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POST-STORM BEACH RECOVERY CAPABILITIES AFTER EL NIÑO WINTER AT ENSENADA BEACH, MEXICO.

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Abstract

This study investigates the recovery capabilities of a single-barred mesotidal beach located in the Pacific Mexican coast before and after the 2015–2016 El Niño winter. Morphological data from August 2014 to December 2016 were analyzed from monthly measured topographic and bathymetric profiles to determine the cross-shore volumetric exchange in relation to the incident wave forcing. Before the 2015–2016 El Niño winter, the subaerial beach successfully recovered from the erosion during the mild wave conditions from June to October, which induced onshore transport from the subtidal beach. After the 2015–2016 El Niño winter, however, the subaerial beach erosion was much larger, and the eroded sediment moved further offshore to deeper waters of 3–4 m. Thus, the beach was unable of transporting onshore the full amount of sediment during the 2016 summer, and consequently, preventing the subaerial beach from fully recovering. It is concluded that the onshore sandbar migration during the summer wave conditions is critical to ensure a full subaerial beach recovery, and that the capabilities of the beach to recover will depend on the wave conditions during the summer and the cross-shore distance and depth at which the sandbar is located.

Key words: sandbars, morphodynamics, sediment transport, climate change.

1. Introduction

Sandbars contain large amounts of sediment that move cross-shore and alongshore, thus, quantifying their migration rates and directions is essential to determine the capabilities of the subaerial beach for post-winter recovery. The offshore sandbar migrations are generally associated to strong mean offshore currents (undertow) occurring under breaking large wave conditions, while the onshore movement takes place during weak-to-nonbreaking waves and is primarily related to near-bed wave skewness (e.g. Ruessink et al., 2007), wave asymmetry (Hoefel and Elgar, 2003) and/or boundary layer streaming and Stokes drift (Henderson et al., 2004).

Most of the sandbar studies have been focused on multi-barred beaches, and single-barred beaches have been surprisingly understudied (e.g. van de Lageweg et al., 2013; Blossier et al., 2016). The most comprehensive studies on sandbar dynamics were undertaken over decades along the multi-barred beaches of Duck (USA), Terschelling and the Holland Coast (The Netherlands) and Wanganui (New Zealand) (e.g. Lippmann et al., 1993; Ruessink and Kroon, 1994; Shand et al., 1999; Plant et al., 1999). These beaches however, lacked of seasonal sandbar movements and presented interannual migration cycles of bar generation near the shoreline, offshore migration across the surf zone and final stage of sandbar disappearance at the outer nearshore zone (Ruessink and Kroon, 1994).

During El Niño years, the track of Pacific storms move farther to the south than usual, thus inducing unusually energetic waves along the southern part of the Pacific US coast (Seymour, 1998; Allan and Komar, 2002; Storlazzi and Griggs, 2000). Previous studies looking at the morphological change caused by El Niño winters indicated extreme subaerial beach erosion during 1982–1983 and a full beach recovery by 1985 along the California coast (Dingler and Reiss, 2002). During the 1997–1998 El Niño winter Sallenger et al. (2002) demonstrated an inversion on the net longshore sediment transport direction resulting in significant subaerial beach and sea-cliff erosion on the southern side of the central California beaches. More recently, during the 1997–1998 and 2009–2010 El Niño winters severe erosion was reported along the subaerial part of the US Pacific beaches (Barnard et al., 2011) and Doria et al. (2016) reported a

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subaerial beach recovery over several years from the 1997–1998 winter while the recovery after the less erosive 2009–2010 winter happened over a season.

Despite all these studies, the association between the seasonal sandbar migration and beach recovery capabilities is still poorly understood. These studies require long-term bathymetric measurements of high spatio-temporal resolution to be able to accurately determine to sandbar shape and position (e.g. Grunnet and Hoekstra, 2004; Di Leonardo and Ruggiero, 2015), and enable the correlation between the sandbar movement and the sediment exchange between the subaerial and subtidal beach. This study aims to quantify the volumetric exchange between the subaerial and subtidal beach before and after El Niño winter 2015–2016 on Ensenada beach, located in a swell-dominated mesotidal environment in the Pacific coast of the Baja California peninsula in Mexico.

2. Field site

The study site comprises the northern 3 km of Ensenada beach, located in the northwestern coast of the Baja California peninsula, within Todos Santos Bay (TSB) (Figure 1). The beach is single-barred and intermediate, with an average slope of 0.025, and is partly protected from the western Pacific swell by Todos Santos Islands (17 km offshore) (Ruiz de Alegria-Arzaburu et al., 2015). 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.

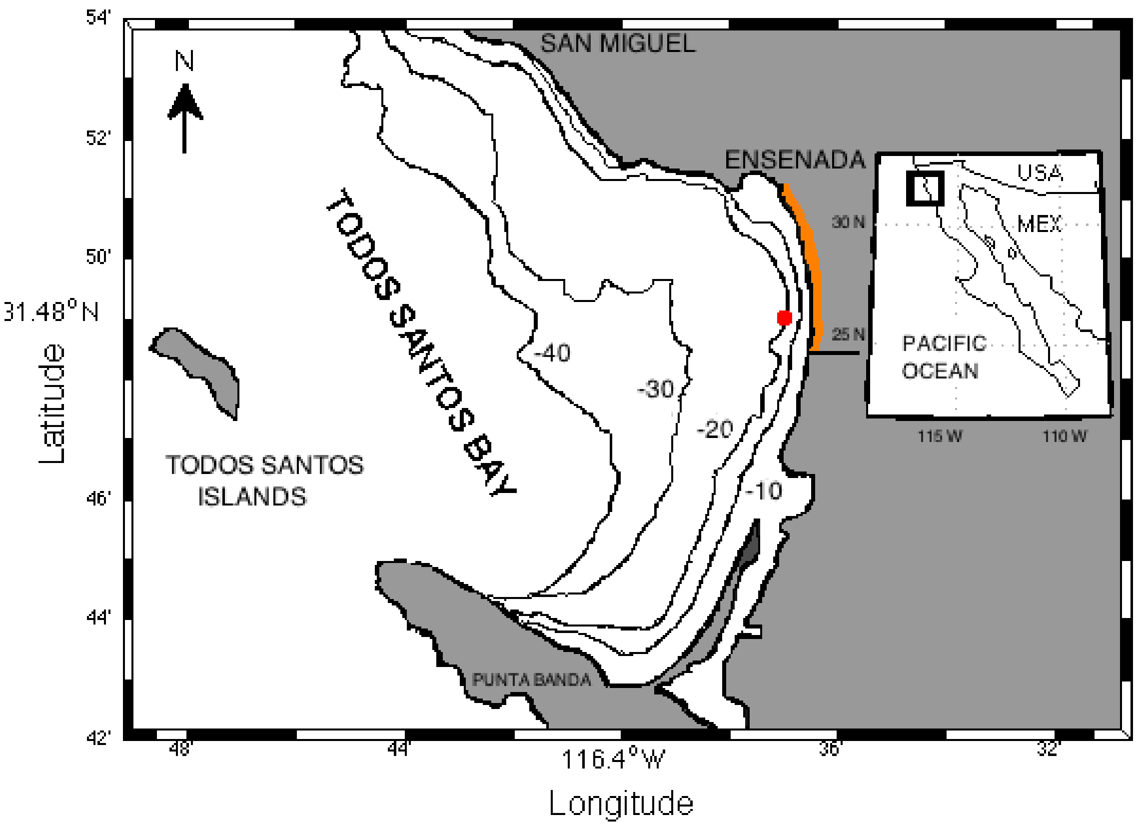

Figure 1. Location of Ensenada Beach (orange line) within Todos Santos Bay in the Mexican Pacific coast. The red dot shows the location of the acoustic Doppler current profiler (AWAC) at 20 m depth.

The subaerial beach width varies from 80–120 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 (Figure 2; Ruiz de Alegria-Arzaburu et al., 2015). The beach is mesotidal, and the tides are semi-diurnal with spring to neap tidal ranges of 2.3 m and 0.5 m (http://oceanografia.cicese.mx/predmar). Northwesterly winds are dominant in TSB, and sporadic easterly winds known as Santa Ana are frequent between October and March, with speeds of up to 10 ms^{-1} and 2–3 days of duration. The mean significant wave height of 1 m, mean maximum significant wave height of 1.5 m and a peak wave period of 11 s, and the incidence of swell-driven storms is common between October and April with waves exceeding 4 m, while calm waves dominate from June to September with an average height of 0.7 m.

Figure 2. Aerial view of Ensenada Beach on the 6th of October 2016.

3. Methods

Morphological measurements were monthly collected over a 2.5 year period (August 2014 to December 2016) across the subaerial and subtidal sections of nearly 3 km of beach length. The morphological evolution of the beach was determined and related to the incoming wave forcing. Digital elevation models and beach volumes were calculated from the measured topographic-bathymetric profiles.

3.1. *Wave measurements*

Hourly nearshore wave data were collected from August 2014 to December 2016 with a 1MHz ADCP (Nortek AWAC) located 2.5 km off the southern end of the study site at a water depth of 20 m (Figure 1). The instrument was installed on the seabed and provided continuous measurements of wave parameters including the significant wave height (H_s), wave peak period (T_p) and wave direction (α). The monthly averaged wave heights were calculated for the years 2014, 2015 and 2016.

3.2. *Topographic and bathymetric measurements*

The subaerial beach morphology was measured monthly from August 2014 to December 2016 along a beach section of 2,867 m measuring a total o ~50 m spaced 61 cross-shore profiles during low spring tides (top lines in Figure 3). 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). All profiles were measured down to the mean low tide level (MLT) at a frequency of 1Hz using a two-wheeled trolley operated by two people on foot. 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 same transect lines were followed at each survey, as these were mapped on the GPS controller.

The subtidal morphology was measured monthly from August 2014 to December 2016, right after or before the topographic measurements. The 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 or to a jetski. 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 et al. (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, when required, linear interpolation was applied. A full survey consisted of 100 m spaced 30 cross-sectional transects (TB in Figure 3) and comprised depths ranging from 1 to 12 m, beyond the depth of closure (~ 8 m).

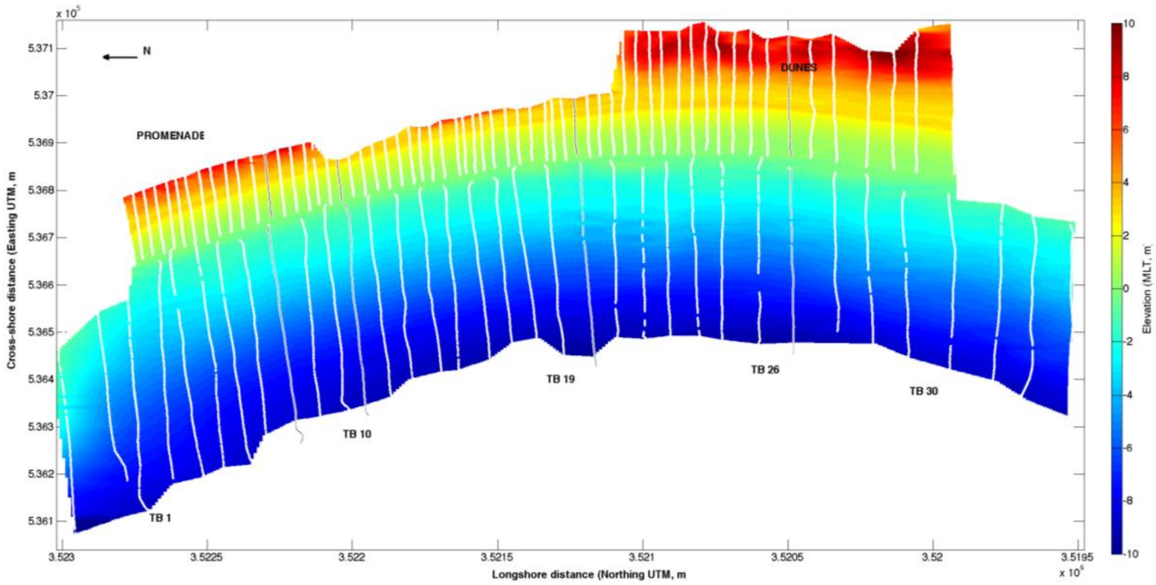

Figure 3. An example of a Digital Elevation Model (DEM) obtained from interpolating topographic (onshore lines) and bathymetric (offshore lines) profiles.

3.3. *Volumes and digital elevation models (DEMs)*

The combination of the topographic and bathymetric measurements resulted in a total of 100 m spaced 30 topo-bathymetric (TB) transect lines. The TB profiles were interpolated at 0.1 m across-shore to obtain digital elevation models (DEMs) per survey period (Figure 3). The three-dimensional morphological variations for the subaerial beach (IS) were obtained subtracting the DEMs from 0 to 5.5 m of elevation; differences for periods between minimum and maximum IS volumes were performed. The three-dimensional morphological variations for the whole beach (TOT) were calculated subtracting the DEMs from -9 to 5.5 m of elevation for the available periods of minimum and maximum IS volumes.

Beach volumes were calculated for each TB by integrating the profile upwards from the elevations of 0 to 5.5 m (subaerial, or intertidal and supratidal, IS), -9 to 0 m (subtidal, SUB) and -9 to 5.5 m (total, TOT), and multiplying the corresponding alongshore length represented by each profile. A hypothetical vertical error of 0.1 m across the whole TB profile (from -9 to 5.5 m of elevation) and extending along the studied beach section would imply a total volumetric error of 2 %. The loss or gain of volume was determined subtracting the mean value to each volume in time, which resulted in de-meaned (Dem) IS, SUB and TOT volumes. The volumetric evolution of the beach was obtained calculating the cumulative volumetric differences (Cum ΔV) per beach profile in time.

4. Results

4.1 Hydrodynamic conditions

Significant seasonal and interannual differences were encountered in the wave conditions between the years 2014, 2015 and 2016 (Figure 4). The waves were significantly more energetic during the 2015–2016 winter than during the previous winters in 2013 and 2014. The average H_s exceeded 1.5 m from December 2015 to March 2016 and the waves were of longer period (sometimes over 20 s) during some of the energetic events than in the previous winters.

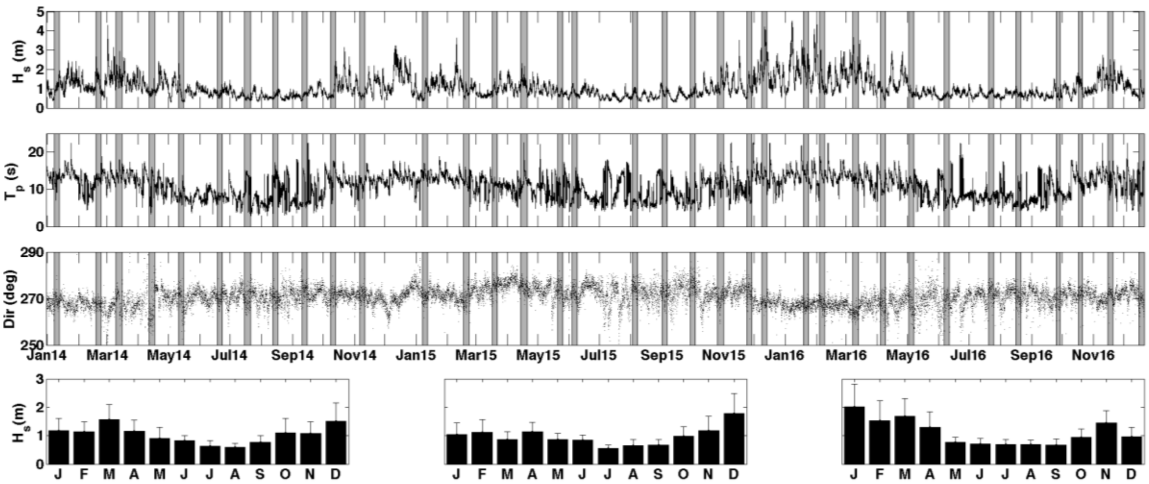

Figure 4. Time series of significant wave height (H_s), peak period (T_p) and wave direction (Dir) from January 2014 to December 2016 (top three panels) and monthly averaged H_s for 2014, 2015 and 2016 (left to right bottom panels). The vertical gray bars indicate the times when the morphological measurements (topography and bathymetry) were undertaken.

4.2 Morphological variability

The subaerial and subtidal morphological variability was determined for the summer and winter seasons in 2014, 2015 and 2016 in order to evaluate the beach erosion and recovery over the study period. The cumulative morphological change for the winter period from December to March in 2015 and 2016 is shown in Figure 5. And Figure 6 represents the cumulative morphological change during the summer periods from August to November 2014, 2015 and 2016.

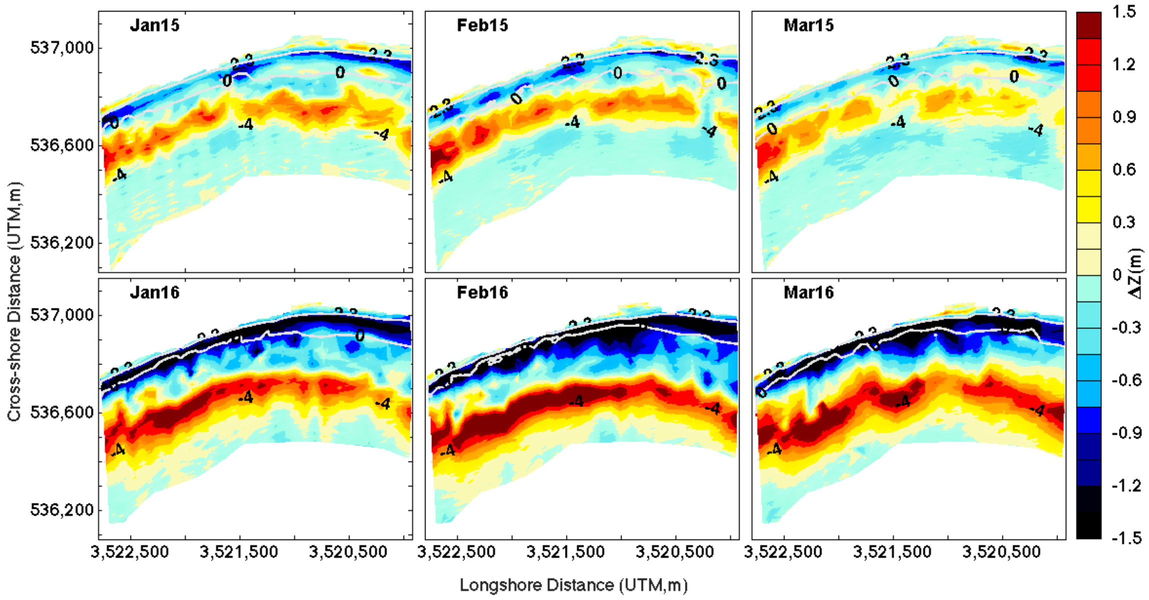

Figure 5. Cumulative morphological differences from December to March 2015 (top panels) and 2016 (bottom panels) for the subaerial and subtidal beach sections. The intertidal beach is defined between the 0 m and 2.3 m contourlines.

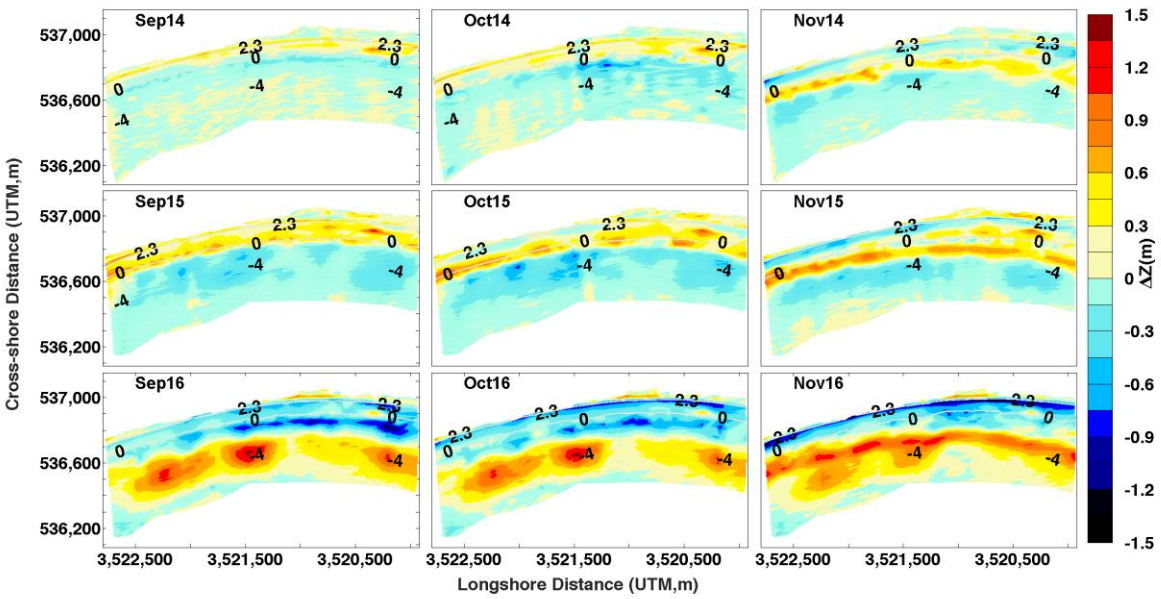

Figure 6. Cumulative morphological differences from August to November 2014 (top panels), 2015 (middle panels) and 2016 (bottom panels) for the subaerial and subtidal beach sections. The intertidal beach is defined between the 0 m and 2.3 m contourlines.

The beach presented very different morphological variability from the winter of 2015 to the 2016. From December 2014 to February 2015 the subaerial beach eroded up to 1 m, and the eroded sediment migrated offshore forming an alongshore sandbar at 2–3 m depth. Between February and March 2015 the sediment started moving onshore and redistributing along the inner subtidal beach (top panels Figure 5). The cumulative morphological change during the 2015–2016 winter was significantly larger than in 2014–2015 with a vertical morphological change of over ±1.5 m. From December 2015 to February 2016 the subaerial beach eroded over 1.5 m and the eroded sediment was transported offshore as a form of a nearshore bar located at a depth of 3–4 m. From February to March 2016 the sediment from the sandbar started moving onshore but in contrast to the observed in March 2015, the sediment did not reach the intertidal beach.

The subaerial beach accreted from August to October in 2014 and 2015, and it started eroding between October and November, resulting in the formation of an inner subtidal bar near the shoreline (0 m contourline) (top and middle panels in Figure 6). During the summer in 2016, however, the beach was unable of accreting the subaerial section. From August to October 2016 most of the sediment was located in the subtidal section, subsequently, the subaerial beach was unable of recovering (left and central panels in Figure 6). Between October and November 2016 the subaerial beach eroded up to 1m and the eroded sediment moved offshore accumulating at a depth of 2 to 3 m.

4.3 Volumetric change

Figure 7 presents the cumulative volumetric change from August 2014 to December 2016 along the subtidal and subaerial (intertidal and supratidal) beach sections. These results indicate that the subaerial beach successfully recovered after the 2013–2014 and 2014–2015 winters during the summer months from June to October; the subtidal beach erosion was of similar magnitude to the subaerial accretion. Thus, the subaerial beach recovery is attributed to the cross-shore exchange of sediment from the subtidal beach, associated to the onshore sandbar migration.

After January 2016 the subaerial beach presented severe erosion that lasted till June 2016 and contributed to the significant build up of the subtidal section, mostly along the southern half of the beach. During the summer in 2015 the subtidal beach eroded from June to October, and the eroded sediment contributed to the build up of the subaerial section (Figure 7). During the 2016 summer, however, the subtidal beach did not erode but accreted, and mostly along the southern beach. Between August and October 2016 the subaerial section decreased the volumetric deficit slightly at the same time as the subtidal beach vaguely eroded; indicative of a minor subaerial beach recovery but far from a full recovery (Figure 7).

5. Discussion

The studied 2015–2016 El Niño winter was characterized by the presence of more energetic waves that lasted for a month or two longer than in previous years. This agrees with previous findings along the southern Pacific US coast (Seymour, 1998; Allan and Komar, 2002; Storlazzi and Griggs, 2000) which indicated the presence of unusually energetic waves during the El Niño winters.

Ensenada Beach was unable of fully recovering the subaerial beach volume after the 2015–2016 El Niño winter, and this agrees with previous studies on beaches along the California coast, which indicated that the beaches took a few years to fully recover from extreme subaerial erosion during the energetic 1982–1983 and 1997–1998 El Niño winters (Dingler and Reiss, 2002; Barnard et al., 2011; Doria et al. 2016).

The capability of the beach to fully recover was attributed to the onshore sandbar migration during the summer mild wave conditions. In contrast to studies in multi-barred beaches (Lippmann et al., 1993; Ruessink and Kroon, 1994; Shand et al., 1999; Plant et al., 1999), this single-barred beach presented a very strong seasonal response. The sandbar in Ensenada Beach usually migrates offshore reaching 2–3 m depth from November to February and moves onshore during the post-winter milder waves after February completely welding the beachface by May, and incorporating the eroded sediment back onto the subaerial beach. During the 2015–2016 El Niño winter, however, the sandbar moved further offshore to deeper depths of 3–4 m and the winter waves lasted for a month or two longer (till April 2016). Thus, the beach was unable of transporting the sediment onshore over the shorter summer, and the subaerial beach did not fully recover.

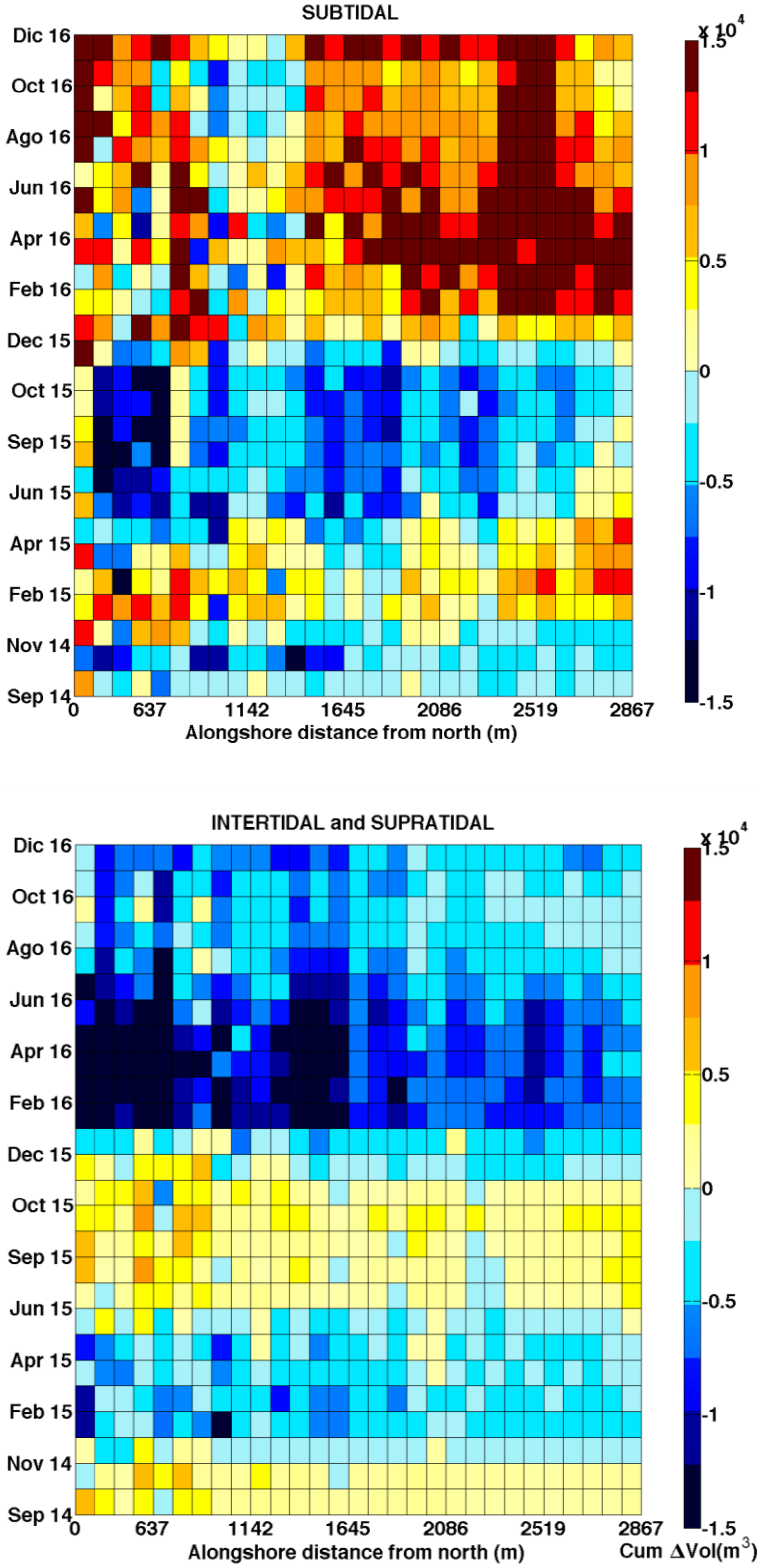

Figure 7. Cumulative volumetric differences for the subtidal beach (top panel) and the intertidal and supratidal or subaerial beach (bottom panel) from August 2014 to December 2016 (bottom to top in the *y* axis).

6. Conclusions

Based on monthly morphological measurements collected over a 2.5 year period, this study investigated the recovery capabilities of a single-barred mesotidal beach located in the Pacific Mexican coast before and after the 2015–2016 El Niño winter. Before the 2015–2016 El Niño winter, the subaerial beach successfully recovered from the erosion during the summer mild wave conditions from June to October that induced onshore sediment transport from the subaerial beach. After the El Niño winter, however, the subaerial beach erosion was much larger, and the eroded sediment moved further offshore to deeper waters of 3–4 m. Consequently, the beach was unable of transporting the full amount of sediment onshore during the 2016 summer, preventing the subaerial beach from fully recovering. It is concluded that the onshore sandbar migration during the summer is critical to ensure a full subaerial beach recovery, since the sediment contained on the sandbar will contribute to the complete build up of the subaerial beach during the accretive phase.

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