Investigating the role of complex sandbar morphology on nearshore hydrodynamics

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ABSTRACT

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Coastal environments are characterized by complex feedbacks between flow, sediment transport, and morphology, often resulting in the formation of nearshore sandbars. In many locations, such as Hasaki (Japan), the Netherlands, and the Columbia River Littoral Cell (CRLC, USA), these sandbars exhibit a net offshore migration (NOM) cycle whereby these features form in the inner surf zone, migrate seaward and decay offshore on interannual cycles. Depending on the stage of the cycle, the number and configuration of the bars may differ widely. It has long been recognized that sandbars act as natural barriers during storm events by dissipating wave energy through breaking far from the beach face. Thus, dependent on the stage of the NOM cycle, one might expect significant variability in nearshore hydrodynamics. Using a non-linear wave model we demonstrate that inter-annual variability in sandbar configuration can significantly alter inner surf zone and swash zone processes. The model indicates that under different end-member NOM stages the same wave conditions can result in up to a 36% variance in the vertical extent of infragravity runup and can alter both the rate and direction of net cross shore sediment transport.

ADDITIONAL INDEX WORDS: *runup, setup, infragravity swash, coastal geomorphology, sandbar migration, cross shore sediment transport*

INTRODUCTION

Sandy coastal systems are highly dynamic and under the combined forces of waves, winds, currents, and water levels are prone to many hazards that threaten valuable ecological, recreational, and commercial resources. Coastal erosion and backshore flooding, two primary hazards to these regions, are both largely governed by local extreme total water levels (TWL) which are defined as the combination of mean sea level, tides, non-tidal residuals including storm surge, and wave runup. The magnitudes of the various components of the TWL are influenced by atmospheric conditions (e.g., pressure, wind), oceanic parameters (e.g., wave height), and coastal morphology (e.g., beach slope). In some settings, such as the US West Coast, the wave-induced components of TWL typically dominate the overall TWL signal, particularly during extreme high water events. The wave induced portion of the TWL, runup, consists of two distinct components. Wave setup is the increase in mean water level due to gradients in radiation stresses whereas swash is the time-varying variance around the setup.

Traditionally, empirical metrics have been widely adopted by scientists and management agencies to predict the wave induced components of TWL. However, recent studies have recognized limitations in applying these empirically based formulae where complex morphologies, such as sandbars, are prevalent (e.g., Cox *et al*., 2013; Stephens *et al*., 2011). In many locations throughout the world, including Japan, the Netherlands, and the US, a systematic trend of interannual net offshore sandbar migration (NOM) has been observed whereby bars form in the inner nearshore, migrate seaward across the surf zone, and eventually decay offshore in cyclic patterns (Walstra *et al*., 2012). The presence of a sandbar that has migrated offshore could result in breaking occurring far from the shoreline during storm conditions and significantly different surf zone and intertidal hydrodynamics relative to a case with no offshore bar. Therefore the stage of the NOM has implications for the risk of coastal flooding and erosion.

Here we explore how nearshore hydrodynamics vary in response to different complex, multi-bar configurations. Specifically we apply a non-linear wave and current model (XBeach) to investigate how wave runup and cross-shore sediment transport vary during differing stages of NOM in the Columbia River Littoral Cell (CRLC, USA).

BACKGROUND

Columbia River Littoral Cell

The CRLC is a high energy, meso-tidal, progradational coastal system that extends approximately 165 km between Tillamook Head, OR and Point Grenville, WA on the Pacific coast of the US (Figure 1). The system consists of four prograded barrier plain sub-cells separated by the estuary entrances of the Columbia River, Willapa Bay, and Grays Harbor. Each barrier is generally characterized by wide, dissipative, gently sloping beaches with

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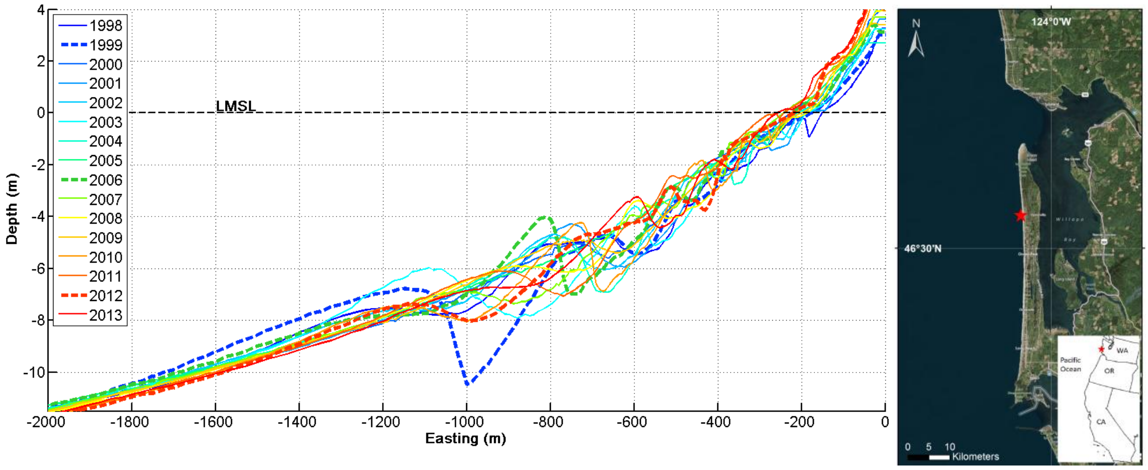

Figure 1. Annual bathymetric profiles from CRLC transect 66 from 1998 to 2013 and map with transect location (red star).

broad surf zones and multiple sandbars with fine sand derived from the Columbia River (Ruggiero *et al*., 2005).

The Pacific Northwest experiences one of the most extreme wave climates in the world with annual deep-water significant wave heights (SWH) of about 3 m and peak wave periods of about 12 s. Large storms in the winter months regularly produce waves in excess of 8 m, with the approximately one storm per year generating SWHs greater than 10 m (Ruggerio *et al*., 2010).

Net Offshore Sandbar Migration

It has long been recognized that nearshore sandbars act as natural barriers to coastal erosion during storm events by dissipating wave energy through breaking far from the beach face. Changes in breaking wave patterns alter surf zone and intertidal wave and current characteristics, which consequently influence sediment transport and morphologic change. The number and configuration of these sandbars can therefore have a major influence on inner surf zone and intertidal processes.

Sandbars are common nearshore features on sandy coastlines throughout the world and are constantly evolving in response to hydrodynamic forces and gradients in sediment transport. Large waves result in a strong offshore directed current in the lower water column (undertow) that results in the seaward migration of sandbar systems (Hoefel and Elgar, 2003). However, during low wave conditions undertow is relatively weak and non-linear properties of the flow can drive net onshore sediment transport. Among the important factors in onshore directed transport are velocity skewness, acceleration skewness, and boundary layer streaming (Thornton *et al*., 1996; Hoefel and Elgar, 2003; Aagard *et al*., 2012). Resulting from the cumulative effects of these competing processes, an interannual trend of net offshore subtidal bar migration (NOM) is observed at many locations throughout the globe. Depending on the stage of the offshore migration cycle, the number of bars, their location, and their size can vary considerably (Ruessink *et al*., 2003). Similarly, there is significant intersite variability in bar behavior. For example in Hasaki (Japan) bars typically are generated nearshore, migrate across the surf zone, and dissipate offshore all within a single year, while this cycle averages 15 years in Noord-Holland (the Netherlands).

A long term morphologic dataset from the CRLC (Ruggiero *et al*., 2005) spanning 1998 to 2013 shows a clear trend of NOM (Figure 1). The data also demonstrates that there is large temporal variability in bar configuration. For example, in 2006 the outer bar crest was located in a water depth of 4 m relative to local mean sea level with a crest to trough height of 3m while in 2012 it was 7.4 m deep with a height of 0.6 m. These conditions represent the shallowest (2006) and deepest (2012) outer bar configurations observed within the CRLC dataset. Further, the relatively shallow depth and proximity to the shoreline of the outer bar in 2006 suggests a much earlier stage of the NOM relative to the 2012 profile. The bar depth in the 1999 profile is between that of the 2006 and 2012 cases at 6.8 m, however exhibits an anomalously large bar height of 3.7 m. Bar height is a function of a number of morphodynamic processes and in the case of the 1999 profile represents an extreme end-member case likely the result of the storm event of record for the CRLC that occurred in March of that year (Allan and Komar, 2002).

The data indicates that the average life cycle of a bar in the Oysterville region of the Long Beach subcell of the CRLC is about 2.4 years. As bars progress through the cycle and migrate further offshore there is a clear trend of increasing mean bar depth as demonstrated in Figure 2. Therefore, depending on the stage of the NOM wave breaking patterns will vary considerably, especially during large storm events. For this reason it is expected that the stage of NOM will have a large control on inner nearshore and intertidal hydrodynamics within multi-barred systems.

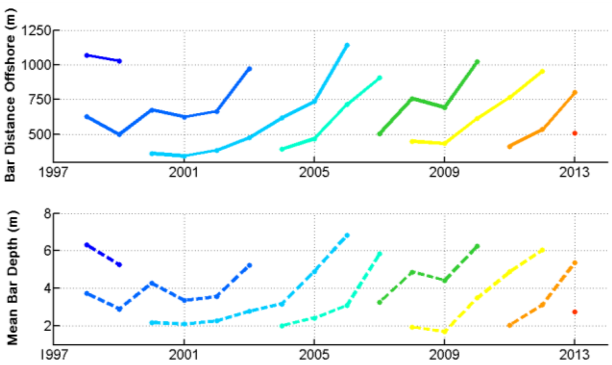

Figure 2. Average bar distance offshore (left panel) and mean bar depth (right panel) from 1998 to 2013 in the Oysterville region of the CRLC. Colors represent individual sandbars.

Wave Runup

The TWL determines the horizontal and vertical extent of the interface between water and land and serves as an important metric for backshore flooding and beach erosion (e.g., Sallenger, 2000). In some physical settings extreme TWLs are primarily driven by storm surge, such as on the East and Gulf coasts of the US during major tropical cyclones. However, along the US West Coast, where the continental shelf width is relatively narrow, the wave induced component of extreme TWLs can dominate.

A number of field experiments using in-situ and remote sensing measurements have been completed in an attempt to correlate the instantaneous wet/dry beach interface to local wave conditions. Derived from Argus video monitoring data, the most commonly used formulation of runup is that of Stockdon *et al.* (2006). Data from 10 experiments on 6 different beaches was used to develop empirical relations of setup (η), incident swash (S_{inc}), and infragravity swash (S_{IG}), which were parameterized as:

$$\eta = 0.35\,B_f\ \ H_o\,L_o\ ^{1/2} \tag{1}$$

$$S_{inc} = 0.75\,B_f\ \ H_o\,L_o\ ^{1/2} \tag{2}$$

$$S_{IG} = 0.06\ \ H_o\,L_o\ ^{1/2} \tag{3}$$

where H_o is the deepwater wave height and L_o is the deepwater wave period. They give the $R_{2\%}$, which is the runup that is exceeded only 2% of the time, as:

$$R_{2\%} = 1.1\ \ \eta + \overline{\frac{S_{inc}{}^2 + S_{IG}{}^2}{2}} \tag{4}$$

Though some of the beaches that were analyzed for these experiments had nearshore sandbars, the only explicit incorporation of the coastal morphology within this formulation is the foreshore slope. The authors did recognize that other metrics such as the surf zone slope could similarly be important for runup, although they did not find statistically significant correlations to justify incorporating those factors into their model.

In reality, however, it seems intuitive that nearshore morphologic features, such as sandbars, might have a considerable influence on runup. Recognizing this, researchers have sought to explicitly correlate swash and setup to properties of simple single bar geometries. Stephens *et al.* (2011) found that overall foreshore slope was a poor descriptor of the beach profile and that wave setup was strongly dependent on the presence and configuration of sandbars in the surf zone. Cox *et al.* (2013) used XBeach to correlate the presence of nearshore bars to infragravity (IG) swash. They found that in cases where waves broke seaward of the bar system that IG swash was reduced at the shoreline relative to cases without a bar. They propose a new model-derived empirical formulation for IG swash accounting for basic geometric considerations of the single bar system as an improvement on the Stockdon *et al.* (2006) model.

Surf Zone Sediment Transport

Sediment transport within the inner surf zone remains poorly understood in part because of flow nonlinearities and the difficulty in obtaining in-situ measurements. However, many factors, including mean currents, incident waves, and IG waves, are known to influence the cross-shore fluxes of sediment in this environment (e.g. Roelvink and Stive, 1989).

A number of approaches exist that attempt to characterize cross-shore sediment transport fluxes often taking a form similar to:

$$q_x\ \ x,y,t\ \ = \frac{\partial hCu^E}{\partial x} + \frac{\partial}{\partial x}\ D_h h\frac{\partial C}{\partial x} \tag{5}$$

where C is the depth averaged sediment concentration, D_h is a sediment diffusion coefficient, h is the local water depth, and u^E is the cross-shore directed Eulerian velocity (Roelvink *et al.*, 2010). Equilibrium sediment concentrations are commonly predicted using the Soulsby-van Rijn formulation (Soulsby, 1997) to solve for advective and diffusive sediment transport along sandy coasts.

Just as sandbars have some influence on runup, morphology likewise alters inner nearshore hydrodynamics and sediment transport. For example wave breaking patterns will alter the asymmetric nature of the waves which will in turn influence advective transport. These morphodynamic feedbacks are important for whether a coastal system will be erosive or accretional. Therefore, in addition to investigating how nearshore morphology influences runup, we explore how bar configuration alters cross-shore sediment fluxes according to the sediment transport formulas available in XBeach.

METHODS

In order to assess how complex morphology affects nearshore hydrodynamics and sediment transport, the eXtreme Beach (XBeach) model is applied for the CRLC under different stages of NOM. XBeach is a state of the art model that simulates spatially varying, depth averaged (2DH) flow characteristics and sediment transport in shallow water coastal environments (Roelvink *et al.*, 2010). The model is short-wave averaged, but resolves wave groups and infragravity wave motions as waves refract, shoal, break, and dissipate in the nearshore. Long period (infragravity) wave motions can dominate the hydrodynamics in the swash zone and are particularly important in the U.S. Pacific Northwest (Ruggiero *et al.*, 2004). As a non- short-wave resolving model, formulations do not directly take into account intra-wave properties. Wave shape induced velocity and acceleration skewness, are therefore parameterized using the Ursell number (Roelvink, 2010). Low frequency and mean flows are predicted using the nonlinear shallow water equations (NSWE). The Soulsby-van Rijn sediment transport formula is used to predict cross-shore and alongshore fluxes of sediment.

The XBeach model was applied to beach profiles from 1999, 2006, and 2012 from the CRLC dataset, which exhibit distinct phases of the NOM cycle (Figure 1). The model domain has variable spacing in the cross-shore direction with sub-meter resolution at the shoreline and up to 25 m resolution in intermediate water depths. The model domain extends 2,000 m offshore, which corresponds approximately to the 12m depth contour. The bathymetry was assumed to be uniform alongshore, however to generate bound long waves the model was run in 2DH mode and was extended 1 km in the alongshore direction with grid spacing of 25 m. For each nearshore bathymetric configuration the model is forced with combinations of offshore waves with SWHs of 1 to 10 m and periods of 6 to 18 s representing a realistic range of wave conditions for the CRLC. Offshore wave spectra using these heights and periods were modelled by the JONSWAP formulation and were linearly shoaled to the local XBeach model domain using the Simulating WAves Nearshore (SWAN) model (Booij *et al.*, 1999). For simplicity all offshore waves input into SWAN were assumed to be propagating normally to shore. All other inputs to SWAN and XBeach were assumed to be the model default although morphologic updating is turned off such that our focus in on nearshore hydrodynamics and sediment transport.

For all 70 simulations that made up the run matrix for each bathymetric profile, XBeach was run for 1 hr and a time series of total water levels was extracted from the model output. Additional outputs such as current velocities and sediment fluxes were also obtained for select runs.

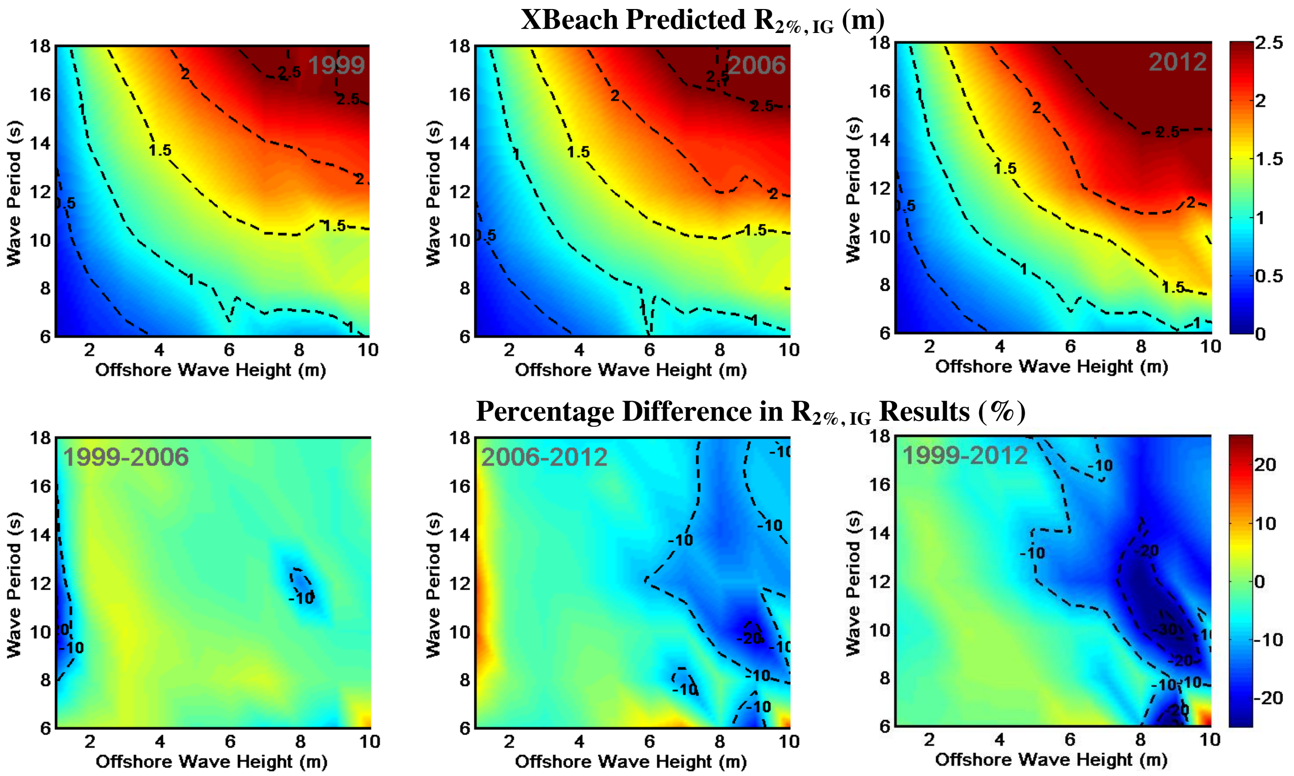

Figure 3. Model predicted $R_{2\%,\ IG}$ for the 1999, 2006, and 2012 CRLC profiles from transect 66 under different combinations of offshore significant wave heights and peak wave periods (upper panels). Difference in results between 1999 and 2006, 2006 and 2012, and 1999 and 2012 (lower panels).

RESULTS

Wave Runup

XBeach simulated wave runup estimates are presented in Figure 3. The $R_{2\%,\ IG}$ metric represents the water level that is only exceeded 2% of the time resulting from setup and infragravity swash (incident swash is not accounted for in XBeach) and is given by:

$$R_{2\%,\ IG} = 1.1\ \eta + \frac{4*\sigma_{IG}}{2} \qquad (6)$$

where σ_{IG} is the standard deviation of the swash maxima. This approach is consistent with that used by Stockdon *et al*. (2006). As expected the results show that runup increases with increasing offshore wave height and increasing peak period. For a 2 m, 8 s wave (characteristic of average wave conditions in the CRLC), the $R_{2\%,\ IG}$ is 0.45 m, 0.46 m, and 0.46 m, for the 1999, 2006, and 2012 cases, respectively. Under these moderate wave conditions, model results indicate that the influence of varying bathymetry is negligible – in part because wave breaking does not occur until relatively close to shore. However in the Pacific Northwest, waves reaching 10 m are not uncommon during winter storm events (Allan and Komar, 2002). An 8 m, 14 s wave (characteristic of a winter storm) results in predicted $R_{2\%,\ IG}$ of 2.04 m, 2.08 m, and 2.45 m, for the 1999, 2006, and 2012 cases, respectively, demonstrating more variability in the predicted runup during high energy conditions. As shown in Figure 3, the differences between the three years can reach up to 36% for the same offshore conditions but differing nearshore morphology.

Numerical model results were also compared against the empirical model of Stockdon *et al*. (2006) for the setup and IG component of swash in Figure 4. The two approaches for computing $R_{2\%,IG}$ show similar trends with some notable exceptions. XBeach underpredicts Stockdon for low energy conditions (small wave height and/or wave period), while XBeach typically predicts higher $R_{2\%,IG}$ when wave height and period are larger such as is typical during storms. The mean difference between Stockdon and XBeach is -0.12 m, -0.12 m, and -0.21 m for the three bathymetries, with negative results representing an overprediction of the empirical model by XBeach. Overall the two approaches yield a difference of up to -0.7 m in magnitude (Table 1). The maximum percentage difference between the two approaches was 42%.

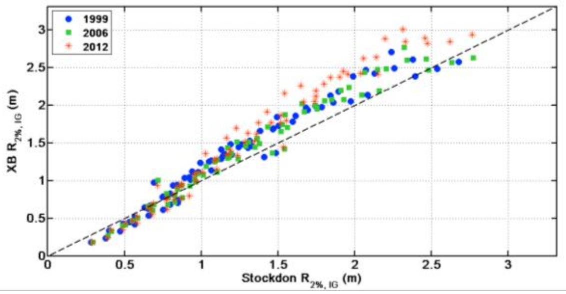

Figure 4. Comparison of $R_{2\%,\ IG}$ between XBeach and Stockdon formulation for 1999, 2009, and 2012.

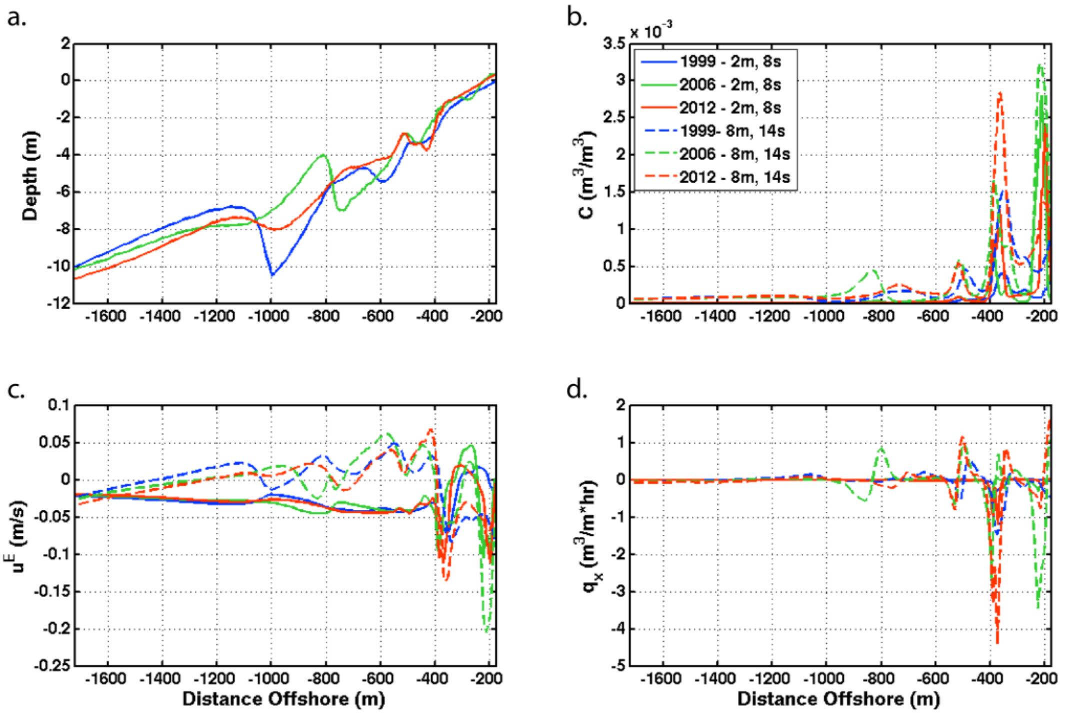

Figure 5. Average (b) total sediment concentration, (c) Eulerian transport velocity, and (d) cross shore sediment transport with distance offshore for the 1999, 2006, and 2012 simulations for **Scenario 1** – H_s = 2m, T = 8s (solid lines), **Scenario 2** – H_s = 8 m, T = 14s (dotted lines). Bathymetry for the three years is shown in (a).

Table 1. Magnitude and percentage (in parentheses) differences between Stockdon and XBeach $R_{2\%,\,IG}$. Negative values represent an overprediction of Stockdon by XBeach.

Metric	**1999**	**2006**	**2012**
Mean	-0.12 m (-6.5 %)	-0.12 m (-6.3%)	-0.21 m (-10.7%)
Minimum	-0.47 m (-41.7%)	-0.49 m (-42.4%)	-0.70 m (-40.0 %)
Maximum	0.14 m (37.5%)	0.12 m (37.2%)	0.16 m (37.4%)

Surf Zone Sediment Transport

While a host of factors affect cross-shore sediment transport, our goal here is to assess the relative role that the net offshore bar migration cycle plays on nearshore hydrodynamics and sediment transport. Two specific scenarios were investigated to look at spatial trends in cross-shore transport: a 2 m, 8 s wave and an 8 m, 14 s wave. These are characteristic of U.S. Pacific Northwest average wave conditions and storm wave conditions as previously described. XBeach was used to calculate sediment transport fluxes for these two scenarios for each of the three bathymetries. Figure 5 shows alongshore and time averaged cross-shore sediment transport properties for the six cases.

In the outer sandbar zone, defined here as the region from the -10 m contour to the outer bar trough, the average total cross shore transport over the one hour simulation is -1.8×10^{-3} m^3 m^{-1}, -3.5×10^{-3} m^3 m^{-1}, and -1.4×10^{-3} m^3 m^{-1} for 1999, 2006, and 2012, respectively, for the average wave case, where negative values represent net offshore transport. For the storm event, the transport is predicted to have transport rates of 0.091 m^3 m^{-1}, -0.022 m^3 m^{-1}, and -0.019 m^3 m^{-1} respectively for the three bathymetries.

The inner sandbar zone is defined here as the region from the outer sandbar trough to the mean water level. In this zone the average cross shore transport rate is -0.024 m^3 m^{-1}, -0.042 m^3 m^{-1}, and -0.047 m^3 m^{-1} for the average wave case and -0.082 m^3 m^{-1}, -0.15 m^3 m^{-1}, and -0.17 m^3 m^{-1} for the storm waves.

The sediment concentrations in the inner bar zone are quite different between the three bathymetries, which ultimately has a major influence on the net cross-shore transport. Unsurprisingly, the total sediment concentration (which here includes both bedload and suspended load transport) is higher for the storm wave cases relative to the average wave condition.

DISCUSSION AND CONCLUSIONS

Many sandy coastal systems are characterized by a trend of net offshore sandbar migration. Dependent on stage of the NOM, the shoreline has different exposure to hazards such as flooding and erosion. The XBeach model results for three unique coastal profiles representing different stages of the NOM cycle in the CRLC show that $R_{2\%,\,IG}$ (runup minus incident band swash) varies by up to 36% for a given set of wave conditions (offshore significant wave height and peak period). The largest differences occur during high energy conditions when wave breaking occurs on the outer bar. The largest computed runup in our model tests generally occurred with the 2012 nearshore bathymetry when the outer bar was the deepest, especially under high wave conditions. This can in part be attributed to the role of the outer bar in dissipating wave energy far from the beach face, altering both the setup and infragravity swash components of runup. Interestingly, the results between 1999 and 2006 showed many similarities despite having about a 3m difference in the depth of the outer bar. There are, however, other morphologic features of these profiles that could similarly alter the impact on nearshore hydrodynamics and offset the variance induced by the outer bar. More work must be completed to understand how the individual swash and setup components are altered by complex morphologic features such as these outer and middle bars. However, despite the profiles having different bar configuration all have generally the same foreshore slope. Therefore, this demonstrates that morphology exerts a strong control on runup and confirms that the foreshore slope alone is a poor descriptor of the nearshore morphology (Stephens *et al*., 2012).

The Stockdon model predicted $R_{2\%,IG}$ within 20 cm of the XBeach results on average. However, there were some conditions that resulted in over a 40% difference between numerical model and empirical estimates of $R_{2\%,IG}$. The largest differences occurred under moderate to high energy conditions where XBeach typically estimated larger $R_{2\%,IG}$. This is perhaps unsurprising given that the Stockdon formulation was developed using only limited high wave measurements. Since this formula is used by a wide range of practitioners for a range of applications, our work indicating possible limitations under high wave conditions with complex bathymetries suggests that further research is warranted.

To investigate the relation of NOM to surf zone sediment transport, two distinct wave scenarios were simulated. Under 2 m, 8 s waves XBeach predicted a net offshore transport of sediment for all three cross shore profiles. In the outer sandbar zone, the lowest rate of transport occurs in 2012 and the largest rate of transport occurs in 2006. This was expected based on the relative depths of the outer bars (2012 being the deepest and 2006 being the shallowest). In the inner bar zone the highest rate of transport occurs with the 2012 bathymetry, which could in part be a result of the deep water depth of the outer bar which results in waves breaking closer to shore, stirring up of sediment, and generating larger undertow.

Under the storm wave condition (8 m, 14 s) there is a net onshore sediment transport in the outer bar zone for the 1999 case and offshore predicted transport for 2006 and 2012. This demonstrates that even under the same wave conditions the morphology can alter both the rate and direction of net sediment transport. In the inner bar zone under storm waves all three profiles are expected to be erosional. However, Figure 5 demonstrates that there are highly complex spatial patterns in transport, with localized areas of onshore directed transport. The lowest net offshore sediment transport occurs with the 1999 bathymetry (intermediate offshore bar depth) and the highest transport occurs with the 2012 profile (deepest offshore bar depth). This suggests that there are other important factors in addition to the outer bar depth that influence inner surf zone sediment transport under very large wave conditions.

From these model simulations we have demonstrated that inter-annual variability in sandbar shape and position can significantly alter inner surf zone/swash zone processes. For this study, we have held the bathymetry constant and thus neglected some morphodynamic processes that would serve to alter the bar geometry in response to large wave events. These feedbacks can be highly complex as the coastal profile is constantly in flux. Thus while our findings may be limited due to the inherently dynamic nature of the system, we can conclude that sandbar configuration has a non-negligible influence on runup and surf zone sediment transport and it is apparent that significant work remains to further resolve the relationships between morphology, hydrodynamics, and ultimately coastal hazards.

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