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Beaches Morphological Variability Along a Complex Coastline (Sinis Peninsula, western Mediterranean Sea).

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ABSTRACT

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Wave climate, sediments, topographic features and tides influence the morphology and the short-term dynamics of beaches. The interactions between these different forcings affect the features of the beach system. In this work the morphological beach responses in relation to the most energetic period of the year were studied in a coastline with high geomorphological complexity. Three beaches, located along the Sinis Peninsula (western Mediterranean Sea, western Sardinia), were monitored for about 6 months. In order to estimate morphological changes, repetitive beach profiles were acquired by means of Differential Global Positioning System. Wave data were collected by an offshore wave buoy and the grainsize features of each beach was determined. A coupled 3D hydrodynamics–wave, finite element model was also applied in order to investigate the current dynamics and the wave propagation along the selected coastal area. During the monitoring period, the beaches experienced relevant changes when consecutive storms occurred. In sediment deprived embayed beaches, the presence of headlands interacting with waves, favored beach rotation and lead to a crenulate shape of the shoreline. In addition, on sediment abundant beach, cross-shore sediment transport and simultaneous shoreline retreats were observed during storms events. Finally, the effects on the wave heights and directions, due complex coastline features of the Sinis Peninsula, were discussed in relation to the morphodynamics response of each beach.

ADDITIONAL INDEX WORDS: *beach recovery, storms, numerical model, beach morphology*

INTRODUCTION

Wave climate, sediment grain size, topographic features and tides can profoundly influence the dynamics of beaches as well as their morphology (Short 1996). The interactions between these factors or alternatively a single factor can influence the characteristics of the beach system. In addition, geological inheritance and the presence of headlands can influence shoaling processes, beach shape and sediment transport in both the submerged and emerged beach (Simeone *et al.*, 2013). Beaches in the Mediterranean Sea experience drastic modifications in morphology and grainsize composition during intense storms and extreme meteorological and marine events, while the effects of tide result negligible (Basterretxea *et al.*, 2004). The geomorphical contexts of coastline can influences the beach response to storms and the presence of buried and emerged beachrock in the proximity of shoreline can affect beach morphodynamics (Vousdoukas *et al.*, 2007). The underlying geology set the limits of morphological evolution and the volume of accommodation space for sediments. Moreover an important factor influencing the beach response, that can be considered as a geological inheritance, is the nature and source of available sediments (Jackson *et al.*, 2005). Morphological changes on beaches are the results of the interplay between the wave forcing with the aforementioned geological controls factors. In fact the storm parameters such as wave height, peak period and wave direction drive the beach response (Loureiro *et al.*, 2014). Furthermore the pre storm morphology seems to be very important on the evolution of beach morphology (Vousdoukas *et al.*, 2012).

The aim of this study was to investigate the morphological beach response, during the most energetic period of the year in terms of storm occurrence. During the studied period, the effects of wave climate was monitored along a coastline characterized by a complex geomorphological setting.. An interdisciplinary approach, consisting on using both numerical and experimental methods was followed to investigate the morphological changes as well as the natural recovery of beaches during winter period.

In particular, the morphological variability of the beach profiles on the sub-aerial part was analyzed by using a Differential Global Positioning System. Wave data recorded by an off shore wave buoy located about 70km north of study area, were used to determine the wave climate. Finally, a high resolution coupled waves-currents numerical model was applied to reproduce the temporal and spatial variability of the main wave features along the whole investigated area during the main storms. The influence of both large and local scale forcings were simulated and the obtained data have been used to investigate the relationship between the morphological changes and the wind waves features in the study area.

STUDY AREA

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The The study area is located in the Sinis Peninsula, on the western coast of the island of Sardinia in the western Mediterranean (Figure 1). The geological setting of the Sinis peninsula includes a sequence of volcanic and sedimentary rocks (marls, sandstone and limestone) dating from the Neogene to the present (Marini and Murru, 1977) and several rocky outcrops and headlands characterize the coastline.

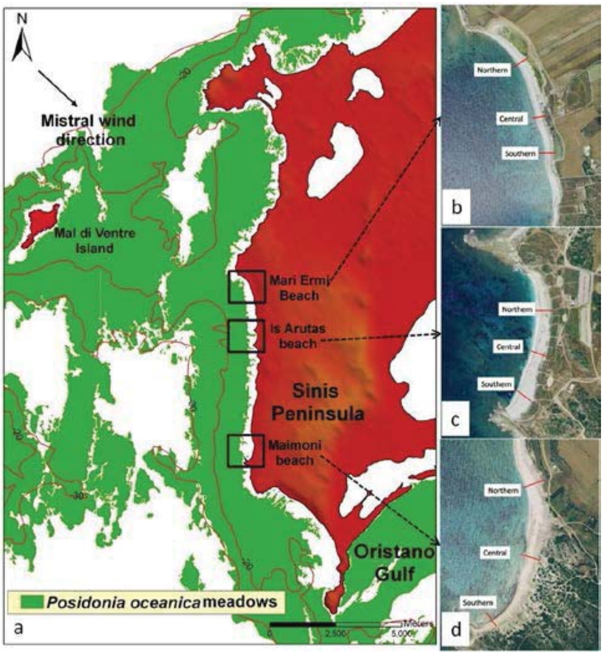

Figure 1. Study area; a) location of Sinis Peninsula; b) location studied beaches; c) position of beach profiles on each beach,

Studied beaches are located in the northern, central and southern sectors of the Sinis Peninsula (Figure 1a). The northern beach, named Mari Ermi (ME hereafter, see Figure 1b) is a beach ridge about 1 km in length, and about 60m wide. Beach sediment is mainly composed of coarse siliciclastic sand and gravel, with a carbonate content of about 20% (De Falco *et al.*, 2003). The orientation of the shoreline, is influenced by the presence of a rocky cape which encloses the beach to the north (Figure1b). The central beach, named Is Arutas (IA hereafter, see Figure 1c), is an embayed beach with a length of 500m, and about 60m of maximum cross shore beach width. The sediment is wholly siliciclastic and composed mainly of very coarse sand and granule (Simeone *et al.*, 2013). A rocky seafloor characterizes the whole submerged domain of the beach. Patchy Posidoniaoceanica meadows colonize the seafloor from a depth of about 5 - 10 m. The southern beach, named Maimoi (MA hereafter, see Figure 1d), is about 1 km in length and 60 m in cross shore beach width, from the toe of the dune up to the shoreline. Sediments of the emerged beach are composed a siliciclastic coarser fraction, mainly located on the foreshore and a finer biogenic carbonate fraction mainly in the backshore, in the dune field and in the submerged beach. The submerged sandy beach is characterized by fine sand (De Falco *et al.*, 2003), however in the central area limited shallow rocky outcrops occur. This beach can be considered as a sediment abundant beach, whereas ME and IA where the sediments are mainly relict, can be considered as sediment deprived beaches.

The prevailing winds are mainly from the north-west (Mystral), often in form of severe storms, especially during winter. In autumn and winter, southwestern winds (Libeccio) are also important (Corsini *et al.*, 2006). The tides are negligible with a maximum water displacement < 0.2 m (Cucco *et al.*, 2006).

METHODS

The morphological variability of beaches was investigated by the analyses of beach profiles variabilty. Wave data, recorded by an off shore wave buoy located about 70 km north of the study area, were used to determine the wave climate. Finally, a high-resolution hydrodynamic and waves numerical model was applied to reproduce the temporal and spatial variability of the main wave features along the Sins coast. The obtained data were used to investigate the relationship between the morphological changes and the wind waves features in the study area.

Table 1. *Summary of the features of studied beaches.*

	Mari Ermi			Is Arutas			Maimoi		
Beach Length (m)		ca 1200			ca 500			ca 1000	
Profile scaling (m)		450			150			300	
	Profile location			Profile location			Profile location		
	N	C	S	N	C	S	N	C	S
Repetition		7			6			7	
Profile length (m)	80	75	60	55	52	50	45	37	40
Min depth (m)		-1			-1			-1	
D50 (mm)	2.74	1.92	1.96	1.82	1.78	1.94	1.98	1.85	1.68
Ws (m/s)	0.33	0.25	0.26	0.24	0.23	0.25	0.26	0.24	0.23
Avg. Ws (m/s)		0.28			0.24			0.24	
Averaged (ξ_0)	1.03	0.94	0.94	1.00	0.97	0.88	0.96	0.92	0.78

N = north, C = centre, S = south

Beach Morphology and Sediments

In order to evaluate the beach morphology and the variability of the different areas of the sub-aerial beach, 3 profiles for each beach were realized (7 times for ME and MA and 6 times for IA) (Figure 1b-c-d, Table 1). Measured beach profiles started from the landward boundary of the beach, marked by the presence of vegetation or other features (man-made structures or physical limits), up to a depth of about 1meter below sea level. For each profile, a position point (X, Y, Z) was collected every 2.5m with the DGPS System. The variations of beach profile volumes (m^3 m^{-1}, corresponding to the section resulted from differences between two profiles consecutive in time, realized on same location: North, Central, South for each beach) were also calculated.

Wave Climate

The wave parameters, including the significant wave height Hs (m), the maximum wave height and the period T (s), were measured by an offshore buoy located in the northwest of Sardinia (Alghero buoy; ISPRA-R.O.N). These data were used to define the wave climate on the western side of Sardinia. The averaged Iribarrean number (ξ_0) was calculated for each mean beach profile and obtained as the averaged value considering the whole surveyed period (Table 1). Furthermore the dimensionless fall velocity Ω (Dean, 1973) (mean values for the period between topographic surveys, as showed in Vousdoukas *et al.*, 2012) was calculated for each beach

$$\Omega = Hb/wsT \quad (1)$$

the breaking wave height Hb (m) used to compute Ω was derived from the Komar and Gaughan (1972) formula:

$$Hb = 0.39g^{0.2}(TH_0)^{0.4} \quad (2)$$

where g is the acceleration due to gravity, T the wave period (s) and H_0 (m) the significant deeper wave height and ws (m s^{-1}) the averaged settling velocity (Table 1). To define the strength of the storms occurred during the monitored period the 'storm power index', as defined in Karunarathna *et al.* (2014), was calculated:

$$Ps = Hs^2 maxD \quad (3)$$

Where Hs max (m) is the maximum significant storm wave height, D is the duration of the storms (hours), Ps is expressed in (m^2 h).

Numerical model

The SHYFEM3D-WWM is a coupled 3D hydrodynamic and wave model based on the finite element method (Umgiesser *et al.*, 2004, Cucco *et al.*, 2012). The wave module was adopted to reproduce the wind wave propagation in the study area, as directly influenced by the wind action, and the wave nonlinear interactions with the sea floor.

The wave module is a phase averaging numerical model, which solves the wave action equations (WAE) by means of the finite element integration method. WAE describe the net source terms defined by the energy input due to wind, the nonlinear interaction in deep and shallow water, the energy dissipation due to white capping and depth induced wave breaking and the energy dissipation due to bottom friction. A comprehensive description of the numeric is found in Roland *et al.* 2009.

The model integration domain includes the whole Western Mediterranean Sea, from the Gibraltar Strait to the western Sardinian. An unstructured mesh based on triangular elements were implemented covering the whole interested area with a spatial resolution varying between 10 km for the open ocean and 50m for the Western Sardinian shallow waters area. The model was already applied with success to simulate the wave propagation in the same area (Simeone *et al.*, 2014). In this study, ad hoc numerical simulations were carried out to reproduce the wave fields in the area as generated by typical storm events from North-West and from West (see Figure 2) that characterized the investigated period. Wind data from the high-resolution atmospheric model SKIRON, were used as model upper boundary conditions.

RESULTS

Figure 3a displays the significant wave heights and peak wave periods, recorded by the Alghero wave buoy during the surveyed period. Events with higher significant wave heights occurred from October 2010 to late January 2011 with peak periods up to 12 seconds. The highest wave height was recorded in November

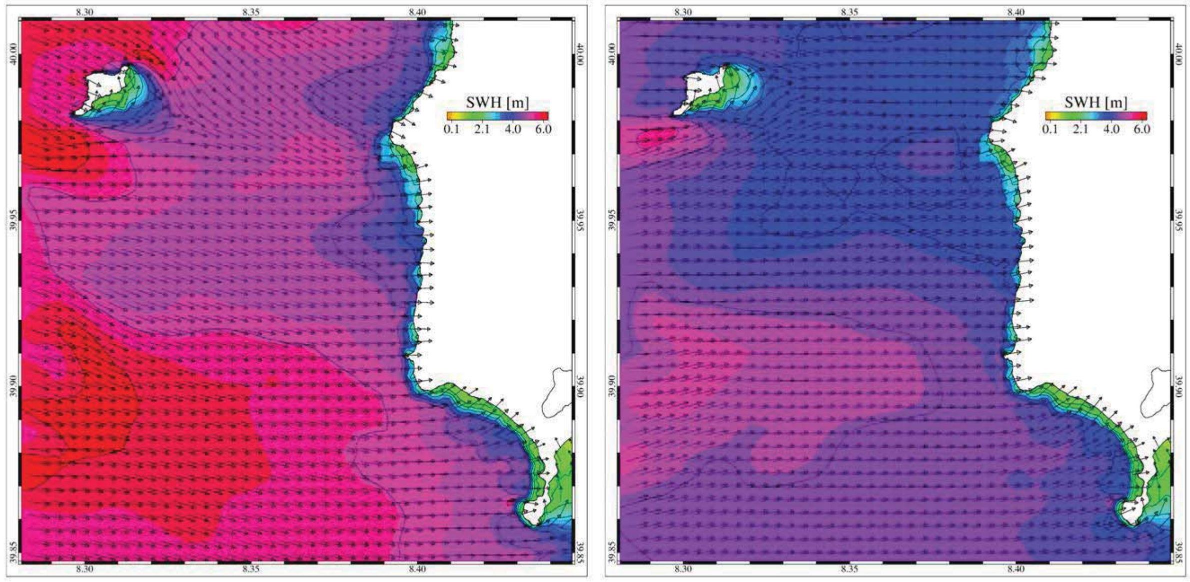

Figure2: Model results: wave height approaching the coastline of the Sinis Peninsula during typical intense storms. Left panels: Northwesterly storm. Right panel; Westerly storm.

16th 2010 (6.65m). During the entire survey period, the majority of the events resulted preferentially from NW direction (Mistral), however W events were also recorded.

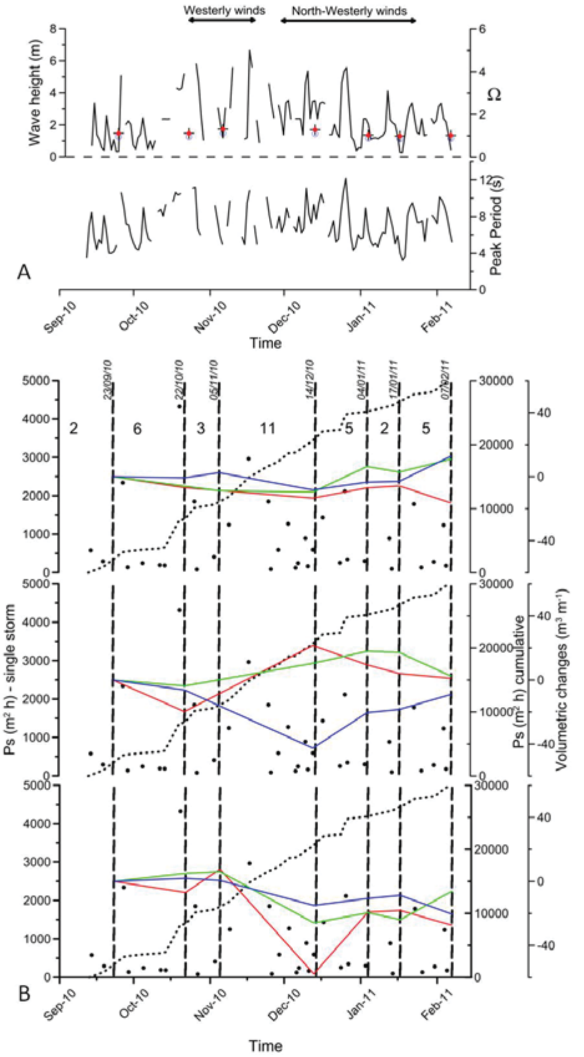

Figure 3. A: maximum measured offshore wave height and peak period. B: volumetric variation along the profiles of ME, IA and MA; lines: blue = south profiles; green = center profiles; red = north profiles. Dots represent the singles 'storm power index' (values in left y-axis); dotted lines represent the cumulative 'storm power index' (values in the right y-axis); dashed vertical lines represent the date of topographic survey.

Figure 3b reports the volumetric changes ($m^3\ m^{-1}$) along each profile, the Ps of the single storms, the cumulative value of the Ps and the number of storms occurred between each topographic survey.

The dimensionless fall velocity remained close to 1 (Reflective state) for each beach and for the whole surveyed period. The averaged Iribarrean number ($\xi 0$) calculated along each beach profile was about 1 and the breaking waves type considered as plunging type ($0.5 < \xi\ 0<3.3$). Major changes occurred on IA and MA beaches from November to January. On ME beach the cumulative volume changes resulted lower in comparison to the other two studied beaches. The cumulative Ps curve shows as the storms become strongest from late October up to late January. The beach profile changes did not exceed 25 m^3m^{-1} on ME beach, accounted for a maximum value of 41 m^3m^{-1} on IA beach and for about 60 m^3m^{-1} on MA. Main changes occurred from October to January along IA and MA and on late January on ME.

According to the displayed beach profiles it is possible to infer that the ME beach has minor variations.,The IA beach displays an accretion of the Northern profile and a contextual erosion of the Southern profile, related to a beach rotation process due to the wave provenance direction. Each surveyed profile along the MA beach shows an erosion between November and December 2010, that leads to a lowering of the beach level and a generalized shoreline retreat during.

The main storm events occurred during the study period were reproduced by the numerical model. In Figure 2 and 4 the distribution of the significant wave height (SWH hereafter) during typical intense storm from Northwest and West are reported for the whole area and for the northern and southern sector of the Sinis Peninsula where the 3 beaches are located.

Wave direction during NW storms approach the Sinis coast mainly from WNW bending to West approaching to the coastline (see Figure 2). The shallow water area between Sinis Peninsula and Mal di Ventre influences the wave energy distribution along the northern and southern coastal sectors, dumping the SWH to values lower than 6 m (see Figure 4 and Figure 5).Wave direction during W storm approach the Sinis coast mainly from West-Southwest with a westward bending of the wave ray approaching to the coast. Only the northern sector is partially sheltered by the shallow areas located in front of the Mal di Ventre Island.

DISCUSSION & CONCLUSION

Wave forcing can be considered as the main factor promoting changes on beach morphology and intense storms can cause severe erosion on beaches (Vousdoukas *et al.*, 2012). The beach responses to single or multiple storms and the consequent beach recovery depend on the beach features and should be considered as site specific (Karunarathna *et al.*, 2014). Our study highlighted that high variability, along three specific beaches of the Sinis peninsula, occurs when the frequency of intense storms increase (Ps values of storms increase from late October, see Figure 3). As depicted in Figure 4, no evidence of significant differences between the SWH approaching to coast, computed for the two storms events (NW and W) on the three sites, were found. In particular, on ME beach and MA beach the wave field near the coast is similar for both NW and W storm events with the same SWH and direction. Conversely, on the IA beach, even if the SWH is similar, the wave direction was different during the two events. A difference of about 20° was found between the wave ray main direction, computed during the NW and W storms. This reflects the morphological behavior of the IA beach, where a beach rotation was observed. During W storms the southern profile was eroded and simultaneously, an accretion of the northern profile occurred. Opposite trend was found when NW storms were more frequent.

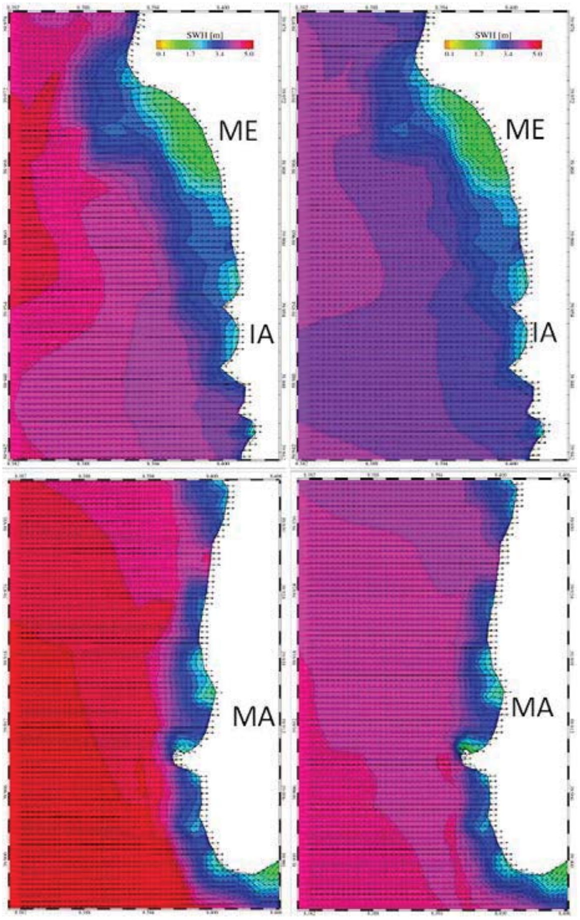

Figure 4. Models results: wave height approaching ME, IA and ME beach during intense storms. Left panels: North westerly storm. Right panel: Westerly storm.

On ME where the changes on beach profiles were less relevant, the wave height and directions were also subjected to the effect of the rocky shallow water, located in front and on the north side of the beach. Along the MA beach the approaching wave directions were influenced by the shallow submerged rocky outcrops in northern and southern area. During the most energetic storms on this beach, the waves eroded sediment from the sub aerial part that could have been deposed on the submerged domain promoting a cross-shore exchange between sub aerial and submerged beach.

Finally, this study highlights that the site-specific conditions of the beach are one of the main factors influencing the beach response to storms, in particular along coastlines with high geomorphological complexity, as in the Sinis Peninsula.

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