**Regional scenarios of sea level rise and impacts on Basque (Bay of Biscay) coastal
habitats, throughout the 21st Century**

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ABSTRACT

Global climate models have predicted a rise on mean sea level of between 0.18 m and 0.59 m by the end of the 21st Century, with high regional variability. The objectives of this study are to estimate sea level changes in the Bay of Biscay during this century, and to assess the impacts of any change on Basque coastal habitats and infrastructures. Hence, ocean temperature projections for three climate scenarios, provided by several atmosphere-ocean coupled general climate models, have been extracted for the Bay of Biscay; these are used to estimate thermosteric sea level variations. The results show that, from 2001 to 2099, sea level within the Bay of Biscay will increase by between 28.5 and 48.7 cm, as a result of regional thermal expansion and global ice-melting, under scenarios A1B and A2 of the Intergovernmental Panel on Climate Change. A high-resolution digital terrain model, extracted from LiDAR, data was used to evaluate the potential impact of the estimated sea level rise to 9 coastal and estuarine habitats: sandy beaches and muds, vegetated dunes, shingle beaches, sea cliffs and supralittoral rock, wetlands and saltmarshes, terrestrial habitats, artificial land, piers, and water surfaces. The projected sea level rise of 48.7 cm was added to the high tide level of the coast studied, to generate a flood risk map of the coastal and estuarine areas. The results indicate that 110.8 ha of the supralittoral area will be affected by the end of the 21st Century; these are concentrated within the estuaries, with terrestrial and artificial habitats being the most affected. Sandy beaches are expected to undergo mean shoreline retreats of between 25% and 40%, of their width. The risk assessment of the areas and habitats that will be affected, as a consequence of the sea level rise, is potentially useful for local management to adopt adaptation measures to global climate change.

Key words: sea level; climate change; coast; habitat; LiDAR; Basque Country

1 INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC AR4, 2007), global mean sea level has been rising during the 20th Century at an average rate of $1.7 \pm 0.5 \text{ mm yr}^{-1}$ (Church and White, 2006; Bindoff et al., 2007). By the end of the 21st Century, global climate models have predicted a global sea level rise of between 0.18 m and 0.59 m (Meehl et al., 2007), although recent approaches estimated higher rises of 0.8 m (Pfeffer, 2008) and 0.5 to 1.4 m (Rahmstorf, 2007). Both past and future sea level changes are regionally variable, as has been shown from the analyses of tide gauge records (e.g., Douglas, 1992; Lambeck, 2002; and Church et al., 2004) and from the global coverage of satellite altimetry in open oceans (Bindoff et al., 2007). Whilst, in some regions, the predicted Sea Level Rise (SLR) will be higher than the global mean, in other regions, a fall in sea level may occur. Recently, within the Bay of Biscay, several studies based upon tide gauge records showed consistently a SLR slightly higher than the global rates: 2.12 mm yr^{-1} at Santander, 2.51 mm yr^{-1} at Coruña, and 2.91 mm yr^{-1} at Vigo, during the period 1943–2001 (Marcos et al., 2005); $1.3 \pm 0.15 \text{ mm yr}^{-1}$ during 1890–1980 (for locations, see Figure 1), $1.77 \pm 0.12 \text{ mm yr}^{-1}$ during 1915–2005, at Newlyn, South-western UK (Araújo and Pugh, 2008), and $1.73 \pm 0.52 \text{ mm yr}^{-1}$ during 1968–2006, at St. Mary's, South-western UK (Haigh, 2009). The long tide gauge data series for Brest, in the northern part of the Bay of Biscay (see Figure 1), has revealed also that sea-level rise is accelerating ($1.3 \pm 0.5 \text{ mm yr}^{-1}$ during 1890–1980, and $3.0 \pm 0.5 \text{ mm yr}^{-1}$ during 1980–2004; Wöppelmann et al. (2006)). Such acceleration is in agreement with the rates obtained in the open ocean

of the Bay of Biscay since 1993, when operational satellite altimetry commenced, by Marcos et al. (2007) (SLR of 3.09 mm yr⁻¹ between 1993 and 2002) and Caballero et al. (2008) (SLR of 2.7 mm yr⁻¹ from 1993 to 2005). Indirect approaches, such as foraminifera-based transfer functions (Pascual and Rodríguez-Lázaro, 2006), have identified a rate of rise of 2 mm yr⁻¹ during the 20th Century along the Basque coast, northern Spain (Leorri et al., 2008; Leorri and Cearreta, 2009).

An increase in mean sea level induces a higher risk of flooding of low-lying coastal areas, erosion of sandy beaches and barrier island coasts, intrusion of saltwater and the loss of wetlands amongst other effects (Wolanski and Chappell, 1996; Morris et al., 2002; Crooks, 2004; Pascual and Rodríguez-Lázaro, 2006; FitzGerald et al., 2008; Kirwan and Murray, 2008a; and Kirwan et al., 2008; Poulter and Halpin, 2008; and Gesch, 2009). These effects will produce geomorphological, ecological and socio-economical impacts in coastal areas; these are sometimes underestimated because they include only the inundation costs without coupling with coastal storms (Michael, 2007). In a previous investigation (Chust et al., 2009), analyses of the three tide gauge records around the Gipuzkoan coast (within the Basque Country, Figure 1) have revealed that relative mean sea level has risen 10 cm from 1954 to 2004; this may have induced already the loss of 2.95 ha of sandy beaches and saltmarshes. Therefore, in order to make decisions to adapt to the expected impacts (e.g. Habitats Directive, 1992), it is mandatory to estimate SLR in the near future. However, regional climate models are still under development and no reliable future projections of the mean sea level change for the Bay of Biscay are yet available. Thus, mean sea level changes will be approximated using the output of global climate models in our region of interest.

The objectives of this contribution are to estimate the sea level change in the Bay of Biscay from 2001 to 2099; likewise to assess the impacts of this change on coastal habitats within the Basque Country. This coast is dominated by rocky substrata with vertical cliffs intercalated by small estuaries with sandy beaches, as occur along the remainder of the Cantabrian coast (Southern Bay of Biscay). In general, a widely extended view is to consider that SLR impacts on such steep coasts are very limited, and efforts are concentrated upon low-lying areas and deltas (e.g. Ericson et al., 2006; McGranahan et al., 2007). However, because the sea cliffs and hilly relief limit and confine the extent of the sandy beaches, saltmarshes, urban settlements and industrial zones along the coast and within harbours, these habitats and infrastructures are vulnerable to small variations in sea level and wave climate (Michael, 2007; Vinchon et al., 2009). Hence, estimating the potential future exposure of coastal habitats and infrastructures to flooding is therefore a critical task for long-term planning and risk assessment (Purvis et al., 2008). To address the objectives, initially, thermosteric sea level has been estimated, using Atmosphere-Ocean Coupled General Climate Models (AOGCMs), within the Bay of Biscay. Secondly, a flood risk map has been generated for the Gipuzkoan coast by delimiting the SLR projected for the end of the 21st Century over a high-resolution Digital Terrain Model (DTM), extracted from airborne laser altimetry data. The impacts, according to land use and biological communities, have been assessed by overlaying the flood risk map and a coastal habitat classification, generated with recent airborne photography.

2 MATERIAL AND METHODS

2.1 Study area

The coast of Gipuzkoa, within the Basque Country (northern Spain) is located within the innermost part of the Bay of Biscay (Figure 1). At a 1-m spatial scale, the Gipuzkoan coastline is approx. 198 km long, at low tide. The coast of Gipuzkoa is very steep, as is the remainder of the Cantabrian coast; it is dominated by rocky substrata with vertical cliffs and abrasion platforms intercalated by small estuaries with sandy beaches at the mouth of the rivers (Borja et al., 2004). This coast is exposed to the prevailing wind and wave directions (N and NW), produced by the evolution of the North Atlantic low pressure systems (González et al., 2004). The Basque coast represents only 12% of the total surface area of the Basque Country; however, it supports 60% of the overall population (2,128,801 inhabitants) and 33% of the industrial activities (Cearreta et al., 2004). Such human pressure on the coastal area has produced changes in its original physical, chemical and biological features over the last two centuries (see Borja et al. (2006b), for the most recent evaluation of pressures). Although the population growth has stabilised since 1975, the impervious artificial surface area has continued to increase up until the present day (Braceras et al., 1997; OSE, 2006; and Chust et al., 2007, 2009).

2.2 AOGCM models and thermosteric sea level computation

Future projections of climate variables provided by the IPCC correspond to future greenhouse gases (GHGs) emission scenarios, based upon demographic and socio-

economical conditions (Meehl et al., 2007). Among the six climate scenarios defined by the IPCC, three are considered here: the committed climate change scenario, the SRES (Special Report on Emission Scenarios) A1B and the SRES A2. The committed climate change scenario considers that the GHGs concentrations in the atmosphere remain constant at levels of year 2000; thus, it is an unrealistic scenario which is used only for comparison purposes. The A1B scenario assumes increasing emissions during the first half of the present century that turn to decreasing in mid-century due to the utilisation of more efficient technologies. The A2 scenario considers acceleration on these emissions throughout the century. In addition, a control run of each model, based upon the pre-industrial gas concentrations, has also been considered. Thus, in terms of GHGs emissions throughout the 21st century, A1B is a scenario at an intermediate level (850 ppm of CO₂-eq concentrations in 2100), whilst A2 is amongst those assuming high levels of emissions (1250 ppm of CO₂-eq concentrations in 2100) (IPCC AR4, 2007).

The main factors affecting global SLR are the ice-melting from glaciers, ice caps and ice sheets and thermal expansion. The contribution of thermal expansion to the global SLR estimated under the main IPCC scenarios by the end of the 21st Century is 70% to 75% (Meehl et al., 2007). It is estimated that the ice-melting will contribute to a global SLR of between 4 and 20 cm by the end of the 21st Century (with respect to the beginning of this century), under both the A1B and A2 scenarios (Meehl et al., 2007). No regional estimations are available presently. The absence of long-term observations, together with accurate modelling of the processes of the ice dynamics, prevents a more reliable estimation. The rate of land subsidence in northern Spain due to post-glacial rebound effects are small (between 0.2 and 0.3 mm yr⁻¹, see Peltier (2004)); therefore it was neglected.

Conversely, the effects of thermal expansion for the study area have been estimated by averaging the ocean temperatures provided by an ensemble of AOGCMs. Monthly ocean temperature data from 23 AOGCMs have been downloaded (from the World Climate Research Programme, WCRP, <https://esg.llnl.gov:8443/home/publicHomePage.do>) for the area of interest (43°N-48°N, 1°W-8°W; Figure 1a) and for the period 2001-2009. Unfortunately, not all of the models have been run for all of the scenarios. Likewise, some of the models show an anomalous behaviour (e.g., abrupt changes from one year to the next). As such, these models have been discarded, following the approach of Marcos and Tsimplis (2008). As a result, 10 models have been considered in this study (Table 1). The average of ocean temperatures and salinity has been calculated with an ensemble of the selected models to reduce errors in the individual global models (Pierce et al., 2009). Although the salinity (S) changes are unimportant at a global scale, they can alter significantly the sea level changes regionally. Higher salinity implies higher density and thus lower steric sea level. Monthly S time series have been downloaded also and processed for the study area in order to establish whether its effects are negligible.

Thermosteric Sea Level (TSL) has been computed by integrating, from the sea surface to the bottom (H), the specific volume anomaly (α) estimated from the modelled potential temperature (T) and salinity (Pond and Pickard, 1983):

$$TSL = \frac{1}{g} \int_{-H}^0 \alpha dp$$

where g and p are the gravitational constant and the pressure, respectively. Annual values have been computed averaging monthly time-series. TSL obtained from the pre-

industrial control runs of the AOGCMs have been subtracted from each scenario in order to remove possible internal drifts of the models.

The estimated total SLR within the area has been computed as the addition of the regional thermosteric sea level and 4 to 20 cm, as the global sea level rise projected due to ice melting.

2.3 LiDAR-based DTM

The LiDAR is a laser altimeter that measures the range to objects on the Earth-surface, from a platform with a position and altitude determined from GPS and an inertial measurement unit. A detailed technical review of several LiDAR sensor types can be found in Wehr and Lohr (1999), whilst the type used here is described in Chust et al. (2008). The Local Government of Gipuzkoa carried out topographic mapping of the entire province (221 700 ha) in 2005 (from January to May) using a LiDAR system. The sensor used was a laser Optech ALTM 3025 (Airborne Laser Terrain Mapper), which belongs to the Cartographic Institute of Catalonia (ICC), operating at the infrared wavelength of 1064 nm. The aerial flights were carried out at mid- to low-tide (from 0.23 to 2.73 m below the mean sea level, at Bilbao Harbour). A terrestrial DTM was generated from the LiDAR data at 1 m resolution by the ICC. The ground (bare-earth) DTM was generated from the LiDAR ground points; these were used to construct Triangulated Irregular Networks (TINs) based upon the ellipsoidal height, by means of linear interpolation. The overall grid of the Gipuzkoan coast has a dimension of 56021 columns by 16002 lines. As an artefactual result of the DTM generation, some areas below flats were detected to have lower height value than the surrounding ground; thus,

they were removed from the analysis. The DTM of Gipuzkoa (available from <http://b5m.gipuzkoa.net/web5000/>) had a vertical accuracy of 0.15 m RMS, in low vegetated and low slope areas. The vertical accuracy is less than 0.5 m within closed forests and steep areas. The accuracy assessment of the topographic LiDAR point data has been undertaken by comparing with field-based GPS data (ICC, 2005). The GPS ground control measurements were located in flat, hard, well-defined surfaces, and free of objects. The GPS measurements were undertaken in 39 control surfaces, and each one contained 40 measurements points. Ellipsoidal heights were transformed to orthometric heights (mean sea level of Alicante Datum, MSLA) using a gravimetric geoid model for the Iberian Peninsula (IBERGE095, http://www.mat.ucm.es/deptos/iag/principa4_data/lineas/texto01_133.htm). The Alicante datum, the reference used in Spain, is 0.37 m below the mean sea level in Bilbao, following the ground levelling of 1998 (REDMAR, 2005b).

Furthermore, LiDAR orthometric heights were validated using GPS control points using two data sources: 1) 8.328 ground control points (ranging from 1.0 to 11.0 m in height above mean sea level) from 1:5.000 topography (Government of Gipuzkoa and Bizkaia, undertaken in 2002 and 2003, respectively), these points were located in relatively stable zones; and 2) 9 GPS ground control points located within the harbours of Gipuzkoa within flat, hard, well-defined surfaces, and free of objects; the GPS ground points were measured using GPS receivers (Trimble R6 with the RTK system) with horizontal accuracies of less than ± 2 cm. In the first larger dataset, a mean difference of 0.46 m was obtained between the two systems (LiDAR heights below control point heights), with 50% of control points lying between 0.29 m and 0.67 m in relation to LiDAR heights. The differences did not present a trend along the coast, although they

were clustered within several zones. In the second dataset (harbour control points), the difference is very similar (0.50 m), with a standard deviation of 0.19 m (Table 2); this confirms that LiDAR heights are systematically below GPS control points. These local differences should be related to the IBERGEO95 geoid model. Therefore, LiDAR data were corrected by 0.46 m for later computation of the tide levels.

2.4 Classification of coastal habitats

A classification of coastal and estuarine habitats was undertaken by photointerpretation (Finkbeiner et al., 2001) of the 0.5-m spatial resolution aerial photographs, acquired in 2004. Habitat ground information was derived from fieldwork carried out in 2005 and 2007. Specific information on community composition and species abundance (macroalgae and macroinvertebrate), within the intertidal and supralittoral zone, was extracted from the biological sampling programme undertaken by Borja et al. (2006a) in the spring-summer of 2005. From all of this ground information, 9 habitat types were defined according to tidal zonation, substrata, and macroalgae or plant cover: sandy beaches and muds, vegetated dunes, shingle beaches, sea cliffs and supralittoral rock, wetlands and saltmarshes, terrestrial habitats (crops, arable land, areas with gardens and urban parks, scrubs, woodland, including riparian woodland), artificial land (excluding piers), piers, and water surfaces. Thus, the habitats were digitised manually by photointerpretation, generating 717 polygons (i.e., habitat patches) for 2004. The global accuracy measurements of the classification of 2004, which was assessed with fieldwork carried out in 2007, were above 97%. Details of the classification process, together with accuracy assessment, is presented in Chust et al. (2007, 2009).

2.5 Tide gauge data

The littoral zone of Gipuzkoa is subjected to a semi-diurnal tide, with two high tides and two low tides daily (González et al., 2004). For sea level and tidal variation along the Gipuzkoan coast, the nearest tide gauge with a long data series has been selected, which is that of Bilbao I (Santurce/Santurtzi Harbour, LAT: 43° 20' 14" N, LONG: 003° 02' 09" W; Permanent Service for Mean Sea Level code: 200/006). On the basis of Bilbao I tide gauge observations (period: 1993-2005), the highest range reported for the Basque coast was 5.32 m, with a minimum of 1.65 m during neap tidal periods (mean observed neap tides) (REDMAR, 2005a) (Table 3). The interest of this study is centred upon the Maximum Astronomic High Tide (MAHT), since it is the maximum tide predicted for the operational period of the tide gauge (19 years). The time frequency to the sea level overtopping the MAHT is low (once every four years, or 0.5 hours per year). The value of MAHT referred to Alicante Datum is 2.81 m ($= 4.83 - 2.016$), where 2.016 is the difference between the mean sea level in Alicante (MSLA) (levelling reference post 1998) and the Bilbao Port datum (zero).

2.6 Generation of flood risk map

With the aim of assessing the impacts of the SLR along the coastal and estuarine habitats and to what extent, the potential area affected by SLR was estimated. As such, the area between the coastlines defined by the MAHT, extracted from the DTM, together with that generated by adding the estimated SLR in 2099 by the AOGCMs, was delimited using Geographic Information Systems, as a raster image which could

then be vectorized. The calculated area is in the orthogonal plane, i.e. without taking into account the slope of the surface. The inundated polygons unconnected to seawater were removed, following Webster et al. (2004, 2006), except for polygons close to the seawater; this was in order to detect vulnerable zones such as crops preserved by walls. Local discrepancies produced by the vertical error of the LiDAR-derived DTM imply that some of the flood areas might be slightly overestimated and others slightly underestimated. Thus, small polygons (groups of less than 4 pixels) were removed from the flood risk map to prevent partially the assignment of these discrepancies as flooded areas.

This flooded area, delimited by the coastline for 2005 and that expected for 2099, was overlain with the 9 habitats present in 2004. Since the area affected by sea level variations is related directly to the slope of the land surface, the mean values of slope for each habitat were calculated.

The redistribution of sediment along sandy beaches, according to the Bruun Rule (Bruun, 1988; FitzGerald et al., 2008) was not taken into account in the flood risk map approach. However, the Bruun Rule suggests that small increases in sea level rise result in relatively large shoreline recessions (e.g., 1 cm of rise might produce 50 to 100 cm of retreat, for typical coastal regions). Specifically, the Bruun Rule predicts a shoreline retreat (R) as a function of $S \cdot L / (B + h)$, where L is the cross-shore distance to closure depth h , B is the berm height or elevation estimate of the eroded area, and S the SLR rate. Thus, the flood risk map approach adopted here is conservative with respect to the Bruun Rule, in the sense that the estimated potential change for sandy beaches is expected to be less than the actual retreat. Therefore, the Bruun Rule was applied to 15

of the main beaches, in order to obtain better estimates of beach shoreline retreat. The parameters for retreat calculation (L , B , and h) were extracted as follows. The closure depth h has been obtained from the significant wave height during extreme conditions for each sandy beach. The cross-shore distance L has been estimated using the bathymetry data obtained from ship-borne multibeam echosounders (SeaBat7125 system), acquired in 2007 (Galparsoro et al., 2009). The berm height B has been estimated using the LiDAR-based DTM. Although criticisms and modifications to the Bruun Rule have been suggested (Cooper and Pilkey, 2004; Davidson-Arnott, 2005), it serves as an indication of how the flood risk map is biased in relation to accounting for movements of material in response to the SLR.

3 RESULTS

3.1 Projections of sea temperature and TSL

The rates of change of projected temperatures of the upper 100 m of the water column averaged for the Bay of Biscay as given by the selected AOGCM models are listed in Table 1. An increase in averaged ocean T over the top 100 m is expected for all three scenarios. Mean temperature estimated for the Committed scenario is $3.49 \pm 2.45 \cdot 10^{-3} \text{ }^{\circ}\text{C yr}^{-1}$. For the SRES A1B and A2, the projected T increase are higher: $14.91 \pm 7.56 \cdot 10^{-3} \text{ }^{\circ}\text{C yr}^{-1}$ and $20.48 \pm 4.42 \cdot 10^{-3} \text{ }^{\circ}\text{C yr}^{-1}$, respectively. Figure 2a shows the yearly evolution of ensemble average T for the 3 scenarios. The rise in T can be seen to be linear, with no accelerations observed. On the contrary, the increase in averaged ocean salinity over the top 100 m by 2099 is not significant for all three scenarios: $0.12 \pm 0.20 \text{ psu}$ (Committed),

0.58±0.53 psu (A1B), 0.38±0.58 psu (A2), see Table 1. Thus, salinity was assumed to be constant in the thermosteric sea level computation.

Following T changes, thermosteric sea level estimated by integrating the entire water column, from the surface to the bottom, projects a sea level rise under the 3 scenarios considered (Figure 2b and Table 1). Ensemble average values result in a mean sea level rise of 1.16±0.24 mm yr⁻¹ for the Committed scenario, 2.45±0.45 mm/yr for SRES A2 and 2.87±1.09 mm yr⁻¹ for SRES A1B. In contrast to the temperature, the highest rise is expected for the SRES A1B, although the difference with that calculated for the SRES A2 is within the uncertainty range. Unlike what happens with T, TSL is projected to accelerate during the second half of the Century under last two scenarios (Figure 2b).

The increase in thermosteric sea level by the end of the 21st Century is 11.6±2.4 cm, 28.7±11 cm and 24.5±4.5 cm for the Committed climate change, SRES A1B and SRES A2 scenarios respectively. The Committed scenario indicates that, even the GHGs concentrations in the atmosphere remain constant at levels of year 2000, the sea level will continue to rise throughout the 21st century. By adding the expected global SLR from the melting of ice-sheets and glaciers, which is between 4 and 20 cm (Meehl et al., 2007), the total increase of the sea level is between 28.5 and 44.5 for the A2 scenario and between 32.7 to 48.7 cm for the A1B scenario, within the Bay of Biscay.

3.2 Flood risk map for the Gipuzkoan Coast

The most pessimistic scenario obtained, i.e. SLR of 48.7 cm (SRES A1B) by 2099, was selected to assess the impacts on coastal habitats. Based on the frequency of

overtopping a particular level (Table 3, Medina and Méndez, 2006), areas which are at present (in 2005) occasionally (0.5 h yr^{-1}) covered by the MAHT, will be covered approx. 100 h per year under the A1B scenario. In turn, the areas covered presently by the mean spring high tide (15 h yr^{-1}) would be flooded for more than 1000 h yr^{-1} .

The projected SLR of 48.7 cm by 2099 was added to the sea level of the maximal astronomic high tide (MAHT) along the Gipuzkoan coast (i.e. 3.30 m MSLA), in order to map the flood risk of the coastal areas. Figure 3 shows the projected flooded area along the coast. The supralittoral area of the Gipuzkoan coast affected by the SLR was estimated to be 110.5 ha (Table 4). The most flooded area is concentrated within the estuaries (55.2 ha, including wetlands and saltmarshes, terrestrial habitats and water surfaces); this is expected since these areas are associated with large and flat plains (mean slope of 5.4° - 5.8°).

Terrestrial habitats are those most affected (45.5 ha, Table 4). Amongst these, croplands and pastures located in estuaries (established within the original upper intertidal zone) lie mostly below the present MAHT level. Although they are protected by walls, in some cases, the SLR will overtop. Figure 4 shows an example of croplands in the Oria estuary that are affected potentially by the present MAHT; this increases with SLR. A wall (3.0 m in height, referred to MSLA) is protecting these croplands. Because the wall is narrow ($<1 \text{ m}$ width), LiDAR resolution was not able to detect all along the wall; this explains why the present MAHT polygon is open to the estuary. Other low-lying areas in estuaries, encompassing suburban areas with gardens and parks, herbaceous and scrub land, riparian woodland, were identified also as being affected by SLR.

The projected flooded area of saltmarshes and wetlands is 3.9 ha, which is 6.5% of the present surface. The orthophotography (Figure 4a) shows that the saltmarshes are at present below the MAHT level. The height profile (Figure 4b) shows the vulnerability of these communities to overtopping by the SLR of the observed mean spring high tide level.

Following on from the terrestrial habitats, the most flooded habitat is the artificial land (34.4 ha, Table 4), located mainly within the estuaries and small embayments. Different urban structures were detected as being affected in future scenarios, e.g. industrial areas, harbours, seafronts, piers, residential and urban areas, roads and tracks. One of the most significant examples is Hondarribia Airport and the adjacent areas (Figure 5), since the landing strip would be largely affected. The wall that presently preserves the landing strip is of 4.5 m (MSLA) along the north side; to the south, the wall height lies close to the projected rise (3.3 m MSLA). Since this important area appears highly vulnerable, a local comparison was undertaken between corrected LiDAR heights and a set of 60 GPS ground control points from 1:5.000 topography (Diputación Foral de Gipuzkoa, Diputación Foral de Bizkaia, undertaken in 2002 and 2003, respectively), see Figure 5a. This comparison has revealed that corrected LiDAR heights were 32 cm ($\pm$ 23 cm) below the GPS control points. As such, flood risk map is overestimating slightly the inundation area within this zone. Finally, all 9 ports would not be overtopped by the 49 cm of SLR, although three of them would be at 21-27 cm above the MAHT in 2099 (Table 2).

A surface of 10.1 ha of sandy beaches and 2.3 ha of vegetated dunes will be potentially affected by 2099 (Table 4), according to the flood risk map. Thus, 15.6% of the present

area occupied by sand beaches and dunes will be flooded under the SLR scenario. Figure 6 shows an example of the effect on Hendaye beach and dunes (Bidasoa estuary, France). This sandy beach would retreat by up to 15 m. Vegetated dunes would be almost completely flooded under the static flooding approach. Estimates of the retreat for the main 15 beaches were between 5 m to 17 m (mean: 9 m). If referred to the supralittoral beach width, the retreats are expected to be highly variable, from 2 to 100% (mean: 25%) (Table 5). Shingle beaches are expected to be affected by 0.82 ha (12.0%). Applying the Bruun Rule, the retreats of the main sandy beaches are also expected to be highly variable, from 5 to 100%, with a higher mean value (40%) than the map-based approach (Table 5). Amongst the main 15 beaches analysed, the supralittoral (dry) zone is expected to disappear with the SLR scenario in 3 beaches according to the Bruun Rule; likewise, in 2 beaches according to the flood risk map approach.

The flood risk area in sea cliffs, supralittoral rock and abrasion platforms was estimated to be 7.3 ha (5.2%). The flooded area and the overall area presently are referred to the orthogonal plane, i.e. without taking into account the slope which is high for these habitats (17° on average). Figure 7a presents the case of an abrasion platform. The area affected by the SLR over the MAHT is limited (horizontal retreats of 1-2 m), although lower tide levels are expected to present higher retreats (Figure 7b).

The area affected by the SLR on water surfaces, which is estimated as 5.7 ha (Table 4), is associated with the MAHT inner limit of estuarine waters, which would migrate to landwards. Frequently, the MAHT inner limit is defined by physical barriers or dams. The migration to landward of the main 7 estuaries of the study area is estimated on average to be 265.2 m, with high variability (ranging from 119 to 464 m).

4 DISCUSSION

4.1 Mean sea level projections

The projected SLR computed for the 21st Century in the Bay of Biscay (A1B scenario: 33-49 cm, A2 scenario: 29-45 cm) are similar to global estimates under the same scenarios (A1B: 21-48 cm, A2: 23-51 cm). In contrast, the SLR in the Southern Bay of Biscay is estimated to be between 2.0 and 2.5 mm yr⁻¹ during the second half of the 20th Century (Marcos et al., 2005; Leorri et al., 2008; and Chust et al., 2009), which is slightly higher than global estimates for this period of 1.8 ± 0.3 mm yr⁻¹ (Church et al., 2004). There are still uncertainties in the projections of temperature and sea level for the period and study area. SLR projections closely depend on the selected models; and in some cases the results highly differ from one model to another. Future improvements on the models would permit to reduce the uncertainties of the SLR projections. Even at global scale, uncertainties exist in the projection of thermal expansion, and estimates of the total volume of ice in mountain glaciers and ice caps (Rahmstorf, 2007). Those uncertainties will presumably be reduced by improving our capability for calculating future sea-level changes in response to a given surface warming scenario (Rahmstorf, 2007), such as including ice flow dynamics (Pfeffer, 2008), and when regional climate models become available. Recent approaches have provided estimates of global SLR higher than those published by the IPCC AR4 (2007) ranging from 0.8 m (Pfeffer, 2008) to 1.4 m (Rahmstorf, 2007). In the mean time, however, the AOGCMs are the unique tool available to forecast their temporal evolution for the Bay of Biscay.

4.2 Impacts of SLR on sand beaches and dunes

Overlaying the future projected sea level with the present morphology, i.e. extracted from LiDAR, sand beaches and dunes are expected to be affected by 15.6% under the SLR scenario by 2099. Specifically, sandy beaches are expected to suffer shoreline retreats of between 5 and 17 m, i.e. 25% of the average beach width. If beach profile change, in response to the new mean sea level conditions along sandy beaches, is taken into account, i.e. according to the equilibrium profile (Bruun, 1988; FitzGerald et al., 2008), the shoreline retreat estimates are higher; they lie between 12 and 31 m, i.e. 40% of the beach width on average. In both the map-based and Bruun approaches (Table 5), the number of beaches in which the supralittoral zone is expected to disappear (MAHT sea level and typical beach morphology) is lower (2 or 3, of the 15 analysed beaches) than the estimates given by Cendrero et al. (2005): 12 of 19 beaches. Cendrero et al. (2005) applied the Bruun Rule on only one representative beach profile; this resulted in enhanced erosion of 1 m for every 1 cm of rise in sea level. Our approaches, using high-resolution height data and taking into account the beach profile and closure depth characteristic of each beach analysed, should, therefore, provide improved estimates of beach loss. Both the new estimates presented here and those reported in the literature are based upon an hypothetical absence of any additional supply of sediments by natural or human-induced causes.

Low-gradient dissipative shores, which hold greater biodiversity than steep coarse-grained beaches, are at most risk; this is due to their erosive nature and the much greater run-up of swashes on gentle gradients (Defeo et al., 2009). Moreover, the confinement of sand beaches by building coastal structures makes them more prone to disappear

(FitzGerald et al., 2008). At present, 17 out of the 19 beaches of Gipuzkoa are already naturally- or artificially-confined (Chust et al., 2009). In the case of vegetated dunes, the entire beach profile would migrate landward under the SLR scenario; as such, in several cases vegetated dunes would disappear because of the presence of the artificial rigid seafronts (e.g. Hendaye beach). A similar risk assessment has been undertaken for this and other beaches within the French Basque Country, using a different approach (Vinchon et al., 2009). Therefore, the joint effect of accelerating SLR and undertaking coastal urbanization processes in the area (Chust et al., 2009) is of particular concern for beach erosion, especially for vegetated dunes (Defeo et al., 2009), and within the context of higher global SLR projections (0.5 to 1.4 m, Rahmstorf, 2007; 0.8 m, Pfeffer et al., 2008).

Concerning the beach biota, the projected rise in sea temperatures might also interact negatively with SLR having implications in terms of loss of coastline biodiversity. On the one hand, the warming of marine waters might displace the migration of intertidal species with narrow-range niche to higher latitudes. On the other hand, the loss of small beaches and the general retreat lead to beach habitat patches along the coast to fragment; as such, to reduce the potential connectivity between local populations (Fahrig, 2003). Finally, many sandy beach species lack dispersal larval stages (Defeo et al., 2009); therefore, populations of narrow-range species, with limited dispersal potential, would be at local extinction risk under projected climate change for the area. This risk can be more severe in plant species dwelling dunes, since these habitats are scarcer, less extended, more fragmented, and more urbanised historically than sandy beaches.

Adaptation strategies to face SLR-induced beach erosion should include measures to promote coastal resilience such as protection, regeneration of dune plants and stabilisation, the maintenance of sediment supply and the provision of buffer zones, providing setback zones which would allow the beach to migrate landward as the sea rises (Defeo et al., 2009).

4.3 Impacts of SLR on saltmarshes, wetlands and croplands

The projected flooded area of saltmarshes and wetlands is 3.9 ha (i.e. 6.5% of the surface). The impact on saltmarshes is not well represented using the MAHT overtopping since these communities dwell below this threshold, developing mainly between spring and neap high tides. However, marshes are dynamic systems which respond to SLR according to a balance between accretion and subsidence, bioproductivity and decomposition, erosion and vegetative stabilization, and tidal prism and drainage efficiency (Morris et al., 2002; FitzGerald et al., 2008; and Reeve and Karunaratna, 2009). In essence, the vertical accretion, as defined as net vertical growth of the marsh, results from both mineral sediment influx and the production of organic matter; this, in turn, determines the future evolution of the marsh in response to SLR (Morris et al., 2002). Many marshes are capable of being near equilibrium in relation to rates of SLR (Friedrichs and Perry, 2001); while under specific conditions, they could lag century-scale sea level rise rate oscillations by several decades (Kirwan and Murray, 2008b). An average accretion rate of 3.7 mm yr^{-1} , as calculated for Basque marshes over the 20th Century by Leorri et al. (2008), suggests that these marshes are potentially able to adjust to the projected SLR rates.

Further, there is a risk of inundation for some croplands and pastures located within estuaries, established within the original upper intertidal and marsh zone. Although these croplands are protected by walls and drained to be used for agriculture purposes, most of them lie below the present MAHT level. The SLR is expected to overtop the walls in some of these areas. In other zones, these humanised habitats are vulnerable to events, i.e. a combination of high tides, SLR, and river floods. In all cases, these walls would need to be reinforced and well maintained to address the projected SLR. In turn, if agriculture activity continues to decline, as throughout the 20th Century (Cearreta et al., 2004), these areas may be abandoned and susceptible to be recolonized by marsh communities (Aguirrezabalaga et al., 2005; Garbutt et al., 2006). On the basis of these socio-economic and SLR scenarios, saltmarshes and wetlands might increase in their overall area, by recolonization and landward migration, as predicted for other areas (CCSP, 2009).

4.4 Impacts of SLR on rocky shores and urban sector

Because of the relative stability of the hard substratum and the urban sector, the approach adopted here for generating flood risk maps is more reliable than for soft substratum and marshes. The flood risk area for sea cliffs, supralittoral rock and abrasion platforms was estimated to be 7.3 ha (5.2%) with small retreats of 1-2 m in the MAHT level. All the intertidal species are expected to migrate according to the SLR. Because of the abrasion platform profile, those species dwelling within the midlittoral zone would be expected to be more affected (reducing its habitat area) than those living within the supralittoral fringe. Although the hard substratum did not appear to be highly affected, according to our assessment, these are the littoral elements most exposed to

storm surges and wave energy. These processes cause severe coastal erosion and morphological changes, as determined for other countries (Paskoff, 2004; Slott et al., 2006; Devoy, 2008; De La Vega-Leinert and Nicholls, 2008; Pruszek and Zawadzka, 2008; CCSP, 2009; and Vinchon et al., 2009). The analysis of long time-series (40-yr) of storm surges and wave heights from nearby Basque coastal locations, such as Santander, have suggested that these extreme events have been stronger over the last decade (Méndez et al., 2008). Moreover, projection models for the Cantabrian coast indicate that wave heights (both the mean regime and extreme events) will increase by 2050 (Ministerio de Medio Ambiente, 2006), as in other northern seas (Debernard and Røed, 2008). Hence, the damages to these and other exposed habitats (especially sandy beaches and dunes) could be higher when considering the joint effect of coastal storms and SLR (Michael, 2007).

The artificial land areas are amongst the most affected habitats (34.4 ha), mainly those areas located within estuaries and small embayments. Different human infrastructures were identified as being affected by future scenarios such as industrial areas, seafronts, piers, harbours, residential and urban areas, roads and tracks. Areas affected lying near to the rivers or exposed to wave action are at greater risk of inundation under extreme events such as river floods and sea storms, respectively. These would create problems in communication, transport, and sanitary sewer systems. One of the most significant examples is Hondarribia Airport and the adjacent areas, since at least the southern side of the landing strip would be affected. Even taking into account the local bias detected in the area by the LiDAR heights, this socio-economically important site appeared vulnerable under the SLR scenario.

Likewise, local differences between ground control points and LiDAR heights along the coast indicates that enhanced transformations from ellipsoidal to orthometric heights are needed to obtain digital elevation models at higher horizontal and vertical resolution for SLR scenarios. Our systematic correction of LiDAR heights means that some of the flood areas were slightly overestimated and others were slightly underestimated. This pattern implies that although local inaccuracies exist in the model, the overall estimates of flood risk for each habitat are reliable. The quality of digital elevation models can significantly affect also the detection of topographic features and, hence, the magnitude of hydrological processes. For instance, the extent of inundation might depend on horizontal resolution and assumptions made on hydrological connectivity (Poulter and Halpin, 2008). In the mean time, LiDAR allows for a more detailed delineation of the potential inundation areas when compared to other types of elevation models (e.g., Gesch, 2009).

5 CONCLUSIONS

According to the analysis of AOGCM projections in the Bay of Biscay, the temperature of the upper 100 m of the water column will increase up to the end of this Century by between 1.5°C (SRES A1B) and 2.05 °C (SRES A2). The sum of the regional projected thermosteric SLR, together with the global increase due to the ice-melting will suppose by the end of this Century a SLR of between 29-45 cm (SRES A2) and 33-49 cm (SRES A1B) in the Bay of Biscay. The highest projected SLR of 49 cm, combined with a high-resolution LiDAR-derived DTM of the Gipuzkoan coast, was used to generate a flood risk map for coastal and estuarine areas. The results of this flooding map have indicated that Gipuzkoan coast will be affected over 110.8 ha of the supralittoral area by the end

of the Century. The largest flooded area is concentrated within the estuaries (55.2 ha), as expected, since these areas are associated with large and flat plains. Terrestrial and artificial habitats are those more affected (45.5 ha and 34.4 ha, respectively). Natural habitats such as saltmarshes and wetlands, and sea cliffs and abrasion platforms are expected to be affected over 3.9 ha and 7.2 ha, respectively. Sandy beaches, identified as one of the most threatened coastal habitat, are predicted to encounter mean shoreline retreats of between 25% and 40% of their width. This study provides an insight into the regional sea level evolution; likewise, highlights, locally, the areas and habitats that will be flooded as a consequence of global climate change. The local, *per* habitat assessment is on the basis of providing long-term, efficient adaptation measures to sea level rise.

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FIGURE CAPTIONS

Figure 1. (a) Study area of Gipuzkoa within the Bay of Biscay. Key: (+) = geographic boundaries considered in the AOGCMs; (b) Gipuzkoan coast with the main estuaries and the intertidal fringe (in blue). Key: e = estuary.

Figure 2. Projected annual temperature (A) and mean thermosteric sea level (B) for the 21st Century under the three climate scenarios (for details, see text).

Figure 3. Flood risk map of the Gipuzkoan coast expected for 2099, with respect to 2001, for a sea level rise of 48.7 cm (SRES A1B). The red areas indicate the inundated zones projected for the end of the Century.

Figure 4. A) Flooded area (in red) on saltmarshes and agricultural zones in the Oria estuary (airborne photography of 2004). The black line is the present Maximum Astronomic High Tide (MAHT). B) Height profile. OMEHT: Observed Mean Equinoctial High Tide. SLR: Sea Level Rise. For location within the Basque Country, see Figure 1.

Figure 5. A) Flooded area (in red) in Hondarribia Airport. The black line is the present Maximum Astronomic High Tide (MAHT). Blue crosses correspond to the ground control points. B) LiDAR elevation profiles for both the North and South sides of the airport. For location within the Basque Country, see Figure 1.

Figure 6. A) Flooded area (red) of Hendaye beach and dunes. B) Height profile. For location within the Basque Country, see Figure 1.

Figure 7. (A) Flooded area (red polygons) of an abrasion platform and sea cliffs located between the Deba and Urola estuaries. (B) Height profile. OMNLT: observed mean neap low tide. For locations within the Basque Country, see Figure 1.

1 TABLES

2 Table 1. Rate of change of temperature ($10^{-3} \text{ }^{\circ}\text{C yr}^{-1}$), salinity ($10^{-3} \text{ psu yr}^{-1}$) and thermosteric mean sea level (mm yr^{-1}) for each selected model
3 and scenarios for the period 2001-2099. Projections of temperature and salinity are referred to the first 100 m of the water column; whilst that of
4 TSL corresponds to the integration of the overall water column, from the sea surface to the bottom. Uncertainties correspond to standard errors
5 estimated. The last two rows indicate the mean rate and standard deviation of the models for each scenario, and the absolute increase ($\pm$ standard
6 deviation) of temperature, salinity, and TSL projected for 2099, with respect to 2001.

	T^a ($10^{-3} \text{ }^{\circ}\text{C yr}^{-1}$)			S ($10^{-3} \text{ psu yr}^{-1}$)			TSL (mm yr^{-1})		
Models	Committed	SRES A1B	SRES A2	Committed	SRES A1B	SRES A2	Committed	SRES A1B	SRES A2
bccr_bcm2_0	3.97 $\pm$ 0.75	16.14 $\pm$ 0.93	18.88 $\pm$ 0.97	-0.45 $\pm$ 0.15	0.52 $\pm$ 0.18	-0.41 $\pm$ 0.16	1.14 $\pm$ 0.08	3.20 $\pm$ 0.09	2.51 $\pm$ 0.07
cccma_cgcm3_1	6.74 $\pm$ 1.13	22.03 $\pm$ 1.36	27.08 $\pm$ 1.10	2.77 $\pm$ 0.29	2.86 $\pm$ 0.56	4.91 $\pm$ 0.38	0.85 $\pm$ 0.05	2.74 $\pm$ 0.04	2.61 $\pm$ 0.05
cccma_cgcm3_1_t63	-	23.55 $\pm$ 1.05	-	-	0.30 $\pm$ 0.26	-	-	5.14 $\pm$ 0.08	-
cnrm_cm3	-	14.53 $\pm$ 0.92	20.33 $\pm$ 0.93	0.52 $\pm$ 0.40	7.39 $\pm$ 0.79	5.87 $\pm$ 0.36	-	3.39 $\pm$ 0.06	3.49 $\pm$ 0.07
csiro_mk3_0	-	0.48 $\pm$ 1.56	-	-	-	-	-	1.71 $\pm$ 0.19	-
csiro_mk3_5	-	12.20 $\pm$ 1.36	14.86 $\pm$ 1.14	-2.92 $\pm$ 1.29	-	-	-	2.06 $\pm$ 0.21	0.63 $\pm$ 0.15
giss_model_e_h	-	17.41 $\pm$ 0.6	-	-	1.87 $\pm$ 0.22	-	-	2.00 $\pm$ 0.07	-
iap_fgoals1_0_g	-	-	-	-	24.04 $\pm$ 0.49	-	-	-	-
mri_cgcm2_3_2a	1.95 $\pm$ 0.98	15.43 $\pm$ 0.90	21.25 $\pm$ 0.92	1.77 $\pm$ 0.29	3.44 $\pm$ 0.34	4.68 $\pm$ 0.31	1.42 $\pm$ 0.05	2.7 $\pm$ 0.07	3.01 $\pm$ 0.12
ukmo_hadcm3	1.31 $\pm$ 1.49	-	-	-	-	-	1.25 $\pm$ 0.12	-	-
Mean $\pm$ St. Dev.	3.49 $\pm$ 2.45	14.91 $\pm$ 7.56	20.48 $\pm$ 4.42	1.16 $\pm$ 1.95	5.77 $\pm$ 5.33	3.76 $\pm$ 5.82	1.16 $\pm$ 0.24	2.87 $\pm$ 1.09	2.45 $\pm$ 0.45
Expected rise	0.35 $\pm$ 0.25 $^{\circ}\text{C}$	1.49 $\pm$ 0.76 $^{\circ}\text{C}$	2.05 $\pm$ 0.44 $^{\circ}\text{C}$	0.12 $\pm$ 0.20 psu	0.58 $\pm$ 0.53 psu	0.38 $\pm$ 0.58 psu	11.6 $\pm$ 2.4 cm	28.7 $\pm$ 10.9 cm	24.5 $\pm$ 4.5 cm

Table 2. Height data (m) of Gipuzkoan Harbours from *in-situ* measurements and orthometric LiDAR. Source: “Referencias de nivel en los Puertos de la CAPV para la Dirección de Puertos y Asuntos Marítimos del Gobierno Vasco” (unpublished data). Key: UTM coordinates at European Datum 1950 30N. MSLA: Mean Sea Level in Alicante; Z: height; SD: Standard Deviation; MAHT: Maximum Astronomic High Tide.

Harbour	x UTM	y UTM	In-situ Z (m, ref. MSLA)	LiDAR Z (m)	SD	dZ	Z above MAHT
Hondarribia	598047.0	4804768.3	4.07	3.32	0.03	-0.75	1.26
AZTI-Pasaia	586774.6	4797336.1	4.32	3.64	0.02	-0.68	1.50
Donostia/San Sebastián	582070.8	4797346.6	4.40	3.92	0.06	-0.48	1.59
Orio	571034.0	4792018.4	3.84	3.43	0.12	-0.41	1.03
Getaria	564773.1	4795208.8	4.06	3.29	0.03	-0.77	1.25
Zumaia	560552.6	4794184.0	3.57	3.30	0.09	-0.27	0.76
Deba	552343.4	4793880.1	3.52	3.01	0.06	-0.51	0.71
Mutriku	550269.4	4795368.5	4.12	3.82	0.06	-0.30	1.31
Ondarroa	547150.0	4797465.4	3.51	3.17	0.04	-0.34	0.70
Mean						-0.50	1.12
Standard Deviation (SD)						0.19	

15 Table 3. Tidal parameters for the Bilbao I tide gauge (for location see Figure 1),
 16 extracted from the Spanish network of harbour tide gauge (REDMAR, 2005a;
 17 Universidad de Cantabria, 2007) (LAT: 43° 20' 14" N, LONG: 003° 02' 09" W). MSLA:
 18 mean sea level in Alicante. Units in meters.

	Height (Bilbao)	Height (MSLA)	Frequency (hours yr ⁻¹)
Maximum observed level	5.05	3.03	0.2
Maximum astronomic high tide (MAHT)	4.83	2.81	0.5
Observed mean spring high tide	4.40	2.38	15
Observed mean neap high tide	3.21	1.19	>1000
Mean sea level	2.40	0.38	*
Observed mean neap low tide	1.56	-0.46	*
Observed mean spring low tide	0.39	-1.63	*
Minimum astronomic low tide	-0.11	-2.13	*
Minimum observed level	-0.27	-2.29	*

19 * Twice a day.

Table 4. Flooded area for each habitat of the Gipuzkoan coast estimated for 2099, with respect to 2001, under a projected sea level rise of 48.7 cm (SRES A1B). Key: na *not accounted for*, applied to those habitats not restricted to the coast such as artificial land, terrestrial habitats and water surfaces.

HABITAT	Flooded area (ha)	Total area in Gipuzkoa (ha)	Flooded area (%)	Slope (°)
Sandy beaches and muds	10.08	68.58	14.7	3.59
Vegetated dunes	2.28	10.88	21.0	4.11
Shingle beaches	0.82	12.03	6.8	11.83
Sea cliffs and supralittoral rock	7.29	141.38	5.2	16.97
Wetlands and saltmarshes	3.94	60.39	6.5	5.44
Terrestrial habitats	45.54	na	na	5.76
Artificial land (excluding piers)	34.38	na	na	9.59
Piers	0.81	17.56	4.6	-
Water surfaces	5.72	na	na	-
TOTAL	110.84			

26 Table 5. Shoreline retreat estimates for the main Gipuzkoan sandy beaches using the
 27 flood risk map approach and the Bruun Rule. Beach width refers to the maximum width
 28 of the supralittoral (dry) beach (i.e. the averaged beach width over the mean spring tide
 29 level). H_s : significant wave height. For explanation of h , L and B , see text.

Beach	H_s	h	L	B	Retreat (m)	Retreat (m) (Bruun)	Beach width (m)	Retreat (%) (Bruun)	Retreat (%) (LiDAR)
					per metre of SLR				
Saturraran	6.0	26	1180	4	39.3	19	50	38.6	16.0
Deba	7.2	30	1966	4	57.8	28	130	21.8	8.5
Zumaia	7.0	18	1035	4	47.0	23	46	50.1	19.6
Zumaia Santiago	2.2	9	449	5	32.1	16	330	4.8	1.5
Getaria Gaztetape	8.5	30	1556	2	48.6	24	14	100.0	100.0
Getaria Malkorbe	2.5	11	372	4	24.8	12	58	20.9	17.2
Zarautz (W)	5.7	24	1709	3	63.3	31	10	100.0	100.0
Zarautz (centre)	6.7	25	1638	4	56.5	28	20	100.0	35.0
Zarautz (E)	7.5	25	1208	10	34.5	17	260	6.5	1.9
Orio	6.2	25	1400	4	48.3	24	170	13.9	10.0
Ondarreta	1.5	2	241	4	40.2	20	80	24.6	20.0
Concha (centre)	4.0	10	539	4	38.5	19	48	39.3	16.7
Concha (E)	3.0	10	558	4	39.8	20	41	47.6	14.6
Zurriola	8.2	18	993	4	45.1	22	100	22.1	7.0
Hondarribi	2.5	10	925	5	61.6	30	190	15.9	5.3
Mean	5.2	18.2	1051.2	4.3	45.2	22.1	103.1	40.4	24.9
Minimum	1.5	2	241	2	24.8	12	10	5	2
Maximum	8.5	30	1966	10	63.3	31	330	100	100

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Figure 1.

Figure 2.

Figure 3.

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16 Figure 5.

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 18 Figure 6. A) Flooded area (red) of Hendaye beach and dunes. B) Height profile. For location within the Basque Country, see Figure 1.
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Figure 7.