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Bathymetric control on the spatial distribution of wave breaking in the surf zone of a natural beach

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ABSTRACT

A non-hydrostatic wave model (SWASH) that phase-resolves the free surface and fluid motions in the water column is applied to investigate wave transformation and the spatial distribution of wave breaking over different morphological features. The model is forced using observed directional energy spectra and results are compared to wave observations collected outside the surf zone using acoustic wave sensors, and over a 100 m nearshore transect using high-frequency measurements of the sea surface from a LIDAR sensor mounted on the beach dune at the Field Research Facility in Duck, NC. The model is applied to four cases with different wave conditions and bathymetry, tested for sensitivity of model parameters to these different natural conditions, and used to predict the spatial variability in wave breaking and correlation between energy dissipation and morphologic features. Model results compare very well with observations of spectral evolution outside the surf zone, and generally well with the remotely sensed observations of wave transformation inside the surf zone with $R = 0.85$-0.93 for H_s along the cross-shore transect. In particular the model is able to spatially resolve wave shoaling and dissipation at the shore break at the same location as observed in the LIDAR data. The results indicate that nearshore morphology has a significant effect on the spatial distribution of wave energy dissipation. Alongshore variability in bathymetry due to bars, rip channels, and larger morphological features such as the scour depression under the pier, causes large alongshore changes in cross-shore wave energy flux that influence the location and intensity of wave breaking.

1. Introduction

Waves transform as they propagate from the ocean to shallow water where they break in the surf zone and typically dominate nearshore hydrodynamics on sandy beaches. Wave breaking drives many coastal processes including generation of alongshore currents (Bowen, 1969a), rip currents (Bowen, 1969b), energy dissipation (Battjes and Janssen, 1978), sediment transport (Kamphuis, 1991) and morphodynamic changes (Stive and de Vriend, 1995). Bathymetric features are well known to have large influence on surface wave processes by causing refraction, reflection, wave–wave, and wave–current interactions with stronger influences in shallower water depths (Apotsos et al., 2008; Holman, 1995; Thomson et al., 2005). As waves propagate into the nearshore zone, the non-linear shoaling and breaking processes drive wave transformation. These complex processes make the development of predictive numerical models and a complete understanding of wave shoaling and energy dissipation in the surf zone a difficult problem.

In order to numerically simulate nearshore hydrodynamic processes, phase-resolving wave models that use the non-linear shallow water (NLSW) equations have been developed. However, the NLSW equations assume a hydrostatic pressure distribution, which results in their invalidity in the vital region from the point of breaking to the shoreline (Zijlema and Stelling, 2008). The effects of non-hydrostatic pressure can be accounted for in Boussinesq-type models (*e.g.*, Kirby et al. (1998), Wei et al. (1995)) by the addition of higher order derivative terms in the NLSW equations (Peregrine, 1967). These models can have considerable accuracy in predicting surf zone hydrodynamics (Chen et al., 2000; Kennedy et al., 2000; Lynett, 2006) but with high complexity and computational expense (Zijlema and Stelling, 2008).

The development of non-hydrostatic models has led to an accurate and computationally affordable solution to modelling in the nearshore zone (Casulli and Stelling, 1998; Ma et al., 2012; Zijlema et al., 2011). Non-hydrostatic models are based on the conservation of momentum using the NLSW equations, extended to include vertical motions and including non-hydrostatic pressure terms, resulting in

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the same expressions as given by the incompressible Navier–Stokes equations (Zijlema and Stelling, 2008). In order to improve accuracy, non-hydrostatic models can have a higher number of vertical grid points, as opposed to including higher-order derivatives as in Boussinesq models. While the reduction of higher-order derivative terms should result in a less computationally expensive model, a vertical grid comprised 10 to 20 layers required by a non-hydrostatic model can make them equally as computationally intensive as Boussinesq models. Recent advances in the development of non-hydrostatic models have overcome this obstacle, by adopting numerical schemes to deal with breaking waves (Ma et al., 2012; Smit et al., 2014; Zijlema et al., 2011). Non-hydrostatic models such as SWASH (Zijlema et al., 2011) and NHWAVE (Ma et al., 2012) can predict wave breaking by applying shock-capturing schemes, and can accurately predict the non-linear processes that dominate the nearshore zone, including shoaling, diffraction, refraction, wave–wave interactions, wave–current interactions, and runup.

In order to accurately simulate waves in the nearshore zone, field observations are required for model validation. In addition to the complexity of modelling coastal processes, measurements of the hydrodynamics of the surf and swash zones provide their own set of challenges. The process of wave breaking results in high rates of energy dissipation, strong currents, and erosion and transport of sediments. This results in an environment that can be damaging and expensive to *in-situ* sensors as well as a wide range of temporal and spatial scales that are difficult to capture (Holman and Haller, 2013). These challenges have led to the use of remote sensing techniques to observe this highly dynamic region. Recent works in developing nearshore remote sensing techniques include optical imagery to investigate shoreline variability on varying temporal scales (Pianca et al., 2015), infra-red imagery to estimate energy dissipation due to breaking waves (Carini et al., 2015), X-band radar to quantify rip currents and circulation (Haller et al., 2014), and terrestrial mounted LIDAR to quantify runup and foreshore change (Brodie et al., 2012).

The use of LIght Detection And Ranging (LIDAR) is well known for accurately measuring topographic data (Irish and White, 1998). Recent technological advances focussing on the swash and inner surf zones have resulted in LIDAR techniques being applied to measure wave-by-wave motion of the sea surface and subtle morphologic changes in the foreshore (Blenkinsopp et al., 2010; Vousdoukas et al., 2014). LIDAR sensors have the ability to continuously scan the inner surf and swash zones and differentiate between morphological changes of the foreshore and wave runup, which can be favourable to video and ultrasonic imagery due to the continuous-capture ability over a wide range of weather and low light conditions (Almeida et al., 2013; Blenkinsopp et al., 2010). Brodie et al. (2015) validated LIDAR observations of the water surface using 6 *in situ* pressure sensors, finding that the LIDAR measures inner-surf waves and setup accurately and differences were related to unsaturation of the beach, foamy aerated bores, and heavy rain that only affect the pressure measurements.

In this paper the results of the non-hydrostatic SWASH wave model and observations from a terrestrial mounted LIDAR sensor are used together to estimate wave breaking and wave energy changes across the surf zone. The model is used to simulate nearshore hydrodynamics on a sandy beach to determine the influence of bathymetric features on wave conditions in the inner surf zone. Model results are validated with LIDAR measurements of the sea surface and observations from four acoustic wave sensors for four distinct morphologic cases in order to investigate morphological control of the surf zone hydrodynamics.

2. Observations

Wave measurements are collected at the Field Research Facility (FRF) in Duck, NC (Fig. 1a), a coastal observatory and research site operated by the U.S. Army Corps of Engineers. Located on a barrier island beach, the FRF has a 500 m long research pier that extends across the typical surf zone and serves as a platform for meteorological and oceanographic observations (Fig. 1b). This study focuses on a period with measurements of bathymetry, waves and water levels in August–October 2011.

2.1. Bathymetric observations

Bathymetric surveys are conducted using the LARC (Lighter Amphibious Resupply Cargo). The LARC is able to traverse throughout the surf zone and survey the nearshore bathymetry up to the base of the beach dunes with an average horizontal resolution of 0.1 m. A uniform area of 1.3 km^2 that extends a distance of 1.0 km alongshore by 1.3 km offshore (to the 11 m mean water depth) was selected for this study. Four surveys denoted S1–S4 are shown in Fig. 2, and are used to investigate varying bathymetric trends at this site. Morphologic features observed during this period include a near alongshore uniform beach with a single bar (Fig. 2a), rip channels and major pier depression after a high energy wave event (Fig. 2b), and continuing evolution of these features through moderate to high wave events (Fig. 2c, d).

2.2. Acoustic wave observations

Water levels and wave statistics are collected at the FRF using four 1.2 MHz Nortek Acoustic Wave and Current (AWAC) sensors at 11 m, 8 m, 6 m, and 5 m mean water depths (sites A–D) and two Nortek Aquadopps at 3 m and 2 m depths (sites E–F) (Mulligan and Hanson, 2016). During the time period for the present study, sensors at A, C, D and F were operational (Table 1). Directional wave spectra and bulk wave statistics including the significant wave height (H_s), peak wave period (T_p) and mean wave direction (α_w) from these sensors are used in this study (Fig. 3).

Incident waves are defined using observations from the AWAC at site A, located at the 11 mean water depth (coincident with the offshore boundary of the model domain discussed in the next section). Directional energy spectra are shown at four times in Fig. 4 corresponding to events E1–E4 indicated in Fig. 3. These times were chosen based on proximity to bathymetric survey dates (S1–S4), and availability and quality of water level data from the LIDAR sensor. Events E1 and E2 occurred before and after Hurricane Irene, respectively.

2.3. Remote sensing observations

A terrestrial mounted LIDAR scanner is used to measure water level elevations across the surf zone, where it can be difficult to obtain accurate observations from acoustic or pressure sensors due to signal attenuation by sediments. The LIDAR scanner (a Riegl LMS-z390i 1550 nm laser with a 0.3 mrad beam width) was used to measure water surface elevations at 4 Hz with a 0.02° angular resolution for 20 min out of every hour (Brodie et al., 2015) and yields data with a spatial density of 0.1 m over approximately a 100 m range. It was mounted on a 4 m tower on the dune, oriented to measure a cross-shore transect (Fig. 5) in-line with the AWAC and Aquadopp sensors. The foamy surface of breaking waves in the surf zone provides a good reflection surface, resulting in instantaneous water surface measurements in the inner surf zone (Brodie et al., 2012). The water surface is captured as a spatially varying point cloud, that is analyzed to determine the mean water level elevation and significant wave height. This study focuses on mild storm conditions with significant wave heights of 1.96–2.26 m. For these wave conditions the majority of the wave breaking zone is typically 100 m wide and located within the range of the LIDAR, resulting in data that spans the surf zone to the foreshore of the beach.