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Combined beach - inner shelf erosion in short and medium term (Maspalomas, Canary Islands)

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ABSTRACT

The analysis of the accurate topo-bathymetric digital elevation model (DEM), the cartography of the submarine sedimentary cover and the monitoring of short (seasonal) and medium-term (2000-2009) morphological changes have permitted depicting the erosional trend in the short and medium-term of the Maspalomas sedimentary system. Short-term analysis showed intense sedimentary fluxes between the beaches and the inner shelf, and sedimentary exchanges with other sectors of the inner shelf, while the steep slope inner shelf fronting La Bajeta cape was identified as a sink area. In the medium-term the sediment budget showed high erosion of the supratidal and intertidal sectors of the beaches due to storm waves in the 2005-2006 winter, followed by accretion over the next four years, but which did not reach the initial sedimentary state. The inner shelf and subtidal sector of the beaches showed negative budgets in the short and medium-term. Interannual variability of the wave and wind regimes determines decadal beach erosion-accretion cycles, while long-term climatic change, evidenced at the study area by a decrease of trade winds and NE wave intensity in 2005, is expected to produce a possible increase of erosion at the El Inglés inner shelf and consequently a decrease in sediment inputs to the El Inglés beach and Maspalomas dune field. Finally, the influence of the geological heritage is depicted by the Fataga gully's control of the present coastal morphology, and by the island relief control of the wind, waves and current directions in the study area.

KEYWORDS **Coastal geomorphology. Sediments. Budget. Storms. Climatic change.**

INTRODUCTION

A proper understanding of the rates and causes of shore erosion and associated land losses requires the integration of climatic, geological and oceanographic data in short-, medium- and long-term perspectives. In order to forecast beach behaviour in response to the occurrence of high energy events and present global sea level rise (Miller and Douglas, 2004) a good knowledge of the morphological and sedimentological characteristics of both emerged and submerged areas of vulnerable littoral zones is necessary. Identification of crosshore sediment transfer between the dune-beach and the inner shelf, and the corresponding calculation of volumes, can be improved by using modern, accurate cartography depicting the simultaneous morphological attributes of both domains (Saye *et al.*, 2005; Shrestha *et al.*, 2005; Houser *et al.*, 2008). Cartographic information is also essential for designing adequate responses in order to protect high-valued environmental and touristic areas, like the Maspalomas sedimentary system, presently facing serious erosion problems partially associated with human activities and the occurrence of frequent storm events.

The main objective of this study is to contribute to the understanding of the short to medium-term (2000-2009) sedimentary interactions between the dunes, beaches and the inner shelf of the Maspalomas sedimentary system, with a special focus on the particular analysis of coastal erosion due to the storm wave events that hit Maspalomas. Therefore, the following specific objectives were established: i) An accurate mapping of the main morphological elements (dunes, beaches and inner shelf) of the Maspalomas sedimentary system, ii) the quantification of short (seasonal) and medium term (interannual) volumes of sand transfer between the beaches and inner shelf of the Maspalomas sedimentary system, and iii) the interpretation of the driving factors controlling the observed changes, including wave and storm-wave regimes, currents, bathymetry and shoreline orientation, among others.

GENERAL SETTING

The Maspalomas area is located at the southernmost tip of Gran Canaria island (Fig.1), in the Canary Archipelago (UTM coordinates: zone 28N, latitude 3065000-3070500N and longitude 441000-445000E); a shield volcano which rises up from a depth of 3,000m and is developed from Miocene times as a result of volcanic extrusions of basic materials due to the activity of a hot spot in the oceanic crust of the African plate (Balcells *et al.*, 1990, Carracedo *et al.*, 2002).

The Maspalomas sedimentary system comprises an area of 10.5km^2, corresponding to its present emerged sector and the adjacent insular shelf down to a depth of 16m, the external limit of our research. Geologically, the emerged sector of the Maspalomas sedimentary system can be described as a cuspate foreland (Alcántara-Carrió and Fontán, 2009) corresponding to the present expression of a Quaternary accretionary prism formed by the accumulation of alluvial materials (gravel and sand) mainly originating from the Fataga gully, a torrential course draining 39.59km^2 off the southeastern slopes of the island of Gran Canaria (Menéndez *et al.*, 2008). These alluvial deposits are overlaying the volcanic basement and their ceiling ranges from a depth of 19m at El Inglés Beach to 4m above present mean sea level at the western boundary of the Maspalomas sedimentary system (Fontán *et al.*, 2007).

Geomorphologically, the Maspalomas sedimentary system is developed over a relict surface of alluvial deposits formed into three terraces. The upper subaerial terrace, nowadays occupied by tourist resorts, is 21m above present mean sea level and determines the NE border of the study area, while the lower subaerial terrace is 2m above present mean sea level and is currently capped by dunes and sandy beach deposits (Balcells *et al.*, 1990). In addition, Criado *et al.* (2001) identified the presence of a shallow submarine terrace of the Fataga gulley, southward of Maspalomas beach. Consequently, the Maspalomas sedimentary system can be subdivided in the following units (Fig. 1):

The Maspalomas dune field which is constituted of several sets of barchan and transversal dunes, with a maximum height of 18m and covering a surface of about 4km^2. The Maspalomas dune field covers the upper surfaces of the Fataga gully alluvial deposits and it is understood to have been formed no more than 200 years ago (Sánchez-Pérez, 2010). Dune sediments of the Maspalomas dune field are predominantly composed of medium to fine-grained sand, containing about 50% (in weight) of biogenic carbonates and 50% of minerals and rocky fragments from terrigenous

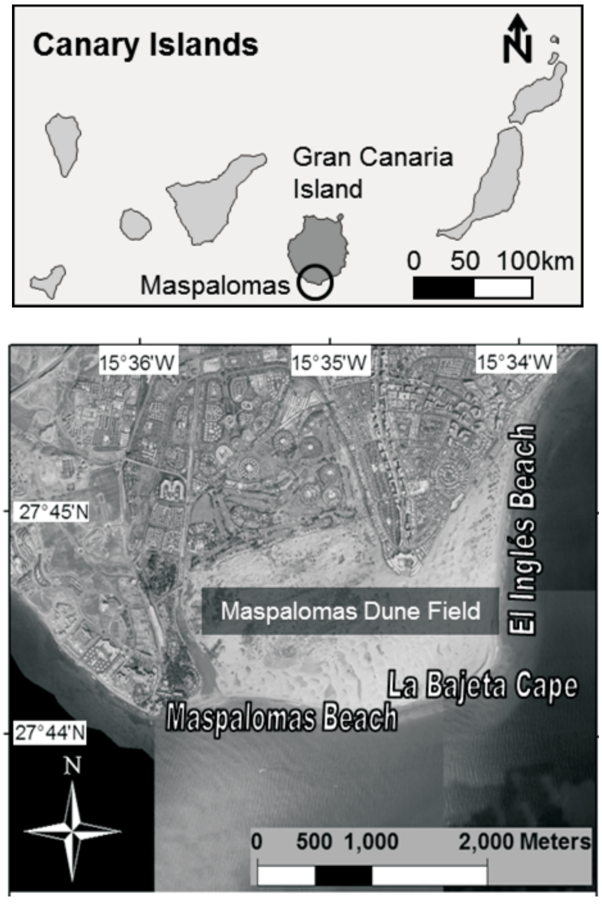

FIGURE 1 | A) Canary Islands and B) Mas Palomas sedimentary system.

sources (Martínez *et al.*, 1986). Aeolian sediment transport in the Canary islands is controlled mainly by the trade winds blowing from the NNE between April and September and by multidirectional winds during the rest of the year (Alcántara-Carrió and Alonso, 2002). Nevertheless, the topographical influence of Gran Canaria determines that the local winds at the Maspalomas dune field present a bimodal distribution, mostly from ENE, but coming also in a minor proportion from WSW (Sánchez-Pérez *et al.*, 2005; Hernández, 2006).

The Maspalomas and El Inglés beaches, which are located along the southern and eastern borders of the Maspalomas dune field, converge at La Bajeta cape. The Maspalomas beach extends from the present mouth of the Fataga gully, which is located at the western limit of the study area to La Bajeta cape, while El Inglés beach extends from La Bajeta cape to the north. The Maspalomas and El Inglés beaches are the morphological transitional zones between the Maspalomas dune field and the sand banks of the adjacent insular shelf. They constitute the main stocks of sand for the Maspalomas dune field and at the same time the main receptacle area for sands resulting from dune erosion (Martínez *et al.*, 1986; Hernández *et al.*, 2006). Typical sediments of the Maspalomas and El Inglés beaches are medium to fine-grained sand with carbonate contents (by weight) ranging between 50 and 70% (Alonso *et al.*, 2001; Hernández *et al.*, 2007). According to Alonso *et al.* (2008), these beaches do not exchange sediments with the adjacent beaches. Usually, Maspalomas beach shows the presence of a gravelly or rocky substrate (Quaternary alluvial deposits of the Fataga gully) frequently exposed at the intertidal zone as a result of high beach erosion due to storm waves (Fig. 2), while there is no rocky substrate outcrop at El Inglés beach after the erosional events.

The insular inner shelf, which, in this study, is considered from the offshore limit of the beaches up to the 16m isobathic lines (Fig. 3). It presents very different width at the adjacent sectors to the Maspalomas and El Inglés beaches and it is mainly covered by medium to fine-grained sand of both volcanic and bioclastic materials. Its carbonates content ranges between 25% and 90% (by weight) with the higher abundances located westward of La Bajeta cape (Criado *et al.*, 2001).

METHODOLOGY

Digital elevation model (DEM) of the Maspalomas sedimentary system

In order to get an adequate base-line for multi-temporal comparisons of morphological changes this study initially included the design of a digital elevation model (DEM) for the entire area of the Maspalomas sedimentary system. This DEM integrated the Maspalomas dune field's topography with the topo-bathymetric data of the beaches and the inner shelf. Topography of the Maspalomas dune field resulted from the restitution of aerial photographs taken in January 2007, while the beaches and inner shelf datasets were acquired by means of differential GPS and multibeam echosounder in February 2007. In the subsequent data processing, all topographic and bathymetric data were referred to a common vertical reference frame (Gesch and Wilson, 2001), *i.e.*, to the UTM coordinates system and to the geodesic net of Canary islands (REGCAN) datum. This DEM, and all maps presented here, were designed using the Surfer 8© software included in the Golden software package.

Sedimentary cover of the inner shelf

The sedimentary cover map of the submerged area of the Maspalomas sedimentary system was carried out from data taken with an Edge-Tech-272-TD side scan sonar (SSS) in August 2007. This SSS operated at 100KHz, with 50º and 1.2º vertical and horizontal angles respectively, which allowed a 0.5m spatial resolution image of the shelf bottom to be obtained. Following the national oceanic and atmospheric administration (NOAA) criteria (Andreasen and Pryor, 1988) the coordinates of the recorded images were determined after the towfish layback and the position of the rubber dinghy, which was measured by differential GPS. The sonogram analysis was complemented with ground truth information obtained by local scuba-divers' observations and by direct sampling along the shoreline.

Analysis of morphological changes

Correlative morphological changes along the Maspalomas and El Inglés beaches were quantified by comparing successive topographies, while accumulated morphologi-

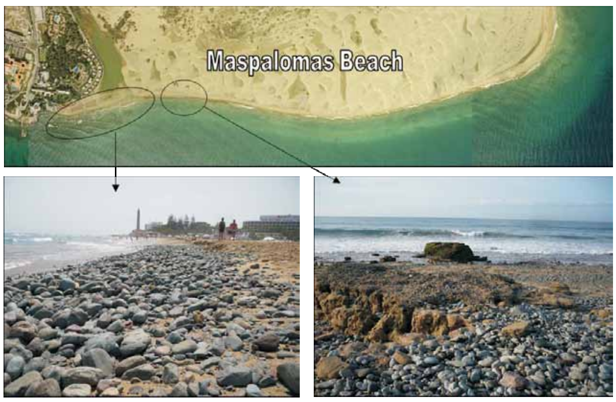

FIGURE 2 | Outcrop of alluvial substrates at Maspalomas Beach due to storm waves.

cal changes were quantified by comparing each topography with the initial one recorded in September 2005. In order to do so, a total of twenty-one differential GPS topographic surveys of the intertidal and upper subtidal zones of Maspalomas and El Inglés (including La Bajeta cape) were carried out during the four years of field work for this study, using Thales differential GPS equipment. All surveys were performed at low spring tides by combining zigzag paths on the supra and intertidal zones with alongshore trajectories in a 4x4 vehicle. More than 30,000 topographic points resulted from each one of these surveys, within a vertical accuracy of 0.07m after the *in situ* calibration (Alcántara-Carrió and Fontán, 2009), which is in accordance with the values obtained for similar studies (Baptista *et al.*, 2008; Poate *et al.*, 2009). Data sets were used for plotting 21 high-resolution topographic maps of Maspalomas and El Inglés beaches, each one with a 1x1m grid obtained by kriging-type interpolations (Cressie 1990; Myers, 1994; Mitasova, 2004) according to previous validations (Fontán, 2007).

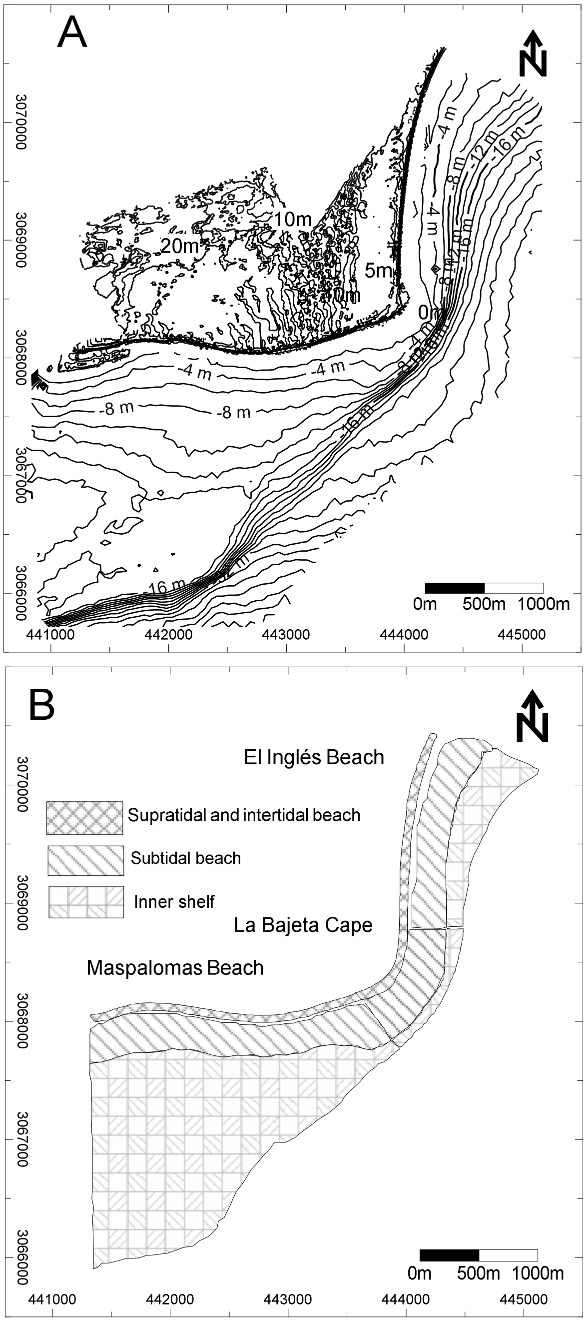

FIGURE 3 | A) Digital Elevation Model of the study area and B) geomorphological sectors delimited in the study area.

In order to obtain an accurate bathymetric grid, with a 2x2m spatial resolution, a bathymetric survey on the subtidal beaches and the inner shelf of the Maspalomas sedimentary system was carried out in February 2007 using a GeoAcoustic Geoswath 250kHz multibeam echosounder. Seasonal short-term topographic changes at the submerged area were monitored via three additional bathymetric surveys (in August 2007, November 2007 and February 2008), taken by a Valeport Midas Surveyor 210kHz monobeam echosounder mounted in a rubber dinghy. Echosounder data were recorded and synchronized with differential GPS data, which permitted the removal of the oscillations due to waves, tides and wind (Anzidei, 2000). Bathymetric maps were referred to WGS84 ellipsoid and to the local geodesic net of Canary islands datum.

Bathymetric surveys were carried out along the same days that beach topographic surveys for high and low spring tides, respectively. Nevertheless, full overlapping between both data series was not achieved for the subtidal sector of the beaches, due to the difficulty of obtaining bathymetric data at the wave breaking zone. Only when wave and tide conditions were favourable was it possible to overlap the topographic and bathymetric measurements. Consequently, the volumetric changes obtained for the subtidal zone presents some inaccuracy, which does not prevent an evaluation of the changes at the inner shelf and the global inner shelf–beach sedimentary interactions.

The topographic changes were quantified by comparing the topo - bathymetric maps with the initial conditions of February 2007, obtained by the combination of the multibeam bathymetric and differential GPS topographic data, and referred to the same datum. Therefore, it was possible to determine the topographic changes over three periods: i) February 2007 to August 2007, ii) August 2007 to November 2007, and iii) November 2007 to February 2008.

This topographic analysis was completed with the calculation of the sediment budget (total volume of sediments and average topographic variations) detailed for three different crosshore morphological units and three alongshore geographical sectors defined after the previously obtained DEM model.

A previous high resolution bathymetry of the Maspalomas inner shelf, measured by multibeam echosounder in January 2000, was made available from the Spanish ministry of environment. Thus, using a similar procedure to the vertical variation analysis of the beaches' topography, the morphological changes in the medium term was obtained by comparing the 2000 and 2007 bathymetric maps.

Wave and wind regime analysis

Offshore wave and wind data were obtained from high resolution limited area model system, which is a complete numerical weather prediction system including four dimensional data assimilation with analysis of observations and a limited-area short-range forecasting model (Unden *et al.*, 2002). This system is currently used operationally by several European weather services, including Spain. In this study, local data where obtained to the 1018010-WANA point (15º30' N, 27º30' N), obtained from the application of the WAM model (Wave Prediction Model) of wave generation (Hasselman *et al.*, 1988) for the October 1995 to March 2009 period by Puertos del Estado, who provided a 3-hour periodicity database of Hs_o(m), Tp(s), wave approach direction (ºN), wind velocity (m/s) and wind direction (ºN). Numerical high-resolution (1-km grid) predictions of offshore mesoscale currents were available for Gran Canaria, considering monthly wind stress and the smoothed island bathymetry (Mason, 2009), but a database of the coastal currents at the study area to take into account the effect of the daily wind conditions and detailed topography was, unfortunately, not available.

The biparametric distribution of Weibull (1951) was fit to over a total of 36,783 wave data to determine the wave regime, as well as $Hs_{0.137}$ and $T_{0.137}$, which are necessary to calculate the depth of closure (Hallermaier, 1981). Furthermore, wave data from February 2007 to February 2008 (2,906 data) were used to describe the wave regime driving the morphodynamics changes on the beaches and shallow shelf over this period.

Available wind data for this study refers to wind values predicted far away from the study area, and consequently they were not adequate to characterise the local winds. However, offshore wind data were useful to analyse the intensity of the trade winds and trends in the medium-term temporal scale.

RESULTS

Main morphological characteristics of the Maspalomas system

The combination of high resolution topographic and bathymetric data allowed us to obtain the most accurate DEM currently available for the Maspalomas sedimentary system (Fig. 3A), which can be a useful tool for the coastal integrated zone management of this natural area that supports the most intense touristic activity of the whole archipelago.

This DEM also enables the determination of the location of three crosshore morphological units, according to the wave and tidal influences (Fig. 3B): i) the supratidal (>1m altitude) and intertidal (+1 to -1m) zone of the beaches, ii) the subtidal zone of the beaches, from -1m to the depth of closure, that is located at a depth of 6.14m after the criteria of Hallermaier (1981) and considering values of 3.1m to $Ho_{0.137}$ and 8.5s to $T_{0.137}$ after the 10-year local wave data analysis, and iii) the shallow shelf, from the depth of closure to the shelf break line, located at about the 16m isobathic line, with all the elevations referred to the local datum. Moreover, three sectors can been defined from the shoreline and isobathic lines orientation: i) the north-eastern sector of the inner shelf and El Inglés beach, ii) the central sector of the inner shelf and La Bajeta cape, and iii) the south-western sector of the inner shelf and Maspalomas beach. The combination of these morphological units and alongshore sectors permitted the definition of nine different zones for the calculation of the morphological changes and sedimentary budgets in the Maspalomas sedimentary system (Fig. 3B). The area and slope range for these nine zones are indicated in Table 1.

Furthermore, the analysis of this DEM confirmed the suggestion of Criado *et al.* (2001) regarding the presence of the third alluvial terrace, which is nowadays submerged. This terrace can be identified by the curvature of the isobathic lines and the gentle slope of the shallow shelf southward from Maspalomas beach, in contrast with the higher slope of the insular inner shelf in front of the El Inglés beach and La Bajeta cape, which are similar to the other sectors of the island (Fig. 4).

The morphological zonation of the area shown by the DEM reveals several first-order relationships among the dune field, beaches and submarine deposits. It indicates that the morphology of both the emerged area and the inner shelf of Maspalomas (*i.e.*, the western sector of the study area) are strongly influenced by their common geological inheritance, since both areas are developed over the surface of the alluvial fans of the Fataga gully. On the other hand, the extent of La Bajeta cape is also controlled by the nearest submarine morphology; this sandy headland cannot migrate seaward because of the proximity of the steep slope of the fronting inner shelf. Finally, morphologic relationships between El Inglés beach and the adjacent eastward inner shelf, related to the input of sediments associated with recent progradation of the shoreline in this sector (Alcántara-Carrió and Fontán, 2009), determine the

TABLE 1 | Area (m^2) and slope ranges (°) of the delimited zones in the DEM

	Maspalomas sector		La Bajeta Sector		El Inglés Sector		Total
	area (m^2)	slope range(°)	area (m^2)	slope range(°)	area (m^2)	slope range(°)	area (m^2)
Supratidal & intertidal beach	137,967	1.2-1.5	51,268	0.5-1.4	130,279	1-1.5	319,514
Subtidal beach	424,765	0.7-0.9	185,269	0.5-0.7	248,532	0.5-0.7	858,566
Inner shelf	2,546,332	0.3-0.5	29,372	1-1.4	324,222	0.8-1.2	2,899,926

gentle morphology of the inner shelf, especially towards its northern limit.

The analysis of reflectivity differences in the sonogram taken in August 2007, combined with direct ground observations, allowed four sedimentary substrates to be identified, covering the seabed of the study area (Fig. 5): i) a hard rocky substrate of volcanic bedrock and sandstone cobbles; ii) a sandy substrate partially covered by algae and seagrass; iii) a combined rocky-sandy substrate with partial coverage of algae and seagrass; iv) a mobile sand substrate including submarine dunes located westward of Maspalomas beach. Field trips during the beach topography surveys enabled us to establish that mobile sand is not the only coastal substrate in the shoreline, but alluvial deposits also frequently outcrop at Maspalomas beach after storm wave erosion. In addition, rocky substrate composed of volcanic bedrock and sandstone cobbles were identified in the shoreline near the western limit of Maspalomas beach.

Medium term sediment budget and interannual feedback

The analysis of topographic changes between September 2005 and December 2009 indicated that the highest beach erosion rates occurred during the winter of 2005-2006 (winter conditions in the Canary islands are typical from October to March). This initial erosive event was followed by four years of partial beach recovery in a series of alternating minor accumulative and erosive episodes. The trend analysis of the sedimentary budget for this 4-year period indicated that it would take about 7.8 years for the beaches to recover to their initial states (Fig. 6), meaning that the stationary equilibrium of these beaches (mainly controlled by storm waves) cannot be reached in an annual period, but in a decadal one.

Monitoring the beach's topographic changes during this 4-year period also showed the different erosion rates and recovery processes among the three alongshore sectors. Thus, final shoreline migration obtained from the 3D topographic maps showed an average accretion of 60m alongshore of Maspalomas beach, in contrast with a retreat higher than 100m at the eastern margin of La Bajeta cape, while El Inglés beach presented a stable shoreline (Fig. 7).

The sediment budget for the inner shelf and subtidal beaches in the medium-term (2000-2007) showed a net erosive trend, with erosion rates of the bottom surface of about 1m. The highest erosion rates (2m) were located in two areas, the shallowest sector southward of Maspalomas beach and the deepest sector eastward of El Inglés beach. On the other hand, the inner shelf fronting La Bajeta cape had a balanced sediment budget, while accumulative trends of about 2m were identified towards the east of the cape and southward from Maspalomas beach (Fig. 8A). In summary, erosion was the dominant process in 80.5% of the submerged area, while only 19.5% of the submerged area showed a tendency towards accumulation, determining a total sedimentary deficit of about $2x10^6 m^3$ (Table 2), which explains the landward displacement of the isobathic lines (Fig. 9).

Short term sediment budget and seasonal feedback

Noticeable topographic changes were identified at the beaches and the inner shelf during the simultaneous monitoring period from February 2007 to February 2008. The highest topographic changes were measured at the beaches, especially at La Bajeta cape, but the total volume of sediment transport was higher at the inner shelf (Table 3).

The inner shelf of El Inglés and La Bajeta cape showed local areas with strong erosion and accretion during the first interval (February 2007 to August 2007), but their total sedimentary budgets were positive or nearly balanced, contrasting with the negative budget for the inner shelf of the Maspalomas sector (Fig. 8B). The second measurement interval (August 2007 to November 2007) was also characterised by conspicuous topographic changes, clearly dominated by erosion at the whole inner shelf (Fig. 8C). Finally, accretion was the generalised behaviour during the third interval of this study (November 2007 to February 2008) (Fig. 8D).

Subtidal sectors showed a similar budget to the inner shelf. However, the supratidal and intertidal sectors of the beaches showed a very different pattern: the first interval was characterised by intense erosion of La Bajeta cape while Maspalomas and El Inglés beaches showed accretion (Fig. 8B); on the other hand, erosion of La Bajeta cape and even El Inglés beach continued during the second interval along with accretion of Maspalomas beach (Fig. 8C); and the opposite behaviour was identified for the third period, with erosion of Maspalomas beach and accumulation of sediments at La Bajeta cape and El Inglés beach (Fig. 8D).

The analysis of the sedimentary feedback between the beaches and the inner shelf showed that the sediment outputs from the inner shelf could not be explained only by the inputs to the beaches (Table 3), and similarly the sediment inputs to the inner shelf exceed the eroded volumes from the beaches (Fig. 8D). There is no other nearby beach that could supply such a significant volume of sediment to the inner shelf; it follows from this evidence that the sediment budgets of the inner shelf need sedimentary exchanges with eastward and westward areas of the inner shelf to be explained. The westward continuation of the mobile sand substrate, deduced from the SSS image, confirmed the fluxes of sediments westward of the monitored inner shelf at the Maspalomas sector. Most significant, the sonogram data showed that the steeply sloped inner shelf fronting La Bajeta cape constitutes a sink where the active offshore transport of sand to deeper zones is causing a permanent loss of sand to the littoral system.

In the annual sediment budget, the evolution of the supratidal and intertidal zones was characterised by the accretion of Maspalomas and El Inglés beaches, and by the erosion of La Bajeta cape, although the total volume of sand accumulated in both beaches slightly exceeded the total eroded volume at La Bajeta cape (Fig. 8F; Table 3). Erosion was also the dominant process at the inner shelf and subtidal zones. In conclusion, taking into consideration all the eroded and accumulated volumes, the total sediment budget of the study area in the annual or short-term scale results is clearly negative.

Analysis of the waves, tides and wind-induced currents influence

Wave data analysis showed the dominance of NE waves during the first monitoring interval (February 2007 to Au-

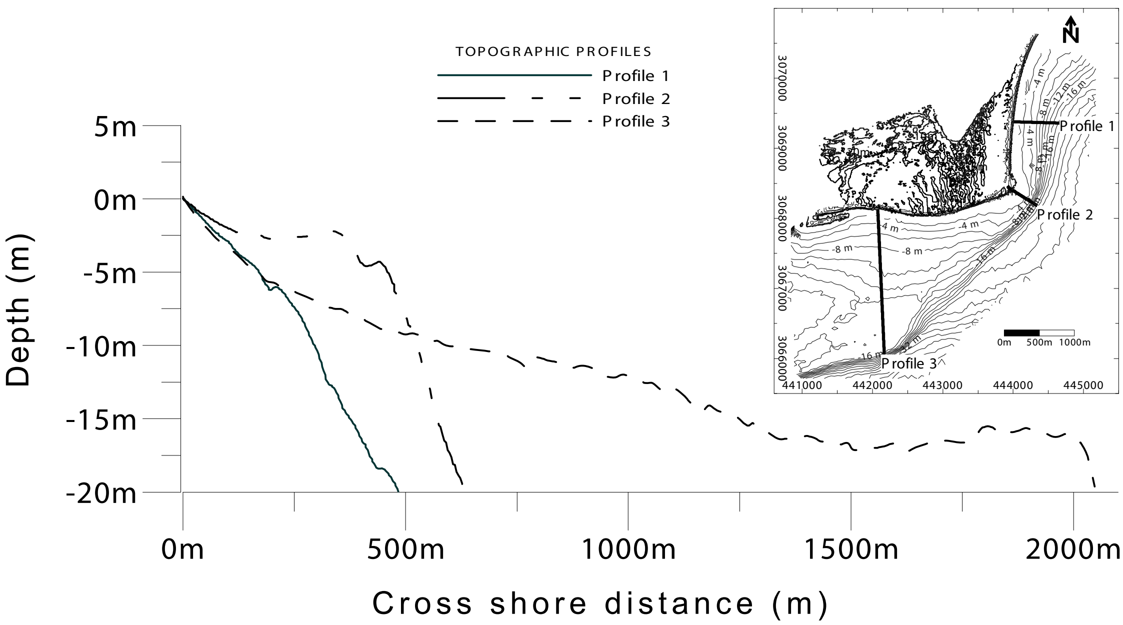

FIGURE 4 | Topographic profiles across the insular inner shelf of Maspalomas with 90, 120, and 170ºN directions to El Inglés, La Bajeta and Maspalomas profiles, respectively. Vertical exaggeration: 40.

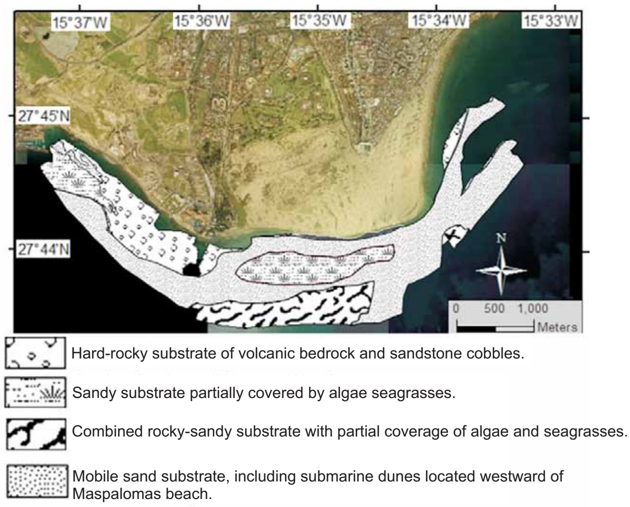

FIGURE 5 | Cartography of the submarine sedimentary substrates in the insular inner shelf of Maspalomas.

gust 2008), including NE swell storm waves, in contrast with dominant NE waves without significant storm waves in the second interval (August 2007 to November 2007), and finally a combination of NE and SW waves, including SW swell storm waves, through the third interval (November 2007 to February 2008) (Fig. 10).

Morphodynamics of the supratidal and intertidal sectors of the beaches is clearly related to this wave regime. The dominance of NE waves and storm waves from February to November 2007 generated higher sediment transport rates at El Inglés and La Bajeta cape, where erosion at La Bajeta cape explained accretion at Maspalomas beach due to the supply of sediments by longshore currents (Fig. 8B, C). In contrast, the occurrence of SW waves from November 2007 to February 2008 caused the erosion of Maspalomas beach and accretion at La Bajeta cape and El Inglés beach (Fig. 8D). However, the highest topographic changes at the inner shelf were measured from August to November 2007, and consequently they cannot be explained

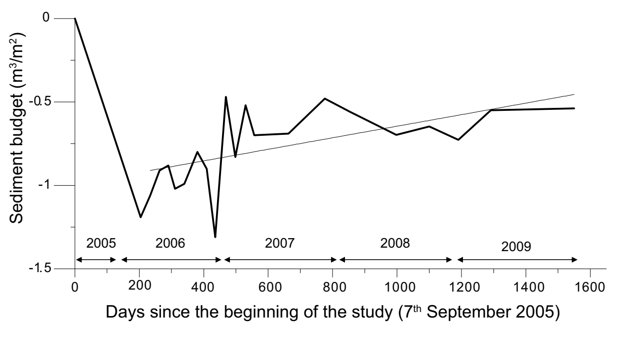

FIGURE 6 | Trend analysis of the sediment budget of the supratidal and intertidal zones of the beaches in the medium-term (September 2005 to December 2009).

by the wave regime, but rather the wind regime and their induced oceanic currents. The Canary current towards the SW, which is associated to NE trade winds blowing from April to September, generated positive budgets at the El Inglés sector, due to the input of sediments from the NE, as well as losses of sediments across the La Bajeta steep slope and erosion of the Maspalomas inner shelf (Fig. 8B, C). In contrast, the current associated to multidirectional winds, blowing during the rest of the year, generated a positive budget at the Maspalomas inner shelf sector from November 2007 to February 2007, where inputs of sediments are only possible from the W due to the presence of the steep slope towards the S and E, while the erosion of El Inglés must be associated to the output of sediments to the NE (Fig. 8D).

Sediment budgets of the subtidal beaches showed an intermediate pattern between the inner shelf and supratidal-intertidal sectors of the beaches. The morphological changes in the shallowest subtidal zone (1 to 4m depth) were associated with the sedimentary processes at the supratidal-intertidal sectors of the beaches, while the deepest subtidal zone (4 to 6.14m depth) showed a similar sediment budget to the close inner shelf, *i.e.*, the morphological changes at the upper and lower subtidal zones were controlled by the wave regime and wind-induced currents, respectively.

Medium-term (1996-2009) analysis of the wave and wind database showed significant differences, with low average wave energies in 1998, 2004 and 2005, in contrast with intense wave energy during the winter of 2005-2006 (Fig. 11). In fact, the highest storm wave of the whole 13-year period corresponded to this winter and

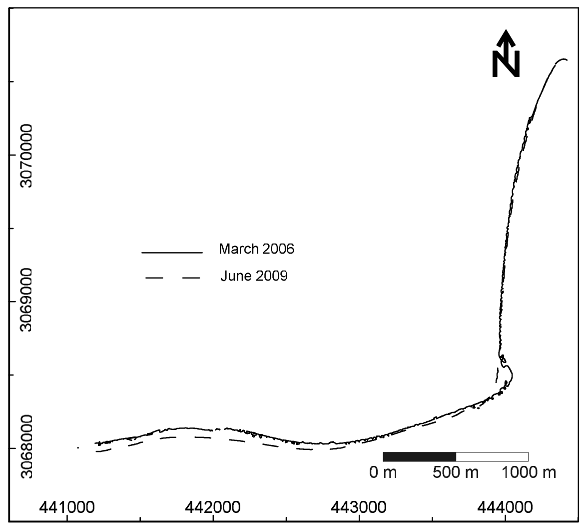

FIGURE 7 | Shoreline displacement along the recovering period (2006-2009) after the high beach erosion of the winter of 2005-2006.

generated the highest recorded erosion rate of the beaches. Finally, a decrease in storm energy during the final years explained the current recovery of the beaches (Fig. 6). On the other hand, the lowest annual average wind velocity has also been identified to have occurred in 2005, as well as a trend towards a decrease in wind intensity for this 13-year period.

Furthermore, the morphodynamics of the Maspalomas and El Inglés beaches is also modulated by the mesotidal regime (1.8m at neap tide and 2.6m at spring tide) in the study area. The occurrence of high spring tides simultaneously with a storm wave event favour greater wave penetration followed by high beach erosion rates. Thus, the coincidence of the storm waves of 28th February 2006 (Hs_o=3.3m; Tp=9.1s) with high spring tides (1.26m above mean sea level) generated a very high run-up and intense dune and beach erosion.

DISCUSSION

Sediment budget of the whole system

Morphological changes measured simultaneously at the beaches and the inner shelf show clear sedimentary bidirectional fluxes between them, in the short and medium-term, with intense sediment transport up to a depth of 16m and deeper zones.

The short-term analysis identified an accumulative pattern at the supratidal and intertidal sectors of the beaches, and this result was confirmed by the medium-term analysis which revealed that it would take about 7.8 years to return to the original sedimentary state, before the very erosive storm wave events of the winter of 2005-2006 (Alcántara-Carrió and Fontán, 2009). Consequently, it becomes clear that a classical one-year sedimentary equilibrium (Wright and Short, 1984; Masselink and Short, 1993) is not a suitable model in this coastal area which is controlled by storm wave activity. In contrast, erosional trends were identified for the shallow shelf and subtidal beach sectors in short-term (Fig. 8; Table 3) and they were once again confirmed by the analysis in medium-term (Fig. 8A; Table 2).

The sediment budget of the whole sedimentary system was negative in the short and medium-term, because the volume accumulated at the supratidal and intertidal sectors of the beaches was much less than the eroded volumes from the subtidal sector of the beaches and the inner shelf. It is in agreement with the erosional trend identified at the Maspalomas dune field in the medium-term analysis (Hernández, 2006; Hernández *et al.*, 2007). Aeolian sediment transport at the Maspalomas dune field (Hernández *et al.*, 2006) is lower than the marine sediment transport at the supratidal and intertidal beaches (Alcántara-Carrió and Fontán, 2009) and the present study shows that sediment fluxes at the subtidal beaches and the inner shelf are even greater (Table 3). Consequently, the shortage of sediments at the Maspalomas dune field must be related to the negative budgets of the submarine sedimentary processes. This possible control of the sedimentary deficit of the inner shelf over the sedimentary shortage of the dune field should be evaluated for other coastal areas with similar erosional trends, located next to inner shelves with high sediment transport rates.

The results of this study are in accordance with previous investigations, which verified that sand is often transported offshore beyond the external limits of the beach during storms (Thieler *et al.*, 2001; Amos *et al.*, 2003) and queries the existence of a depth of closure (Hallermaier, 1981) in the case of beaches included in sedimentary systems of high sediment transport at the inner shelf. The study area shows that these systems do not present a depth limit to the crosshore sediment transport between the beach and the inner shelf, even far away from the area influenced by the storm wave.

Causes of the beach and inner shelf erosion

Coastal erosion is nowadays a chronic hazard for many coastal areas (Bird, 1996), making it necessary to analyse it further, by the calculation of the sediment budget and the determination of its causes, in order to predict its evolution and possible solutions.

Coastal erosion has mainly been associated with meteorological and oceanographic causes (Bryant, 2005) as well as with human alterations to the natural system (Nordstrom, 2000; Syvitski *et al.*, 2005; Correa *et al.*, 2005), but the role of the geological inheritance of the coast should not be underestimated (Trenhaile *et al.*, 1999; Short, 2010).

Impact of local human activities

Previous studies at the Maspalomas dune field suggested that the building of tourist resorts close to and over the dune field, as well as the installation of stands or deckchairs at the backshore, are the main causes of the dune field's erosion (Hernández, 2006). It is in agreement with typical tourism induced impact to other coastal areas (Alonso *et al.*, 2002; García and Servera, 2003). However, this study has shown that erosion is also the dominant trend in the beaches and the shallow shelf. Consequently, additional natural and human causes of erosion must be considered.

Human activities not only alter the sedimentary processes at the subaerial zone, but also at the submarine zone, *e.g.*, by the pollution and degradation of seagrass meadows,

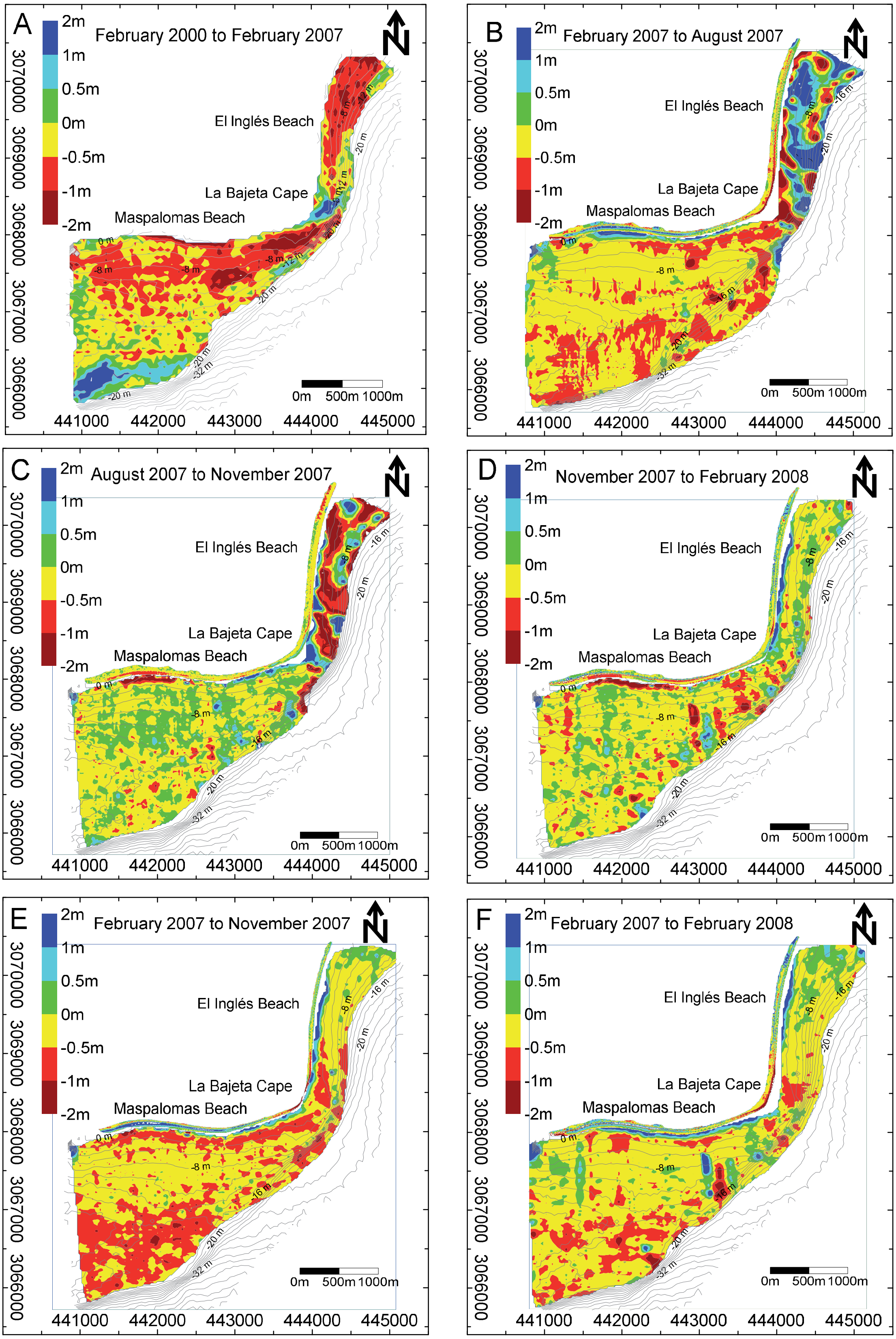

FIGURE 8 | Sediment budget (topographic variations) A) for the submerged zone in medium-term and B-F) for the whole study area in short-term (correlative changes in B, C, and D; accumulated changes in E and F).

TABLE 2 | Sediment budget (m^3) and height (m) variations of the subtidal beaches and the inner shelf in the medium-term (2000 to 2007)

Medium-term sediment budget	Maspalomas Sector volume (m^3)	Maspalomas Sector height (m)	La Bajeta Sector volume (m^3)	La Bajeta Sector height (m)	El Inglés sector volume (m^3)	El Inglés sector height (m)
Subtidal beach	-387,459	-0.91	-26,989	-0.14	-265,424	-1.06
Inner shelf	-1,020,413	-0.40	-52,154	-1.77	-266,081	-0.82

key ecosystems for diminishing the near-bottom hydrodynamics and sand mobility (Bryan *et al.*, 2007). Destruction of seagrass meadows facilitates higher mobility of sediments and thus higher erosion rates. The ecocartographic study of the southern littoral of Gran Canaria, elaborated in 2002 by the Spanish ministry of environment, showed the occurrence of *Cymodocea nodosa*, with dense and dispersed meadows at the inner shelf of El Inglés and Maspalomas, respectively. This cartography enables deducing that the conservation of these meadows is better at El Inglés than at Maspalomas submerged areas. Therefore, erosion of the Maspalomas beach and inner shelf fronting can be induced by the partial destruction of these meadows, while the effects of human impact due to this seem to be lower in the sedimentary budget of the El Inglés sector.

Impact of climatic change

In long and medium-term analysis it is necessary to evaluate the influence of the present global sea level rise (GSLR) and the wind and wave variability. Hydrographical data analyses determined a GSLR of 1.5-2.0mm/yr over the last century, but an average sea level rise in the Canary islands region for the period of 1910-2000 of only 0.23mm/yr (see Miller and Douglas, 2004; Fig. 3). Consequently, the Canary islands can be defined as a region without a strong influence from the rise in mean sea level over the last century.

On the other hand, trade wind intensity is related to differences between the Azores high and Equatorial low pressures. Therefore, with a similar approach to the analysis of the North Atlantic oscillation influence in the wave regime of Portugal (Semedo, 2005), the inter-annual wind and wave variability has been identified at the study area (Fig. 11). The effects of global warming have been especially intense over the last decade, where 2005 has been described as the warmest year in the northern hemisphere since 1850 (Jones *et al.*, 2009). The year 2005 was characterised at the study area for having the lowest average energies of the trade winds and NE waves, although the decrease of wind velocity was not as clear for other warm years (*i.e.*, 1998 and 2008) (Fig. 11). It seems to provide evidence of the current predicted decrease of both wave height and trade winds intensity towards the end of the present century (2071-2090) due to climatic change (de Castro *et al.*, 2005). This year (2005) was also characterised by the highest SW storm waves of the whole study period. In accordance with the sediment budget determined in this study, this weakening of trade winds and increase of SW storm waves will suggest lower inputs of sediments to the inner shelf of the El Inglés sector, and consequently higher erosion of this sector and lower inputs to the El Inglés beach, as well as lower erosion rates of the inner shelf southward from Maspalomas beach.

Tidal water levels also control the morphological response because they determine the type, intensity and duration of the wave processes operating on the cross-hore profile (Masselink *et al.*, 2006; Reichmüth and Anthony, 2007). The influence of astronomic tides was

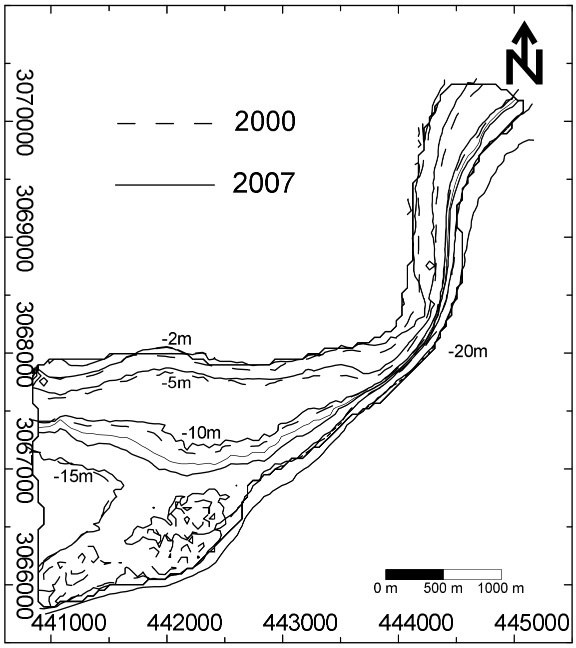

FIGURE 9 | Landward displacement of the isobathic lines from 2000 to 2007 due to erosion of the submerged zone.

TABLE 3 | Accumulated sediment budget of the beaches and the shallow shelf in the short-term (volume (m^3) and height (m)) showing variations from the initial conditions of February 2007 to August 2007, November 2007 and February 2008

Short-term sediment budget		Maspalomas sector volume (m^3)	Maspalomas sector height (m)	La Bajeta sector volume (m^3)	La Bajeta sector height (m)	El Inglés sector volume (m^3)	El Inglés sector height (m)
February 2007 to August 2007	Supratidal & intertidal beach	46,137	0.23	-48,919	-0.86	22,773	0.16
	Subtidal beach	-171,645	-0.25	-113,753	-0.43	236,878	0.56
	Inner shelf	-1,115,930	-0.41	2,953	0.04	137,535	0.36
February 2007 to November 2007	Supratidal & intertidal beach	100,217	0,49	-64,318	-1.13	1,002	0.01
	Subtidal beach	-320,267	-0.48	-102,610	-0.39	-51,506	-0.12
	Inner shelf	-1,308,767	-0.49	-44,422	-0.58	-107,147	-0.28
February 2007 to February 2008	Supratidal & intertidal beach	28,083	0.14	-40,955	-0.72	29,889	0.21
	Subtidal beach	-110,305	-0.16	-82,808	-0.32	30,127	0.07
	Inner shelf	-825,765	-0.30	-29,142	-0.38	-51,500	-0.13

evidenced by the coincidence of the 28th February 2006 storm with high tidal levels and the consequent extreme run-up and overwash processes, but it is clear that astronomical tides are not affected by climatic change. However, this is not the situation with respect to meteorological tides. Trade wind velocity is directly related to the Azores High intensity and, therefore, the identified decrease of trade wind intensity at the study area in a medium-term analysis, due to the current climatic change, involves an increase in water levels for the meteorological tides, another erosional factor to take into account.

Role of geological inheritance

The morphology and evolution of the Maspalomas sedimentary system over a long-term period can be explained as the result of their volcanic origins and activity of the Fataga gully, combined with sea level oscillations and other clima-tic conditions (wind and wave regimes). The volcanic origin of the island of Gran Canaria determines its present tectonic condition, which is characterised by active tilting toward the W or WSW (Menéndez *et al.*, 2008), but the effects of the uplift rates at the study area (lower than 0.015mm/yr) are not relevant to our medium-term analysis of coastal changes. Another consequence of its volcanic origin is the dip slopes of its talus, partially compensated at the study area by the formation of alluvial terraces at the Fataga gully.

Finally, the topography of Gran Canaria controls the bidirectional wind, waves and currents regime at the study area. The influence of the Canary islands on the oceanic currents by generating eddies has been depicted by mesoscale studies (Sangrà *et al.*, 2007, 2009; Jiménez *et al.*, 2008; Mason, 2009). Thus the acceleration of the Canary current due to the submarine relief of the Gran Canaria island is a very important factor in understanding the high sediment transport rates at the inner shelf of the study area. In addition, the orientation of the shoreline and the isobathic lines at the study area are essential in the understanding of the occurrence and effects of the bidirectional wind and current regimes around this cuspate foreland in the southern limit of the island.

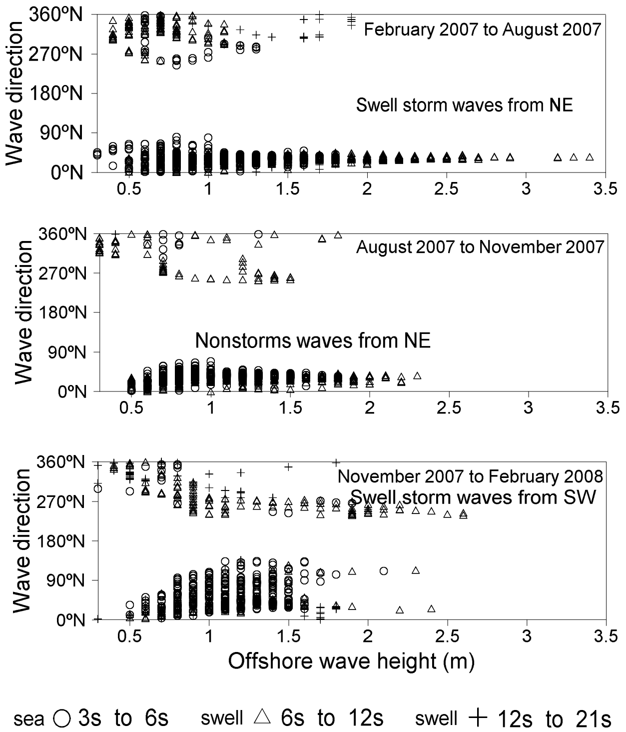

FIGURE 10 | Offshore wave height (Hs_o) versus wave approach direction, after three period (Tp) ranges and for each monitoring interval. Wave data available from Puertos del Estado.

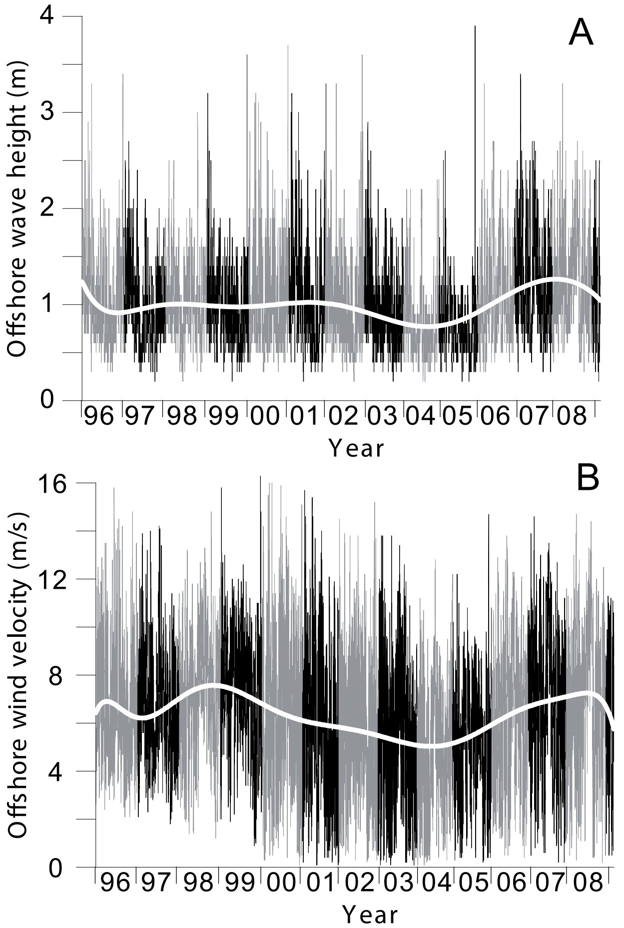

FIGURE 11 | Medium-term analysis of wave height and wind velocity trends. Solid lines represent the polynomial fits.

CONCLUSIONS

Noticeable sediment changes have been identified at the beaches and the inner shelf of the Maspalomas Sedimentary System during the simultaneous short-term (1-year) monitoring study. The highest erosion rates (topographic changes) were measured at the beaches, but the highest eroded volumes were measured at the inner shelf. In the medium-term analysis (2000-2007) accretion was the dominant process at the supratidal and intertidal sectors of the beaches, while erosion was dominant at the inner shelf and subtidal zones. Summed up, an erosional trend in the sediment budgets of the whole study area has been identified in short and medium-term.

The analysis of the feedback between the beaches and the inner shelf shows the occurrence of noticeable sedimentary exchanges with other sectors of the inner shelf, located north-eastward and westward of the study area. The characteristics of the submarine sedimentary cover confirmed these sedimentary fluxes, highlighted in the depiction of the mobile sand westward of Maspalomas beach. The DEM and sedimentary cover map also showed the location of a sink area of this sedimentary system at the steeply sloped inner shelf zone fronting La Bajeta cape.

Climatic control of the sediment budget in the short-term becomes evident because the morphodynamics of the beaches in this cuspate foreland and that of the fronting inner shelf were clearly related to the bidirectional wave and wind-induced current regime, respectively. Similarly, medium-term evolution of this sedimentary system was clearly controlled by the inter-annual variability of the wave and wind regimes. Thus, the highest erosion rates at the beaches were due to the extreme storm waves during the winter of 2005-2006, and the subsequent net accretion was due to a reduction of wave energy, where minor storm wave periods were reflected as short erosional events. The medium-term evolution of the inner shelf was characterised by an erosional trend, which necessarily affected, or even controlled, the shortage of sediments at the beaches and the dune field. Therefore, due to the influence of the sedimentary processes of the inner shelf the sediment budget of the beaches at the study area did not fit the classical pattern of the one-year cycle of erosion and accretion.

Moreover, the predicted effects of climatic changes were evidenced at the study area during 2005, *i.e.* the warmest year in the Northern Hemisphere since 1850. During this year the study area showed the lowest average annual values of wave height and wind velocity (after the high resolution limited area model prediction). A similar pattern of wave energy was detected in 1998, the warmest year in the whole world since 1850, but not for the wind intensity. In contrast, the influence of the global sea level rise was defined as a minor factor in this area, in comparison with most of the coastal systems in the world.

Finally, the role of the geological inheritance was shown in the morphology and evolution of this system over the long-term, determined by the combination of the slow, tectonic tilting of Gran Canaria, the inputs of sediments from the Fataga gully and the sea level oscillations. Thus, the present morphology of the submarine sector of this sedimentary system has been related to the morphology of the lowest alluvial terraces, to their altitude and extension and to the orientation of the talus. The existence of bidirectional wind, wave and current regimes in the study area is due to the influence of the subaerial and submarine relief and it determines the sedimentary budget and evolution of the study area in every temporal scale, from short to long-term.

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