SEDIMENT BUDGET ON AN URBAN EMBAYED BEACH UNDER DIFFERENT EROSION PROTECTION STRUCTURES: LA BARCELONETA BEACH (CATALONIA, NW MEDITERRANEAN)

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Anaïs MOLLIER

Training supervisor:

Mrs. Ruth DURÁN, Department of Marine Geosciences Instituto de Ciencias del Mar, CSIC. Paseo Marítimo de La Barceloneta, 37 - 49. 08003, Barcelona (Spain)

Academic advisor:

Mr. Eric CHAUMILLON, Department DPL Littoral Environnement et Sociétés, LIENSs – UMR 7266. 2, rue Olympe de Gouges. 17000, La Rochelle (France)

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« *Le succès n'est pas la clé du bonheur. Le bonheur est la clé du succès.*
Si vous aimez ce que vous faites vous réussirez. »
Albert Schweitzer

« *Il faut collectionner les pierres qu'on vous jette.*
C'est le début d'un piédestal. »
Hector Berlioz

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Summary

The city of Barcelona (NW Mediterranean) suffered a significant transformation of the sea front because of the Olympic Games in 1992. *La Barceloneta*, located between the Barcelona Commercial Harbour and the Olympic Marina, used to be the largest beach of the city. In this beach, several sand nourishments have taken place since 1991, and a detached breakwater and associated tombolo were built in 2006-2007 dividing the beach in two sections. The aim of this study is to quantify and compare the morphological changes of this beach before and after the detached breakwater construction. Using orthophotos, bathymetric and topographic data covering the period 2003-2017, the morphological changes are analysed, including variations in the emerged and submerged beach areas, volume and shoreline displacement. Results reveal an important erosion before the breakwater construction. Interestingly, an intensification of the erosion appears immediately after the construction of the detached breakwater, particularly in the northern part of the beach. The sediment budget was partially balanced with new nourishments that led to a strong accretion of the beach for a short time-scale. These protection measures contribute to reduce beach mobility and losses of sediment of the beach system, but the sediment budget is still negative due to the absence of new natural sedimentary inputs.

Keywords*:* Topography, Bathymetry, Volumes, Nourishment, Shoreline position

Résumé

En Espagne, et plus précisément en Catalogne, la ville de Barcelone (NO Méditerranée) a subi une transformation significative de sa frange côtière notamment dû à une urbanisation accrue de celle-ci, avec l'organisation des Jeux Olympiques de 1992. *La Barceloneta*, située entre le Port Commercial et la Marina Olympique, est la plage la plus importante de la ville. Elle a subi de nombreux rechargements sédimentaires depuis 1991, enfin entre 2006 et 2007, un brise-lame détaché associé à un tombolo a été érigé divisant ainsi la plage en deux sections. Le but de cette étude est de quantifier mais aussi de voir les changements ainsi que les évolutions morphologiques qui ont pu s'opérer sur cette plage, avant et après la construction du brise-lame. À l'aide d'orthophotos, de données bathymétriques et topographiques, les changements morphologiques ont été analysés incluant les variations de la plage émergée et submergée, les volumes et les déplacements de position du trait de côte, sur une période qui s'étend de 2003 à 2017. Les résultats révèlent qu'une érosion importante existait déjà avant la construction de ce brise-lame. Fait intéressant, qui s'additionne avec une intensification de l'érosion instantanément après la construction du brise-lame détaché, et ce, particulièrement dans la partie nord de la plage. Le budget sédimentaire a été partiellement maintenu en équilibre grâce à de nouveaux rechargements sédimentaires, qui ont permis une forte accrétion de la plage, temporairement. Ces mesures de protection contribuent à réduire la mobilité de la plage et les pertes dues à une interruption du transit sédimentaire. Cependant, le budget de la plage de *La Barceloneta* reste encore déficitaire en raison de l'absence de nouveaux apports naturels.

Mots clés*:* Topographie, Bathymétrie, Volumes, Rechargement sédimentaire, Trait de côte

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1. Introduction

According to the 2004 EUROSION report, about 40 % of the European coasts are subject to erosion (Eurosion report, 2004). Coastal erosion becomes more critical because coastal zones are optimal places for population concentration. It has been estimated that 23 % of the world's population lives both within 100 km distance of the coast and lower than 100 m above sea level, and population densities in coastal regions are about three times higher than the global average (Small and Nicholls, 2003). Humans try to fight against this threat by installing hard structures for coastal protection. As a result, spending on coastal protection is increasing. Indeed, according to the *Intergovernmental Panel on Climate Change* (IPCC), they reached 3.2 billion euros for the year 2001 alone and could reach 5.4 billion euros over the period 1990-2020. However, it appears that these measures are not effective in the long term and they must to be combined with "soft" protection methods.

According to the 2007 IPCC report, the geomorphological vulnerability of the coastal zone can be defined as the ability to cope with climatic forcing and geomorphological hazards and the coast as the interface between the continent, the sea and the atmosphere (Haslett, 2000). However, until recently, there has been relatively little attention to measure the interactions between the socioeconomic system and the environmental variability (Bowen and Riley, 2003), with consequent limited understanding of the linkages of between coastal system dynamics and the social benefits associated with therm for *Integrated Coastal Zone Management* (ICZM) (Brenner et al., 2008). Therefore, it is essential and even more important today to understand the coastal geomorphological response for a regional integrated assessment.

The Mediterranean is a good example of a coastal region where human stresses are significant, linked in particular to tourism, which is the most important driver of coastal related changes in this area (Ariza, 2010). It symbolizes the meeting place between an exceptional natural and cultural heritage (greater variety and diversity of coastal environments of the world), a considerable and constant development of human activities endangering it (Parliamentary Assembly, 2003), represents one third of world tourism and depicts the primary economic resource of many countries (Institut Oceanographique de Monaco). The erosion occurring on the Mediterranean coast is attributed to wave action and the development of protective measures and human settlements causing changes in sediment transport (Hanson et al., 2002).

Within Europe, Spain has the longest coastal zone (Sarda et al., 2005), which is also threatened by the ever-present coastal erosion. It should be noted that the use of beaches in Spain increased strongly during the second half of the 20th century (Ariza, 2010). Humans have to succeed in reconciling economic expansion and permanence of their environment to make on which the demographic and economic factors not much do not have an impact or coastal erosion but also to reduce influence of administrations and technical criteria in the conception of the measures of defenses. It is therefore essential to develop, in this sector, an integrated management of the coastal zone by trying to reconcile economy and environmental heritage.

The Catalan coast, in the northwest of Spain, is about 700 km long and includes a wide variety of coasts (Mendoza and Jimenez, 2006). It consists of a diversity of uses and resources, enabling it to expose more than 40 % of its sandy coasts on the northeastern part, which concentrate about 50 % of the population in the coastal zone (Mendoza et al., 2011) and contributes more than 10 % of the *Gross Domestic Product* (GDP) (Ariza et al., 2008). However, it undergoes a significant withdrawal of about 2 m/yr on 70 % of these beaches (Jiménez et al., 2011). This situation has led to the development of several studies focused on the evolution and vulnerability of the coastal area, with particular emphasis on urban beaches and low-lying coasts threatened with erosion (Guillén et al., 2008; Ojeda and Guillén, 2008; Jiménez et al., 2011; Mendoza et al., 2011; Sancho-García et al., 2013).

The aim of this study is to quantify and investigate the morphological response of an urban beach, *La Barceloneta* beach using orthophotos, bathymetric and topographic data covering the period 2003-2017, with the aim of improving knowledge on these artificial embayed beaches. Morphological changes include: variations in the shoreline position, changes in the beach area and variations in the emerged and submerged volume. Particular attention is paid to the interaction between natural factors (storms and waves) and anthropogenic factors (hard and soft protection measures). Before and after the breakwater construction is calculate to improve changes for each year, to evaluate the construction impacts and determine the geomorphological behavior between each year.

When environmental studies are made, there exist various scale types which vary according to time and from space: micro-scale, meso-scale, macro-scale and mega-scale. For *La Barceloneta* beach study, the shoreline changes are analysed at a macro-scale considering a space scale of kilometers and a temporal scale of years (Fig 1).

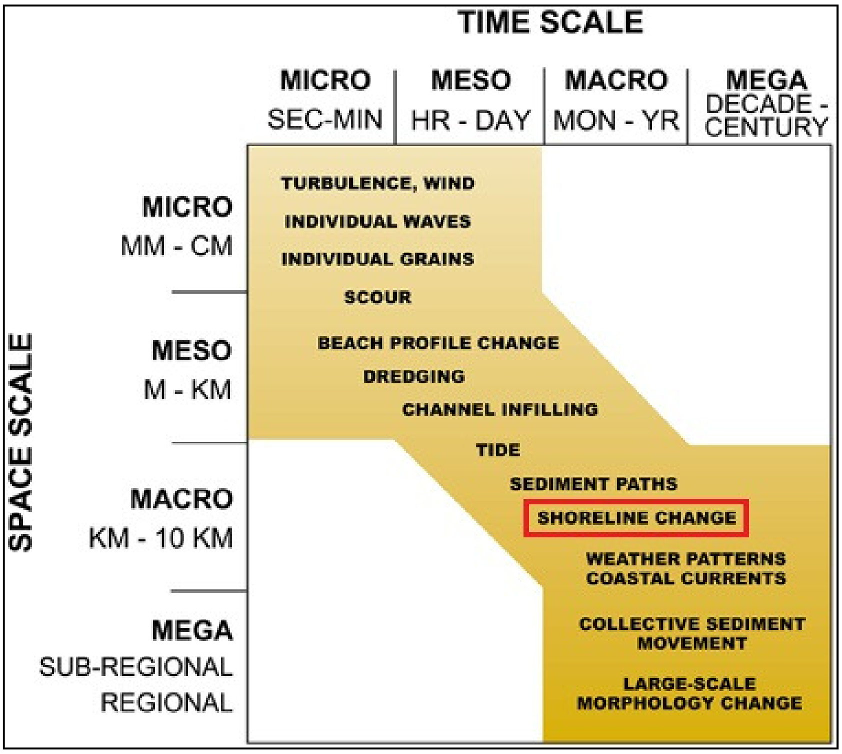

Fig 1. Compatible temporal and spatial scales for sediment transport and beach morphology. The red rectangle means the main topic of this study (Gallop et al., 2015).

2. Study area

The Barcelona district has 115 km coasts among which more than 70 km represent beaches (Breton et al., 1996). Before 2000's, the sector of *La Barceloneta* beach represented an only beach delimitate by the Hotel W in the south and by both parallel dams in the north (Fig 2). The Olympic Games of 1992 (www.olympic.org) allowed the city to open with the world and notably with the sea in development of many buildings and to provide Barcelona of a marina, Harbour of an Olympic city and many beaches (Provancal et al., 2007). The set represents an important economic benefit but also a social and an environment interest. In term of erosion, 70 % of the Barcelona beaches are in erosion and 50 % of the coastal municipalities suffer or have sudden damages on the infrastructures present on the beaches (Mendoza et al., 2011).

La Barceloneta beach (41°22′51.2″N, 2°11′21.8″E), located between the Barcelona Commercial Harbour and the Olympic Marina, is the largest beach of the city (Fig 2). It is an artificial embayed beach which is the most popular beach of the city with tourists especially during summer season (Guillén et al., 2008).

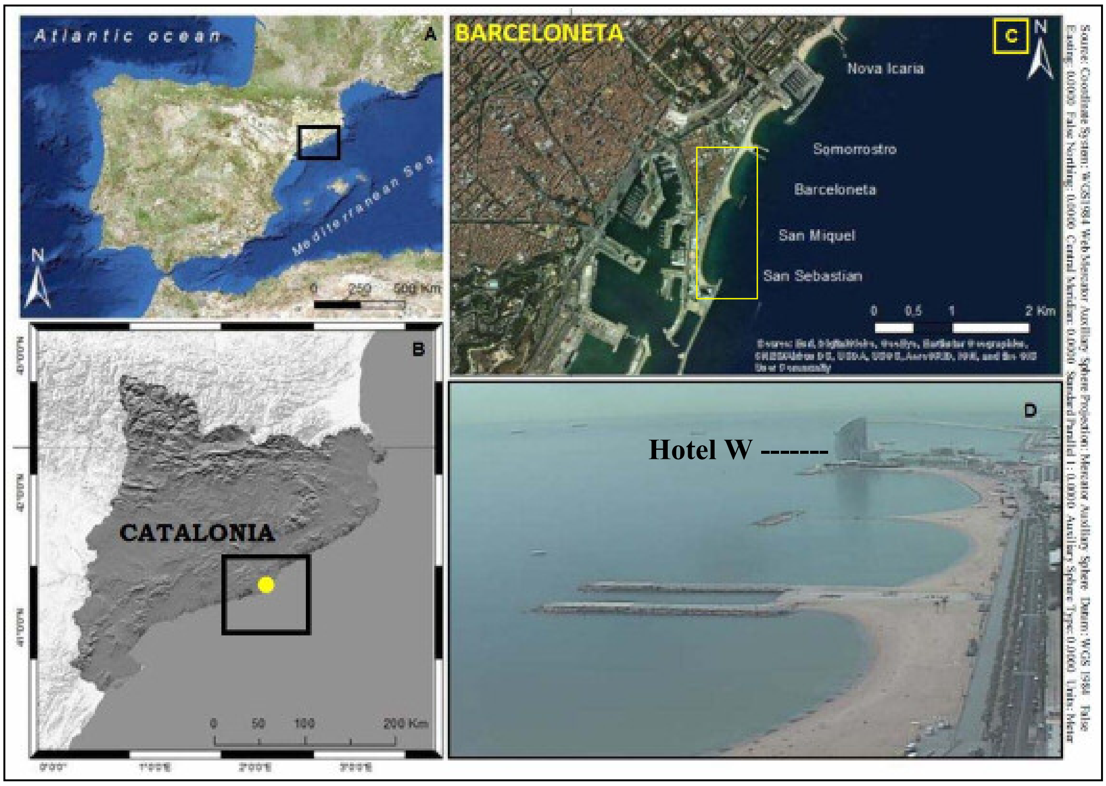

Fig 2. Location map of the study area: (A) Spain. (B) Catalonia: *La Barceloneta* beach (yellow marker). (C) Othophoto of study area (yellow rectangle). (D) *La Barceloneta* view from camera (Coastal Ocean Observatory, ICM-CSIC), NW Mediterranean, Catalonia (Spain).

In this beach, several sand nourishments have taken place since 1991, and a detached breakwater and associated tombolo were built in 2006 and 2007 dividing the beach in two sections: *La Barceloneta* in the north and San Miquel and San Sebastian in the south, but we refer these three small beaches to as *La Barceloneta* beach in this study (Fig 2). This beach is bounded by the Barcelona harbour in the south and the Somorrostro double dike in the north. It is 520 m long and 18-252 m wide. The median grain size of the sand ranges between 0.27 and 0.88 mm (CIIRC, 2010). The San Miquel and San Sebastian beaches are 1175 long (inclufing both beaches) and 45 m wide. They are characterized by medium to coarse sand with median grain size between 0.45 and 0.88 mm (CIIRC, 2010) (see APPENDICE I; APPENDICE II for detailed description of these beaches).

From a hydrodynamic point of view the tide is define as microtidal system (range below 20 cm). The average height of the significant waves offshore (Hs) is of 0.74 m and a period (Tp) of 5.74 s on average (CIIRC, 2010). The storms coming from the East are the most energetic and have a typical duration of a few days in Catalonia and therefore the most destructive because it exists a link between the *fetch* (surface on which winds blow) and the wind regimes. In addition, storms are responsible for major changes in the patterns of sandy beaches (Sancho-Garcia et al., 2013).

3. Data sets and Methods

1. Wave climate

Wave data from the SIMAR model (www.puertos.es) were used to characterize the wave climate in the study area. Data series includes the SIMAR_44 (1958-2000) at three points: SIMAR_2111137, SIMAR_712018014 and SIMAR_2111136, and WANA (1996-present) model (Fig 3). The set of SIMAR data consists of a time series of wind parameters and numerical modeling waves. The data collect are therefore not direct measurements but simulated data. The SIMAR_44 database has 44 years of sea and wind states extending from 1958 to 2000 with a time resolution of 1 hour and a spatial resolution of 1/24 degree. This database was generated using an advanced version of the *WAveModel* (WAM) with the forcing terms coming from the downscaling of the *National Centre for Environmental Prediction* (NCEP).

Fig 3. Location map of the SIMAR buoys: SIMAR_2111137, SIMAR_2111136 and SIMAR_712018014 of the Spanish Port Authority. The yellow square represents the study area.

From this datasets, measurements of *significant wave height* (Hs), *peak wave period* (Tp) and *wave direction* (Θ) were taken at hourly intervals. The significant wave height is approximately equal to the average of the highest one-third of the waves, as measured from the trough to the crest of the waves. Following Ojeda and Guillén (2008), significant storms were defined by Hs higher than 2.5 m at the peak of the storm and a minimum duration of 12 h. If the interval between two consecutive storms was shorter than 12 h, they were considered as a single double-peaked storm, as was proposed by Mendoza and Jiménez (2009).

2. Orthophotos

Morphological changes in the study area were quantified using high-resolution (0.5, 1 and 2.5 m) orthophotos, *Global Positioning System* (GPS) and *LIght Detection And Ranging* (LiDAR) derived beach topography, and single beam and multibeam bathymetric data. Orthophotos were used as primary data source for shoreline extraction. They were downloaded on the platform Vissir3 of the ICGC (www.icc.cat) between 1946 and 2016 (Table 1). The *European Terrestrial Reference System* 1989 (ETRS89) was used and points were projected to the *Universal Transverse Mercator* (UTM) system (Zone 31 N). The ETRS89 is the geodetic frame of reference official in Spain. It should be noted that the difference between both system ETRS89 and *World Geodetic System* 1984 (WGS84) is of 10 cm +/-5 cm (Institut Cartogràfic i Geològic de Catalunya).

Table 1
La Barceloneta orthophoto characteristics (Institut Cartogràfic i Geològic de Catalunya).

Date	Image type	Scale	Pixel size (m)
1946	B/W aerial	1:5000	1
1956	B/W aerial	1:5000	0.5
1987	B/W aerial	1:5000	0.5
1990	B/W aerial	1:25000	2.5
1993	Colour aerial	1:25000	2.5
1994	B/W aerial	1:5000	0.5
1996	Colour aerial	1:25000	2.5
2000	Colour aerial	1:25000	2.5
2003	Colour aerial	1:25000	2.5
2004	Colour aerial	1:25000	2.5
2006	Colour aerial	1:25000	2.5
2008	Colour aerial	1:25000	2.5
2009	Colour aerial	1:25000	2.5
2010	Colour aerial	1:25000	2.5
2011	Colour aerial	1:25000	2.5
2012	Colour aerial	1:25000	2.5
2013	Colour aerial	1:25000	2.5
2014	Colour aerial	1:25000	2.5
2015	Colour aerial	1:25000	2.5
2016	Colour aerial	1:25000	2.5

3. Topography and Bathymetry

Topographic and bathymetric data were obtained between October 2003 and October 2016 (Table 2). Topography surveys were made using a Leica 1200 (GNSS RTK) respectively with 5 mm and 10 mm of horizontal and vertical accuracy. Reference frame WGS84 used by GPS was therefore projected to ETRS89. The LiDAR data are obtained by l'Institut Cartogràfic I Geològic de Catalunya using a Leica ALS50-II airborne laser scanning. The GRS80 ellipsoidal heights of LiDAR data were transformed into orthometric heights by adding the geoid undulations of local geoid EGM08D595, which is an adaptation of the EGM2008 geoid to the local leveling network (Grau et al., 2012). Bathymetric data were obtained using Atlas Deso 20 single beam and a Sonarmite HPR OHMEX multi beam echosounder.

Table 2
Characteristics of *La Barceloneta* topography and bathymetry surveys used in this study.

Date	Topography	Bathymetry
Oct. 2003	GPS	Single beam
Nov. 2003	GPS	Single beam
Mar. 2005	GPS	Single beam
Oct. 2005	GPS	Single beam
Apr. 2006	GPS	Single beam
Nov. 2006	GPS	Single beam
Jan. 2007	GPS	Single beam
Jun. 2007	GPS	Single beam
Nov. 2008	LiDAR	-
May 2009	LiDAR	-
Oct. 2010	GPS	Single beam
Jul. 2011	GPS	Multi beam
Mar. 2012	GPS	Multi beam
Sep. 2013	GPS	Multi beam
Oct. 2014	GPS	Multi beam
May 2015	GPS	Multi beam
Oct. 2016	GPS	Multi beam

Topographic and bathymetric data were referred to the same reference level to calculate the emerged and submerged beach volumes. While LiDAR data are referred to *Mean Sea Level* (MSL) in Alicante (*Nivel Medio del Mar en Alicante* (NMMA)) RedNap 2008, bathymetric and the GPS derived topographic data are referred to NMMA 1995 (Zero REDMAR). LiDAR data were thus converted to NMMA 1995 by adding 0.179 m (Fig 4).

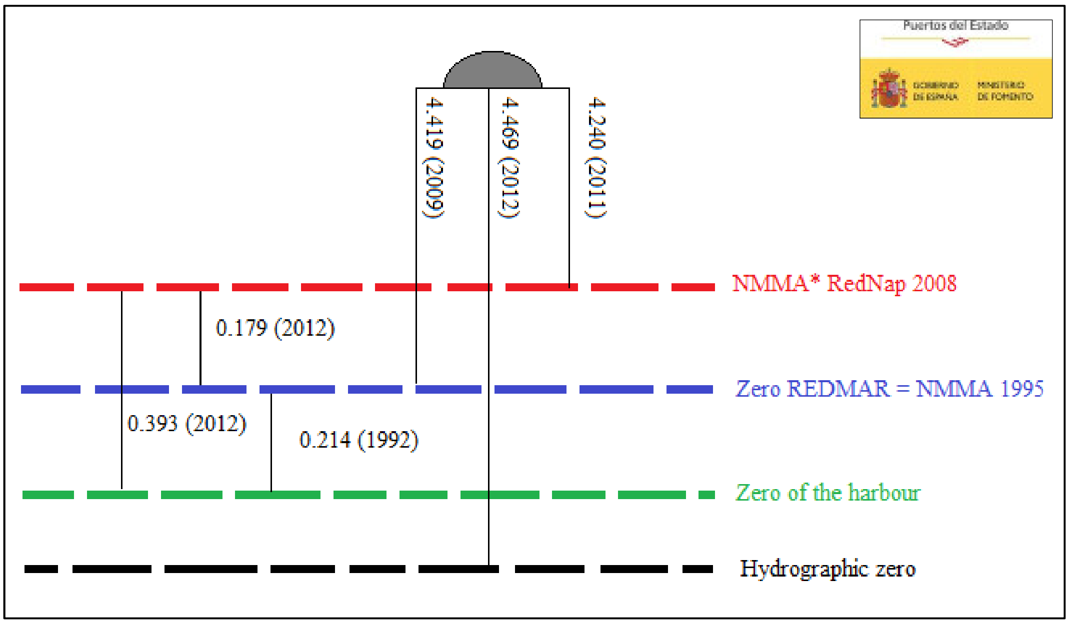

Fig 4. Scheme datum tide gauge REDMAR Barcelona (dimensions in meters) (Puertos del Estado).

4. Morphological analysis

4.1. Shoreline changes

The discrete shorelines, defined as the interface between land and water, were extracted from the orthophotos using ArcGIS 10.3 software. Thereafter, the different time series layers of the coastal area were added to a personal geo-database with the following attributes: namely feature ID, name, length, and feature characteristics. This database was further used in *Digital Shoreline Analysis System* (DSAS) program for shoreline change analysis to store and retrieve information of the multiple shorelines. The DSAS is an extension of ArcGIS 10 software, which was developed jointly by the *United States Geological Survey* (USGS) and the TPMC Environmental Services (Thieler et al., 2009). The pre-defined statistical algorithm of this software allows the user to measure the shoreline change rate using geo-rectified multiple time series shorelines in each transects at user defined interval. In this analysis, the baseline was drawn at 250 m distance, parallel to the shoreline orientation and 151 transects were generated by the software automatically with a 10 m interval between transects.

The movement of shoreline with respect to position of reference line (baseline) is considered as landward shift (erosion) and seaward shift (accretion) at each transects of the segments and the statistical values of the measurement have been denoted as negative for erosion rate and positive for accretion rate. From the shoreline positions extracted for all transects, the *Net Shoreline Movement* (NSM) between consecutive surveys was obtained (Fig 11). As a result, the following differences were obtained: 1993–1990, 1994–1993, 1996–1994, 2000–1996, 2003–2000, 2004–2003, 2006–2004, 2008–2006, 2009–2008, 2010–2009, 2011–2010, 2012–2011, 2013–2012, 2014–2013, 2015–2014 and 2016–2015. The three oldest orthophotos (1946, 1956 and 1987) were not considered in this study due to their low quality.

In addition to this information, the *Linear Regression Rates* (LRR) were calculated for all transects during the study period (1990-2016) using Matlab software (Fig 9, Fig 10). The LRR is used to represent the trend of shoreline changes during the short-term periods (Mendoza and Jiménez, 2006; Ojeda and Guillén, 2008; Ojeda et al., 2010). This is determined by fitting a least-squares regression line to all shoreline points for a particular transects. The LRR represents the slope of the line and so the sum of the squared residuals. LRR method has advantage to use all the data, regardless of trend changes or accuracy, be based on accespted statistic concepts and easy to use. The disadvantages are that this method can outlier effects and underestimate the change rate (Thieler et al., 2009). Besides, the coefficient of determination (R-square) is determined in order to improve the quality of the relation between data and LRR. This coefficient allows to quantify the variability of data. If R is close to 1, it implies that we have a good correlation, while if R close to 0 imply that the best-fit line not explains or little of the dependant variable variation (Thieler et al., 2009).

4.2. Area and Volume

The final step is the calculation of area and volume changes in the emerged and submerged beach using ArcGIS 10.3 and Matlab softwares. Ground points (x-, y-, and z-data points) derived from topographic and bathymetric data were gridded using natural neighbour interpolation in ArcGIS with 10 m grid spacing to generated *Digital Elevation Models* (DEMs). Resulted maps extend from the promenade that represents the landward boundary of the beach to the seaward location of the submerged breakwater, at more or less 4 m water depth (Fig 5). Area and volume changes between successive surveys were calculated above and below an imaginary plane slicing the DEM subtraction maps at 0 m.

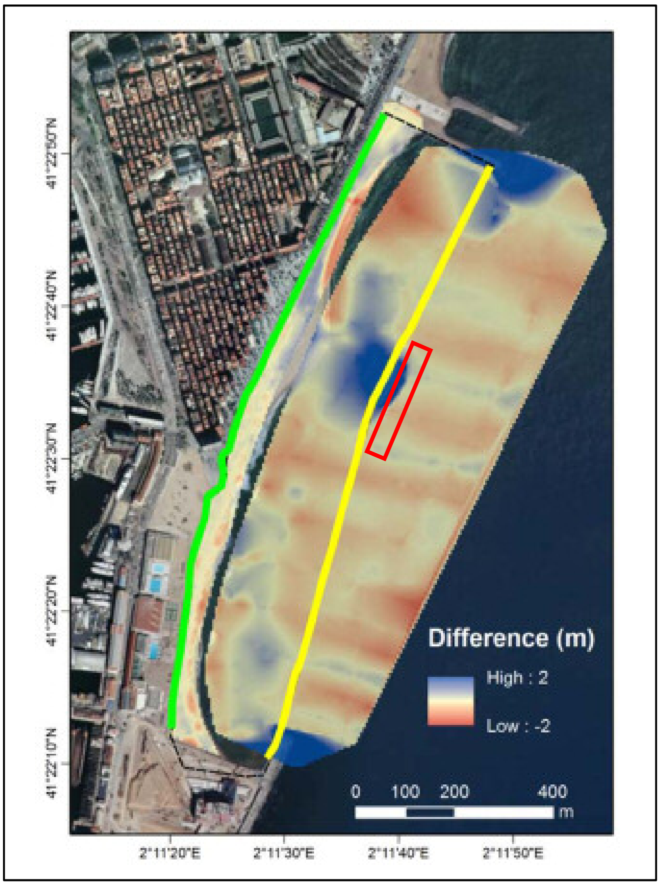

Fig 5. Scheme of the methodological approach used for assessing the morphological changes. Green line represents the landward boundary of the study area and corresponds to the seaward limit of the promenade. Yellow line is to the seaward boundary of the beach and corresponds to the location of the submerged breakwater (red rectangle).

Beach-profile data were derived from the DEM maps by extracting shore-normal transects every 10 m along the beach (151 transects) for the study period (1990-2016). Cross-shore profiles were located at the same position than transects used in the shoreline analysis in order to compared the alongshore variations in the shoreline position with emerged beach volume changes. Volume is estimated from all profiles as the sum of the elevation extracted from all transects. Beach volumes were calculated above (emerged) and below (submerged) the zero elevation to assess the emerged and submerged beach volume, respectivelly.

4. Results

The morphological evolution of *La Barceloneta* beach during the period 2003-2017 is addressed based on the analysis of wave data, orthophotos and top-bathymetries. Results are divided in three main parts: (1) wave climate and storms, focused on the characterization of the regional wave climate and the main storm events occured furing the study period, (2) shoreline trends during the period 1990-2016 focussing on the influence of the human interventions started with the Olympic Games in 1992 in the beach evolution, and (3) area and volume changes between 2003 and 2017, focussed on the influence of the breakwater construction and beach nourishments on the beach morphology.

1. Wave climate and storm data

Times series of the main forcings in Barcelona beaches between 2001 and 2017 is illustrated in Fig.5. Recorded waves show typical climatic conditions of the area. Significant wave heights (Hs) varied between 0.1 m and 8.5 m with an average value of 0.7 m. Peak periods (Tp) had an average value of 5.7 s.

According to the criteria proposed by Ojeda and Guillén (2008) for storm classification, 89 storms have been identified during the study period (APPENDICE III). The most energetic storm occured on 15 November 2011. It was characterized by a Hs of 8.5 m and an associated Tp of 13.2 s at the peak of the storm, with a predominant easterly direction.

The storm corresponded to category-V (extreme storm) following the storm intensity scale for the Catalan Sea proposed by Mendoza et al. (2011). In addition, 2 storms of category-IV occurred in October 2008 and November 2011 with Hs of 4.6-4.8 m, associated with Tp of 12.5 s and easterly direction. Other less energetic storms appeared during the study period: 12 storms of category-III (Hs of 3.6-4.6 m and Tp of 7.7-11.7 s), with waves coming from South East (SE) and East (E) directions, 26 storms of category-II (Hs of 2.9-3.5 m and Tp of 5.9-11.8 s), with waves approaching the coast from differen directions (North East (NE), E, S and SE), and 48 storms of category-I (Hs of 2.5-2.8 m and Tp of 6.1-10.5 s), with waves coming from different directions .

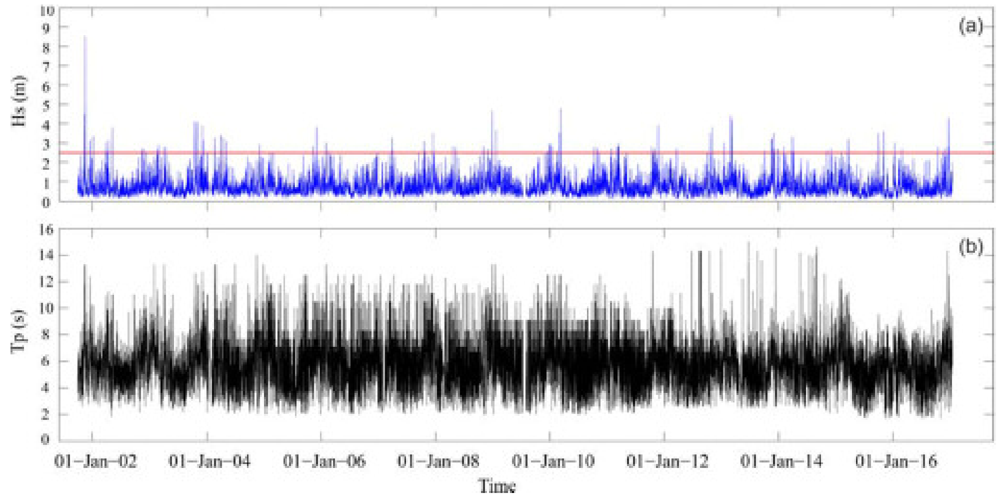

Fig 6. Time series of (a) significant wave height (Hs) and (b) peak period (Tp) in Barcelona during 2001-2017.

2. Shoreline trends

Shoreline trends were evaluated using orthophotos in order to observe the changes between each year. So as to assess the influence of the breakwater construction in the shoreline behavior, two time periods were considered: 1990-2006 (before the breakwater construction) and 2008-2016 (after construction.

The difference in the shoreline position between consecutive surveys before breakwater construction is displayed on Fig 7. The shoreline changes along *La Barceloneta* beach before the breakwater construction fluctuated between -32 m and +29 m, with larger variations in the northernmost sector of the beach. Overall, net advances of the shoreline position are observed after beach nourishments, whereas shoreline erosion is commonly observed in the surveys carried out in autumn of early spring, after storms.

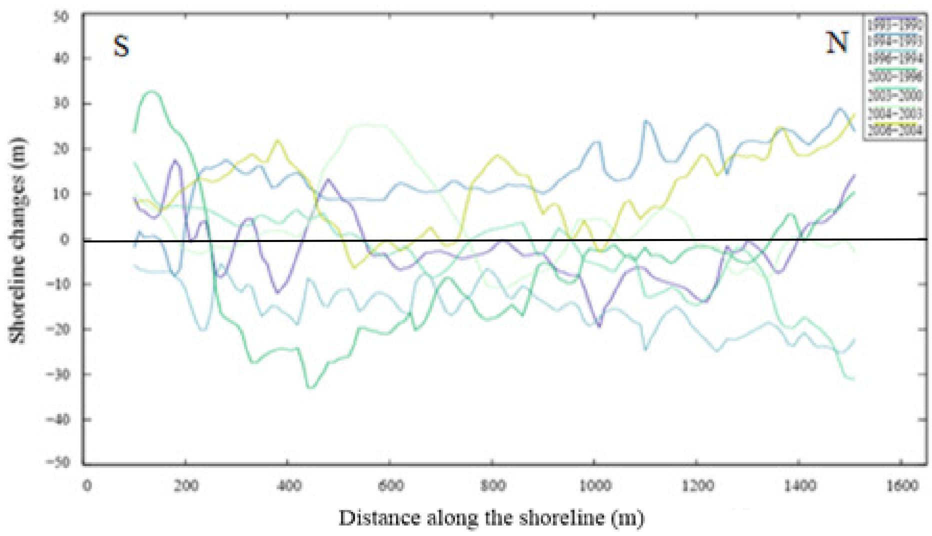

Fig 7. Shoreline differences of *La Barceloneta* beach (1990-2006) before the breakwater construction. The grey line shows the limit between the landward and seaward movement.

Between 2006 and 2007, the breakwater was constructed leading significant changes in the beach morphology: in the northern part, changes were more important than in the southern sector, which appeared more stable, especially at its extremity. The northern part was affected by erosive processes that were much more intense and destructive. While the southern sector presents, in its central part, important changes, and its outer part, minimal changes were observed. The shoreline changes along *La Barceloneta* beach after the breakwater construction fluctuated between -52 m and +46 m, with the largest differences at the breawater location, associated to the formation of a tombolo (Fig 8). In addition, an intense erosion was observed just after the construction in November 2008 and May 2009.

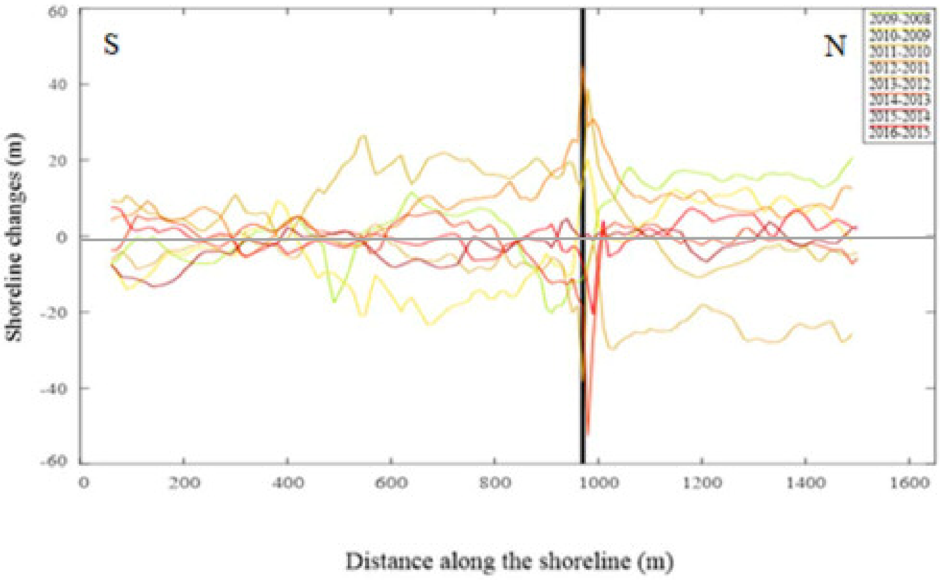

Fig 8. Shoreline differences on *La Barceloneta* beach (2008-2016). The black line represents the breakwater position and the grey line shows the limit between the landward and seaward movement.

In addition to the NSM, LRR were calculated along the beach. These statistics were computed before and after the breakwater construction to highlight its impact of the shoreline trend. Each calculation of LRR is associated with the determination (R-square) to qualify the roughness of the fit.

Before the construction of the breakwater, the shoreline trend showed a negative trend along the whole beach, except the southernmost sector that acreated significantly (Fig 9). Values fluctuate between -1.2 m/yr and +4.2 m/yr, but it was up to 4.2 m/yr in the southernmost sector. This increase in the beach area is likely due to the construction of the Hotel W at the Barcelona harbor (Fig 2), which required a large supply of sediments to stabilize the structure. Variations in the R-square evidence the high variability of the LRR along the beach, with smaller variations in the middle and southernmost sectors of the beach.

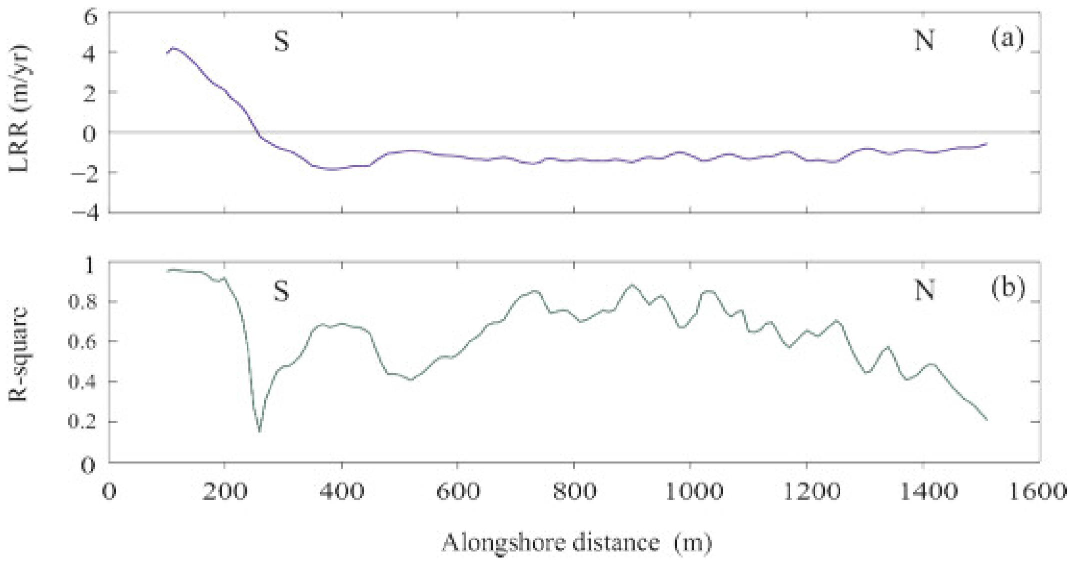

Fig 9. Before the breakwater construction (1990-2006) along *La Barceloneta* beach: 8a) Linear regression rates (LRR). 8b) Coefficient of determination (R-square).The grey line represents the limit between the landward and the seaward movement.

The breakwater construction had a significant geomorphological influence on the beach morphology. The erosive trend of the beach increased especially in the northern part of *La Barceloneta* beach, where the LRR oscillates between -2.4 m/yr and +5.1 m/yr (Fig 10). Only at the location of the breakwater, the shoreline advanced significanty due to the formation of a tombolo.

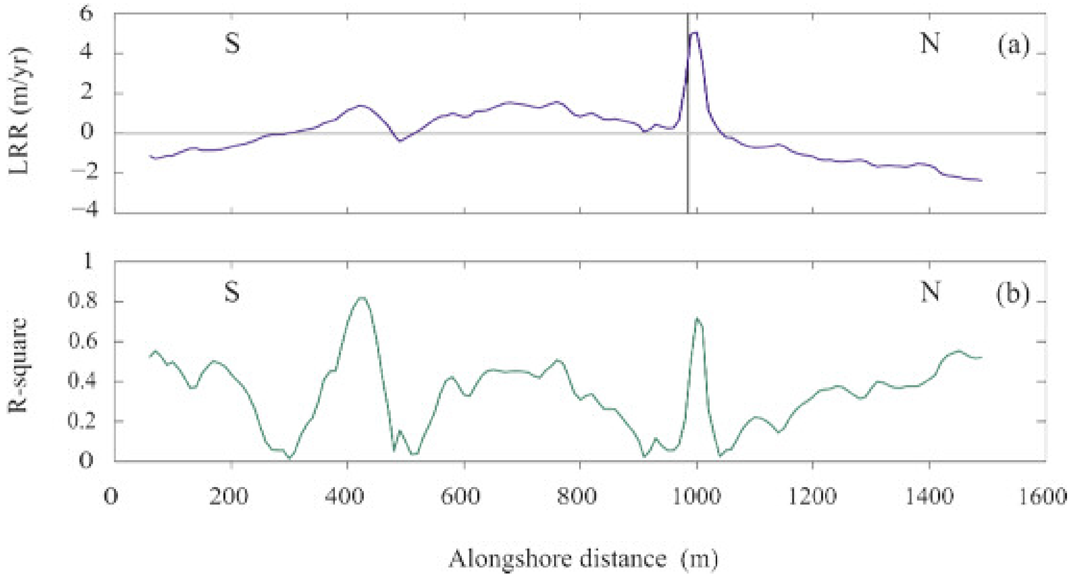

Fig 10. After the breakwater construction (2008-2016) along *La Barceloneta* beach: 9a) Linear regression rate. 9b) Coefficient of determination (R-square). The black line represents the breakwater position and the grey, the limit between the landward and the seaward movement.

In order to know quantitatively the value of this displacement and to observe the changes before and after the breakwater construction, the net changes in the shoreline position (NSM) along time between consecutives years were calculated (Fig 11). Results revealed that before the Olympic Games in 1992, the NSM increases from -1.2 m to +14 m. Then, between 1992 and 1996, the NSM decreases strongly from +14 m to -16 m. Before the construction, the values showed an erosive trend but stable until 2003. After this year, the NSM begin to increase, particulary between 2004 and 2006, having a maximum shoreline position of +11 m in 2006. After the construction (2006-2007), the NSM decreasing strongly and reached -1.1 m in 2008 (similar situation as before the Olympic Games), after, little advance of the shoreline was observed. Between 2009 and 2010, the NSM decreases until -3.1 m, then the NSM in 2011 increasing at a similar rate until a certain stability between 2011 and 2012, when an important decrease of the net displacements was observed between 2012 and 2013: the values having gone from +7.5 m to -11 m. A new advance was observed between 2013 and 2014, the NSM increases from -11 to almost 0. Between 2014 and 2015, the trend is negative but nearly zero.

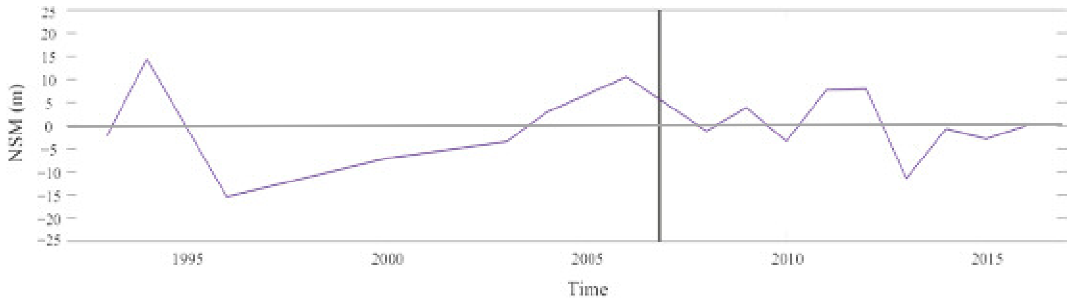

Fig 11. Average shoreline net displacements (NSM) along *La Barceloneta* beach (1990-2016). The vertical black line represents the period of the breakwater construction and the horizontal grey line shows, the limit between the landward and the seaward movement.

3. *Areas and Volume changes (emerged and submerged)*

La Barceloneta beach can be divided into two parts: the emerged and submerged beach. The volume differences between these two sectors were quantified (Table 3, Fig 12) and analyzed over the period October 2003 to May 2017. It should be noted that the area including the emerged and submerged beach is constant (314 023 m^2), which makes it possible to quantify the volume changes for the same area. Variations in the emerged beach volume area fluctuate between a minimum value of 130 000 m^3 in November 2003 and a maximum value of 220 000 m3 in October 2010. Increases in the beach volume were observed in April 2006, January 2007, October 2010 and March 2012, associated to repeat beach nourishments carried out in June 2004, March and June 2006, June 2009 and June 2010. Important volume declines were recorded in November 2008, May 2009, July 2011 and September 2013. Particularly in September 2013, the beach show a volume reduction of 17 % of the emerged beach volume. Since 2014, volume changes begin to be stable with an average emerged beach volume of about 170 000 m^3 with small fluctuations.

Table 3
Area and volume changes in the emerged and submerged area of *La Barceloneta* beach during the period 2003-2017.

Data survey	Emerged area (m^2)	Emerged volume (m^3)	Submerged volume (m^3)	Total volume (m^3)
Oct. 2003	72 461	136 445	761 966	898 411
Nov. 2003	68 370	130 779	774 296	905 076
Mar.2005	54 581	147 676	-	-
Oct. 2005	-	-	735 600	-
Apr. 2006	67 321	167 239	-	-
Nov. 2006	-	-	710 611	-
Jan. 2007	81 966	183 121	712 802	895 923
Jun. 2007	-	-	811 056	-
Nov. 2008	74 622	165 818	-	-
May. 2009	61 647	144 637	-	-
Oct. 2010	82 167	215 499	-	-
Jul. 2011	80 226	196 306	764 343	960 649
Mar. 2012	91 036	206 638	796 528	1 003 166
Sep. 2013	82 985	172 569	708 445	881 014
Oct. 2014	84 331	168 780	700 647	869 427
May. 2015	71 074	171 879	778 559	950 439
May. 2017	71 057	170 546	796 983	967 529

Along the beach, emerged beach volume changes show important variations between the emerged and submerged sector (Fig 13). To the north of the breakwater, the beach shows predominant erosion in the whole beach, particularly in the northernmost sector, which was intensified after the construction of the breakwater (Fig 12, Fig 13, APPENDICE IV). The southern sector, however, show predominant accumulation in the middle and southern sector with local erosion in ther northern part, near the breakwater (Fig 13, APPENDICE IV). These variations along each sector of the beach, erosion in the northern and accumulation in the southern, results in a shift of the shoreline orientation clockside.

The behavior of the submerged beach differs significantly from the emerged area, periods of increasing emerged beach volumen not always corresponds with increases volumes in the submerged area (Fig 12). Volume variations in this part varied between 700 000 m^3 in October 2014 and 810 000 m^3 in June 2007. Positive volume changes were recorded in November 2003, June 2007, March 2012 and May 2015, with big losses in January 2007, July 2011 and September 2013.

The largest gain of volumes corresponds to the construction of the breakwater in 2006-2007, which led to an increases in the submerged beach volumes of 14 %. Since 2015, the submerged beach volumes remained nearly constant. Important negative values in the submerged area in 2014 are related to the survey coverage, with a gap between 2008 and 2010 in the area closest to the shoreline.

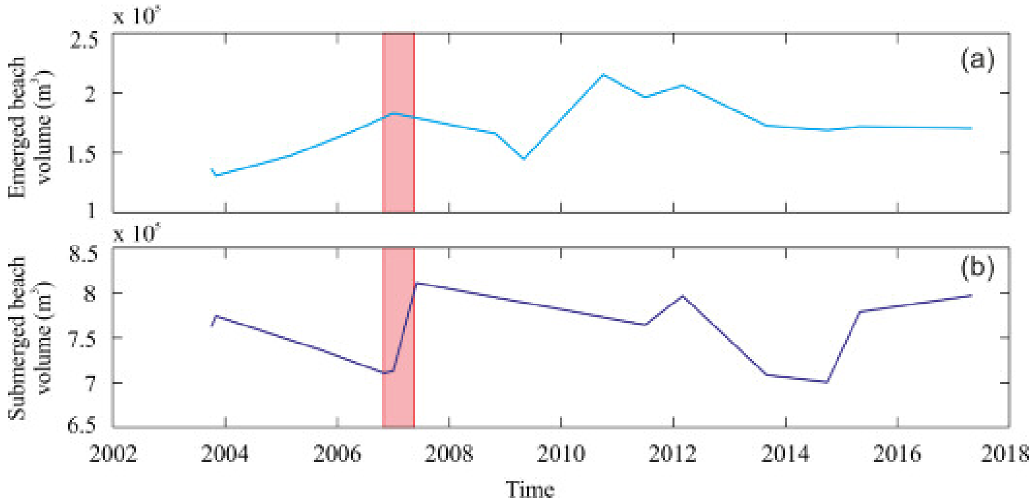

Fig 12. (a) Emerged and (b) submerged volumes in *La Barceloneta* beach (2003-2017). The red rectangle represents the period of the breakwater construction.

Volume changes on the submerged beach revealed the presence of a submerged bar that is better developed on the southern sector of *La Barceloneta* beach (Fig 13). During the study period, the bar showed a dynamic behavior: it was absent in some surveys but it showed migration in other periods (e.g. 2015-2016). It appears on the submerged beach in some surveys but in other ones it is attached to the beach (Fig 13, APPENDICE IV).

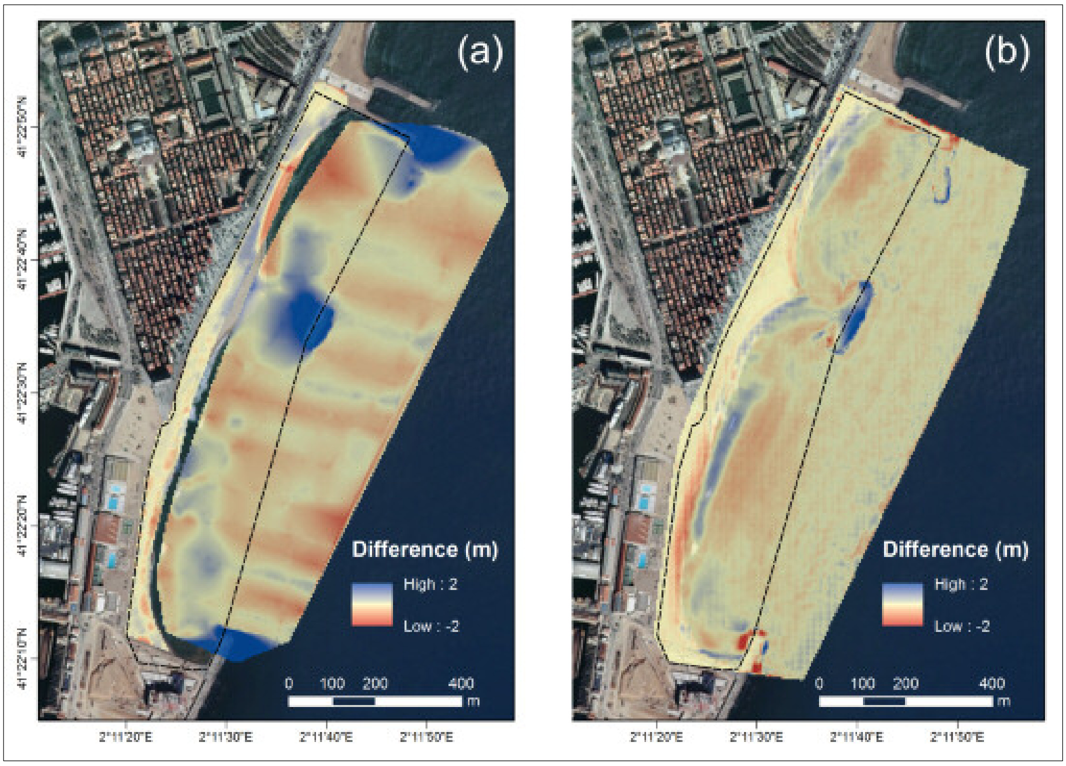

Fig 13. Differences in beach elevation: (a) 2007-2006 (b) 2016-2015. Note the increase of the submerged beach volume associated to the breakwater construction in 2007 and the seaward movement of the submerged bar in 2016. Negative values (red colours) represent erosion. Positive values (blue colours) correspond to volumes gain.

5. Discussion

The morphological evolution of artificial embayed beaches is strongly controlled by the presence of protection structures that limit their mobility. Perpendicular groins reduce alongshore sediment transport outside the beach boundaries and protect the beach, from waves approaching from a range of directions, therefore these beaches are quite isolated sedimentary cells affected by specific wave conditions. The beach mobility is also limited because the rear section of the beach is normally occupied by promenades, houses or other types of urban structures. These constraints restrict the movement of the shoreline in comparison with open beaches, so embayed beach have often been designed in order to respond to coastal erosion problems (Short and Masselink, 1999; Hanson et al., 2002). In addition, human interventions can also reduce the beach mobility in two opposite ways: it is decreased by the wave energy loss caused by protection structures, and it is increased by the artificial advance of the shoreline caused by beach nourishments (Ojeda and Guillén, 2008).

The morphological evolution of *La Barceloneta* beach reveals that a combination of natural and anthropic factors that play an important role in its morphological evolution, particularly on the emerged beach.

1. Morphological changes in La Barceloneta beach

Waves are the hydrodynamic force that causes the most morphological changes on beaches (Stepanian, 2012). Previous works in the Barcelona beaches revealed that storms are the primary cause of morphological changes (Sancho et al., 2013) and represent the second largest forcing in the evolution of sedimentary recharge (Ojeda and Guillén, 2008). In order to determine their impacts on the coasts, the energy content has been used as a proxy because it's a good marker to highlighting the link between stroms and shoreline position changes (Jiménez et al., 2011). It was highlighted that the most destructive storms were from the east and the biggest erosive events are also (Ojeda and Guillén, 2008). This phenomenon on the Catalan coast occurs because it forms an union between the fetch and the wind regimes that lead to an storm energy increase (Mendoza et al., 2011). The analysis of the storms occurred during the study period revealed the occurrence of 89 storms between 2001 and 2016. Most of these storms (43 storms) came from the East, particularly the most intense storm on December 2008 (APPENDICE III). As a result of the eastern storms, the shoreline orientation shifted clockside, caused by erosion in the northern and accumulation in the southern sector of the beach (Fig 13, APPENDICE IV).

This phenomenom, named as beach rotation has been previously described in *La Barceloneta* beach as as result of variations in the direction of wave incidence in response to storms or seasonal changes (Ojeda and Guillén, 2008; Sancho et al., 2013). Beach rotation occurs when there's an opposing behavior between erosion and accretion with similar magnitude between two beach sections that would be separated by a pivot point. In *La Barceloneta* beach, accretion is commonly found in the southern part of the beach and intensive erosion in the northern part, any net change in the sedimentary budget (Sancho et al., 2013). The rotation of *La Barceloneta* beach was observed in 2005-2003, 2007-2006, 2011-2010, and 2013-2012 (APPENDICE IV). Despite these changes, a direct relationship between waves and morphological changes in the emerged beach was not observed during the study period mostly due to the continuous human interventions on the beach, particularly beach nourishments and sand movements along the beach, that mask the effect of storms.

In the submerged beach, however, morphological changes differ from the emerged area. Variations in the submerged beach volume are strongly related with prevailing wave conditions that result in the movement landward and seaward of the submerged bar. Shhore-parallel bars are dynamic morphological features that can migrate along and across-shore, depending on the wave conditions. This direct relationship between the morphology of the beach and the movement of the bars is used to interpret different beach states (Wright and Short, 1984). In general, the submerged bars follow the general cyclic morphological behaviour observed in natural beaches, switching among the four intermediate morphodynamic states. After storms, onshore reworking of storm deposits in the submerged profile usually result in onshore bar migration, followed by bar welding and foreshore accretion (Wright and Short, 1984). In *La Barceloneta* beach, the dynamics of the submerged bars also show a cyclic behavior: when the energy conditions are low, bars migrated onshore as crescentic bars (Ojeda et al., 2010). When energy conditions become more dynamic, bars migrate offshore as shore-parallel bars. On *La Barceloneta* beach, the morphology of the beach in 2010, 2011, 2012, evidences post-storm beach aggradation through bar type morphologies attached to the shoreline (APPENDICE IV). On the contrary, the beach morphologies in 2006, 2007, 2013 and 2014 are characterized by the presence of a submerged bar offshore, as result of energetic conditions (Fig 13, APPENDICE IV).

2. Influence of beach protection measures on the beach mobility

The mobility of the beaches, i.e. changes in the width beach, presents a great variability depending on the exposition to wave conditions, but also on the beach protection. The temporal evolution of the shoreline position and volume changes on *La Barceloneta* beach show a strong correlation with the construction of a submerged of the breakwater construction and continuous beach nourishments.

La Barceloneta beach evidences an erosive behavior before the breakwater construction in the whole beach, only compensate with continuous beach nourishments in July 2002, June 2004, March 2006 and June 2006. These nourishments allowed maintaining *La Barceloneta* beach, compensating the impacts caused by storms and human interventions. However, once the construction is completed, intense erosion occur in the northern sector, leading to an intense loss of part of the beach that has to be balanced with continuous nourishments in the emerged part of the beach, as those carried out in June 2009 and June 2010, as well as continuous sand relocalisation. Evidences of this erosion can be observed in the beach morphology in 2008, 2009, 2011, 2013 and 2015 (Fig 13, APPENDICE IV). At present, the sediment budget is still negative due especially to the absence of new natural sedimentary inputs. These protection measures contribute to reduce beach mobility and losses of sediment of the beach system. Despite the fact that nourishments are stoped in June 2010, volumes of the emerged beach in *La Barceloneta* beach continue to increase due to the relocation of sand along the beach.

6. Conclusions

The morphological response of an urban beach *La Barceloneta* beach on the period 2003-2017 reveals the role of natural and anthropic factors in its morphological evolution. The morphological changes in the submerged beach are strongly determined by natural factos like storms and waves that result in a landward and seaward movement on the submerged bar. However, the analysis of the shoreline positional variations and the volumes of the emerged beach revealed a direct link between the construction of the breakwater and the important nourishments.

The construction of a submerged breakwater have allowed to recover partially the sediment balance of a beach that was threatened by important erosion, but it led to an intensification of erosion in the northern sector of the beach that has to be balanced with continuous nourishments that lead to a strong accretion of the beach only for a short time-scale. These protection measures contribute to reduce beach mobility and losses of sediment of the beach system, but the sediment budget is still negative due to the absence of new natural sedimentary inputs.

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APPENDICES

APPENDICE I. MAIN CHARACTERISTICS OF *LA BARCELONETA* BEACH (CIIRC, 2010).

LA BARCELONETA					
GENERAL DESCRIPTION		MORPHODYNAMIC		HYDRODYNAMIC	
Longitude (m)	212/520	Beach type	Urban, embayed	Wave climate :	
Width (m)	18/52	Evolution :		- Hs average (m)	0.74
Area (m^2)	6065/38342	- mean (m/y)	- 4.9 / - 1.2	- Tp average (s)	6.00
Height berm (m)	2.6	- erosion (m/y)	- 4.9 / - 1.4	- Main direction	202º SSW
Foreshore slope (m)	0.9	- main erosion area (m)	208/438	Sea level (astronomic and meteorologic) (m)	0.44
Sediments :		- accretion (m/y)	0 / + 0.2	Return period 10y :	
- d50	0.271	- main accretion area (m)	0 / 86	- Hs (m)	4.69
- ө	0.093	- main stable area (m)	0 / 0	- Sea level (m)	0.54
- color	Toasted	Obstacles	Detached breakwater	Return period 100y :	
Beach orientation	30ºN	Longitudinal transport :		- Hs (m)	5.90
		- net (m^3/y)	164 000	- Sea level (m)	0.75
		- gross (m^3/y)	369 000		

APPENDICE II. MAIN CHARACTERISTICS OF *SAN MIQUEL* AND *SAN SEBASTIAN* BEACHES (CIIRC, 2010).

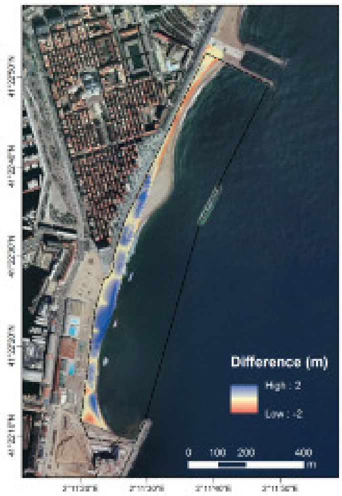
SAN MIQUEL AND SAN SEBASTIAN					
GENERAL DESCRIPTION		MORPHODYNAMIC		HYDRODYNAMIC	
Longitude (m) Width (m) Area (m^2) Height berm (m) Foreshore slope (m) Sediments : - d50 - ɵ - color Beach orientation	1175 45 53 930 2.4 0.14 0.878 0.266 Toasted 20ºN	Beach type Evolution : - mean (m/y) - erosion (m/y) - main erosion area (m) - accretion (m/y) - main accretion area (m) - main stable area (m) Longitudinal transport : - net (m^3/y) - gross (m^3/y)	Embayed - 1.3 - 2.2 1014 + 3.9 146 0 164 000 369 000	Wave climate : - Hs average (m) - Tp average (s) - Main direction Sea level (astronomic and meteorologic) (m) Return period 10 y : - Hs (m) - Sea level (m) Return period 100 y : - Hs (m) - Sea level (m)	 0.74 6.00 202º SSW 0.44 4.69 0.54 5.90 0.75

APPENDICE III. MAIN STORM DATA CHARACTERISTICS (2001-2016) NEAR *LA BARCELONETA* BEACH (Puertos del Estado).

Events	Initial Day	Hs (m)	Tp (s)	Storm time (h)	Pic time (h)	Wave direction	Storm category
1	11/11/2001	4.5	11.5	79	1	E (102)	4
2	15/11/2001	8.5	13.3	93	3	E (111)	5
3	15/12/2001	3.2	9.8	82	1	E (110)	2
4	04/01/2002	3.3	10.2	42	1	SE (125)	2
5	29/03/2002	3.0	10.8	73	1	SE (126)	2
6	02/04/2002	2.6	7.6	71	1	SE (118)	1
7	12/04/2002	3.1	11.3	48	1	SE (113)	2
8	08/05/2002	3.8	11.0	81	3	SE (118)	3
9	15/11/2002	2.7	8.5	51	1	S (175)	1
10	21/11/2002	2.7	9.9	28	3	S (173)	1
11	10/12/2002	2.5	10.1	43	1	SE (134)	1
12	20/02/2003	2.6	7.5	40	1	SE (148)	1
13	26/02/2003	2.9	10.1	103	1	SE (129)	2
14	03/04/2003	2.8	13.3	60	3	E (94)	1
15	14/04/2003	2.8	8.4	33	1	SE (130)	1
16	17/10/2003	4.1	9.9	120	1	E (109)	3
17	31/10/2003	4.1	9.7	62	1	S (175)	3
18	04/12/2003	3.9	11.7	50	1	SE (116)	3
19	08/12/2003	3.2	8.9	28	1	SE (113)	2
20	20/02/2004	3.3	7.7	70	1	E (91)	2
21	29/03/2004	3.4	9.1	77	1	E (98)	2
22	16/04/2004	3.3	10.0	56	1	E (105)	2
23	03/05/2004	3.1	8.3	36	2	E (97)	2
24	02/12/2004	2.9	9.1	34	1	SW (204)	2
25	09/02/2005	2.5	9.1	94	1	E (104)	1
26	01/03/2005	2.5	10.5	52	1	E (98)	1
27	10/11/2005	2.8	7.1	33	1	NE (62)	1
28	02/12/2005	3.8	10.0	47	1	S (195)	3
29	30/01/2006	3.0	10.0	50	1	E (96)	2
30	19/02/2006	2.6	8.3	41	1	SW (205)	1
31	24/12/2006	2.5	8.3	58	1	E (97)	1
32	28/03/2007	3.3	7.7	42	1	E (96)	2
33	02/04/2007	2.6	8.3	47	1	E (96)	1
34	14/09/2007	2.5	6.7	33	1	E (79)	1
35	20/10/2007	3.1	8.3	55	1	E (68)	2
36	25/10/2007	2.5	7.7	60	1	E (73)	1
37	15/12/2007	3.5	10.0	91	1	E (86)	2
38	10/05/2008	2.8	8.3	62	1	SE (134)	1
39	31/10/2008	2.7	8.3	66	3	S (170)	1
40	02/11/2008	2.8	9.6	33	3	S (165)	1
41	30/11/2008	2.7	11.0	111	3	S (177)	1
42	26/12/2008	4.6	12.5	96	1	E (83)	4

43	24/01/2009	3.6	8.3	44	1	SW (217)	3
44	24/12/2009	3.0	7.7	90	1	S (198)	2
45	01/01/2010	2.9	8.3	71	1	S (198)	2
46	07/01/2010	2.9	7.7	61	1	E (87)	2
47	16/02/2010	2.6	7.7	53	1	SE (128)	1
48	04/03/2010	3.5	11.8	49	1	E (91)	2
49	08/03/2010	4.8	12.5	65	1	E (100)	4
50	12/10/2010	2.7	10.0	49	1	E (97)	1
51	31/10/2010	2.7	7.7	34	1	S (197)	1
52	28/01/2011	2.5	9.1	77	1	E (96)	1
53	08/03/2011	2.8	9.1	46	1	E (84)	1
54	12/03/2011	2.5	9.1	48	1	E (110)	1
55	15/10/2011	2.8	8.7	39	1	NE (63)	1
56	20/10/2011	2.6	6.7	19	1	E (68)	1
57	04/11/2011	2.7	6.9	70	1	S (188)	1
58	22/11/2011	3.9	10.0	72	1	E (88)	3
59	20/03/2012	2.7	6.7	52	1	E (77)	1
60	28/09/2012	2.5	6.1	52	1	NE (61)	1
61	19/10/2012	3.5	8.0	72	1	E (97)	2
62	31/10/2012	3.8	10.0	46	1	E (81)	3
63	19/01/2013	2.8	8.2	42	1	S (193)	1
64	01/03/2013	4.4	8.0	70	1	E (100)	3
65	06/03/2013	4.2	10.3	78	1	E (97)	3
66	04/10/2013	2.6	7.7	67	1	E (109)	1
67	16/11/2013	3.2	7.6	93	1	E (85)	2
68	27/11/2013	2.7	6.5	32	1	NE (66)	1
69	01/12/2013	3.5	8.5	34	1	NE (62)	2
70	03/12/2013	2.5	9.8	35	1	E (87)	1
71	25/12/2013	2.7	7.8	52	1	S (198)	1
72	29/01/2014	2.5	7.9	34	1	SW (208)	1
73	05/02/2014	2.8	7.3	39	1	S (199)	1
74	26/03/2014	2.6	8.3	27	1	E (75)	1
75	30/03/2014	3.3	8.9	64	1	E (110)	2
76	03/04/2014	2.5	7.7	66	1	SE (135)	1
77	04/11/2014	2.6	8.3	45	1	S (189)	1
78	30/11/2014	2.7	6.4	39	1	E (82)	1
79	04/02/2015	2.5	6.1	29	1	E (79)	1
80	21/03/2015	3.2	9.6	106	1	E (107)	2
81	30/09/2015	3.5	8.6	80	1	E (78)	2
82	02/11/2015	3.6	7.7	85	1	SE (121)	3
83	11/01/2016	3.0	5.9	60	1	SW (204)	2
84	27/02/2016	2.7	7.6	45	1	S (190)	1
85	14/10/2016	2.8	8.6	70	1	E (100)	1
86	21/11/2016	2.5	8.1	46	2	S (187)	1
87	23/11/2016	2.7	6.7	58	1	SE (119)	1
88	17/12/2016	2.8	7.6	46	1	E (77)	1
89	20/12/2016	4.3	10.9	91	1	E (94)	3

APPENDICE IV. DIFFERENCES IN BEACH ELEVATION BETWEEN CONSECUTIVE SURVEYS (2003-2016).



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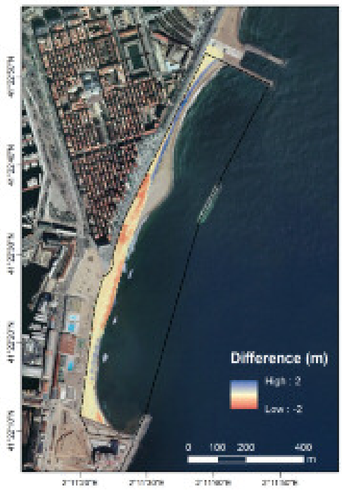
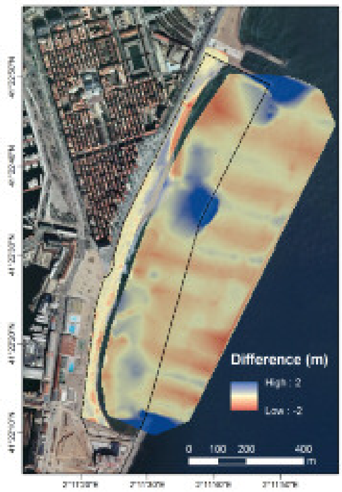
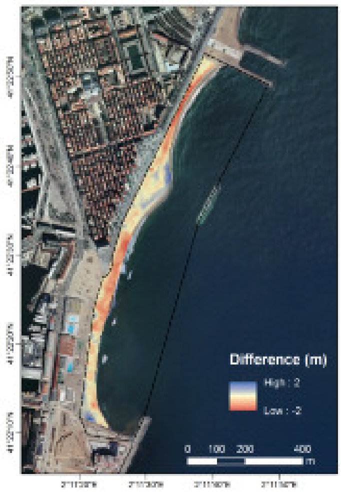


2006-2005



2007-2006



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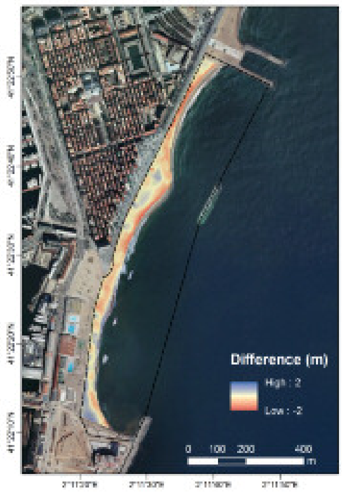
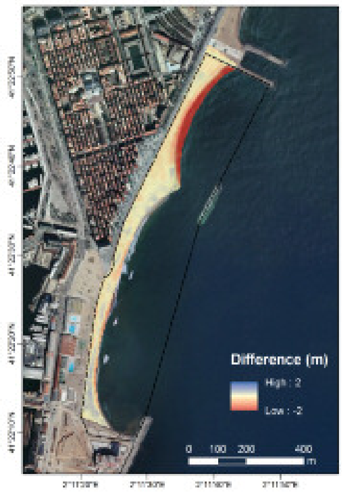
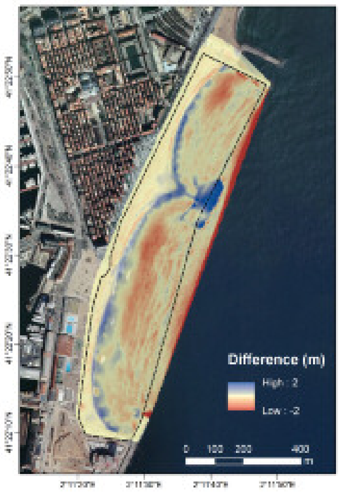


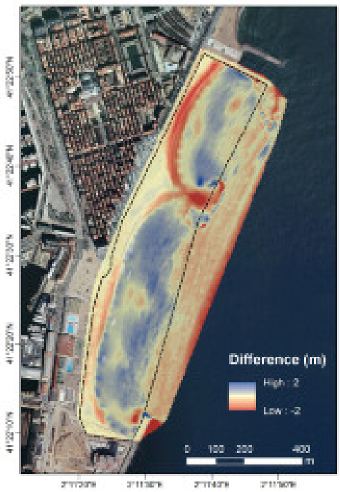
2009-2008



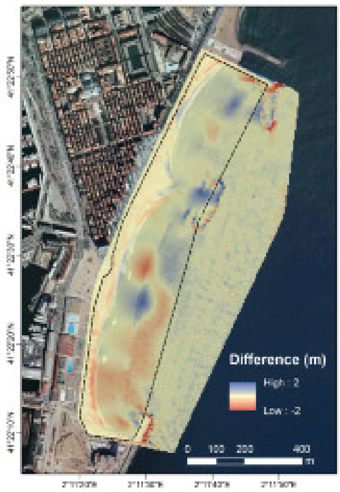
2011-2010



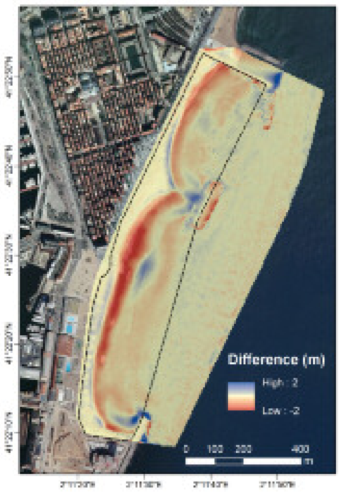
2012-2011



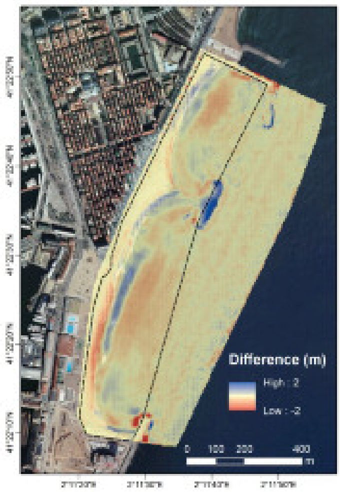
2013-2012



2014-2013



2015-2014



2016-2015