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Divergent behavior of the swash zone in response to different foreshore slopes and nearshore states

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ABSTRACT

Ultrasonic distance sensors were used to measure changes in bed elevation to a resolution of ~0.1 mm following individual swash excursions in the high-tide swash zone of an intermediate foreshore. Changes in bed elevation are related to depth-averaged Eularian swash velocities, estimated by assuming mass balance of the swash discharge also measured using the ultrasonic distance sensors. Early in the study (May 21–25, 2008), the alongshore uniform foreshore had a cross-shore slope of 0.18 and was fronted by a nearshore bar that forced wave breaking at low tide. Towards the end of the study (June 5–9, 2008), the foreshore had a slope of 0.12 and was fronted by a nearshore terrace that developed as the innermost bar migrated landward. Despite similar inshore wave heights and periods during these times, the steeper foreshore eroded by 0.69 m^3 m^{-1}, while the more gently-sloped foreshore accreted by 0.21 m^3 m^{-1}. The divergent behavior of the swash zone is attributed to the welding of the innermost bar to the foreshore creating a shallow nearshore terrace that saturated the inshore wave field. This in turn led to a faster uprush velocity that promoted the landward advection of sediment picked-up over the shallow terrace. It is argued that accretion in the upper swash zone was the result of a larger supply of sediment at the base of the foreshore, and a transformation of the wave field by the shallower depths of the welded feature. In this respect, swash hydrodynamics and morphological change can only be made if the swash zone is considered within the context of the broader nearshore state.

1. Introduction

The swash zone is the morphologically dynamic region landward of the surf zone, where the shoreline sweeps back and forth across the beachface. As a consequence of large sediment concentrations (Osborne and Rooker, 1999; Beach and Sternberg, 1991), the swash zone is an important part of the littoral sediment budget (see Elfrink and Baldock, 2002). However, sediment transport and morphological change in the swash zone remains a difficult challenge, given the high flow velocities and the shallow depths. Relating sediment transport to morphological change is also complicated by the high concentration of sediment (Hughes et al., 1997; Osborne and Rooker, 1999), contrasting flows (Raubenheimer and Guza, 1996; Hughes et al., 1997) and the different modes of transport (Horn and Mason, 1994). Most models of swash zone transport and change are guided by the use of a Bagnold-type energetics model that relates bedload to the third power of velocity and suspended load to the fourth power of velocity.

$$I_b = ku^3T \tag{1}$$

$$I_s = ku^3|u|T \tag{2}$$

where k is a transport coefficient and T is the duration of the event. Foreshore accretion occurs in opposition to the force of gravity and requires an asymmetry in the transport of sediment or the velocities of the uprush and backwash. In both laboratory and field studies it has been found that accretion results from larger suspended sediment concentrations during the uprush compared to the backwash (Puleo et al., 2000; Masselink et al., 2005). To account for the larger sediment concentrations and to allow for net onshore transport, the coefficient k is assumed to be large for the uprush and requires calibration against measured concentrations of sediment. Otherwise a net offshore transport would always be predicted in response to the asymmetries of the swash velocity.

The inability to directly relate sediment concentrations to bed shear stresses calls for a suite of models capable of dealing with non-equilibrium conditions and treat entrainment (p) and deposition (d) independently (see Nielsen, 1992; van Rijn, 1984). As described by Nielsen (1992), bed elevation change ($dz\ dt^{-1}$) at a point can be estimated through the conservation of sediment as the difference between sediment entrainment (pickup) and deposition:

$$(1-n)\frac{dz}{dt} = d-p \tag{3}$$

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where n is the sediment porosity. Similarly, Kobayashi and Johnson (2001) suggest that changes in bed elevation change in the swash can be characterized as a balance between the upward suspension potential (S) and the amount of advected sediment settling out of the water column:

$$\frac{dz}{dt} = \frac{\overline{wC} - \overline{S}}{(1-n)} \tag{4}$$

where C is the depth-averaged sediment concentration including both bed and suspended load, and w is the sediment fall velocity. Assuming frictional dissipation (D_f) is greater than breaking friction in fully-developed swash bores (Raubenheimer et al., 2004), the upward suspension potential is related to the wave energy dissipation rate as:

$$S = \overline{\left(\frac{D_f}{h}\right)} \tag{5}$$

where h is the local water depth. Predicting bed elevation change depends on an accurate estimate of the potentially large advected sediment concentration (e.g. Hughes et al., 1997; Puleo and Holland, 2003; Butt et al., 2004; Pritchard and Hogg, 2005; Hughes et al., 2007), which is directly related to the foreshore slope (Jackson et al., 2004). A dependency on foreshore slope suggests that the relative importance of advected sediment may also be linked to nearshore state (e.g. Wright and Short, 1984). This is consistent with the boundary controls described by Guard and Baldock (2007), in that specific combinations of wave and tide define the shape and asymmetry of the swash for a given nearshore state.

The pickup model of Kobayashi and Johnson (2001) can be used to estimate the required concentration of sediment to balance the change in bed elevation, if the latter can be measured for individual swash excursions. The introduction of high-frequency and high-resolution optical and sonic devices to measure wave-scale changes in bed elevation has shown that the swash zone is very dynamic and that the amount and direction of bed elevation change can vary from wave to wave (see Turner et al., 2008; Houser and Barrett, 2009; McDermott and Sherman, 2009). In the present study, the relative balance of the suspension potential and the sediment concentration is estimated using ultrasonic distance sensors in the high-tide swash zone of an intermediate foreshore. The ultrasonic distance sensors were also used in a companion study (Houser and Barrett, 2009) that only examined the different timescales over which bed elevation changes in the swash zone. The present study characterizes the sediment concentration required to balance the bed elevation change in relation to changes in the foreshore slope and the nearshore bar morphology before and after a large frontal storm that forced the innermost bar to weld to the foreshore.

2. Study site

The instrumented field study was completed within the Fort Pickens Unit of the Gulf Islands National Seashore in northwest Florida (Fig. 1). The beach and dune system at this site are recovering from Hurricanes Ivan, Dennis and Katrina during the 2004/2005 hurricane season, when the island experience widespread shoreline retreat and widespread overwash and breaching (Houser et al., 2008; Houser and Hamilton, 2009). The area has an average tidal range of 0.43 m (Armbruster, 1997) and the dominant wave approach is from

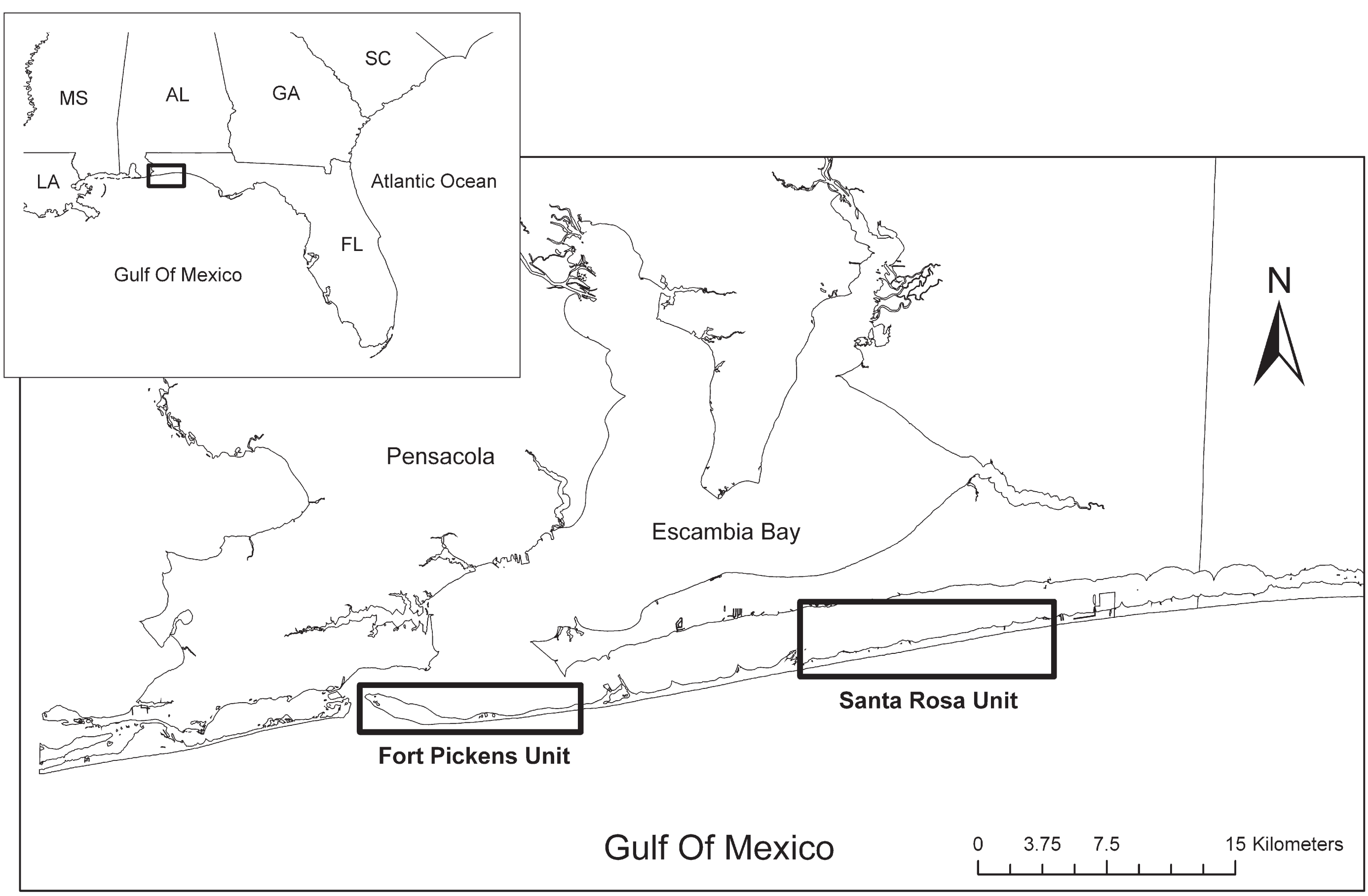

Fig. 1. Location of study site in the Fort Pickens Unit of Santa Rosa Island in northwest Florida. Also shown is the relative location of the study site to the tracks of Hurricanes Ivan and Dennis and Tropical Storm Arlene that lead to widespread overwash and beach erosion, and the present state of beach and dune recovery.