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The influence of seasonal to interannual nearshore profile variability on extreme water levels: Modeling wave runup on dissipative beaches

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ABSTRACT

Wave runup, an important contributor to storm-induced extreme water levels, is commonly predicted via empirical formulations that parameterize coastal morphology using simple metrics such as the foreshore beach slope. However, spatially and temporally complex nearshore morphology, such as subtidal sandbars, have the potential to alter surf zone wave dissipation patterns and therefore influence setup, swash, and runup levels observed at the shoreline. In this study, a suite of numerical experiments using XBeach demonstrate reasonable skill in reproducing wave runup observations in dissipative settings, explore the relative influence of seasonal to interannual variability in nearshore morphology on runup and its constitutive components, and illustrate differences between empirical and numerically modeled estimates of runup. The numerical model results show that interannual variability in sandbar configuration, associated with net offshore sandbar migration, has a larger influence on wave runup than does seasonal sandbar variability. Although the particular configuration of sandbars was estimated to influence runup by as much as 0.18 m during storm conditions, natural variability in subaerial beach topography has a stronger influence on runup than subtidal morphology. XBeach demonstrates that both wave setup and infragravity swash have morphologic controls. In experiments simulating storm conditions in which both nearshore and beach morphology was varied, natural interannual variability in beach topography explained about 80% of the variance in runup and its constituents. While XBeach predictions of setup, swash, and runup compare favorably with empirical predictors for low wave conditions, the numerical model predicts higher runup levels for storm-conditions on dissipative beaches raising potential concerns about coastal hazards assessments that use these empirical models to estimate extreme total water levels.

1. Introduction

Storm-induced, elevated water levels pose a major hazard to low-lying coastal communities, occasionally generating severe backshore flooding and erosion. Recent events such as Hurricanes Katrina and Sandy have highlighted community vulnerability to anomalous high water events which can result in substantial environmental and economic damages (Benimoff et al., 2015; Vigdor, 2008). While wind-driven storm surge can dominate damages during large landfalling hurricanes, often one of the most important components of storm-induced extreme total water levels (TWLs) is wave runup (e.g., Stockdon et al., 2007). In a recent U.S. West Coast study, Serafin and Ruggiero (2014) showed that wave runup contributed approximately 60% of the TWL during the maximum high water level event on record. In more than half of the ~150 events (~5 events per year) included in that studies' extreme value analysis, wave-induced water levels accounted for >50% of the TWL signal.

Many studies have related runup, and its constituent components of setup and swash, to local beach characteristics and to the incident wave climate (e.g., Holman, 1986; Ruessink et al., 1998; Stockdon et al., 2006). For example, working on high energy dissipative beaches in the U.S. Pacific Northwest (PNW), Ruggiero et al. (2001) [henceforth R01] found that >95% of swash variance was in the infragravity band and related the 2% exceedance elevation of runup maxima, $R_{2\%}$, as

$$R_{2\%} = 0.27\sqrt{\beta_f H_o L_o} \quad (1)$$

where β_f is the foreshore slope, H_o is the deep-water significant wave height, and L_o is the deep-water wavelength. Stockdon et al. (2006) synthesized video data from 10 field experiments at 6 different beaches, including the dissipative beach data from Ruggiero et al. (2001), and generated empirical models relating wave setup ($\overline{\eta}$), incident band swash (S_{INC}), infragravity band swash (S_{IG}), and $R_{2\%}$ to offshore wave conditions and characteristics of the coastal profile.

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The general form of the Stockdon et al. (2006) model [henceforth SG06] for extreme wave runup is given as

$$R_{2\%} = 1.1\left(\overline{\eta} + \frac{\sqrt{{S_{INC}}^2 + {S_{IG}}^2}}{2}\right) = 1.1\left(0.35\beta_f\sqrt{H_oL_o} + \frac{\sqrt{H_oL_o\left(0.563\,{\beta_f}^2 + 0.004\right)}}{2}\right). \quad (2)$$

For data with Iribarren numbers (ξ_o; Battjes, 1974) less than 0.3, Stockdon et al. (2006) developed a formulation specific to dissipative beaches [henceforth SD06]

$$R_{2\%} = 0.043\sqrt{H_oL_o}. \quad (3)$$

While the SD06 relationship is independent of the beach profile, SG06 and R01 both have dependencies on β_f, which is defined as the mean slope between $\overline{\eta} \pm$ twice the standard deviation of the swash time series. Stockdon et al. (2006) explored $\overline{\eta}$, S_{INC}, S_{IG}, and $R_{2\%}$ dependencies on other metrics representing the nearshore profile, such as the surf zone slope, yet found no statistically significant relationships. However, a number of field studies have suggested that complex nearshore morphology, such as the presence of sandbars, may influence swash processes (e.g., Brodie et al., 2012; Cox et al., 2013; Guedes et al., 2012; Senechal et al., 2013) and therefore β_f alone may not fully explain the morphologic control on runup.

Nearshore sandbars act as a perturbation to the coastal profile causing waves to break further offshore during storm events, potentially limiting coastal erosion by dissipating wave energy away from the beach face (Castelle et al., 2007; Holman et al., 2014; Shand et al., 2006). Likewise, temporal variability in tides on a barred beach alters surf-zone wave breaking patterns which may also in turn influence swash processes (e.g., Holman and Sallenger, 1985). For example, Guedes et al. (2011) found that runup height could vary by up to a factor of 2 between high tide (no waves breaking on a bar) and low tide (waves breaking on a bar) on an intermediate, micro-tidal beach. Similarly, Senechal et al. (2013) found a 30% reduction in runup during low tide caused by a reduction in infragravity energy associated with sandbar-induced wave breaking. Although these observations support the notion that sandbars influence wave runup, developing field datasets that directly link the influence of nearshore bathymetric variability to setup and swash statistics has proven challenging. For this reason, numerical models have increasingly been used to explore runup and its relationship to variable morphology. For example, using the Thornton and Guza (1983) wave transformation model, Stephens et al. (2011) demonstrated that, in the presence of a sandbar, the nearshore profile could explain at least as much variance on $\overline{\eta}$ as H_o. Using XBeach (Roelvink et al., 2009), Cox et al. (2013) [henceforth C13] found that S_{IG} is reduced when waves break over a bar relative to a non-barred beach profile. Based on these model results, C13 presented the following empirical model for infragravity swash

$$S_{IG} = 0.08F\sqrt{H_oL_o} \quad (4)$$

where F is 0.71 on a non-barred beach (collapsing to the SG06 relationship for S_{IG} in Eq. 2) and is equal to $\left(\frac{h_{bar}}{h_{no\ bar}}\right)^{0.39}$ on a barred beach, which represents the ratio of the bar depth (h_{bar}) to the local water depth in the absence of the bar ($h_{no\ bar}$). Conversely, using a nonlinear shallow water equations solver Soldini et al. (2013) found little difference in maximum predicted runup for a barred beach profile as compared to an equilibrium beach profile with the same onshore topography. Collectively, these studies indicate that the presence of nearshore sandbars, and their inherent variability, may influence $\overline{\eta}$, S_{IG}, and maximum runup in as yet unexplained ways.

To deepen understanding of the influence of nearshore morphological variability on wave runup, here we present a series of numerical XBeach experiments performed on observed and simulated beach profiles from the PNW. This region contains long stretches of sandy coast characterized by flat, dissipative beaches with wide surf zones and multiple nearshore sandbars (Haxel and Holman, 2004; Ruggiero et al., 2005). Since much of this coastline is characterized as a morphodynamic end-member (Wright and Short, 1984) and sandbars in the region have been shown to vary significantly both spatially and temporally on seasonal to interannual time scales (Di Leonardo and Ruggiero, 2015), the PNW is an ideal region to explore the influence of coastal morphology on swash zone hydrodynamics. Here we first demonstrate that XBeach skillfully reproduces runup statistics on high energy dissipative beaches by simulating conditions from the High Energy Beach Experiment (HBE) at Agate Beach, OR (Ruggiero et al., 2004). We then turn our focus to investigating the implications of natural variability in nearshore bathymetry and topography on $\overline{\eta}$, S_{IG}, runup, and TWLs along a characteristic dissipative beach. A wide range of wave conditions are simulated in order to analyze the general behavior of the model and to assess relationships between the coastal profile and wave driven components of TWLs.

The paper is organized as follows. Descriptions of the study sites, Agate Beach, OR and Long Beach, WA, are given in Section 2. In Section 3 the modeling approaches for five distinct numerical experiments are described, each of which explore runup behavior under differing environmental forcing conditions and nearshore morphological configurations. Results of these numerical modeling simulations are presented in Section 4 followed by comparisons of the results to existing empirical predictors of runup from the literature in Section 5. Concluding thoughts are provided in Section 6.

2. Study sites

Classically, beaches have been defined as being in a dissipative state when the Iribarren Number, $tan\beta_f/\sqrt{H_o/L_o}$, is less than approximately 0.3 (Wright and Short, 1984). During storms this criterion is often satisfied because of large H_o while on beaches with very low β_f this criterion is satisfied under most sea states. Many PNW beaches are modally dissipative as a result of characteristically flat, low sloping profiles (Ruggiero et al., 2005). The PNW also has one of the most energetic wave climates in the world, with average annual H_o of about 2.4 m with peak wave periods of about 10.8 s and typically experiences about three storm events per year with wave heights exceeding 8 m (Allan and Komar, 2002, 2006).

For this study, two relatively similar, meso-tidal, high energy, dissipative PNW beaches are investigated (Fig. 1). The High Energy Beach Experiment took place at Agate Beach, OR in 1996, providing a runup dataset during dissipative conditions with H_o up to 3.1 m. Agate Beach is a 2.5 km sandy, bluff-backed stretch of coast located at the northern end of the Newport littoral cell in Newport, OR (Fig. 1b). Repeat topographic surveys reveal large seasonal variability at Agate Beach, with an estimated 31.4 ± 8.5 m^3/m of beach sediment lost to the nearshore during the winter and reworked onshore during summer (Haxel and Holman, 2004). Over the longer term the beach is net progradational, with an average shoreline change rate of about 2 m/yr between 1967 and 2002 (Ruggiero et al., 2013). While Argus image analysis indicates a dynamic nearshore with sandbars migrating onshore in summer and offshore in winter (Alexander and Holman, 2004), long-term in-situ observations of nearshore morphology do not exist for this site.

To take advantage of an existing PNW long-term dataset of in-situ coastal morphology measurements, our second study site is on the Long Beach Peninsula (LBP), part of the Columbia River Littoral Cell (CRLC). The CRLC is a dissipative, progradational coastal system that spans the Oregon and Washington border. The 165 km sandy coastal