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Beach response to a sequence of extreme storms

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ABSTRACT

A sequence of daily beach surveys acquired over one month covering an area larger than 100,000 m^2, was analyzed to study morphological changes resulting from a cluster of storms. The beach response was highly variable in both the cross- and alongshore. A cumulative storm effect was not observed, despite one storm being characterized by a 10-year return period that had significant wave height (H_s) of 8.1 m and a peak wave period (T_p) of 17 s. Instead, storms that can potentially cause significant erosion in terms of H_s had a limited effect on the morphology because the large wave height was coupled to either neap tides, normally-incident short-waves ($f > 0.04$ Hz), or low levels of infragravity ($0.004 < f < 0.04$ Hz) energy. Multiple linear regression analysis shows that volumetric changes in the upper part of the beachface are explained by offshore wave characteristics (period, height and direction), tidal range or by infragravity energy in the inner surf zone (assessed using pressure and velocity measurements). The results indicate that it is not possible to scale-up single-storm erosion studies into predictions of cluster-storm erosion.

1. Introduction

Long-term recession is a common feature of shorelines worldwide (e.g., Bird, 1985; Komar, 1998). Short-term recession can be traced to anthropogenic effects (e.g., Frihy and Komar, 1993), while climate change or variations in sediment supply are potentially the main driver of long-term erosion (Stive, 2004; Zhang et al., 2004). These recession patterns are the result of cross- and alongshore gradients in sediment fluxes, which cause sediment redistribution between the onshore and offshore areas, between up and down the coast, and ultimately induce net erosion and accretion. The intrinsic difficulties in estimating sediment transport due to the presence of thresholds, non-linearities, bedforms, and different modes of transport make the up-scaling from short-term (~minutes) and small-scale (~centimeters) predictions of sediment transport to long-term (>days) and large-scale (~kilometers) predictions of beach evolution an extremely challenging exercise. Depending on the magnitude of the forcing conditions, the role of waves can quickly change from accretive small wave conditions to erosive storm wave conditions. Although simplistic, this approach holds also when describing subaqueous sandbars that tend to move slowly onshore during calm, accretive conditions and more rapidly migrate offshore during stormy, erosive conditions (Gallagher et al., 1998; Plant et al., 2006). However, such simplistic models do not provide the level of detail needed by planners to define coastal hazard zones or by engineers to estimate fill quantities needed for post-storm re-nourishment.

Studies have shown that shorelines can partially recover from storm-induced erosion and that the initial recovery can be extremely fast. For example, Wang et al. (2006) showed that substantial beach recovery in the form of re-establishing the pre-storm beachface slope and berm occurred within 90 days. Even more impressively, Birkemeier (1979) showed that up to half of the sand eroded during the storm was recovered within one day of the storm. On the other hand, a full recovery from major storms can also last for years, especially if erosion of the dunes backing the beach has occurred (Thom and Hall, 1991). In fact, the 'vulnerability' of a beach, intended as the potential of a beach to be affected by a major storm, depends on the balance between storm frequency and recovery rates. Studies of beach vulnerability depend on understanding the role of dunes that act as sediment reservoirs, sandbars that shelter the beach from wave action, and the three-dimensional (3D) response of the whole coastal system.

The difficulty in collecting adequate datasets makes the study of the role of storms on long-term beach change challenging (Zhang et al., 2002; Anderson et al., 2010) with most studies focusing on detailed measurements of fast-scale hydrodynamic and sediment transport processes at a selected location (e.g., Aagaard et al., 2005), or on the analysis of beach profiles which are usually sparse in time (e.g., Almeida et al., 2012). Datasets with adequate resolution in both time and space are uncommon, and even fewer studies have addressed the effect of 'clusters' of storms on beach response (Birkemeier et al., 1999; Ferreira, 2006). Lee et al. (1998) and Birkemeier et al. (1999) analyzed long-term beach profile surveys from Duck (North Carolina, USA) and concluded

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that a sequence of storms has a 'cumulative' effect on beach erosion, and if the beach has no time to recover, clusters of storms have an effect comparable to that of a less frequent and more energetic storm with respect to both intensity and storm duration. Numerical modeling studies show that wave chronology also affects beach profile evolution (Southgate, 1995; Ferreira, 2005). These findings need more corroboration by comprehensive observational studies over various beach types before they can be translated into beach management practices.

In the present work, we discuss whether the response to multiple storm events is equal to the linear sum of the effect of each storm or whether the last storm results in increased or decreased erosion. Both hypotheses are viable and in this context recent data-driven models have shown that shoreline erosion tends to diminish if erosive conditions are maintained (Yates et al., 2009). At the same time, because of the difficulty in collecting an appropriate dataset, little is known about the alongshore variability in beach response to storms. Here, we use detailed topographic surveys that were obtained daily over an area of 100,000 m^2 for 30 days and concurrent hydrodynamic measurements to describe the beach response of volumetric erosion and alongshore morphologic evolution caused by a series of storms. Each storm response is characterized as a function of its offshore and inner surf zone hydrodynamic characteristics estimated from an offshore directional buoy and a current meter located in the surf zone. Finally, we take advantage of the fortuitous sequence of extreme storms to analyze and discuss the beach response to extreme storms of varying duration and magnitude.

2. Field site

A surf zone field experiment was performed at Truc Vert beach, located south of Bordeaux, France, in close proximity to the Arcachon lagoon (Fig. 1) in March to April 2008 (Senechal et al., 2011a). The beach is a typical representation of the south Atlantic coastline of France, which is characterized by an undisturbed sandy shoreline and by well-developed aeolian dunes (Senechal et al., 2009). Truc Vert beach is characterized by the presence of two sandbars, one subtidal and one intertidal, whose shape ranges from linear to the more commonly-observed crescentic shape. The inner sandbar is usually more dynamic with the presence of well-formed rip channels (Castelle et al., 2007). The mean grain-size of the beachface is 0.35 mm. Truc Vert is a macro-tidal beach with a tidal range varying from 1.5 m during neap tides to 5 m during spring tides. The mean annual offshore significant wave height (H_s) and period (T_p) are 1.4 m and 6.5 s (Butel et al., 2002), and events that are characterized by $H_s > 4.1$ m and $T_p > 10.1$ s are classified as storms (Le Cozannet et al., 2011).

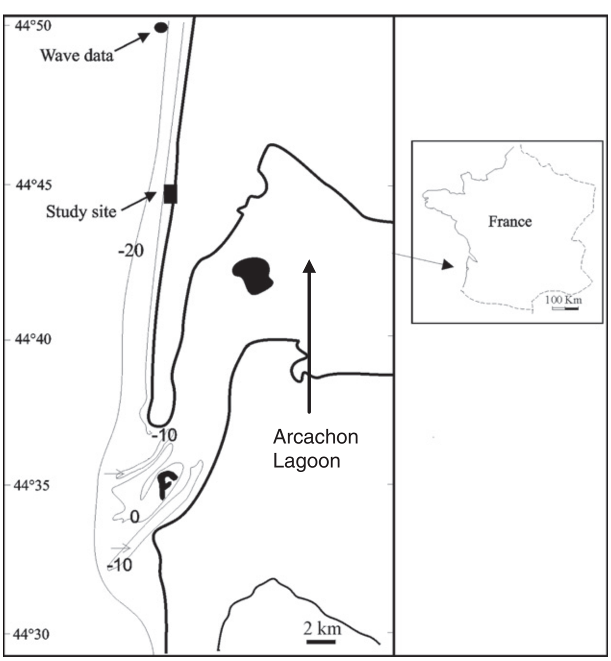

Fig. 1. Map of the Truc Vert study site.

3. Methods

Twenty nine topographic surveys were conducted daily around low tide from March 4 to April 8, 2008, using four Differential GPSs (DGPSs) with horizontal and vertical errors of less than 0.05 m. One DGPS was positioned on an all-terrain vehicle and three DGPSs were mounted to human walkers to survey the inner surf zone, swash zone, and the dunes. Cross-shore beach profiles were measured from the dune to the edge of the swash with an alongshore spacing of 20 m (an average of 50 profiles was obtained during each survey). Additional information about the surveying technique and the errors associated with the beach survey are described in Parisot et al. (2009). Two larger offshore bathymetric surveys were performed by the SHOM (Service Hydrographique et Oceanographique de la Marine) on February 14 and April 7–9 (Fig. 2). In addition, images from a two-camera system were collected at 2 Hz from March 8 to April 7 to infer the position and dynamics of the subaqueous sandbars (results are presented in Almar et al., 2010).

H_s, T_p, and wave direction (θ_p) were measured every 30 min by a directional wave buoy located in 20 m water depth offshore of the area surveyed. Water levels were extracted every 30 min from a regional tidal model that was corrected with a tide gauge in the Arcachon lagoon. In order to analyze temporal variations in the offshore wave climate and so in the amount of breaking-related dissipation, we used the Iribarren number which is defined as:

$$\zeta = \tan\beta/\sqrt{H_0/L_0}, \tag{1}$$

where $\tan\beta$ is the beach slope, calculated as the alongshore average of the cross-shore slope between 1 and 3 m contours, L is the wave length, and the subscript 0 refers to deep water conditions.

Surf zone hydrodynamics were measured throughout most of the experiment using a collocated pressure (p) sensor and horizontal electromagnetic current meter that measured cross- (u) and alongshore (v) velocity components, referred to as a PUV sensor. The location of this array is shown in Fig. 2. Using these measurements, we calculated 3-h means of p, u, and v for different frequency bands: very low frequency (vlf, $0.0005 < f < 0.004$ Hz), infragravity (ig, $0.004 < f < 0.04$ Hz), and swell (sw, $0.04 < f < 0.2$ Hz). Instrument heights off the bed were collected for 30 days and are accounted for when calculating wave properties and the total water depth.

4. Results

4.1. Hydro- and morphodynamic changes

The pre-experiment bathymetry showed three-dimensionality of the outer bar characterized by a crescentic shape with an alongshore horn spacing of around 600 m (Fig. 2, left panel). Similar to the observations of Ruessink et al. (2007), the pattern of the outer bar, although subdued, is reflected onto the morphology of the inner bar (Fig. 3, top panel). A cross-correlation between the detrended vertical elevations along the outer and inner bar measured around cross-shore positions 650 and 250 m resulted in a low, but 95% statistically significant, regression coefficient ($r = 0.4$, $p < 0.05$) at zero spatial lag. In the cross-shore direction, beach profiles display different characteristics depending on their alongshore position. Cross-shore profiles corresponding to the horns of the crescents (Fig. 4) show an asymmetric outer sandbar with a crest that is much shallower than the one corresponding to profiles at the bays of the crescents. Following the sequence of storms (Fig. 2, middle panel), the outer sandbar still displayed a strong crescentic pattern with