MORPHOLOGIC CHANGE AND MORPHODYNAMICS AT HIGH-ENERGY EMBAYED BEACHES IN SOUTHWESTERN PORTUGAL

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Abstract: Along the southwestern coast of Portugal, a high-energy, swell dominated environment with a markedly seasonal wave climate, morphologic change in three embayed beaches was regularly monitored over a two year period. While a general seasonal pattern was identified, the occurrence of a storm group induced dramatic beach response, producing marked interannual variability. Significant spatial variations in behaviour emerged during the monitoring period, inducing alongshore non-uniform beach change within each embayment. Megarips were the prevailing mechanism responsible for the extreme erosion experienced in all three beaches, and their specific location (controlled by topography) contributes to the variability observed within each beach. Despite severe beach erosion, dunes were unaffected, which suggests long-term stability of these high-energy, dissipative, embayed coastlines.

Introduction

Cycles of erosion and accretion in wave-dominated beaches have been extensively studied and documented around the world's coastlines. Initial models of winter "cut" and summer "fill" were progressively replaced by models of cyclic beach change in response to changing wave conditions (Hayes and Boothroyd, 1969; Nordstrom, 1980), and further extended to fully integrate the three-dimensional behaviour of beaches and surf zones (Wright and Short, 1984). Nevertheless, for coastal environments with a strong seasonal wave climate, as in swell-dominated beaches, morphologic change is commonly reflected in erosion and accretion patterns in phase with the seasons (Quartel *et al.*, 2008). Although periodic storm erosion is not unique to any particular season, there is a general tendency for higher intensity and frequency of storms during the winter season (Hayes and Boothroyd, 1969; Fox and Davis, 1978; Quartel *et al.*, 2008). More frequent storms means a shorter timeframe for the slow pace post-storm recovery to occur, and only partial recovery is accomplished before the following storm occurs, preventing complete recovery

until the end of the storm season (Fox and Davis, 1978). This pattern of morphological change on swell-dominated beaches creates a seemingly seasonal cycle of beach change, with beach volume variation characterized by a post-winter minimum and reaching a maximum volume at the beginning of the winter, following summer accretion (Quartel *et al.*, 2008).

On high-energy dissipative beaches observations of the seasonal pattern of morphological change increased in recent years, highlighting marked alongshore variations in shoreline change (e.g. Ruggiero *et al.*, 2005; Hansen and Barnard, 2010). Alongshore non-uniform morphological change on high-energy dissipative beaches arises because beach response, especially during storms, does not linearly depend on wave conditions (Russell, 1993), due to reduced contribution of the incident wave frequency band in the beach and inner surf zone (Wright *et al.*, 1982; Russell, 1993). Instead, it depends on a combination of waves and infragravity oscillations, tidal phase and surge level, antecedent morphology and geomorphologic control (Cooper *et al.*, 2004; Ruggiero *et al.*, 2005). For embayed beaches on high-energy coastal environments, conditions for alongshore non-uniform response are even more pronounced, as geomorphologic control in beach morphodynamics is highly significant (Jackson *et al.*, 2005), and sediment movement and hydrodynamics in embayed beaches are heavily impacted by headlands (Short, 1999). Earlier reports of alongshore variation in morphological change of embayed beaches exposed to energetic wave conditions identified complex interactions between large scale embayment circulation, particularly those associated with rip currents developed during storms (Eliot and Clarke, 1982). The beach response associated with such large scale rip currents, later termed megarips by Short (1985), was found to vary alongshore and deviate from the seasonal trend of morphological change (Eliot and Clarke, 1982). Recent work has highlighted megarips as an important mechanism of morphological change on embayed beaches (Short, 2010), but they still remain a little studied coastal process (MacMahan *et al.*, 2005).

The aim of this paper is to investigate the variability of beach change in embayed beaches exposed to high-energy wave conditions. The temporal variation, associated with seasonal and episodic changes, as well as the non-uniform alongshore patterns of beach change are analysed, and the morphodynamic mechanisms that drive the observed behaviour are discussed.

Study area

The southwestern coast of Portugal, a high-energy swell environment, is a bedrock-framed coastline where beaches occur generally in embayments associated with small streams or in coastal re-entrants within the rocky cliffs. Along this coastline three beaches, Amoreira, Monte Clérigo and Arrifana, were selected as study sites (Figure 1). The first two are directly exposed to the

dominant north-westerly waves while Arrifana roughly faces west and is partially protected by a prominent northern headland. These three relatively short beaches (between 500 and 750 m long) are composed of well sorted medium sand and, being exposed to a high-energy wave climate, are modally dissipative or intermediate skewed to dissipative in state. Amoreira embayment contains a bay-barrier estuary, with a small tidal stream meandering along the intertidal zone. The beach is wide and backed by an extensive dune field, presenting a persistent low tide terrace occasionally crossed by the tidal stream, which creates a ridge and runnel-like morphology. Monte Clérigo also presents a wide beach backed by dunes in the south and centre, while the northern sector is narrow and backed by 50-m high cliffs. During most of the year the beach is typified by a gently sloping beach face, extending shoreward to the toe of the cliffs on the northern sector. A similar gentle sloping beach face extending to a gravel deposit at the cliff base characterizes Arrifana, a swash aligned beach enclosed by up to 100 m high cliffs. The subaerial beach is narrow and rarely contains a well defined berm, while the intertidal beach is wide and planar.

Being exposed to the North Atlantic, the coastline of south-western Portugal experiences energetic conditions throughout the year, although with markedly seasonal variation. Mean monthly offshore significant wave heights (H_{so}) between 2 and 2.5 m occur from November to March, while during the remaining months H_{so} varies from 1 to 2 m (Costa and Esteves, in press). Wave period follows a similar variation, with monthly peak periods (T_p) between 12 and 14 s from November to March and 9 to 12 s during the rest of the year. Peak wave direction (Dir_p) is constant throughout the year from NW-W direction (97.4% of the records) (Costa *et al.*, 2001; Costa and Esteves, in press). Energetic wave conditions are relatively frequent, with H_{so} exceeding 3 m on 10% of the time. Storms along the western Portuguese coast are normally associated with $H_{so} \geq 5$ m (Pita and Santos, 1989), and are generally caused by high to mid-latitude depressions crossing the North Atlantic towards Western Europe (Costa *et al.*, 2001). Storm groups occur frequently on the west coast of Portugal, on average once every year for groups of two storms and once every four years for a group of three storms (Ferreira, 2005). Tides along the south-western Portuguese coast are semidiurnal and mesotidal, with maximum spring tidal range of 3.6 m and maximum tidal elevation approximately 2 m above mean sea level (MSL). Barometric pressure effects can increase the water levels by up to an additional 0.5 m (Gama *et al.*, 1994).

Methods

Topographic surveys were conducted along cross-shore beach profiles on the three beaches. Surveys were performed regularly every two months between September 2007 and September 2009. Episodic surveys were also undertaken

after each storm and 15 to 30 days later to monitor beach recovery, as survey-storm timing is decisive to understand the variability in beach changes driven by storm events (Quartel *et al.*, 2008). In total, 20 surveys were completed on each beach over the two year period. Three profiles representative of different beach sectors and with alongshore spacing between 100 and 200 m (Figure 1), were monitored on each beach using RTK-GPS. Surveys were performed always during low tide, preferentially during spring tides, at least up to the mean low water spring level (MLWS), 1.4 m bellow MSL, or further seaward.
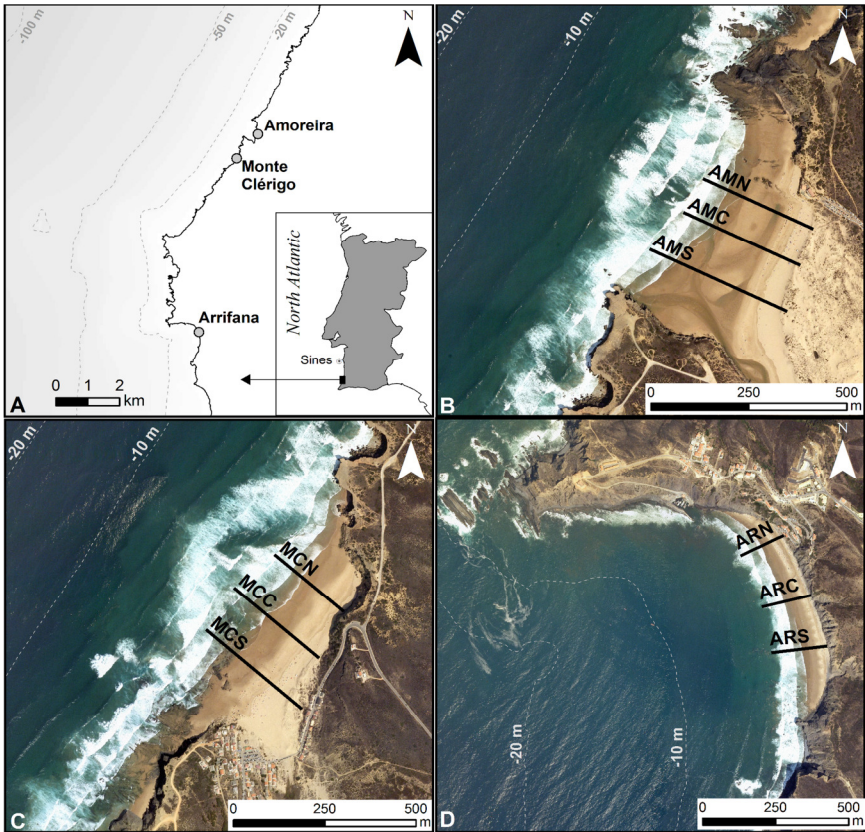

Fig. 1. Location of the study area in the south-western coast of Portugal (A). Amoreira (B), Monte Clérigo (C) and Arrifana embayments with profile identification (black lines).

Wave and tide data were obtained continuously for the entire monitoring period from the Sines deepwater directional wave buoy, located in 97 m water depth, and from the Port of Sines tide gauge, both approximately 65 km north of the study area (Figure 1). Gaps in the observed tidal record (~2% of the total record)

where filled using the predicted tide levels, while gaps from the measured wave record (~20% of the total record) where filled using modelled data from a close WANA network deepwater grid point (Lahoz and Albiach, 2005), as significant correlation was obtained for H_{so} ($\rho \leq 0.001$, $n = 6137$, $R = 0.88$) and T_p ($\rho \leq 0.001$, $n = 6137$, $R = 0.61$). Correlation analysis was also performed between several WANA grid points along the southwest coast of Portugal to determine whether wave conditions close to Sines buoy were representative of the deepwater conditions further south, in locations closer to the study areas. Results indicate a highly significant correlation for both H_{so} and T_p at all points ($\rho \leq 0.001$, $n = 8276$, $R \geq 0.92$), suggesting a close similarity of deepwater wave conditions along this stretch of coastline.

Time series of beach width and volume variability were used to quantify beach changes. Beach width was calculated as the horizontal distance from the MSL shoreline position to the cliff base of frontal dune, which has not changed during the monitoring period. MSL was selected for beach width following several works using datum-based shorelines as proxies for beach width change (Farris and List, 2007), particularly using the intersection of the MSL with the foreshore on high-energy environments (*e.g.* Hansen and Barnard, 2010). Beach profile volume was obtained using trapezoidal integration with the upper limit defined by the profile surface and the MLWS level as lower limit. By taking MLWS level (-1.4 m MSL) as the lower limit for volume calculation it was possible to incorporate the intertidal and subaerial beach change. A similar level, -1.3 m MSL, was recently identified for an exposed beach in southern Portugal by Almeida *et al.* (in press) as a nodal depth separating the cross-shore sectors dominated by berm and subtidal terrace changes, respectively above and below that depth. The existence of a nodal point at a depth close to MLWS level appears to indicate a vertical morphodynamic separation of the profile at this level, rendering it as an appropriate lower level for volume calculation. Net gain or loss of sediment over the MLWS level is then considered an indicator of cross-shore exchange of sediment between (i) the subaerial and intertidal beach and (ii) the subtidal beach. Profile volumetric mobility and envelopes where computed following Dolan *et al.* (1978). Mobility is defined as standard deviation of the mean profile volume ($\pm \sigma$), while the envelope corresponds to the maximum and minimum values of the detrended beach volume time series.

Results

Wave forcing

Daily averages of offshore wave conditions, (Figure 2) indicate that the largest values typically occur during winter (October to March), although most severe events are generally concentrated between December and February. During the

remaining months wave conditions are moderate, even though energetic events occasionally occur, with H_{so} exceeding 3 m (*e.g.* April 2008 or September 2008). The seasonal character of the wave climate in southwestern Portugal is highlighted by the 3-month running average in Figure 2. Both H_{so} and T_p display a similar seasonal variation, with average H_{so} around 2m and T_p above 12s in the peak of the winter season. Summer values range between 1 and 1.5m and 8 and 10s for H_{so} and T_p, respectively. Average wave approach from WNW to NW shows little seasonal variation.
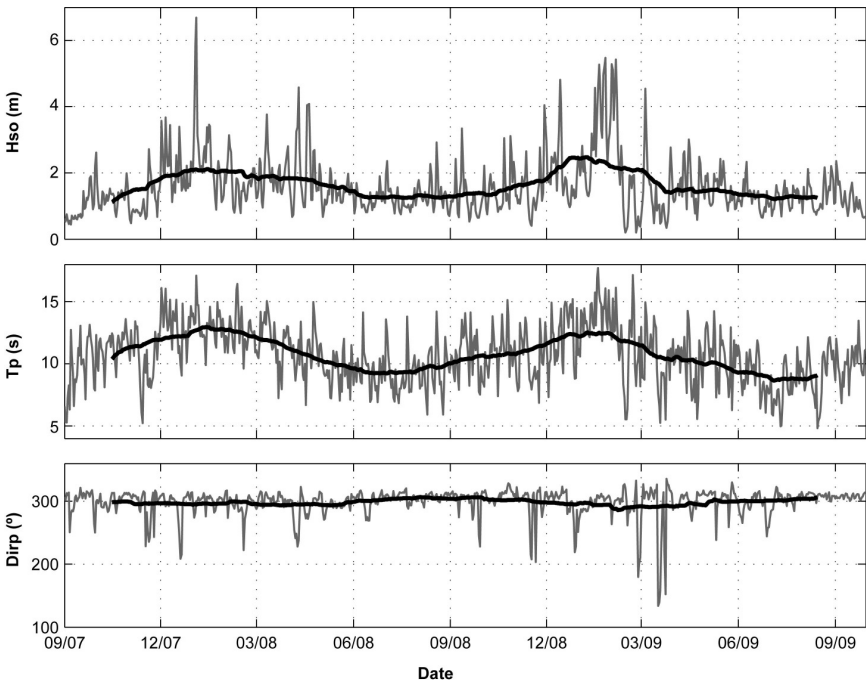

Fig. 2. Daily averages of offshore wave conditions for Sines buoy between September 2007 and September 2009. Thick black line depicts smoothed values using a 3-month running average

The most significant events during the monitoring period occurred in January 2008 and January-February 2009 (Figure 2). An extreme single storm, with daily H_{so} exceeding 6 m and maximum H_{so} up to 8 m, reached the coast during neap tide in early January 2008, with waves in excess of 5 m for 36 hours. By mid-January 2009 a series of storms in rapid succession was initiated, lasting for 22 days with continuously high waves. Considering a storm independence criterion of 30 hours between wave extremes, following Morton *et al.* (1997) according to the time-scale of mid-latitude depressions, 5 individual storms

compose this storm group (Figure 3). The storm group spanned through neap and spring tides, although no storm peak was coincident with the highest tides between the 27th and 31st of January. Surge levels were significant, especially during the 4th and 5th storms, but maximum surge of 0.32 m did not reach the threshold of 0.35 m defined by Gama *et al.* (1994) as the yearly very significant surge level (above the 99th percentile) for the southwestern coast of Portugal.
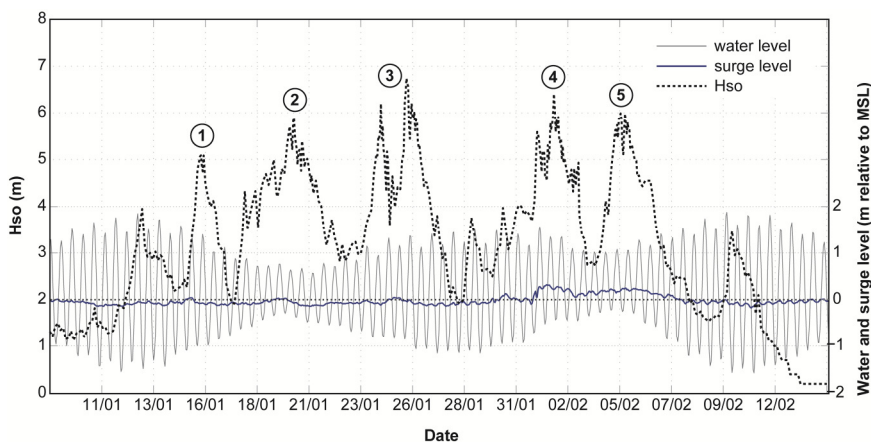

Fig. 3. Offshore significant wave height, water level and surge level during the January-February 2009 storm group

Seasonal and storm induced beach change

Morphological change was evaluated using the variation of beach profile volume above MLWS level and beach width up to MSL (Figure 4). Both proxies for beach change are significantly correlated at every profile ($R \geq 0.80$, $\rho \leq 0.001$), except Amoreira south profile ($R = 0.31$, $\rho > 0.05$). Peak profile volumes and widths are generally recorded in late October to early November, following a gradual accretion during the summer months. Abrupt changes took place during the winter, especially during the months of December to February, when high-energy events are more frequent. During the first year of monitoring the mean beach variation, in either volume or width, fluctuated between ±100 m^3/m for profile volume and ±50 m for beach width. The variation in most individual profiles was also within these ranges, with exceptions of Amoreira north and south profiles and also Monte Clérigo south profile. By early November 2008 most profiles presented volumes or widths similar to the ones recorded in November 2007, before the winter storms, suggesting a yearly cycle characterized by winter erosion and summer accretion, without significant sediment loss. Within this general seasonal variation in mean beach volume or width, however, individual profiles exhibit shorter term cyclic changes related to

storm – post-storm cycles. Profiles Amoreira south and north, Monte Clérigo north and Arrifana south reveal more clearly these cycles that, despite the short-timescale, still involve sediment volumes and beach width changes similar to the values previously reported for the mean beach variation.
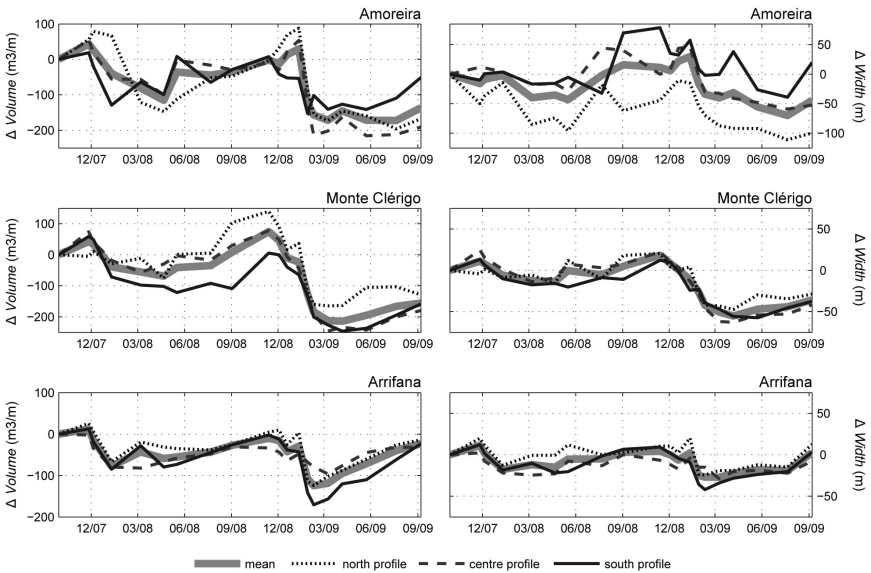

Fig. 4. Cumulative beach change for each profile and averaged per beach. Left panels represent the beach volume (m^3/m) and beach width (m) is shown in the right panels.

The January-February 2009 storm group promoted general erosion on all three beaches, being responsible for the most dramatic changes during the monitoring period. Erosion of 100 to 200 m^3/m occurred on most profiles during this cluster of 5 storms, and average shoreline retreat was 40 m. The response of the beaches to this storm group was not uniform, and there were variations especially in terms of magnitude of beach width change. These variations are evident in Amoreira beach, where changes are of higher magnitude (note the different y axis scale in Figure 4). Following the storm group, beach recovery initiated immediately in Arrifana beach, while Amoreira and Monte Clérigo beaches still experienced moderate erosion, reaching the lower sediment volumes by the beginning of the 2009 summer season, after which beach recovery was initiated.

By the end of the monitoring period net sediment loss was significant in Amoreira and Monte Clérigo beaches, amounting to approximately 150 m^3/m with a corresponding net shoreline retreat of roughly 50 m. Sediment losses were, however, restricted to the foreshore, resulting in significant berm retreat

and intertidal beach lowering. Despite the significant erosion observed, mostly under the action of the January-February 2009 storm group, there was no dune scarping or retreat on the profiles backed by dunes in Amoreira and Monte Clérigo beaches.

Alongshore non-uniform beach change

Regardless of the reduced dimensions of the three beaches, with lengths of less than 1 km, differences in beach profile response within each beach were observed. Alongshore variations in profile response are generally in terms of *magnitude* of change, since erosion and deposition were mostly synchronous in all profiles. Differences in profile variation within the same beach reached maximum values of 200 m^3/m in volume (Monte Clérigo beach in September 2008; Figure 4), or 100 m in width (Amoreira beach in September 2008; Figure 4). The non-uniform beach response is evident in the mobility and envelopes of change for each profile (Figure 5). Alongshore ranges for both envelope and mobility in Amoreira beach are similar for profiles north and centre, while for profile south both indexes are approximately 50 m^3/m smaller in both positive (accretion) or negative variation (erosion), indicating lower range of variation. Monte Clérigo beach evidences also alongshore variations in profile variability, with the centre profile presenting a wider mobility. Considering absolute ranges of profile envelope at Monte Clérigo, all profiles present envelopes around 300 m^3/m, but the envelope of profile centre presents lower values, indicating higher erosion. Profile mobility and envelopes at Arrifana beach also show distinct alongshore variations. Profiles south and north present approximately twice the profile centre mobility, and change envelopes are significantly wider, implying that profile centre is less variable than the profiles at both ends of the beach. It is important to note that the magnitude of change in terms of average mobility and envelope is similar between Amoreira and Monte Clérigo, and both are approximately twice the average values for Arrifana.

Profile behaviour was also marked by diverse association between profiles at each embayment, as confirmed by correlation of temporal changes of volume and width for individual profiles within each beach (Table 1). Significant correlation was found between Amoreira north and centre profiles, for both volume ($R = 0.86$, $\rho < 0.01$) and width ($R = 0.82$, $\rho \leq 0.01$), while profile south was uncorrelated to any other profile in terms of beach width. For Monte Clérigo there is a slightly higher agreement between profiles south and centre, despite all profiles being well correlated in both volume and width ($R \geq 0.76$, $\rho < 0.05$). At Arrifana higher correlation is found between profiles at each end of the beach, where profiles north and south present the highest correlation for beach volume ($R = 0.96$, $\rho < 0.01$), despite being 400 m apart.
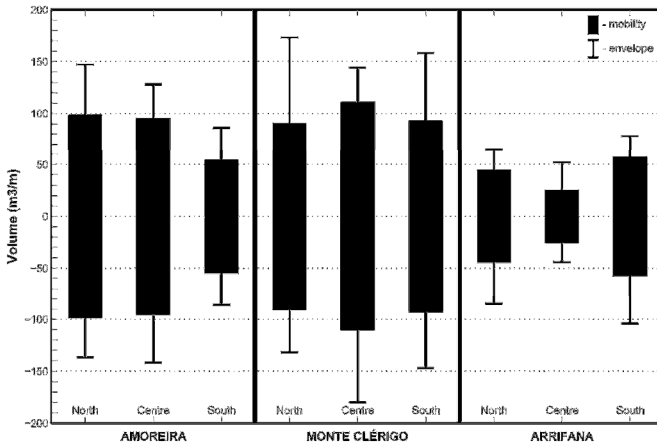
Fig. 5. Profile volumetric mobility and envelope

Table 1. Correlation coefficients for beach profile volume and width variation

Profile Name	AMN	AMC	AMS
AMN		0.82 *	0.29 ***
AMC	0.86 *		0.41 ***
AMS	0.51 **	0.75 *	
Profile Name	MCN	MCC	MCS
MCN		0.91 *	0.81 *
MCC	0.89 **		0.95 *
MCS	0.76 **	0.92 **	
Profile Name	ARN	ARC	ARS
ARN		0.67 *	0.82 *
ARC	0.73 *		0.68 *
ARS	0.96 *	0.75 *	

* statistically significant for $\rho < 0.01$
** statistically significant for $\rho < 0.05$
*** statistically not significant
Note: Correlation for profile volume at the left side (no shading) and correlation
for profile width at the right side (in light gray shading)

Discussion and conclusion

Seasonality in the wave forcing drives a seasonal cycle in beach change,
particularly in swell-dominated beaches (Quartel *et al.*, 2008), and was notable
in the three beaches during the first year of monitoring, despite the occurrence of
an extreme single storm in January 2008. Nevertheless, over the two-year period

of monitoring, the temporal variation at the three embayed beaches suggests that the seasonal winter erosion/summer accretion pattern of morphological change is not the dominant signal in the data. The occurrence of a storm group in January-February 2009 created the most conspicuous change, highlighting the importance of storm groups as drivers of morphological change. Storm clustering over weekly to monthly timeframes has been shown to produce highly significant erosion on exposed sandy beaches of western Portugal (Ferreira, 2005), eastern Australia (Thom, 1974) and the US Pacific northwest coast (Ruggiero et al., 2005). Such extreme event grouping, by inducing severe erosion may require recovery periods of several years, promoting interannual variability that is noticeable in the beach and volume time series for Amoreira and Monte Clérigo beaches.

Despite a similar general evolution pattern, differences between beaches have also been observed, and these are mostly the result of geomorphologic constrains specific to individual beaches, as embayed coastlines are prone to site-specific storm responses (Cooper *et al.*, 2004). Higher envelopes of shoreline change are expected for inlet-associated embayed beaches in comparison to headland-embayment systems in high-energy dissipative environments (Cooper *et al.*, 2007; O'Connor *et al.*, 2007). At Amoreira, the existence of a tidal stream that migrates and meanders across the intertidal beach influences shoreline variation, resulting in a more varied behaviour of beach width compared to the other two beaches. This higher shoreline variability within the embayment, however, is not matched by high volumetric variability. This suggests that sediment exchanges between the intertidal and subaerial beach affect the shoreline position but not the overall sediment volume. Local geomorphologic constraints are also responsible for lower magnitude volume and width changes at Arrifana beach. Diffraction around the prominent northern headland and refraction on the gentle shoreface significantly reduce breaking wave heights from the dominant north-westerly waves, leading to lower energy wave conditions compared to Amoreira and Monte Clérigo. Because of lower waves and higher confinement of Arrifana embayment, storm impacts are likely to be less severe. This is confirmed by the lower mobility and envelopes of change, as well as by the ability of the beach to regain its sediment volume and width by the end of 2009 summer, in contrast to Amoreira and Monte Clérigo, which experienced net erosion of >100 m^3/m and shoreline retreat of ~50 m.

Embayed high-energy dissipative beaches exposed to modally energetic swell are considered to be attuned to high-energy conditions and, therefore, require extreme events to cause significant morphological change (Cooper e*t al.*, 2004). Despite H_{so} reached a maximum of 8 m during the January 2008 storm, the short duration of the event and its occurrence during neap tides, led to only moderate erosion (within what is assumed to be the seasonal variation). The response to

the January-February 2009 storm group was, however, much more significant even though maximum H_{so} was significantly lower, not even reaching 7 m. As erosion on high-energy dissipative beaches is not directly related to the incident storm waves, but with the lower frequency motions generated in the inner surf zone (Russell, 1993), the duration of the storm events and their occurrence during periods of elevated water levels during spring high tide or significant surges, seem to be more important in determining beach response. When storm waves persist for long periods of time, as in the January-February 2009 storm group, infragravity motions, with their dominant offshore directed sediment transport (Russell, 1993), provide conditions for continued sediment erosion, leading to the extreme erosion observed in all beaches. Such extreme erosion on Amoreira and Monte Clérigo beaches had, however, no effect in the dunes and was restricted to the beach and nearshore. The ability of dissipative embayed coastlines to accommodate increasingly high waves, due to energy dissipation on progressively wider surf zones (Cooper *et al.*, 2004), implies that most of the waves that reach the backshore are already not competent for inducing significant morphological change, as observed in Monte Clérigo and Amoreira. At the same level, the infragravity motions that convey the energy of the storm waves to the inner surf zone and beach, creating pulses of offshore sediment transport (Russell, 1993), are not active beyond the foreshore and therefore are unable to impact the backshore and dune. This has implications for the long-term behaviour of dissipative embayed coastlines, as even extreme events, if followed by moderate conditions that enable beach recovery, may not have long lasting effects on the coastline behaviour.

Variations in magnitude (but not overall pattern) of change were observed in each embayment. Embayment topography, particularly the presence of rocky headlands, significantly impacts morphodynamics of embayed beaches (Short, 1999). During high wave conditions the topographical influence of headlands on the surf zone dynamics is increased, inducing longshore gradients and forcing the development of cellular circulation (Short, 1985). Under these conditions, megarips develop and become the major mechanism of surf-zone circulation (Short, 1985; 1999), creating conditions for alongshore variation in beach response (Eliot and Clarke, 1982). Observations of surf-zone conditions during high waves on the three beaches, along with the measurement of profile change immediately after storms, confirmed the presence of megarips and quantified their impact on beach morphological change. Large rip channels connected to deep feeder channels along the intertidal beach were observed on the centre of Amoreira and Monte Clérigo embayments, while at Arrifana two megarips developed at both extremities of the beach. Profile erosion was always higher in the profiles fronting megarips or intersected by feeder channels, as evidenced in Arrifana. Similarity in behaviour of profiles north and south for Arrifana beach, for both volume and width (Table 1), supports the hypothesis that megarips are

responsible for alongshore variability in profile and shoreline change in embayed beaches (Eliot and Clarke, 1982). The development of a megarip in the centre of Monte Clérigo embayment is also associated with higher profile mobility (Figure 5). Similarly, increased variability was observed in profiles centre and north in Amoreira beach, as the wide megarip developed in the centre of the beach migrated towards the northern section.

Extreme erosion on high-energy dissipative embayed beaches (as experienced during storm groups) appears to be associated with the development of cellular circulation with megarips persisting for extended periods of time. Because megarips tend to occupy topographically fixed positions on the beach, they induce variations in morphological change even along small beaches. High temporal and spatial variability in high-energy embayed beaches can, therefore, be expected, with significant deviations from the seasonal signal and alongshore non-uniform responses.

Acknowledgements

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