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Invited review

Seasonal morphodynamics of the subaerial and subtidal sections of an intermediate and mesotidal beach

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ABSTRACT

This study provides a detailed insight into the seasonal morphological evolution of the subaerial and subtidal sections of an intermediate and mesotidal beach in relation to the nearshore wave conditions. For this purpose, fortnightly – to – monthly topographic and bathymetric measurements were collected on Ensenada Beach (Baja California, Mexico) from November 2012 to February 2016. Wave data were concurrently measured at 20 m water depth, enabling the correlation of the observed morphological changes to the hydrodynamic forcing. The seasonal morphological variability of the beach comprised ± 200,000 m^3 (± 70 $m^3\,m^{-1}$) and resulted primarily from the cross-shore exchange of sediment. The volumetric fluctuations alongshore were up to ± 100,000 m^3 and event-driven, and played an inportant role in the overall sediment balance. In association with the incoming wave conditions, the subaerial and subtidal beach sections experienced a strong seasonal variability. The subaerial beach reached the maximum volumes in the end of summer (September – October) and minimum in winter (January – February) while the opposite response was obtained for the subtidal beach, with the largest and smallest volumes occurring during the same months in winter and summer, respectively. The morphological fluctuations of the upper and lower beach sections were associated with the preceding monthly averaged wave conditions. The subtidal volume variations were highly and positively correlated to the wave height and period, while the subaerial section was highly but negatively correlated to the same variables. The morphological beach response to energetic waves was more rapid than to low-energy conditions. The largest subaerial erosion and subtidal accretion happened in three months (October – January) while the subaerial accretion and subtidal erosion occurred smoothly over nine months (January – October). The total beach volume (subaerial and subtidal) lacked of seasonal variability, and an annual loss of 50,000 m^3 (17 $m^3\,m^{-1}$) occurred from August 2014 to August 2015, indicating that the beach remained fairly stable over that period of time. The largest volumetric variations of 300,000 m^3 (105 $m^3\,m^{-1}$) occurred during the beginning of the 2015–2016 El Niño winter.

1. Introduction

Beaches can display dramatic spatio-temporal changes at different scales (Wright and Short, 1984; Larson and Kraus, 1994; Ranasinghe et al., 2004; Ruggiero et al., 2016) and significant efforts have been conducted to construct conceptual models that predict the morphological variations in relation to the prevailing hydrodynamic conditions. Identifying the physical mechanisms that cause the morphological changes is critical to enable accurate predictions of these variations, and in the mid- to long-term (days to years) this has been largely achieved for the subaerial beach.

Most of the subtidal beach research has focused on the morphodynamics of nearshore bars using video data and/or numerical modelling (Ruessink and Kroon, 1994; Ranasinghe et al., 2004; Sedrati and Anthony, 2007) or short-term beach shape variations during intensive field campaigns (Brander, 1999; Masselink et al., 2008; Coco et al., 2014). Very little effort has been applied to the understanding of the volumetric evolution of the subtidal beach in a time span of months to years (Aubrey, 1979; Larson and Kraus, 1994; Yates et al., 2009; Roberts et al., 2013). And this is related to the lack of measurements that can resolve the relationship of sediment gains and losses between the subaerial and submerged sections (e.g. Harley et al., 2015).

On wave-dominated environments beaches typically exhibit subaerial erosion during high-energy wave periods and accretion in the presence of low-energy waves, and this is generally attributed to a seasonal variability (Shepard, 1950; Winant et al., 1975; Aubrey, 1979;

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Wright and Short, 1984; Wright et al., 1985). From a morphological perspective, the average seasonal extreme beach states are the summer and the winter, while the spring and autumn represent transitionary periods, both with similar morphological characteristics (Larson and Kraus, 1994)., During the summer low-to-moderate wave energy conditions a net onshore sediment transport is generated inducing the onshore migration of the nearshore bars and contributing to the subaerial beach accretion. Instead, a net offshore sediment transport is dominant during the energetic winter waves, causing erosion on the subaerial beach, and as consequence, the formation of nearshore bars that supply sediment to the subtidal section.

Recent observations on intermediate microtidal (Quartel et al., 2008) and meso-to-macrotidal beaches (Senechal et al., 2009; Ruiz de Alegria-Arzaburu and Masselink, 2010; Bird et al., 2017) restate the strong association between the subaerial beach morphological variability in response to the incoming wave conditions, and usually responding to the 'bar-berm' and 'storm-post-storm' models. It is overall accepted that the accretionary phase of the subaerial beach results primarily from the welding of subtidal bars to the intertidal beach (e.g. Masselink et al., 2006). While storms induce rapid subaerial beach erosion, the recovery during calm wave conditions is slower due to the need of a minimum period of low-to-moderate wave energy that ensure onshore-directed cross-shore sediment transport. The physical processes responsible for the beach recovery are, however, still poorly understood (Senechal et al., 2009; Ruggiero et al., 2016), and this is particularly relevant after extreme energetic events such as El Niño (Allan and Komar, 2002; Storlazzi and Griggs, 2000; Barnard et al., 2011; Dingler and Reiss, 2002; Sallenger et al., 2002; Barnard et al., 2017).

This study contributes to the understanding of the spatio-temporal volumetric evolution of the subtidal and supratidal sections of an intermediate mesotidal beach located on the Pacific coast of the Baja California peninsula in a time span of months to years. First, the morphological and volumetric variability of the subaerial beach is studied over three years. Then, the subaerial response is compared to the subtidal and total beach change over a year and a half. The cross-shore and alongshore morphological variations are evaluated through a sediment balance and the seasonality of the beach is discussed. The volumetric changes on the subaerial, subtidal and total beach are finally related to different wave parameters to determine their relevance on the cross-shore or longshore exchange of sediment between the foreshore and the nearshore.

2. Study site

Located in the northwestern coast of the Baja California peninsula, Todos Santos Bay (TSB) comprises sandy, gravel, mixed and cobble beaches (Fig. 1). The bathymetry within TSB is fairly shallow (depths of up to 50 m) but a deep canyon of over 400 m is present between Todos Santos Islands and the Punta Banda headland. The coastline in northern TSB (between the San Miguel headland and Ensenada city) contains pocket beaches made of gravel, cobble and mixed sand/gravel, while the beaches in central TSB are made of siliceous medium sand (D_{50} of 0.25 mm). The sandy stretch of coast has a length of 14 km and is interrupted by the mouth of the Punta Banda Estuary (Fig. 1).

Ensenada beach comprises the northern half of the sandy coastline within BTS and is partly protected from the western Pacific swell by Todos Santos Islands (17 km offshore). It is a single-barred intermediate beach with an average slope of tan β of 0.025 (Ruiz de Alegria-Arzaburu et al., 2015). Coastal structures are present along the northern 2 km of the beach, such as a promenade in the northern end and a seawall and rip-rap further south. The southern beach preserves a natural dune backed by a shallow and intermittently dry freshwater lagoon. The subaerial beach width varies from 80 to 120 m to 220–240 m in the walled and non-walled sections, and the supratidal beach elevations are up to 6.5 m and 10 m above mean low water (MLW) along both sections, respectively (Ruiz de Alegria-Arzaburu et al., 2015).

The semi-diurnal tides in the study area are mesotidal with spring and neap tidal ranges of 2.3 m and 0.5 m (http://oceanografia.cicese.mx/predmar). Northwesterly winds of 4 ms^{-1} are dominant in the study area, and sporadic easterly winds known as Santa Ana are frequent from October to March, with speeds of up to 10 ms^{-1} and 2–3 days of duration (Alvarez-Sanchez, 1977; Castro and Martínez, 2010).

The incoming swell is bimodal, northwesterly waves are common during the winter, originating in the north Pacific extratropical zone, and southwesterly waves are frequent during the summer, originating in the south Pacific extratropical region. The annual nearshore waves (measured at 20 m depth) are characterised by mean significant wave height (H_s) of 1 m, mean maximum significant wave height of 1.5 m and a peak wave period of 11 s (Ruiz de Alegria-Arzaburu et al., 2016). The incidence of storms is common between October and April with H_s exceeding 4 m, and calm wave conditions dominate from June to September with an average H_s of 0.7 m (Ruiz de Alegria-Arzaburu et al., 2016). The convergence of energetic waves during the winter have been found to induce significant morphological changes along the beaches within TSB, such as the reported for the Punta Banda estuary mouth during the 1998 El Niño year (Delgado-Gonzalez et al., 2005).

3. Methodology

3.1. Morphological measurements

The subaerial morphology of the beach was measured fortnightly to monthly from November 2012 to February 2016 (Fig. 2). A beach section with a length of 2867 m was studied, and a total of 45 topographic surveys were conducted (except from April to August 2013) measuring ~50 m spaced cross-shore profiles during low spring tides. The profiles were measured using a differential GPS (Global Positioning System) with a precision of ± 0.03 m, and a threshold elevation value of 0.05 m was established to discard post-processed erroneous data as established in other research studies (e.g. Coco et al., 2014). In addition to the regular surveys, pre- and post-storm surveys were also conducted. All profiles were measured down to the mean low tide level (MLT) at a frequency of 1 Hz using a two-wheeled trolley operated by two people on foot. The same transect lines were followed at each survey time, as mapped on the GPS controller, and a total of 61 topographic profiles were consistently measured. The measurements were referred in Universal Transverse Mercator (Easting and Northing coordinates in metres), and the elevations were referenced to the local MLT (+ 36.135 m from ellipsoidal heights).

The subtidal morphology was measured monthly from August 2014 to February 2016 (Fig. 2). Bathymetric data were acquired using the Sontek M9 Hydrosurveyor Accoustic Doppler Current Profiler (ADCP) synchronized to the differential GPS and fixed to a small boat. The frequency of 0.5 MHz was used to obtain the bathymetric data with a sound speed corrected depth accuracy of ± 0.02 m. Similar to Wijnberg and Terwindt, 1995, an accuracy of ± 0.1 m was estimated when ship-dependent errors were included. In all surveys an overlap with a few topographic lines was obtained, and it was used to verify the adjustment of the submerged elevations to the subaerial. Due to limitations on data acquisition across the surf zone, linear interpolation was applied when required. A full survey consisted of 100 m spaced 30 cross-sectional transects and comprised depths ranging from 1 to 12 m, beyond the visually estimated depth of closure of ~9 m (see Fig. 2). The combination of the topographic and bathymetric measurements resulted in a total of 100 m spaced 30 topo-bathymetric (TB) transect lines. An example of the temporal evolution of two of the TB profiles (for the northern and southern beach ends) is shown in Fig. 2.

Beach volumes were calculated for each TB by integrating the profile upwards from the elevations of 0 to 5.5 m (subaerial, or