Relative sea-level changes in the Basque coast (northern Spain, Bay of Biscay) during the Holocene and Anthropocene: the Urdaibai estuary case

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Abstract

In order to reconstruct the environmental evolution process of the Urdaibai estuary in response to sea-level changes in the Basque coast (northern Spain, Bay of Biscay) during the last 8500 years, 10 boreholes were drilled in different estuarine areas using a rotary drill until the pre-Quaternary basement was reached. One manual short core (50 cm) was obtained from a salt marsh environment located in the middle part of the estuary. Micropalaeontological (benthic foraminifera), sedimentological (grain size) and geochemical (^{14}C, ^{210}Pb and ^{137}Cs radioisotopes and total Pb and Zn) analyses were performed on these materials aiming to quantify the sea-level changes both of natural origin (Holocene) or derived from recent human activities (Anthropocene). Based on the obtained results, and by comparison with previously published information for this coastal area, the Holocene environmental evolution of the Urdaibai estuary has been interpreted as the result of relative sea-level variation that exhibits a rapid rise until 7000 cal BP followed by a moderate rise since then, and a stabilization during the last 3000 years until modern rates of sea-level rise (20th century: 1.7±0.2 mm y^{-1}) were reached.

Keywords: foraminifera, sea-level changes, Holocene, Anthropocene, northern Spain

1 Introduction

A substantial and rapidly increasing proportion of global population lives in the coast (within 100 km of a shoreline and 100 m above sea level; Small and Nicholls, 2003), which occupies 18% of the world's land mass (Smith et al., 2005). In Spain, 44% of people live in coastal cities and towns that represent only 7% of the total national land area (Dias et al., 2013). As result of the great human concentration in this coastal fringe, it is essential to understand the anthropogenic impacts on coastal zones derived from major drivers such as recent global sea-level rise (1.7±0.2 mm y^{-1} during the period 1900-2009 following Church and White, 2011), resulting from thermal expansion of seawater due to ocean warming and water mass input from land ice melt and land water reservoirs (IPCC, 2014). More recently, the analysis of satellite altimeter records (available since 1993) provided a global sea-level rise rate of 3.1±0.4 mm y^{-1} for the period 1993-2012 (Henry et al., 2013), suggesting an acceleration in the last few decades.

The IPCC AR5 report (2014) predicted that global mean sea-level rise rate during the 21st century (median values: 4.4-11.2 mm y^{-1}) will exceed the observed rate for the period 1971–2010 of 2.0 (1.7 to 2.3) mm y^{-1} under all Representative Concentration Pathways (RCP) scenarios. Regional factors such as tectonic and glacial isostatic movements need to be considered (Gehrels et al., 2011, 2012; Engelhart and Horton, 2012). Results obtained by Marcos et al. (2012) predict that mean sea level (MSL) might increase by up to 40 cm by the end of the 21st century with respect to modern values in northern Spain, resulting in up to 202 ha of supratidal coastal areas under risk of flooding. Hence, sea-level rise presents a hazard and elevated economic costs regarding coastal flood damage and adaptation. Bosello et al. (2012) estimated US$ 13.52 million of land losses by floods and US$ 2.95 million needed for coastal protection in Spain by 2085. The variability in costs of flooding and damage are related in part to the imprecision of the projections.

These future estimates are constrained by the tide-gauge instrumental records which are geographically-limited and usually cover only the last 60 years (even a shorter period covered by satellite altimetry), with the exception of a few tide-gauge records concentrated in the northern hemisphere that can reach up to the last 150 years (Woodworth et al., 2011). The brief instrumental period captures only a single mode of rising sea level. Geological reconstructions extend the instrumental records of sea level back in time and, therefore, can capture multiple phases of climate and sea-level behaviour for model calibration (Bittermann et al., 2013) and predictions.

Holocene coastal peats have been widely used as sea-level indicators in other regions (Allen, 1995), but in northern Spain they are not present. Therefore, precise sea-level indicators (SLIPS: sea-level index points) were obtained by combining the indicative depositional meaning (micropalaeontological and sand content) and radiocarbon ages (Leorri et al., 2012). Scott and Medioli (1978) first explained qualitatively, and later quantitatively (Scott and Medioli, 1980), the vertical distribution of salt marsh foraminifera, together with plants, with respect to the tidal frame, proving their value as proxies for salt marsh elevation. In recent decades, quantitative studies have developed into transfer functions, in order to obtain high-resolution reconstructions (e.g. Horton et al., 1999; Gehrels, 2000; Gehrels et al., 2005; Kemp et al., 2011b), which are the most used tool to reconstruct past sea-level variations in temperate regions. Foraminiferal distribution in estuaries from northern Spain was determined by both elevation respect to the tidal frame and salinity, which represent the main controls respect to other environmental variables (Cearreta et al., 2002; Leorri and Cearreta, 2009a). Elevation is the dominant environmental parameter in foraminiferal distribution in salt marshes on the SW European coast (Leorri et al., 2010). Foraminifera present in sedimentary records from salt marshes have been used as indicators of salt marsh palaeoelevational changes based on the quantification of the modern relationship between these microorganisms (the relative abundance of different species) and the environmental data (elevation as a proxy of tidal flooding frequency).

In this work, the analysis of foraminiferal assemblages together with radiometric dating (radiocarbon and short-lived radionuclides) and heavy metals of various Holocene and Anthropocene sedimentary sequences have allowed the reconstruction of relative sea level (RSL) in northern Spain. Based on the micropalaeontological and sedimentological content of modern sedimentary environments and their relationship with topographic elevation, the original depositional environment of the borehole samples (depositional elevation range of the SLIPs) were deducted by Leorri et al. (2012) following Gehrels et al. (2006) and Mauz and Bungenstock (2007).

Previous studies in northern Spain have shown that foraminifera correlate to elevation with respect to mean tidal level (Cearreta and Murray, 1996; Leorri and Cearreta, 2004; Leorri et al., 2008b). To date, only regional transfer functions have been carried out in the Basque coast (Leorri et al., 2008a, b, 2010) and used for the reconstruction of sea level in different salt marshes from this region (Leorri et al., 2008b; García-Artola et al., 2009; Leorri and Cearreta, 2009b). Therefore, it has been demonstrated that the observed recent sea-level rise during the 20th century represents a regional rather than a local process (García-Artola et al., 2011). Woodroffe and Long (2010) concluded that local transfer functions are more appropriate than regional ones. In this work, relative sea level is reconstructed using a short core obtained from recent materials by comparison with the modern distribution of similar elevation local surface samples. These results were compared with Holocene records from 10 long boreholes obtained in the Urdaibai estuary, with the aim to study the sea-level changes during the last 8500 years in northern Spain.

2 Study area: northern Spain

2.1 Geomorphological and geological features

The northern coast of Spain lies in an E-W orientation and is characterized by an erosive feature with continuous cliffs (Mesozoic-Caenozoic age), derived from tectonical activity (mountain building and uplifting) during most of the Cenozoic (Cearreta et al., 2002), limiting the natural space for estuaries to areas of structural weakness where sediment deposition takes place. Hence, sheltered salt marshes are confined to the inner parts of those small estuaries. In this coast, detrital sediment supply is the main control of salt marsh vertical accretion. Sediment depositional rates are a function of elevation and slow down as the salt marsh surface gains elevation in response to reduction of the frequency and duration of tidal inundation (Allen, 2000). As a consequence, salt marsh accretion is relatively slow and these environments appear underrepresented in the Holocene sedimentary sequences.

Along the northern coast of Spain, estuaries discharge their waters through their western side, while the eastern side is occupied by sand bars, beaches and dunes, controlled by the general E-W orientation of the coast and the dominant NW wind direction and wave approach (Cearreta et al., 2004). The powerful littoral dynamics, although dominated by NW winds, are also defined by westward transport of sediment due to less significant NE wind (Diez, 1999; Monge-Ganuzas et al., this volume).

The Urdaibai estuary (Fig. 1), located in the Basque coast (northern Spain, Bay of Biscay), is formed by the tidal part of the Oka River, showing a wedge shape in the inner zone and broadening and deepening seaward. The estuary covers an area of 765 ha, overlying an 11.6 km long and 1 km wide alluvial valley. The lower estuary is dominated by sand, while in the upper estuary mud becomes dominant, where salt marshes are more abundant.

The estuary has a semidiurnal tidal regime and a mesotidal range, with a mean tidal range of 2.5 m, a minimum variation of 1 m (neap tides) and the maximum variation of 4.5 m (spring tides) (Monge-Ganuzas, 2008). The average surface flow from the Oka river catchment area is 3.74 m^3 s^{-1} (Monge-Ganuzas, 2008) and rainfall varies seasonally from 145 mm during the wet season (November-April) to 74 mm during the dry season (May-October) (averages for the period 2001-2013; Gobierno Vasco, 2002-2014). The lower estuary presents higher salinity values throughout the year (31-42‰) reflecting the sea water entrance with tidal currents and waves, while the mid and upper estuary show variations as a consequence of the seasonal rainfall regime with lower values (1-25‰) during winter and increasing values (27-40‰) during summer, when the rainfall reaches its minimum (Cearreta, 1988).

2.2 Recent human impact

There is a large human pressure on the Basque coast, where 69% of people live within 15 km of the sea (Collet and Engelbert, 2013), causing an important human impact in the area since Roman times (Irabien et al., 2012). During the last three centuries, coastal ecosystems have been occupied initially with agricultural purposes and later to support the more recent urban and industrial settlement, covering around 50% of the original salt marshes (Cearreta et al., 2002). This human occupation has led to the destruction, size reduction and degradation of the environmental quality of these coastal areas. Rivas and Cendrero (1991) concluded that human occupation of salt marshes and other coastal intertidal areas has been the main geomorphological process in this coastal area during the last three centuries, creating new space for human activity and changes in the productivity of affected environments. This, in turn, has been proposed as a cause for the acceleration of geomorphic processes and the related increase in natural disasters at a global scale (Bruschi et al., 2013).

Since the agricultural decline during the 1950s, these previously reclaimed lands have been naturally regenerated and recolonised by halophytic vegetation, due to the lack of dyke maintenance and the entrance of estuarine water that invaded these once artificially isolated areas. In the last three decades, local authorities have implemented political decisions for their preservation, due to their ecological importance as highly productive environments. Hence, the Spanish Coastal Law passed in 1988 includes these coastal areas into the public domain, promoting their conservation. Furthermore, in 1984 the Urdaibai estuary was given UNESCO Biosphere Reserve status (Monge-Ganuzas et al., 2008).

3 Material and methods

3.1 Field techniques

3.1.1 Boreholes and short core extraction

In order to study the environmental evolution of the estuary during the Holocene, 10 boreholes (LA, SK, AN, MU, S2P, ER1, ER3, ER6, GK4 and S9) have been collected from different estuarine areas (Fig. 1; Table 1) using a rotary drill and obtaining a continuous record of approximately 10 cm in diameter. All boreholes reached the Mesozoic basement rock down to 49 m depth (Cearreta and Monge-Ganuzas, 2013).

Furthermore, in order to reconstruct the recent evolution (last ca 150 years), a short core (MUc) was collected in the central part of the Murueta salt marsh (Fig. 1; Table 1), in a small unvegetated area surrounded by halophytic vegetation, where two 50-cm long and 12.5-cm diameter PVC tubes were inserted by hand into the sediment.

The boreholes and short core were split longitudinally in two halves and different analytical methods were carried out. Once visually described and photographed, the boreholes were sampled at 30 cm intervals and the short core was divided in 1-cm thick samples.

Compaction of the sediment during the sampling process for the boreholes was corrected by measuring individual sections at the time of coring. This effect is considered negligible in the case of the short core due to the detrital nature of the sediment (Cearreta et al., 2002, 2013; Irabien et al., 2008). The effect that autocompaction can have in Holocene sea-level reconstruction was corrected by Leorri and Cearreta (2009c) by comparing samples with statistically similar radiocarbon ages recovered at different elevations above the basement-Quaternary contact, while in Anthropocene sea-level estimates the effect of autocompaction is considered negligible (Cearreta et al., 2013). Brain et al. (2012) analysed detrital sediments from salt marshes and concluded that autocompaction influence can be minimised by selecting short <1m uniform successions.

3.1.2 Surface sample collection

In 2010, ten surface samples were collected randomly around the Murueta short core (MUc; Fig. 1) and within the complete elevation range covered by the Murueta salt marsh (Table 1), in order to avoid possible autocorrelation between environmental variables (Telford and Birks, 2005). At each sampling site, two pseudoreplicates of 40 cm^2 each were collected by pressing a hard plastic ring into the sediment to minimize the patchiness of the foraminiferal distribution (Swallow, 2000; Kemp et al., 2011a). The top 1 cm of sediment, where modern foraminifera are concentrated (Cearreta et al., 2002; Leorri et al., 2008b), was placed in a plastic bottle containing ethanol for preservation until preparation in the laboratory for foraminiferal analysis.

3.1.3 Geographic location and topographic elevation measurement

Precise location and elevation of boreholes, short core and surface samples were determined in the field using a Global Positioning System-Real Time Kinematic (GPS-RTK) and a total station, with a horizontal precision of ±0.020 m and a vertical accuracy of ±0.035 m. UTM coordinates X, Y of samples are referred to the ED50 geographical system in planimetry and coordinate Z is referred to the local ordnance datum (LOD) (lowest tide at the Bilbao Harbour on 27th September 1878) in altimetry (Table 1), which is located 2.40 m below Bilbao MSL (Puertos del Estado, 2005, 2009).

3.2 Laboratory analyses

3.2.1 Micropalaeontological analysis

Samples were wet sieved through 1 mm and 63-micron sieves to remove large organic fragments and fine-grained sediments respectively. Sand size material (retained in 63-micron sieve) was oven dried at 50 °C and weighed. Foraminifera were concentrated by flotation in trichloroethylene as described by Murray (1979). Holocene samples were subdivided into fractions using a splitter and all specimens contained in a fraction were picked, and surface samples were stained using rose Bengal in order to recognise individuals that were alive at the time of collection following Walton (1952). In the surface samples, only dead assemblages were analysed because they are considered better analogues for past environmental reconstructions (Horton, 1999), since they represent a time-averaged accumulation of foraminifera. Foraminiferal tests were picked until a representative number of at least 300 individuals for each sample was obtained. Otherwise, all the available tests were picked and studied under a stereoscopic binocular microscope using reflected light. Short core foraminiferal results are expressed as number of foraminiferal tests per 50 g of dry sediment for standardisation.

3.2.2 Sedimentological analysis

Sand content (percentage of total dry weight) was determined during samples preparation for foraminiferal analysis by weighing the dry sediment retained at the 63-micron sieve after washing the whole sample to remove fine-grained material.

3.2.3 Geochemical analyses

Beta Analytic Inc. (Miami, USA) carried out radiocarbon dating and calibration of Holocene samples (12 shell, 6 wood, and 1 bone samples) and results were published in Leorri et al. (2012). Four of them were sufficiently abundant for standard radiometric analysis and the ^{14}C was quantified by measuring the amount of radioactivity produced during the radioactive transformation. The other 15 samples were dated through accelerator mass spectrometry (AMS) which permits the use of smaller samples and shorter counting periods, by separating and counting of ^{14}C atoms. Age estimates were calibrated using CALIB 5.0.1 (Stuiver et al., 2005) and reported as radiocarbon calibrated years before present (present=1950 CE). The dates obtained on shell material were also corrected for the marine reservoir effect (apparent surface-water age), which has been estimated to be around 400 years on the Bay of Biscay (Cearreta and Murray, 2000).

Recent sediments (less than 120 years) from the Murueta short core were dated through the short-lived isotope ^{210}Pb and supported by ^{137}Cs and total concentrations of Pb and Zn (see Leorri et al., 2008b and 2014 for discussion). ^{210}Pb and ^{137}Cs were analyzed at the Universitat Autònoma de Barcelona (Spain). Samples were dried in an oven at 60 °C until constant weight, dry bulk density and water content were determined. The activities of ^{137}Cs and ^{226}Ra were determined by gamma spectrometry using a coaxial high-purity Germanium detector (EG&G Ortec). Determination of total ^{210}Pb activities was carried out through the measurement of its daughter nuclide ^{210}Po by alpha spectrometry, following the methodology described in Sanchez-Cabeza et al. (1998). Excess ^{210}Pb activities were determined by subtracting the ^{226}Ra activity (assumed to equal the supported ^{210}Pb activity) from the total ^{210}Pb activity. The Constant Rate of Supply (CRS) model (Appleby and Oldfield, 1978) was applied to develop ^{210}Pb chronologies.

Metal concentrations were determined at Activation Laboratories Ltd. (Canada) by inductively coupled plasma-optic emission spectrometry (ICP-OES) after microwave digestion with aqua regia (Leorri et al., 2013).

3.3 Tide-gauge records analysis

Past sea-level reconstructions based on foraminiferal analysis were compared with tide-gauge records from Santander and Brest (locations indicated in Fig. 1) provided by the Permanent Service for Mean Sea Level (PMSL; Woodworth and Player, 2003).

4 Results and discussion

4.1 Relative sea-level changes during the Holocene

The foraminiferal assemblages found in 10 borehole sedimentary records from the Urdaibai estuary allowed the study of its environmental transformation (Cearreta and Monge-Ganuzas, 2013) and the reconstruction of relative Holocene sea level (Leorri et al., 2012). Cearreta and Monge-Ganuzas (2013) identified three systems tracts characterised by specific foraminiferal assemblages relative to their location within the upper, middle or lower estuary, and separated by a continuous stratigraphic surface that permits correlation. During low sea-level conditions sedimentary deposits (lowstand systems tract) were characterized by fluvial gravels and coarse sands without foraminifera and other marine fauna. As the marine transgression took place (locally dated between 8500-3000 cal BP; Leorri and Cearreta, 2004), coarse sediments were preserved by overlying estuarine deposits moving towards the continent (transgressive systems tract). The bottom part of this systems tract is represented by large volumes of marine sediments in the lower estuary, a mixture of marine and brackish sediments in the middle estuary and brackish materials in the upper estuary, and the top part (seaward), by open sea materials (such as abundant allochthonous foraminiferal tests) until a maximum flooding surface was reached at its upper limit. Finally, the highstand systems tract, that was deposited during the late Holocene (since 3000 cal BP until the salt marsh occupation at the beginning of the 18th century), represents intertidal and supratidal brackish conditions in the inner estuary, since this sedimentary sequences were formed during stable sea-level conditions, when modern salt marshes developed (Leorri and Cearreta, 2004; Cearreta and Monge-Ganuzas, 2013).

Leorri et al. (2012) selected representative samples of different estuarine environments and topographic elevations from these boreholes collected in the Urdaibai estuary (together with samples from the Bilbao and Deba estuaries), that combined with radiocarbon dating were used as sea-level index points (SLIPs) in order to reconstruct the relative sea-level curve over the last 10,000 years in northern Spain that shows two main phases: 1- rapid relative sea-level rise from -27 m asl at ca 10,000 cal BP to -5 m asl at ca 7000 cal BP; 2- a relatively slow sea-level rise ca 7000 cal BP between 0.3-0.7 mm y^{-1} (apparently stabilized around 3000 cal BP) until present anthropogenic rates were reached at the beginning of the 20th century. These results agree with previous studies that did not show evidence of sea levels above present position during the late

Holocene in the Basque coast (Leorri and Cearreta, 2004). Furthermore, these are also similar to background rates shown for southwest England and the Netherlands (Gehrels and Woodworth, 2013).

4.2 Relative sea-level changes during the Anthropocene

The Murueta salt marsh is located on the eastern bank of the Urdaibai estuary (Fig. 1), in the middle zone, where in 2010 a 50-cm long short core (two replicates) was extruded from an area dominated by *Halimione portulacoides* (L.) Aellen, *Elymus pycnanthus* (Godron) Melderis and *Juncus maritimus* Lam. vegetation (Benito and Onaindia, 1991). The short core was composed of light brown mud with plant roots in the upper 35 cm. Historical aerial photography shows no evidence of human impact in the recent past (Fig. 2), hence a natural evolution of the salt marsh at least during the time span between 1957 and 2008 was expected.

Benthic foraminiferal tests are abundant, considering the salt marsh environment, throughout the short core, as values of foraminiferal density/50g show an average of 27,289 tests (range 4417-131,316 tests). This short core contains exclusively agglutinated tests (Fig. 3): *Jadammina macrescens* (Brady, 1870) (average 74%; range 52-92%) and *Trochammina inflata* (Montagu, 1808) (average 23%; range 8-47%) are the dominant taxa. Species number (average 4 species; range 2-6 species) is very low throughout. The assemblages in the Murueta short core are invariable with depth and can be related to a high marsh environment (Cearreta et al., 2002; Leorri et al., 2008b), always above mean highest high water (Leorri et al., 2010).

Sand content (average 3%; range 1-8%) is very low throughout the sedimentary record (Fig. 3) in response to the lower energy of these areas with less tidal influence. The dominance of fine-grained sediments supports the palaeoecological interpretation as a high salt marsh.

In order to make good palaeoenvironmental reconstructions, it is assumed that buried foraminiferal assemblages are closely similar to modern assemblages (Jennings and Nelson, 1992; Guilbault et al., 1995) and the distribution of modern assemblages has to be understood (Phleger and Walton, 1950; de Rijk and Troelstra, 1997). Preliminary studies in the region (Cearreta et al., 2002; Leorri et al., 2008b; 2010) indicate that modern analogues derived from surface samples can be used to interpret buried assemblages and reconstruct palaeoenvironmental changes including quantitative sea-level reconstructions (Leorri et al., 2008b; Garcia-Artola et al., 2009; Leorri and

Cearreta, 2009b). In this sense, the analysis of the surface samples collected in the Murueta salt marsh showed that they are entirely composed of agglutinated species, where *J. macrescens* (average 76%; range 58-86%) and *T. inflata* (average 24%; range 14-40%) are dominant. The rest of the species are very scarce (maximum relative abundance =2%) and species number is low (average 3 species; range 2-5 species). Hence, foraminiferal assemblages in surface and core samples are similar. Since the Murueta short core has been interpreted as a high marsh environment through time, the salt marsh has maintained its elevation, remaining as a persistent environment at least during the time span recorded. We, therefore, conclude that palaeomarsh elevation (PME) is equivalent to modern elevation (4.128 m above LOD) and determine that vertical core samples error is ±6 cm (corresponding to the standard deviation of the modern surface samples elevations that cover the current salt marsh platform) (Fig. 3). This method resembles the visual assessment described by Long et al. (2010). These authors indicated that this interpretation is based on the narrow distribution of certain species to reconstruct palaeomarsh elevation and it performs best in high marsh elevations where taxa occupy small vertical zones. As indicated above, this setting corresponds to high marsh environment dominated by only two species (*J. macrescens* and *T. inflata*) with a vertical range of 4.13±0.06 m.

The ^{210}Pb profile shows a typical exponential decline with depth, which suggest minimal sediment mixing or does not indicate any sedimentological disruption. This, in turn, suggests that this short core can supply a reliable chronology based on ^{210}Pb. This chronology has been provided by means of the CRS model and supported by a clear ^{137}Cs activity peak at 16 cm depth that can be assigned to 1963 (Fig. 3).

Chronology is further supported by total Pb and Zn profiles that suggest two concentration peaks in 1975 (at 12 cm depth) and 1965 (at 16 cm depth), respectively (Leorri et al., 2008b, 2014; Leorri and Cearreta, 2009b). The total Pb concentration profile shows a clear deviation from pre-industrial (background) values at 20 cm depth that has been associated with the 1900s (Leorri et al., 2014). Error ranges in Fig. 4 are estimated from the atmospheric emissions compiled in Olendrzyński et al. (1996).

The reconstructed RSL curve was obtained by subtracting the above explained PME from the modern elevation of each short core sample and plotted against the age, obtaining the consequent sea-level variation curve for the last 150 years (Fig. 4). Applying a mid-point linear regression we obtain a sea-level rise rate of 1.7±0.2 mm y^{-1} during the 20th century (error calculated at the 95% confidence). When the vertical error of individual samples is included in the calculations the trend error increases up to ±0.4 mm y^{-1} (Lyons, 1991). The rate obtained here is comparable to previous regional studies that range from 2.0±0.3 mm y^{-1} for the period 1884-1994 (Leorri et al., 2008b) and 2.0 mm y^{-1} for the 20th century (Garcia-Artola et al., 2009) to 1.9±0.3 mm y^{-1} since 1923 (Leorri and Cearreta, 2009b). However, the sea-level rise rate obtained based on the local transfer function is lower and improves the vertical error of the previous reconstructions that has been reduced from ±7.8 cm reported by Leorri et al. (2008b) and ±5.3 cm reported by García-Artola et al. (2009) to the present ±3.5 cm. Comparable 20th century accelerations have been determined based on similar foraminifera-based reconstructions developed in SW Europe (Rossi et al., 2011) and the Atlantic coast of North America (Gehrels et al., 2005; Kemp et al., 2009). Kemp et al. (2011b) reported a more abrupt acceleration at the beginning of the previous century than other authors for the West Atlantic coast, whereas Long et al. (2014) ascribed it to a local sea-level signal.

In order to validate this information, we compared the geological reconstruction with the closest tide-gauge record located at Santander (Fig. 4), and despite the differences in the time covered by both reconstructions, they present similar trends. The Santander tide-gauge record provides a rate of 2.08±0.33 mm y^{-1} for the period 1943-2004 (Chust et al., 2009), a figure slightly higher than the geological reconstruction. But if we constrain the analysis of the geological record to an analogous time period (1937-2004) we obtain a rate of 2.1 mm y^{-1}, similar to the rate presented by the Santander tide-gauge record. The Brest tide-gauge record provides a comparable trend, although it exhibits a lower rate (1.4 mm y^{-1}) for the 20th century (Wöppelmann et al., 2007). These disagreements could be explained by different vertical land motions (e.g., Leorri et al., 2012; 2013) or water masses redistribution resulting from atmospheric (Marcos and Tsimplis, 2008) and steric contributions (Tsimplis et al., 2011). At the same time, these differences strongly suggest the need to perform local reconstructions since sea-level changes occur at different time and spatial scales.

We can conclude that sea-level rise rate in the Urdaibai estuary during the 20th century was 3-6 times higher than the reconstructed rate for the last 7000 years. No such rates have been found during the upper Holocene, although the analytical resolution of the boreholes and the short core is very different. Therefore, longer salt marsh records should be analysed, which would provide higher resolution reconstructions in order to check possible similar rates through the late Holocene and help to improve future estimations of sea level by comparison with the sedimentary records of the past.

5 Conclusions

The Holocene relative sea-level rise rates obtained using estuarine sedimentary records are essential to understand the significance of the modern and future sea-level behaviour. Sea-level changes show two main phases based on the analysis of SLIPs defined from the Holocene sedimentary records and the information previously published for this coastal area indicates that a rapid relative sea-level rise of 9-12 mm y^{-1} from -21 m to -5 m took place since 8500 until 7000 cal BP, and it was followed by a moderate sea-level rise of 0.3-0.7 mm y^{-1} since 7000 cal BP until 20th century. However, the recent sea-level rise rate reconstructed based on the modern vertical distribution of microfossils in the Urdaibai estuary is 1.7±0.2 mm y^{-1} during the 20th century, which is 3-6 times higher than the sea-level rise rate registered for the upper Holocene, probably related to the human impact of climate change.

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Figure and Table captions

Figure 1. Geographic location of the Urdaibai estuary in the Basque coast (northern Spain, Bay of Biscay), collected boreholes and short core. 1: Brest tide gauge. 2: Santander tide gauge.

Figure 2. Location of the Murueta core (dot) in historical (1957: left side) and modern (2009: right side) aerial photographs.

Figure 3. Core photograph, sand content (%), main foraminiferal species (1: *J. macrescens*; 2: *T. inflata*) (%), palaeomarsh elevation (PME, m), ^{210}Pb and ^{137}Cs activities (Bq kg^{-1}) and total Pb and Zn distribution (mg kg^{-1}) with depth (cm) in the Murueta salt marsh core. Ages based on the CRS model, the ^{137}Cs peak and total Pb and Zn are shown.

Figure 4. Relative sea-level curves for the last two centuries in the Bay of Biscay based on geological and instrumental data. A: Relative sea-level curve from the Murueta salt marsh based on foraminiferal reconstructions. The normal and dashed lines represent sea-level trend derived from Anthropocene data and ranges of sea-level trends derived from late Holocene data respectively (see text for discussion). B: Annual relative sea-level values recorded at the Santander tide gauge. C: Annual relative sea-level values provided by the Brest tide gauge.

Table 1. Geographical location of boreholes, short core and surface samples from the Urdaibai estuary. X, Y: ED50 UTM coordinates; Z: m above LOD (see text).

Figure 1

Click here to download high resolution image

Figure 2

Click here to download high resolution image

Figure 3

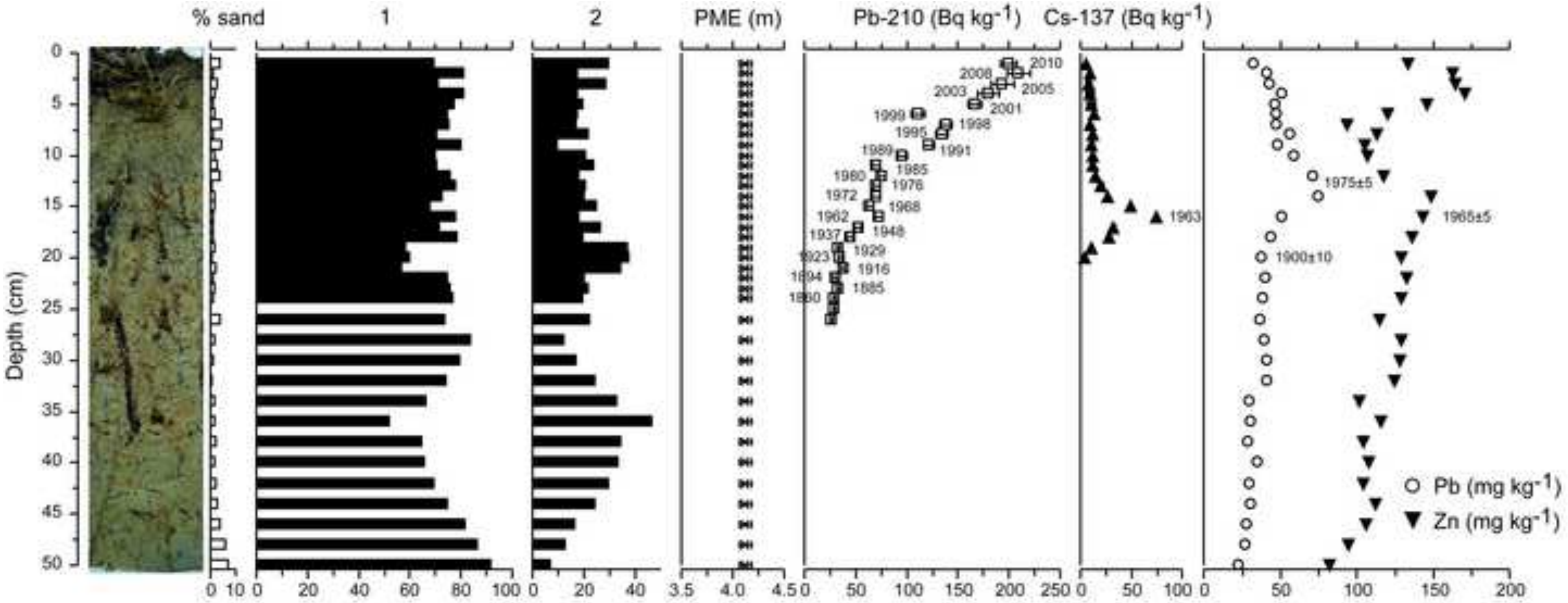
% sand
1
2
PME (m)
Pb-210 (Bq kg^{-1})
Cs-137 (Bq kg^{-1})
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
0 10
0 20 40 60 80 100
0 20 40
3.5 4.0 4.5
0 50 100 150 200 250
0 50 100
0 50 100 150 200
2010
2008
2005
2003
2001
1999
1998
1995
1991
1989
1985
1980
1976
1972
1968
1962
1948
1937
1929
1923
1916
1894
1885
1880
1963
1975±5
1965±5
1900±10
○ Pb (mg kg^{-1})
▼ Zn (mg kg^{-1})

Figure 4

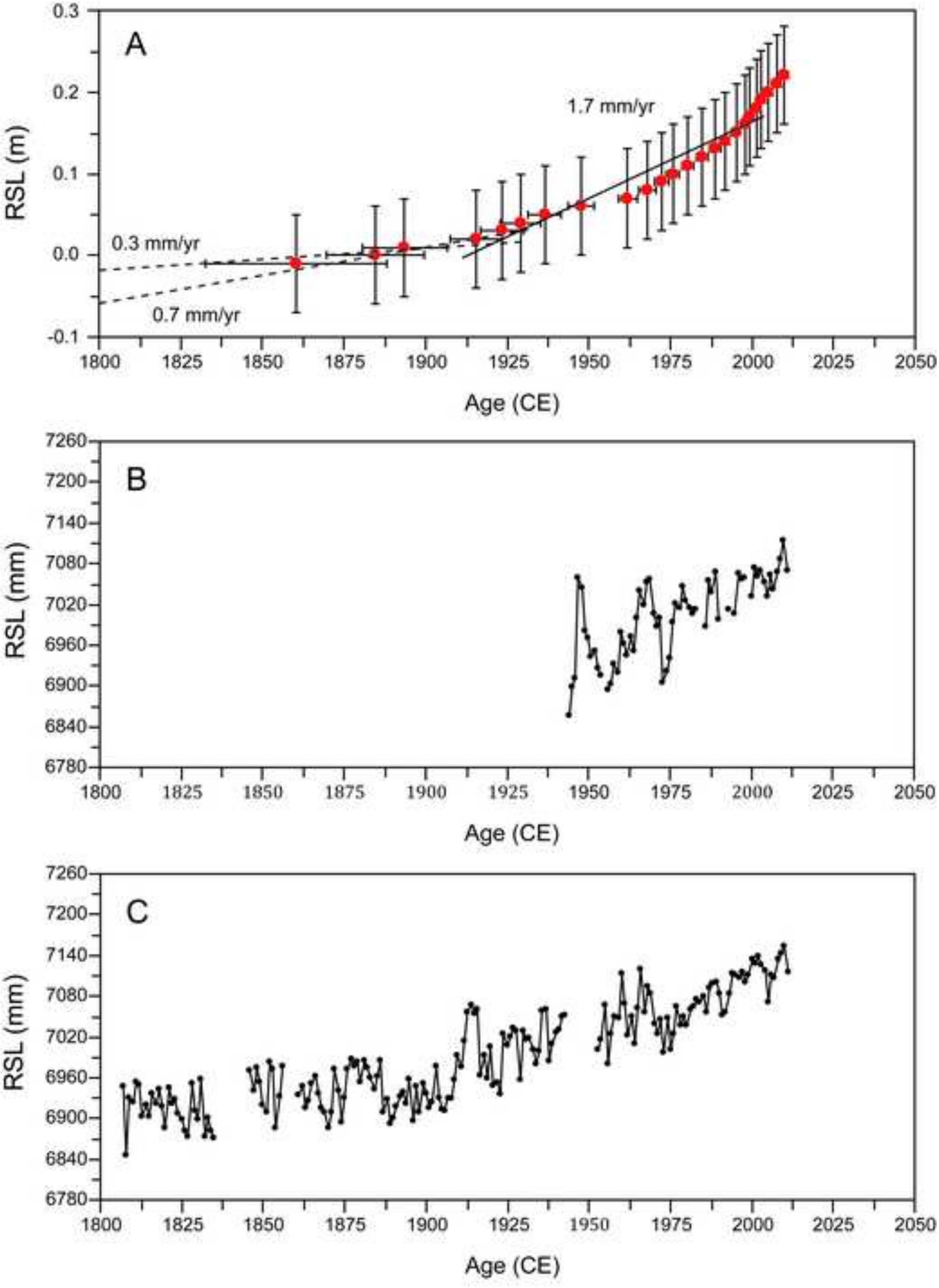
A
0.3
0.2
0.1
0.0
-0.1
RSL (m)
1.7 mm/yr
0.3 mm/yr
0.7 mm/yr
1800
1825
1850
1875
1900
1925
1950
1975
2000
2025
2050
Age (CE)
B
7260
7200
7140
7080
7020
6960
6900
6840
6780
RSL (mm)
Age (CE)
C
RSL (mm)
Age (CE)

Table 1

	COORDINATE X	COORDINATE Y	COORDINATE Z
BOREHOLES			
LA	525,428.556	4,805,410.499	4.700
SK	525,660.058	4,802,137.528	5.290
AN	526,362.994	4,801,715.831	3.510
MU	526,703.438	4,800,533.678	4.130
S2P	527,019.780	4,798,361.520	4.680
ER1	526,320.441	4,796,642.703	5.490
ER3	526,360.201	4,796,626.788	6.390
ER6	526,387.007	4,796,622.489	6.380
GK4	526,413.524	4,795,971.361	7.200
S9	526,379.117	4,795,889.287	7.730
SHORT CORE			
MUc	526,802.569	4,800,597.458	4.128
SURFACE SAMPLES			
1	526,827.528	4,800,589.605	4.057
2	526,816.239	4,800,567.973	4.100
3	526,795.276	4,800,559.135	4.180
4	526,783.436	4,800,574.667	4.088
5	526,778.928	4,800,592.849	4.065
6	526,791.666	4,800,607.952	4.057
7	526,803.214	4,800,614.118	4.026
8	526,818.468	4,800,633.504	4.009
9	526,843.827	4,800,611.543	4.039
10	526,845.816	4,800,583.283	4.169