. Correlations coefficients for environmental variables and bar morphometric parameters. Correlations that are significant at the 95% confidence level are bold and blue.

	Effective Width of Bar Zone	Maximum Position	Mean Position	Mean Depth	Depth Range	Mean Height
Slope	-0.64	**-0.78***	**-0.74***	0.54	-0.15	0.11
Grain Size	0.029	-0.18	-0.56	0.26	-0.15	-0.15
Breaking Wave Height	0.40	0.31	0.48	0.30	**0.77**	-0.17
Wave Period	0.51	0.51	0.61	-0.16	0.61	-0.28
Mean Wavelength	0.41	0.33	0.50	0.24	**0.77**	-0.20
Wave Direction	-0.62	-0.70	-0.62	0.52	-0.24	0.33
Wave Power	0.54	0.50	0.60	0.10	0.68	-0.18
Longshore Component of Wave Power	-0.28	-0.41	-0.10	0.55	0.63	0.24
Spring Tide Range	0.70	0.71	0.57	-0.38	0.37	-0.28
Iribarren Number	-0.64	**-0.78***	**-0.74***	0.54	-0.15	0.11
Dimensionless Fall Velocity	-0.15	-0.027	0.33	-0.29	0.43	-0.20
Relative Tide Range	0.70	**0.73**	0.54	-0.48	0.25	-0.28

*Slope and Iribarren number are strongly correlated.

Table 6. Selected Bar Statistics for Temporal Data

Littoral Cell	Mean distance from shoreline (m)	Width of effective bar zone (m)	Mean bar depth (m)	Depth range of bar zone (m)	Mean bar height (m)	Percent Terraces
North Beach	545	600	3.0	3.4	0.4 (0.7)	41
Grayland Plains	560	735	3.4	5.1	0.4 (0.8)	48
Long Beach	660	865	3.9	5.2	0.9 (1.3)	28
Clatsop Plains	570	935	3.8	6.7	0.7 (1.2)	27