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Morphological changes, beach inundation and overwash caused by an extreme storm on a low-lying embayed beach bounded by a dune system (NW Mediterranean)

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ABSTRACT

The geomorphological evolution of a low-lying, micro-tidal sandy beach in the western Mediterranean, Pals beach, was characterized using airborne Light Detection and Ranging (LiDAR) data. Data were collected in prior to and six months after the impact of an extreme storm with a return period of approx. 50 years, with the aim of characterizing the beach's response to the storm. The use of repeated high-resolution topographic data to quantify beach geomorphic changes has allowed assessment of the accuracy of different proxies for estimating beach volume changes. Results revealed that changes in the shoreline position cannot accurately reproduce beach volume changes on low-lying beaches where overwash processes are significant. Observations also suggested that volume estimations from beach profiles do not accurately represent subaerial volume changes at large profile distances on beaches with significant alongshore geomorphological variability. Accordingly, the segmentation of the beach into regularly spaced bins is proposed to assess alongshore variations in the beach volume with the accuracy of the topographic data. The morphological evolution of Pals beach during the study period showed a net shoreline retreat (−4 m) and a significant sediment gain on the subaerial beach (+7.5 m^3/m). The net gain of sediment is mostly due to the impact of the extreme storm, driving significant overwash processes that transport sediment landwards, increasing volume on the backshore and dunes. The increase of volume on the foreshore and the presence of cuspate morphologies along the shoreline also evidence post-storm beach recovery. Observed morphological changes exhibit a high variability along the beach related to variations in beach morphology. Changes in the morphology and migration of megacusps result in a high variability in the shoreline position and foreshore volume changes. On the other hand, larger morphological changes on the backshore and larger inundation distances occur when the beach and the dunes are lower, favouring the dominance of overwash. The observed storm-induced morphological changes differ from predicted beach storm impacts because of spatial and temporal variations in the beach morphology, suggesting that detailed morphological parameters and indicators used for predicting beach vulnerability to storms should be regularly updated in order to represent the pre-storm beach conditions. Finally, observed morphological changes in Pals Bay evidenced a different behaviour between natural and urban areas, with better post-storm beach recovery on natural areas where the beach is not artificially narrowed.

1. Introduction

Understanding how low-lying coasts respond to storms is crucial for assessing the vulnerability of these areas to natural hazards and developing tools and management approaches to reduce risk and increase coastal resilience. Low-lying coasts are highly sensitive to storm-induced hazards such as beach erosion, breaching of the dune system, overwash and inundation (e.g. Sallenger, 2000; Morton, 2002). Furthermore, human activities such as flow regulation of river systems, coastal construction and tourism add additional pressure on the coastal system by increasing vulnerability in already highly vulnerable areas (Morton et al., 1994; Willis and Griggs, 2003; Richter et al., 2013). In relation to climate change, low-lying coasts are particularly vulnerable because of rising sea levels and accelerated coastal erosion (Nicholls et al., 2014). Sea-level rise will increase storm-induced maximum water levels (Fiore et al., 2009), enhancing the impact of storms by increasing the potential for erosion and coastal flooding (Zhang et al., 2002). Assessing

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vulnerability to inundation of these areas by identifying coastal areas at risk of flooding and defining flood extent is therefore a key issue at both European and global level. In Europe, the assessment of flood risks is dealt with in the European Flooding Directive 2007/60/EC on the Assessment and Management of Flood Risks (Directive 2007/60/EC) and the Protocol of Integrated Coastal Zone Management (PAP/RAC, 2007).

The vulnerability of a coast to inundation during storms depends on the morphology of the beach and dune relative to the intensity of the ocean's forcing (Wright and Short, 1984; Sallenger, 2000). Even in the context of steady forcing, some areas of the beach may experience severe erosion and/or overwash while adjacent areas may appear unaffected, mostly due to the spatial variability of the beach width and slope, or the dune elevation (Sallenger et al., 2003; Stockdon et al., 2007). Recent studies have found that foredune accretion is dominant in wider and low-gradient beaches while eroding dunes are associated with narrower, steeper beaches (Saye et al., 2005; Keijpers et al., 2014). Similarly, small variations in the elevation, volume and alongshore extent of the foredune also lead to a more spatially variable beach response to storms (Sallenger, 2000; Houser et al., 2008, 2015). In locations where storm-induced water levels exceed the crest of the dune or the dune is breached, sediment is transported landward as overwash and deposited on the backdunes (Sallenger, 2000; Stockdon et al., 2007; de Vries et al., 2012). The detailed assessment of the magnitude and alongshore variability of the beach response to storms is therefore required to accurately predict the coastal response to storms and to identify areas at risk of erosion and flooding.

Remote sensing techniques such as airborne laser altimetry (LiDAR) are now commonly used to quantify storm-induced morphological changes and post-storm beach recovery (e.g. Zhang et al., 2005; Stockdon et al., 2009; Keijpers et al., 2014; among others). LiDAR technology provides elevation data with high vertical accuracy (less than 20 cm) and horizontal resolution (about 50 cm), high point density and large coverage areas (~400 m of swath wide), which resolve the small-scale variability of the beach and dune morphology for an accurate assessment of coastal vulnerability during storms (Sallenger et al., 2003). In addition, the highly automated aspect of LiDAR collection lends itself to resampling areas quickly and efficiently, which is particularly important in the coastal zone, where storm-induced changes can be dramatic and rapid.

The aim of this paper is to characterize and quantify the impact of an 'extreme' storm and the post-storm recovery of a large bay on the NW Mediterranean coast, Pals Bay, using LiDAR-derived topographic data collected prior to and six months after the storm. The morphological evolution of the backshore during the study period is primarily due to the extreme storm. On the other hand, the recorded changes in the foreshore are also influenced by other storms of smaller magnitude, as well as the post-storm beach recovery. Thus, only morphological changes that occurred at elevations higher than the maximum storm-induced water during the moderate storms are associated with the impact of the extreme storm. More specifically, this work aims to: (i) evaluate the beach's response to the impact of the storm by characterizing morphological changes between both surveys; (ii) quantify the maximum observed inundation and compare it with predicted vulnerability to storm-induced inundation; and (iii) assess the anthropogenic influence on the beach response.

2. Field site

Pals Bay, on the northern coast of Catalonia (NW Mediterranean), is a low topographic coast bounded by two rocky headlands, the Montgrí massif to the north and Cape Begur to the south (Fig. 1A). It belongs to the Baix Empordà littoral plain, which includes extensive marshes, river channels, a complex dune system, urbanized areas such as L'Estartit, Els Griells, El Mas Pinell and Pals beach golf course, and embayed beaches (Fig. 1B, C). Much of the littoral plain is currently considered a protected area at regional and European levels because of its great natural value (Fig. 1B).

Two rivers flow into Pals Bay: the Ter River, which is 212 km long and has a draining area of about 3000 km^2, and the Daro River, which is 35 km long and has a drainage area of 300 km^2 (Fig. 1A) (ACA, 2002; Liquete et al., 2009). These rivers have a typical Mediterranean torrential regime, with most of the discharge concentrated in short-lived flood events, particularly between December and February (Sabater et al., 1992; Liquete et al., 2009). During the study period, the highest river flow (120 m^3 s^{-1} in the Ter River and 7.6 m^3 s^{-1} in the Daro River) was registered on 26 December 2008 associated with heavy rainfall of up to 3.36 mm h^{-1}, recorded by the Girona rain gauge (Fig. 2). Changes in the course of these rivers together with the local geomorphology and anthropogenic activities played an important role in the formation and evolution of the Baix Empordà dune system (Cros and Serra, 1993). The main changes in the Ter River course have occurred during the last millennium as a result of periods of high fluvial activity, widespread deforestation and accelerated sedimentation (Marquès and Julià, 2005). The main course of the Ter River frequently changed along two active channels from a river bifurcation at the Verges site (Montaner et al., 2010). The northern branch flowed into the Roses Bay, contributing to the sedimentary infill of the Alt Empordà littoral plain and acting as a natural barrier to the sediment transported by northern winds (Fig. 1B). In the early 14th century AD, the avulsion of the Ter River at Verges produced the abandonment of the northern branch in favour of the eastern course (Montaner Roviras and Solà Subiranas, 2004), contributing to the progressive infill of the Baix Empordà plain and the formation of the Baix Empordà dune system (Marqués and Julià, 2005). At present, the configuration of the dune system is controlled by the strong northern winds, the west-east orientation of the main river courses and the presence of local topographic highs such as the Montgrí massif and Cape Begur, which act as natural barriers against aeolian processes (Fig. 1B).

Pals Bay is characterized by a large sandy beach, named hereafter Pals beach, and two small pocket beaches, Illa Roja and Sa Riera (Fig. 1B). Pals beach is a typical embayed beach extending 6800 m from L'Estartit to Cape Begur (Fig. 1B). The beach width is highly variable alongshore between 25 m at Els Griells and 130 m in the south (Fig. 1C). Sediment grain size shows high spatial variability, with a median grain size (d50) ranging between 230 μm in the north and 1260 μm in the south (CIIRC, 2010). This trend in the grain is reflected in the beach slope and the berm height, which also increases southward from 1.3 m at L'Estartit to 2.7–3.2 m in the southernmost sector of the beach (CIIRC, 2010). Pals beach is backed by a discontinuous vegetated foredune that covers an area of 205,000 m^2, with a predominant NNW-SSE orientation. The dunes show a variable height along the beach, varying from 0.5–1.5 m in the north to 3.5 m in the south. Illa Roja and Sa Riera are small pocket beaches located in the southern part of Pals Bay and bounded by 45 m-high cliffs (Fig. 1B). Illa Roja has a length of 185 m, a variable width (8–35 m), and a mean grain size of 1670 μm. Sa Riera has a length of 186 m, a variable width (50–95 m), and a mean grain size of 1770 μm (CIIRC, 2010).

Pals Bay is a microtidal environment with a tidal range of about 0.2 m. Dominant winds in the area are from the north and northwest in December and January and from the south and east in February, March, April and November. High velocities have been recorded for marine winds (E winds) during storm conditions associated with cyclonic activity over the NW Mediterranean (Font, 1990). Wave climate in the region is highly seasonal, with the severest conditions usually occurring from late autumn to early spring (Bolaños et al., 2009). Statistical analysis of wave conditions in the region showed a yearly mean significant wave height (H_s) of 0.77 m with a maximum H_s of 7.8 m (Mendoza et al., 2011). Storms with H_s between 3.5 and 4.25 m are the most frequent, but severe events (H_s up to 5) and even extreme events (H_s higher than 5 m) are also recorded. Severe and extreme storms have a predominant easterly direction, whereas less energetic storms arrive from the south (Mendoza et al., 2011).