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Monitoring the spatiotemporal variability of beach mesoforms by analyzing Sentinel-2 images

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ABSTRACT

Beaches are extremely dynamic natural environments that experience significant variations at different spatial and temporal scales. The processes of appearance and maintenance of morphological features as the beach mesoforms, as well as their characterization, may provide useful information on the morphodynamic evolution of a beach and the spatial variability of nearshore processes. The high availability of Sentinel-2 satellite images together with the development of tools such as the system SHOREX allows the automatic extraction of the position of the shore. The high accuracy of the resulting satellite-derived shorelines (SDS) offers high potential for the definition of relatively detailed morphological features. This work assesses the ability to apply the SDS for characterizing beach mesoforms appearing at Cala de Mijas, in Málaga (S Spain) as well as characterising their changes over time. The extraction of the SDS enables the characterisation of rhythmic coastal forms through the undulations described by the shoreline position along the beach face by using a sinuosity index and to start to address the study of their relationship with the registered wave conditions. This proves that the information derived from mid-resolution satellite images can become a key source of information to characterize the morphological dynamics of beach environments.

I. INTRODUCTION

Beaches represent a vital resource for the coastal regions (Kuriyama *et al.*, 2012). They sustain unique ecosystems while sheltering the inland human settlements from the action of the waves and offering the physical space needed for the activities sustained on the 'sun, sea and sand' principles (Pranzini *et al.*, 2018).

Beaches are natural spaces that experience great dynamism along different spatial and time scales (Hansen *et al.*, 2010). Their morphology can experience strong variations from hourly and sub-weekly scales such as in the case of storm episodes (Senechal *et al.*, 2015), while cyclical oscillations or marked trends may appear over the years as a response to local and regional impacts or even to planetary drivers (Cooper, 2022).

As a response to diverse phenomena, beaches experience changes that may homogeneously affect their profile, while others may provoke different alongshore responses. Related with that latter one, the most obvious effect is the alteration of the subaerial beach width (Pranzini *et al.*, 2018) which may negatively affect and even jeopardize the recreational use of these spaces (Cabezas-Rabadán *et al.*, 2019a; 2019b). Sometimes the alongshore differences are not progressive but oscillatory, with the shoreline position following a recurrent alongshore pattern of undulations. Thus, a nearly periodic spacing leads to cuspate shapes with dimensions ranging from several to tens of meters (Schwartz, 2006). The rhythmic shoreline features may present different behaviours along the coast, sometimes being static along time and sometimes disappearing. Among the different theories describing their formation (Coco *et al.*, 1999; Holland *et al.*, 1998) the combination of swash mechanics, edge waves and self-organization seems to play a significant role in their appearance. Nevertheless, for the moment the current literature has not found a clear response to explain their evolution mechanisms (Vousdoukas, 2012).

The information describing mesoforms as the beach cusps is extremely valuable to increase the knowledge in this field, as well as to properly characterise the beach system. The mesoscale features may act as descriptors of the predominant nearshore processes taking place and controling the dynamism of the coast (Montes *et al.*, 2018). Thus, a strong relationship appears between the oceanographic conditions, the presence of mesoscale forms as cusp systems and bars, and the formation of rip currents, which is of importance for the recreational use of the beaches (Silva-Cavalcanti *et al.*, 2018).

Having updated information on the morphology of the beaches and their dynamism has strategic importance for coastal managers to make appropriate decisions. Nowadays satellite multispectral images are broadly used as a source of environmental information. Among those available free of charge, the Sentinel 2 images (acquired and managed by the European Space Agency) stand out due to their high frequency of acquisition (5 days) of the whole planet. These images may be systematically applied for monitoring purposes, constituting a great opportunity to obtain information on the physical reality of the coast.

The shoreline position appears as a feature able to represent the morphology of the beach (Boak and Turner, 2005) and, therefore, to describe its state and variability along time and space. In order to obtain large packages of shoreline position data, its definition has to be efficient and accurate. Recently, different algorithms and tools have been developed for this purpose, leading to the obtention of the so-called satellite-derived shorelines (SDS). This is the case of CoastSat (Vos *et al.*, 2019), CASSIE (Almeida *et al.*, 2021), SAET (Palomar-Vázquez *et al.*, 2021) and SHOREX (Cabezas-Rabadán *et al.*, 2021), being the accuracy of the latter one robustly checked in Mediterranean coasts (Pardo-Pascual *et al.*, 2021; Sánchez-García *et al.*, 2020)

Many studies have already started to apply the SDS to analyse the sub-weekly and decadal changes of the shoreline position (Cabezas-Rabadán *et al.*, 2019a; 2019c; Konlechner *et al.*, 2020; Liu *et al.*, 2017) as well as the consequences it may have over the beach use (Cabezas-Rabadán *et al.*, 2019b). Nevertheless, the recently increased accuracy of these extraction techniques may help to study relatively detailed features such as the emerged beach mesoforms.

The present study aims to assess the potential of the satellite-derived shorelines for characterising the changes registered by the beach face mesoforms along time and space. For that purpose, the shoreline positions were extracted from Sentinel-2 imagery using the SHOREX system enabling to define a Sinuosity Index and to establish relations with the incident wave conditions.

II. Study area

The study focuses on Cala de Mijas beach. It is a sandy beach located in the Málaga province, within the Costa del Sol (Andalusia, S Spain) (Figure 1). This coast is predominantly a low-lying beach and shore platform system composed of narrow and relatively steep beaches. They are usually sandy, with a grain size of about 1.5 mm or more (Málvarez and Navas, 2019).

It is a region defined by high anthropic pressure, with dense urbanization of the land close to the coast. This occurs linked to its activity as a renowned global tourist destination (Guisado-Pintado *et al.*, 2016). Partly as a consequence of this human occupation the vulnerability and the risk are high and require the attention of territorial managers. Concerning this, since the middle of the last century the Mediterranean Coast of Andalusia has experienced a negative sedimentary balance. The sector of Cala de Mijas appears relatively stable, although registering a moderate erosion in a 20% of the coast, and a high erosion at 15% of it (Molina *et al.*, 2019).

Figure 1. Location of the study area in Cala de Mijas in the province of Málaga (Costa del Sol, S Spain). The distribution of the points of the SIMAR model for the wave hindcast is also presented (green points). The closest point to the study area was selected for retrieving the oceanographic data.

Regarding the sediment, Cala de Mijas constitutes an independent cell related to the inputs offered by the Arroyo Cala del Moral and a large deposit accumulated on the platform which probably results from the combination of the transport of sediment from the Ensenada de Marbella and the bay of Fuengirola (Málvarez and Navas, 2019). In the past, the beach showed a semi-dissipative behaviour thanks to the accumulation of sand on the nearshore. Nevertheless, the insufficient beach width has led coastal managers to carry out nourishments which could result in a shift towards an intermediate/reflective behaviour more prone to erosion.

Hydrodynamically, this coast is controlled by a microtidal range (average 50 cm) and low-energy wave (Hs = 1.0 m) conditions (Málvarez and Navas, 2019), influenced by two prevailing winds parallel to the main direction of the coast. Thus, the wave direction follows a bimodal pattern dominated by westerlies and easterlies, while the effective fetch is limited to an average of 500 km. This results in a predominant swash-aligned sector for Cala de Mijas (Molina *et al.*, 2019). These characteristics and the steep nearshore regions lead to beach types highly dependent on short-term sediment supply, which mainly takes place around seasonal heavy rainfall by reworking fluvial sands.

III. Materials and Methods

This study is based on the information provided by the images of the Sentinel, and the shoreline positions extracted using the SHOREX extraction system. The oceanographic data provided by the SIMAR model is considered as complementary information in order to understand the influence of the hydrodynamic forcing on the shoreline morphology.

A. *Satellite imagery*

This analysis employed 84 images acquired during 2018-2019 by the optical satellite Sentinel 2, sensor MSI (Figure 2). These mid-resolution images may be obtained free of charge from the Copernicus Open Access Hub (https://scihub.copernicus.eu/). They include the bands RGB, NIR, SWIR1, and SWIR2 with a spatial resolution between 10 and 30 m subsequently employed within the extraction process.

B. *Oceanographic data*

The SIMAR model for the wave hindcast (Spanish Port Authority) was employed for obtaining the wave conditions during the study period. In order to do so, the closest point of the grid to the studied beaches was selected (SIMAR 2029078) for acquiring the wave data. Thus, significant wave height, direction, and mean and peak period were retrieved, and their monthly averages were calculated (Table 1).

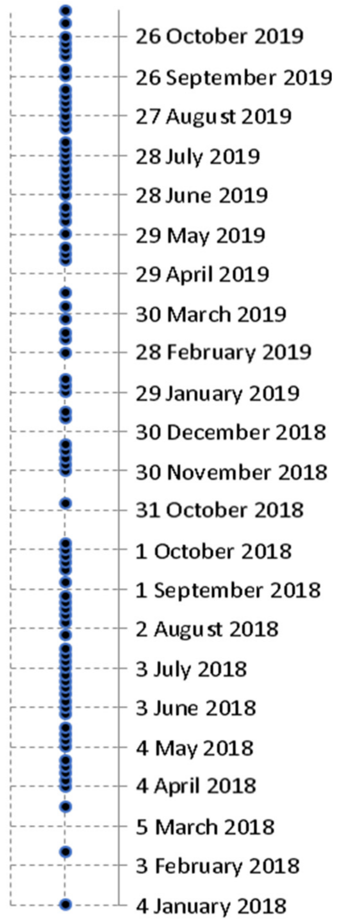

Figure 2. Sentinel 2 satellite imagery employed in this work.

Table 1. Monthly averages of the significant wave height (Hs), direction (Dir), mean (Tm) and peak period (Tp) according to the data retrieved from the SIMAR point 2029078. The information is publicly available at https://www.puertos.es/

Month	Hs [m]	Dir [º]	Tm [s]	Tp [s]
Jan 2018	0.73	202.75	3.19	4.63
Feb 2018	0.46	183.64	2.95	4.16
Mar 2018	0.83	229.80	3.33	4.94
Apr 2018	0.94	169.89	4.07	5.85
May 2018	0.54	165.07	3.41	4.94
Jun 2018	0.58	174.50	3.78	5.21
Jul 2018	0.54	188.83	3.60	5.12
Aug 2018	0.53	113.00	3.93	5.48
Sep 2018	0.65	117.70	4.15	5.79
Oct 2018	0.68	149.75	3.53	4.98
Nov 2018	0.63	193.43	3.23	4.63
Dec 2018	0.53	156.26	3.02	4.33
Jan 2019	0.65	182.67	3.29	4.62
Feb 2019	0.87	141.08	3.77	5.58
Mar 2019	1.18	144.53	4.18	5.76
Apr 2019	0.76	183.73	3.62	5.45
May 2019	0.81	155.95	4.01	5.64
Jun 2019	0.73	153.60	3.99	5.74
Jul 2019	0.75	168.61	4.01	5.62
Aug 2019	0.61	149.58	3.95	5.70
Sep 2019	0.59	127.77	3.78	5.47
Oct 2019	0.53	182.53	3.36	4.61
Nov 2019	0.69	228.72	3.35	4.69

C. *Shoreline extraction and smoothing process*

The definition of the shoreline position was carried out using the extraction system SHOREX as described by Cabezas-Rabadán *et al.* (2021). It is a tool developed by CGAT – UPV intended to allow the automatic download and pre-processing of the satellite images. A manual checking enabled discarding those images affected by significant cloud coverage over the coast prior to the georeferencing of the useful images using a orthorectified aerial photography. From the resulting images, the shoreline positions (Satellite-Derived Shorelines, SDS) were automatically defined as the water/land intersection in a polyline format. This definition was carried out at the subpixel level by applying the algorithm proposed in Pardo-Pascual *et al.* (2012). This solution was applied over the Short-Wave Infrared bands (SWIR1) using a third-degree polynomial, and 3x3 analysis kernel. According to previous assessments at micro-tidal beaches, the resulting SDS is expected to offer an accuracy of 3-4 m RMSE (Sánchez-García *et al.*, 2020).

A smoothing process was applied over each of the resulting shorelines (Figure 3). In order to do so, the Polynomial Approximation with Exponential Kernel (PAEK) is applied in Python allowing to obtain a smoothed shoreline that may have more vertices than the original one.

Figure 3. Satellite-derived shoreline from Sentinel-2 (red colour, 2075.39 m length) and the shoreline resulting from applying the smoothening process (yellow, 2019.09 m).

D. *Definition of the Sinuosity Index*

For each of the resulting polylines, the Sinuosity Index (SI) was obtained as the length of the smoothed SDS divided by the length of the simplified definition of the coastal shape (Figure 4). Thus, values close to 1 indicated a straight shoreline, while values far from 1 were associated with a more sinuous and undulating shoreline.

Figure 4. Definition of the sinuosity index for a certain SDS (pink, 1081.85 m length). The black line is a simplified definition of the coastal shape (1054.44 m). The SI (0.97) is obtained as the division of both lengths.

IV. Results

The shoreline positions were extracted at 83 different instants and, after applying the smoothing process, the resulting lines were used to define the shoreline sinuosity index as a representative value of the occurrence of mesoforms on Cala de Mijas. This smoothing process is a necessary step so that the results can be processed metrically. Furthermore, it allows to remove the inflections associated with sub-pixel extraction, that on several occasions offered unrealistic results for describing the morphology of the shore (Figure 5).

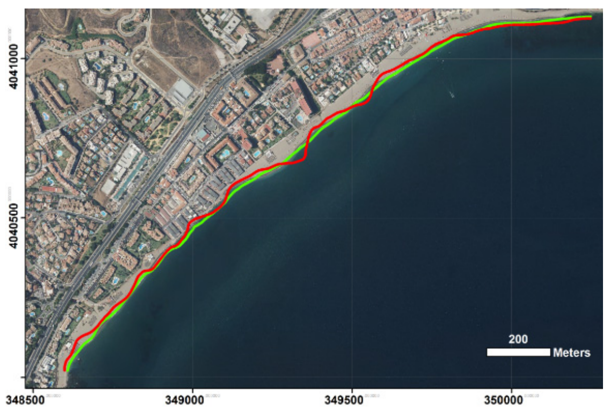

Figure 5. Example of the different level of undulations recorded by the shoreline position. This is the case on the days 10/12/2018 (in green colour, SI=0.993) and 28/07/2018 (red colour, SI=0.955).

When analysing the temporal evolution of the SI, a series of variations appear over time, between values close to 0.955 and 0.994 (Figure 6). It is also noteworthy that large variations sometimes are registered between very close dates. Regarding the mid-term oscillations, there is no clearly defined seasonality in them. However, it is striking that the minimum annual SI values are recorded during the summer months. Thus, in 2018 a minimum SI value of 0.955 is reached on the 28th of July (the minimum of the series), while in 2019 the minimum SI value (0.962) appears on the 18th of July. Thus, during certain dates of the summer months, the shoreline would be registering a more marked undulating pattern. On the other hand, the higher values of SI, related to a more rectilinear shoreline morphology, follow a less homogeneous distribution. Thus, in 2018 the maximum SI value (0.993) was recorded on 10 December, followed by other dates during winter and autumn. Similarly, in 2019 the maximum SI value (0.991) was recorded in autumn, followed by other dates during winter.

Since the morphology of the beach is to some extent determined by the wave conditions it can be assumed that there will be a relationship between the SI value of a given date and the wave values recorded nearby. As we do not know which period should be taken into consideration for this analysis in this first approach to the problem we have only tried to detect which wave parameters may be playing a more significant role. Thus, an analysis was carried out in an attempt to establish relationships between wave height, direction, and period on a monthly scale. For this analysis, the monthly average SI was also defined, and the months with less than two SDS (and therefore SI values) were discarded (Figure 7). A statistically rather low relationship appeared between the SI values and the wave characteristics averaged over each of the months and treated individually. Still, it is noticeable how the monthly wave mean peak period does describe a pattern of changes that is to some extent the inverse of the SI, reaching a correlation of r= -0.38.

V. Discussion

The present work is a preliminary study of the application of satellite-derived shorelines with sub-pixel precision for the recognition of mesoscale features on the emerged beach. The results show that the SDSs enable characterising the rhythmic undulations on the beach at the land-water interface, demonstrating its usefulness in providing information on the beach cusps.

The SI values show how during certain dates of the summer months the shoreline would be registering a more marked undulatory pattern that would be associated with the presence of mesoforms on the emerged beach such as beach cusps. The joint analysis with the wave conditions registered in the area prior to the definition of the shoreline position shows how these more pronounced wave patterns are associated with periods of higher Tp.

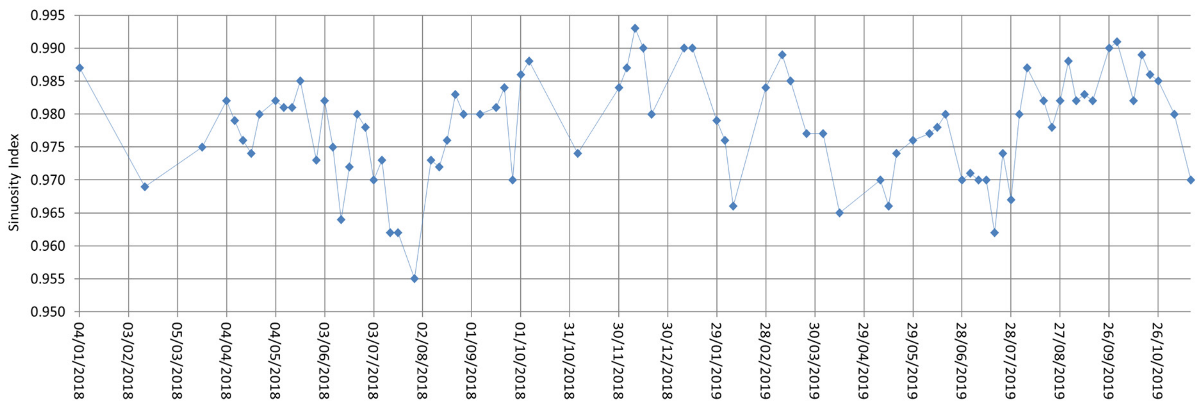

Figure 6. Evolution of the sinuosity index along time in Cala de Mijas.

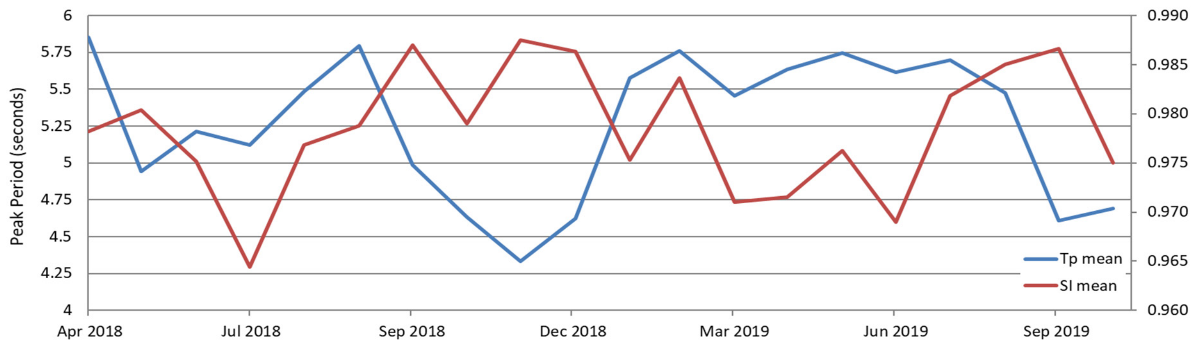

Figure 7. Relationship between the average monthly Sinuosity Index (red colour) and the monthly wave mean peak period (blue). Only those months with more than one SDS measurement have been considered.

These differences could be caused by to the presence of westerlies winds and the associated change in wave direction contrary to the eastern winds and the associated wave regime. Together with the simplicity of the preliminary analysis performed, the low correlation between the wave characteristics and the SI is largely caused by the multitude of oceanographic and geomorphological factors that may affect the formation of the coastal mesoforms. This is for example one of the reasons why is still unclear the role of the different parameters controlling the formation of beach cusps (Vousdoukas, 2012). While its origin may be linked to different wave characteristics, certain breaker types appear correlated with them (Coco *et al.*, 1999), which would enhance the importance of the beach morphological conditions prior to the SDS definition.

At this point, it is necessary to investigate further what morphological reality these SDS inflections are representing, as well as the utilization of other parameters more representative of the mesoforms than the SI. The alongshore oscillations may in part be a reflection of the three-dimensional morphology of the beach in the beachface zone. This morphology would define successive shoreline incurvations along the shore as a result of the position maintained by the total water level (TWL) over time. However, previous works have highlighted the impact that swash and foaming phenomena can have on the definition of the shoreline, both SHOREX (Cabezas-Rabadán *et al.*, 2020; Pardo-Pascual *et al.*, 2018) and other extraction tools. (Castelle *et al.*, 2021; Hagenaars *et al.*, 2018). Thus, the inflections defined by the SDS could respond exclusively to spatial oscillations of the TWL, but also the maximum position reached by the swash. Thus, in addition to the morphological conditions of the emerged beach, the defined position of the shoreline would also be greatly affected by the specific wave conditions and the morphology of the submerged beach, which determine the wave breaking and the space covered during the swash processes.

Future analyses should be aimed at establishing relationships between shoreline morphology and hydrodynamic conditions using different representative parameters, as well as focusing the analysis on different spatial and temporal scales. With respect to beach morphology, the advance and retreat of the mean position of the shore, as well as its change of orientation, can play an essential role in the formation or maintenance of undulating forms. This analysis could be supported not only by the Sentinel-2 satellite presented in this work but also by the Landsat-8 and Landsat-9 satellites (the latter recently available), which would greatly increase the amount of data available over time, observing fields on more detailed time scales. Similarly, the characteristics of sediment and bottom morphology (bars) varying along the coastline are essential in the occurrence of this type of oscillating mesoforms on the shore. A correct characterisation of these elements along the coastline and an analysis divided into different segments according to their nature can help to better understand the interrelationships with oceanographic features. This analysis, by narrowing down the studied coastal segment, is especially relevant on this coast where the prevailing drift currents, which can greatly condition the morphology of the beach phase, may change very abruptly between sectors (Molina *et al.*, 2019).

VI. Conclusions

The present work is a first step towards the application of satellite-derived shorelines with sub-pixel precision for the study and monitoring of mesoscale features. The results of this work allow us to observe that the SDS clearly localise the existence of rhythmic waves on the beach and therefore demonstrate that they can be very useful for monitoring them.

The relationship observed with the wave regime, although statistically low, seems to indicate the existence of this logical relationship, with waves being the main modulator of the morphology of this coastal segment. The role of the different factors in the formation of beach cusps is not yet clear, so providing more information on their spatial and temporal evolution may be of great interest in this field.

Analysing the influence of these factors recorded over different periods may provide clues as to their influence on the behaviour of Mediterranean beaches such as the one presented in this paper.

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