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To cite this version:

Guillem Chust, Angel Borja, Ainhoa Caballero, Xabier Irigoien, Sáenz Jon, et al.. Climate change impacts on coastal and pelagic environments in the southeastern Bay of Biscay. Climate Research, 2011, 48, pp.307-332. 10.3354/cr00914 . hal-01550539

HAL Id: hal-01550539
https://hal.science/hal-01550539

Submitted on 29 Jun 2017

Vol. 48: 307–332, 2011
doi: 10.3354/cr00914

CLIMATE RESEARCH
Clim Res

Published August 30

Contribution to CR Special 27 'Climate change in the NW Iberian Peninsula'

Climate change impacts on coastal and pelagic environments in the southeastern Bay of Biscay

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ABSTRACT: The impacts of global climate change on the Basque coast and the pelagic systems within the southeastern Bay of Biscay are reviewed. Climate projections under greenhouse gas emission scenarios indicate that this area will experience changes in climate throughout the 21st century, including warming of surface air (especially heat wave episodes), intensification of extreme daily rainfall (10 %), warming of the upper 100 m of the ocean layer (1.5 to 2.05°C), and sea level rise (SLR; 29 to 49 cm). Observations made in the bay throughout the 20th century for air temperature and mean sea level are in agreement with these projections. Trends in ocean-climatic historical observations within the area, including sea temperature, precipitation, upwelling/downwelling, turbulence and wave climate, are also reviewed. The main impacts on the coast are expected to be from SLR, especially in low-lying areas (mostly urbanised) within estuaries. Sandy beaches are also expected to undergo significant mean shoreline retreats of between 25 and 40 % of their width. As the sea level rises, the natural migration of saltmarshes and intertidal seagrasses landward will be constrained, in most cases, by existing anthropogenic fixed boundaries. Empirical relationships between the distribution and dynamics of the long-term biological measures (plankton, primary production, benthos, and fisheries) on the one hand, and ocean-climatic variability on the other, indicate that pelagic and coastal water ecosystems will be affected by ocean warming, increased stratification, shifts in anomaly patterns and streamflow regimes. The largest uncertainties are associated with the lack of downscaled projections within the bay on ocean circulation, ocean-meteorological indices, wave climate and ocean acidification.

KEY WORDS: Climate change · Bay of Biscay · Basque Country · Coast · Sea level · Temperature · Precipitation · Saltmarsh · Review

1. INTRODUCTION

According to the projections of global climate models provided by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4, IPCC 2007), under future greenhouse gas (GHG) emission scenarios, a warming of the mean surface air and sea of the Bay of Biscay (for locations, see Fig. 1a), especially in the upper layers of the water column, is expected by the end of the 21st century (Meehl et al. 2007). A direct consequence of seawater warming is the thermal expansion of oceans, together with a rise in the thermosteric mean sea level (Reid et al. 2009), which may affect the coastal zones of the bay. Extensive literature covers future threats of global climate change expected for the next century over the world oceans (e.g. Reid et al. 2009) and coasts (see reviews by Nicholls et al. 2007 and FitzGerald et al. 2008). However, the resolution of all of the atmosphere–ocean general circulation models (AOGCMs) is insufficient for predicting changes in

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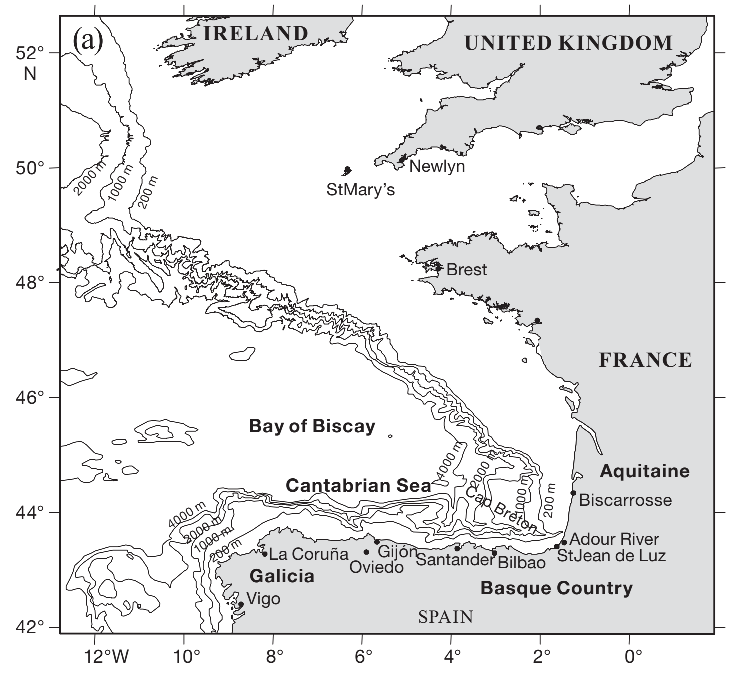
ocean current circulation in the southeastern Bay of Biscay (Fig. 1). Likewise, the location of the Iberian Peninsula, within a transitional zone between oceanic temperate and the dry subtropical climate (Barry & Chorley 2003), makes it difficult to predict the future climate regime (especially precipitation) over the area. Downscaling data from global climate models to represent smaller areas is important in obtaining accurate climate projections at regional scales (e.g. Penduff et al. 2010), and for defining local adaptation strategies to climate change.

The vulnerability of the Basque coast and its marine environment to potential change in present climate regimes is increased by the demographic pressure, the overexploitation of resources and the high human use of the marine space. The coastal zone supports 60% of the overall population of the Basque Country (2.1 million inhabitants) and 33% of the industrial activities (Cearreta et al. 2004), including other activities, such as fisheries, tourism and renewable energies (Galparsoro et al. 2010). This coast is dominated by rocky substrata with vertical cliffs intercalated with small estuaries with sandy beaches; it 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). Hence, the sea cliffs and hilly relief limit and confine the extent of the sandy beaches, saltmarshes, urban settlements and industrial zones along the coast. Concerning specifically the environmental and biological conservation of intertidal systems, the demographic and urban pressure on the Basque coast has led to extensive loss, squeeze and degradation of the littoral habitats during the 20th century (Chust et al. 2009). Similarly, fishing stocks within the bay can also be vulnerable to climate change (Clemmesen et al. 2007), especially when they are overexploited (Planque et al. 2010). An efficient adaptation of these human activities, in response to global climate change, requires an integrated understanding of regional climatic changes to local impacts on habitats and species.

Hence, the objective of this paper was to review the scientific literature on climate change impacts within the Basque coastal systems and the pelagic environment, within the regional context of the Bay of Biscay (Fig. 1). An integrated 'state-of-the-art' review of the climate change in the area, based upon the main studies undertaken to date, is presented. Climatic observations throughout the recent past (most within the 20th century), together with the regional climate change scenarios for the 21st century, are reviewed. Subsequently, the anticipated impacts according to these scenarios on coastal systems (sandy shores, estuaries, saltmarshes and biodiversity) and on the pelagic environment (primary production and fisheries) are presented, together with the observed trends and variability throughout the past decades. The main conclusions are then presented, summarising the review.



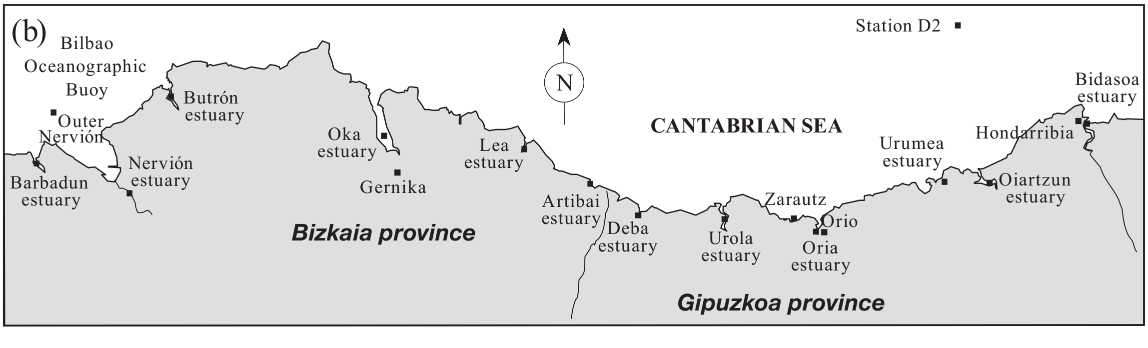


Fig. 1. (a) Bay of Biscay and (b) Basque Country. All locations cited in the text and the most important features are shown

2. CLIMATIC VARIABILITY AND TRENDS

2.1. Air temperature and atmospheric variability

2.1.1. Observations in the 20th century

Brunet et al. (2007) used the Spanish Daily Adjusted Temperature Series (SDATS) dataset to identify the main patterns of spatial and temporal variability of daily maximum and minimum temperature over Spain. A very important latitudinal gradient of variability exists over the Iberian Peninsula. During the period 1901–2005, the trend in the annual temperature of the northern part of the Iberian Peninsula was about 0.13°C decade^{-1} (dec^{-1}), with a 95% confidence interval lying between 0.09 and 0.16°C dec^{-1}. This trend in the annual temperature is much higher during the last part (1973–2005) of the instrumental period, with a central estimate of the trend given by 0.51°C dec^{-1}, with a 95% confidence interval of 0.36–0.69°C dec^{-1}. The analysis performed in terms of percentiles showed an increase in the number of hot days and a decrease in the number of cold days, with a 99% confidence level (Brunet et al. 2007). Other studies (Sáenz et al. 2001b) showed similar trends (0.2–0.3°C dec^{-1}) during winter, for a denser set of stations over land locations along the Cantabrian coast (reference period 1950–1996).

Aravena et al. (2009a) used monthly anomalies of temperatures and teleconnection indices (1997–2006) and found a significant correlation between air temperature over the Basque Country and the North Atlantic Oscillation (NAO) index. This result is not consistent with previous results obtained by other researchers who focused upon longer winter temperature series (Pozo-Vázquez et al. 2001, Sáenz et al. 2001a, Castro Díez et al. 2002, Frías et al. 2005). Therefore, it seems that the relationship between the NAO and the temperature over the area is dependent upon season or the length of the time series being analysed.

Following Sáenz et al. (2001b), winter temperature over southwestern Europe is dependent on the variability of the sensible heat fluxes under average circulations, with eddy (baroclinic) heat fluxes playing no significant role in the temperature variability. Conversely, variability in precipitation is driven by variability in baroclinic disturbances over the area and the structure of the Atlantic storm track. This explains the different sensitivity of temperature and precipitation to teleconnection indices over the area. However, recent studies have emphasised that a small fraction of the predictability of winter precipitation over the Cantabrian coast might depend in a non-linear way on the state of the El Niño Southern Oscillation (ENSO) events (Frías et al. 2010).

2.1.2. Projections for the 21st century

Based upon future projections of climate at a 50 × 50 km^2 horizontal resolution, provided by the EU project PRUDENCE (Christensen et al. 2007a) for different IPCC emissions scenarios (Nakicenovic et al. 2000), Abanades et al. (2007) analysed the expected change of several climatic variables. They showed that the seasonal mean temperature anomaly, for the period 2071–2100 compared to the period 1961–1990, over the Basque Country will vary from 5 to 7°C in summer and 3 to 4°C in winter for the A2 scenario. In the coastal area, these values will reduce to 2°C for the A1 scenario, both in summer and winter, and 3°C in summer and 1°C in winter for the B1 scenario. Depending upon the season, the maximum temperature anomalies will vary between 1.5 and 2.5°C in winter and 4.5 to 7°C in summer. During the last third of the 21st century, the increase of the monthly maximum temperature is expected to be 1.5°C at the coast and 3.5°C inland. The increase in monthly minimum temperatures (Tmin) during the same period will probably range between 1 and 1.5°C at the coast and 2.5 to 3°C inland.

Abanades et al. (2007) identified a positive trend in the daily thermal oscillation (Tmax – Tmin), with daily maximum temperatures increasing more than the mean and minimum temperatures. In the last third of the century, for the A2 scenario, the increase in maximum temperatures will be 0.5°C higher than those of the mean temperatures, whereas daily minimum temperatures will be 0.4°C lower than those of the mean temperatures. These changes will be weaker during winter and more pronounced during spring and summer, particularly along the southern parts of the Cantabrian coast.

The 2 m air temperature and humidity outputs in the Basque Country have been studied (authors' unpubl. data) using 6 Regional Climate Models (RCMs) from the ENSEMBLES project (Hewitt 2005), which performed simulations for Europe at 25 × 25 km^2 horizontal resolution for the A1B emission scenario (Nakicenovic et al. 2000). The control period was 1978–2000. In winter, the 10th percentile of the minimum temperature showed a positive trend (Fig. 2a) with an increase of up to 3°C at the end of the century with a maximum standard deviation of 0.9°C. The range in the 10th percentile of minimum temperatures within the control period is –5.5 to –2.0°C; in turn, for the period 2070–2099, this value will range from –3.5 to 1.0°C. All of the models showed a 50% decrease in the number of frost days (Tmin < 0°C) at the end of the century. Consequently, both the duration and frequency of cold waves will decrease. Cold-wave episodes (6 consecutive days having temperatures lower than the seasonal temperature for the control period by 5°C) are expected to dis-

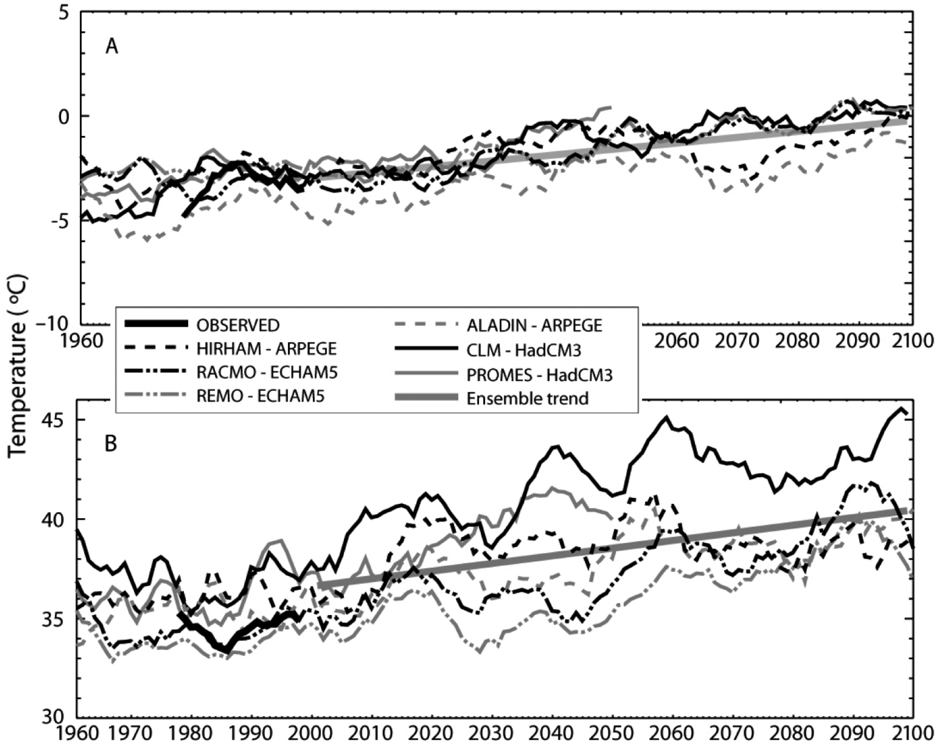


Fig. 2. Time-series of (A) 10th percentile of winter minimum temperature and (B) 90th percentile of summer maximum temperature for 6 regional climate models compared with observations during the control period (1978–2000)

appear beyond 2020. In summer, a positive trend of the 90th percentile of daily maximum temperature is expected (Fig. 2b), with an increase of up to 3°C and a maximum standard deviation of 1.4°C. The range of the 90th percentile of maximum temperatures in the control period is 34 to 38°C; for the last 3 decades it was 37 to 45°C. Heat-wave episodes (6 consecutive days having temperatures higher than the seasonal temperature for the control period by 5°C), will increase in duration and, to a lesser extent, occurrence. In the control period, only 12% of the days in the summer could be considered as a heat wave episode. Nevertheless, the rate of change is likely to increase between 2020 and 2050, when the number of heat waves is expected to increase to 16%, with further increases to 22% by the end of the century.

2.2. Mean and extreme precipitation

2.2.1. Observations in the 20th century

Global warming could cause a regime change in average and extreme rainfall at regional and local levels (Allan & Soden 2008, O'Gorman & Schneider 2009). However, due to the high natural variability of precipitation, it is difficult to observe these changes during the short time series of available observations (Rodrigo et al. 1999). Over the Iberian Peninsula, total annual precipitation generally showed no significant changes during the 20th century, except for the most southern areas (deCastro et al. 2005). During the second half of that century, some northern inland areas showed a decrease in annual rainfall, for example at the station of Oviedo (–7 ± 3 [SE] mm yr^{-1}; Serrano et al. 1999, Mossmann et al. 2004, De-Luis et al. 2008), especially in spring and winter (Lopez-Bustins et al. 2008; Table 1). The decrease in rainfall is particularly marked in March (Serrano et al. 1999, Mossmann 2002), as in the rest of western Europe (Kiely et al. 1998), and could be due to an increase in the NAO index (Bárdossy & Caspary 1990, Hurrell 1995), since it causes a decrease in the frequency of Atlantic low-pressure systems crossing southern Europe during March (Visbeck et al. 2001, Mossmann 2002). However, this was not observed in the Basque Country, where mean rainfall did not change between 1961 and 2000 (–1 ± 3% dec^{-1}; Fig. 3), a result derived using monthly and daily data from 132 meteorological stations (Moncho et al. 2009). These results are consistent with a similar analysis undertaken by Trigo et al. (2008). The NAO is probably not the main factor affecting precipitation over the northern coast of the Iberian Peninsula (Trigo et al. 2008, Aravena et al. 2009a), particularly during the winter season (Sáenz et al. 2001c).

Table 1. Changes in regimes of precipitation within the Iberian Peninsula and northern Europe for the 20th century. Changes are statistically significant (5% significance level) except where noted. NS: not significant

Location	Period	Precipitation	Observed change	Source
Igeldo	1951–1995	Annual	NS	Serrano et al. (1999)
Oviedo	1921–1995	Annual	-7 ± 3 mm yr^{-1}	Serrano et al. (1999)
Basque Country	1961–2000	Annual	-1 ± 3% decade^{-1} (NS)	Moncho et al. (2009)
Basque Country	1961–2000	Winter and spring	-0.3 ± 0.6% decade^{-1} (NS)	Moncho et al. (2009)
Iberian Peninsula	1958–2000	Winter	<0 (NS)	Lopez-Bustins et al. (2008)
Northern Spain	1958–2000	Winter	<0	Lopez-Bustins et al. (2008)
Northern Spain	1961–1990	September	<0	Mosmann et al. (2004)
Northern Europe	1901–2000	Extreme	$+6 \pm 4$%	Mokhov et al. (2005), Khon et al. (2007)
Iberian Peninsula	1958–1997	Extreme	<0	Gallego et al. (2006)

Regarding extreme events, a significant increase (4 to 8%) in heavy rainfall over the 20th century has been observed in northern Europe (Mokhov et al. 2005, Khon et al. 2007; see Table 1). Over the Iberian Peninsula, some studies have reported a slight tendency to an increase in light-rain days and a decrease in heavy-rain days for observatories located over the region (Gallego et al. 2006), together with an increase in dry spells in autumn and a decrease in summer. However, reanalysis of climate showed no significant changes over the Iberian Peninsula, revealing discrepancies between the different reanalyses (Zolina et al. 2004).

2.2.2. Projections for the 21st century

According to different regional projections of climate change for the 21st century, changes in the mean and extreme precipitation regimes are expected over most of Europe (Christensen et al. 2007b), with an annual precipitation increase (10 to 40%) in northern Europe, and decreases (10 to 20%) in the Mediterranean basin. Over the northern Iberian Peninsula, a decrease in annual rainfall of 10 to 30% is expected according to the A2 scenario, and 15 to 20% under the A1B scenario (Rummukainen et al. 2004, Christensen et al. 2007b), with high uncertainty (Tapiador et al. 2007). The average summer rainfall for 2070–2100 will decline over most of Europe, being more important in France, Spain and Portugal (25 to 75%; Déqué et al. 2007, Goubanova & Li 2007). In the south of Europe, a decrease in the average rainfall in winter and spring is also expected (Goubanova & Li 2007, De-Luis et al. 2008).

The projections for 2070–2100 in intense precipitation indicate a significant increase over almost all European regions, even where the average precipitation is expected to decrease (Semenov & Bengtsson 2002, Semmler & Jacob 2004, Goubanova & Li 2007). However, for the Iberian Peninsula there is no consensus on the changes in extreme precipitation for 2070–2100. On the one hand, Semmler & Jacob (2004) predicted a decrease of 50% in extreme rainfall within return periods of 10 and 20 yr, compared to 1961–1990. However, Goubanova & Li (2007) found an increase of 10–20% for extreme rainfall (30 yr return period) by the 21st century, in comparison to the period 1970–1999. The location of the Iberian Peninsula within a transitional climate regime between oceanic temperate and the dry subtropical climate (Barry & Chorley 2003) makes it difficult to predict future rainfall over the area.

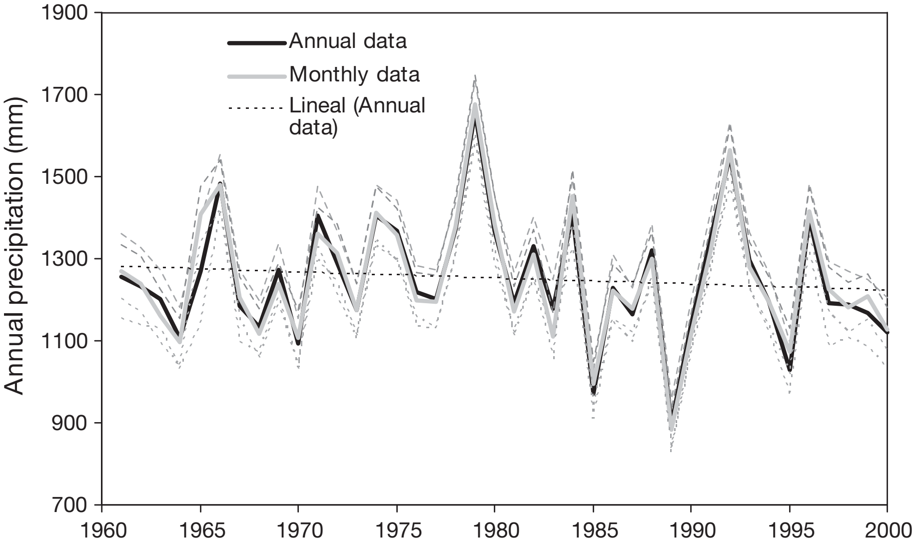


Fig. 3. Time-series of annual precipitation in the Basque Country for 1961–2000, reconstructed with monthly and annual available data. Grey dashed lines: 95% confidence interval. Modified after Moncho et al. (2009)

For the Basque Country, Moncho (2009) used 4 RCMs (METNO-HIRHAM, UCLM-PROMES, KNMI-RAKMO2 and CNRM-RM4.5), under the A1B scenario, extracted from the ENSEMBLES project (Niehörster et al. 2008), to assess rainfall projections throughout the 21st century. The average of the simulated trends for the period 1961–2050, according to the calibrated climate models, gives a slight decrease (–0.7 ± 0.3% dec^{-1}; $p < 0.05$). With a return period of 50 yr for a meteorological station on average, the 2 models (METNO and UCLM) that best fit the 1961–2000 reference period show an increase of 12 ± 1% in daily rainfall for the period 2001–2050, with respect to 1961–2000. The KNMI model projects an increase in extreme rainfall for the period from 2051–2100 of 7.7 ± 0.7%. Thus, these results suggest that extreme precipitation over the Basque Country may be expected to increase by around 10% throughout the 21st century. The decrease in the mean precipitation in the Basque Country for the 21st century, together with the increase in the extreme regime, could be due to increased influence of the Mediterranean by the expansion of the Hadley cell (Hu & Fu 2007, Lu et al. 2007).

2.3. Sea temperature

2.3.1. Observations in the 20th century

A great part of the heat excess produced in the atmosphere in the 20th century, as a result of anthropogenic activities and from natural events, has been exchanged with the ocean; this is due to the high specific heat of water. In the world ocean, the mean temperature from the surface to a 700 m depth has increased 0.17°C between 1969 and 2008 (Levitus et al. 2009). This temperature rise has not been geographically homogeneous. In particular, the temperature increase that occurred in the Atlantic Ocean (0.30°C) within the 1969–2008 period is more than twice that observed in the Indian (0.11°C) or Pacific Oceans (0.12°C; Levitus et al. 2009).

Within the Bay of Biscay, the sea surface temperature (SST) decreased at a rate of 0.01°C yr^{-1} from 1867–1910; subsequently, it began to increase until 1945 (0.02°C yr^{-1}), when another cooling period remained until 1974 (0.01°C yr^{-1}). From 1974–2007, the temperature increased at a rate of 0.02°C yr^{-1} (deCastro et al. 2009; Table 2). Based on different sources of measurements, Koutsikopoulos et al. (1998) found that between 1972 and 1993, the Bay of Biscay SST showed an increase of 0.064°C yr^{-1} (Table 2). In general, sea temperature is highly dependent upon spatial and temporal scales. Besides the long-term trends, sea temperature follows its own natural cycles (e.g. daily and seasonal cycles, 11 yr cycle of solar activity, 18.6 yr lunar nodal cycle). Therefore, it is possible to observe opposing trends when different time periods are considered. In addition, when longer time series are considered, natural cycles can be determined and removed from the time series in order to compute the long-term change. With regard to the spatial variability, Koutsikopoulos et al. (1998) concluded that within the Bay of Biscay and for the analysed time period, the highest SST increase occurred in the southeastern part. Different results were obtained by Gómez-Gesteira et al. (2008) for the period 1985–2005. In this case, the SST warming rate was higher to the north, being the highest in the northwestern Bay of Biscay.

For the southeastern Bay of Biscay, the SST time series recorded on a daily basis at the Aquarium of San Sebastián (see Fig. 1b) for the period 1947–2001 indicates a decreasing trend in the mean annual temperature; this is due to the warm periods at the end of the 1940s and the 1960s (Borja et al. 2000). However, Koutsikopoulos et al. (1998), investigating a series com-

Table 2. Annual mean rates of sea surface temperature (SST) within the Bay of Biscay, according to different locations, methods and authors (for locations, see Fig. 1). All measurements at surface depth, except santander (200 to 1000 m). CTD: conductivity, temperature and depth casts

Location	Time period	Method	Rate (°C yr^{-1})	Source
Open water of Bay of Biscay	1867–1910	Satellite and reconstructed SST	–0.01	deCastro et al. (2008b)
	1910–1945	Satellite and reconstructed SST	0.02	deCastro et al. (2008b)
	1945–1974	Satellite and reconstructed SST	–0.01	deCastro et al. (2008b)
	1974–2007	Satellite and reconstructed SST	0.02	deCastro et al. (2008b)
	1972–1993	Vessels and meteorological buoys	0.064	Koutsikopoulos et al. (1998)
San Sebastián	1947–1977	Thermometer	–0.023	González et al. (2008); Goikoetxea et al. (2009)
San Sebastián	1977–2007	Thermometer	0.026	González et al. (2008); Goikoetxea et al. (2009)
Station D2	1986–2008	CTD	0.01	Revilla et al. (2010)
Santander	1992–2003	CTD	0.02–0.03	González-Pola et al. (2005)

mencing in the 1970s cool period and extending until 1993, found an increasing temperature trend for the southeastern Bay of Biscay. Of several SST time series, the monthly and seasonal analyses indicate increasing trends for 1971–1998, or for some specific sub-periods such as 1991–1995 (Lavín et al. 1998), 1986–1990 (Valencia 1993) and 1986–2003 (ICES 2004). This pattern shows that increasing trends are related more to mild winter SST periods than to very high summer SST values (Koutsikopoulos et al. 1998, Borja et al. 2000). As for seasonal variability, the highest temperature rise (0.08°C yr^{-1}), corresponding to the 1985–2006 period, was observed in spring (deCastro et al. 2009). Additionally, recent studies have revealed an SST increase over the last 3 decades in San Sebastián and at another station (D2) also located on the continental shelf of the southeastern Bay of Biscay. The SST time series recorded in San Sebastián reflects a decrease of 0.23°C from 1947–1977, together with an increase of 0.026°C yr^{-1} from 1977–2007 (González et al. 2008, Goikoetxea et al. 2009, Table 2). At the D2 offshore station (see Fig. 1b), the SST from 1986–2008 showed an increase of 0.01°C yr^{-1} (Revilla et al. 2010; Table 2).

In relation to the temperature of the intermediate waters of the southeastern Bay of Biscay, measured off the coast of Santander (see Fig. 1a), the Eastern North Atlantic Central Water and the Mediterranean Water warmed up from 0.02°C yr^{-1} to 0.03°C yr^{-1}, from 1992–2003 (González-Pola et al. 2005, Table 2).

2.3.2. Projections for the 21st century

According to the AOCGMs, global ocean warming is expected to evolve more slowly than increases in global mean surface air temperature (Meehl et al. 2007). In particular, warming in the ocean will progress from near the surface and in the northern mid-latitudes early in the 21st century, to gradual penetration downward during this century. In the Bay of Biscay, Chust et al. (2010) estimated the future sea temperature trends (from the surface to 100 m depth), using the outputs from a set of selected AOGCMs for this region, under 3 different scenarios. Thus, under the more optimistic scenario, the temperature will increase at a rate of 0.003°C yr^{-1} during the 21st century. This scenario (committed scenario), which assumes a GHG concentration constant at the levels existing since 2000, is not realistic, since the emission of GHGs has increased since 2000; however, it indicates that the sea temperature will continue to increase even if the emissions cease. The A1B scenario considers an increase in the GHG concentration during the first half of the century and a decrease during the second half. In this scenario, the expected increase will be on the order of 0.015°C yr^{-1} for the period 2001–2099 (Fig. 4). In contrast, the A2 scenario does not anticipate an increasing use of more efficient technologies during the second half of the century; as a consequence, the concentration of the GHGs will increase throughout the 21st century, together with the sea temperature (0.02°C yr^{-1}; Fig. 4). These projections are subjected to some uncertainties arising from different sources, i.e. the remarkably different results depending on the selected AOGCM. Nevertheless, if a partially or totally anthropogenic origin of the rise in ocean temperature over the last decades is assumed, this is a first step in the prediction of future temperature within the area of study.

2.4. Sea level rise

2.4.1. Observations in the 20th century

Long-term global mean sea level variations are attributed to steric changes caused by variations in the thermohaline properties of the ocean and to mass addition or subtraction by changes in water reservoirs, mainly ice sheets, glaciers and ice caps. Based upon historical tide gauge records, the global mean SLR rate during the 20th century has been estimated to be 1.7 ± 0.5 mm yr^{-1} (Church & White 2006). More recent estimates have obtained an averaged sea level trend of 1.6 ± 0.2 mm yr^{-1} for the period 1961–2003; of this, 0.8 ± 0.1 mm yr^{-1} is caused by thermal expansion (Domingues et al. 2008), although uncertainties remain

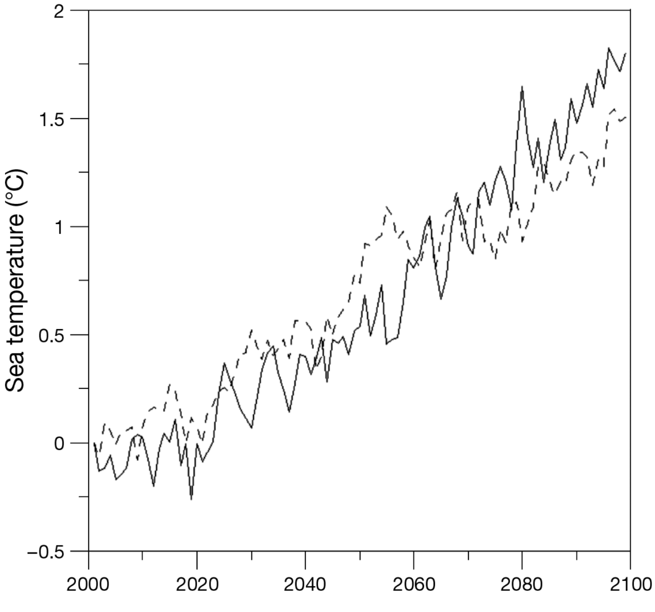


Fig. 4. Projected annual sea temperature (upper 100 m layer) for the 21st century under the special report on emissions scenarios (SRES) A1B (solid line) and SRES A2 (broken line). Modified from Chust et al. (2010)

Table 3. Annual mean rates of sea level rise within the Bay of Biscay and southwestern UK, according to different locations, methods and authors (for locations, see Fig. 1)

Location	Method	Time period	Rate (±SE) (mm yr^{-1})	Source
Vigo	Tide gauge	1943–2001	2.91 ± 0.09	Marcos et al. (2005)
La Coruña	Tide gauge	1943–2001	2.51 ± 0.09	Marcos et al. (2005)
Santander	Tide gauge	1943–2004	2.08 ± 0.33	Chust et al. (2009)
Santander	Tide gauge	1993–2004	2.67 ± 3.24	Chust et al. (2009)
Bilbao	Tide gauge	1993–2005	2.98 ± 1.08	Chust et al. (2009)
Socoa/St Jean de Luz	Tide gauge	1942–2006	2.09 ± 0.42	Chust et al. (2009)
Brest	Tide gauge	1890–1980	1.3 ± 0.5	Wöppelmann et al. (2006)
Brest	Tide gauge	1980–2004	3.0 ± 0.5	Wöppelmann et al. (2006)
Newlyn	Tide gauge	1915–2005	1.77 ± 0.12	Araújo & Pugh (2008)
St. Mary's	Tide gauge	1968–2006	1.73 ± 0.52	Haigh et al. (2009)
Open water of Bay of Biscay	Satellite altimeters and tide gauge	1993–2002	3.09 ± 0.21	Marcos et al. (2007)
Open water of Bay of Biscay	Satellite altimeters	1993–2005	2.7	Caballero et al. (2008)
Basque coast	Foraminifera-based transfer functions	20th century	2.0	Leorri et al. (2008)
Basque coast	Foraminifera-based transfer functions	20th century	1.9	Leorri & Cearreta (2009)

regarding the contribution of the mass changes (Cazenave et al. 2009). The sea level changes are regionally variable, as has been shown on the basis of the analyses of tide gauge records (e.g. Douglas 1992, Lambeck 2002, Church et al. 2004) and from the global coverage of satellite altimetry in open oceans (Bindoff et al. 2007). In some regions, the SLR is higher than the global mean; in others, a fall in sea level is occurring (Cazenave & Nerem 2004).

Within the Bay of Biscay, several studies based upon tide gauge records have consistently shown a rise in sea level (Table 3, and see Fig. 1a for locations): 2.12 mm yr^{-1} at Santander, 2.51 mm yr^{-1} at La Coruña and 2.91 mm yr^{-1} at Vigo, during the period 1943–2001 (Marcos et al. 2005); 1.77 ± 0.12 mm yr^{-1} during 1915–2005 at Newlyn, southwestern UK (Araújo & Pugh 2008), and 1.73 ± 0.52 mm yr^{-1} during 1968–2006 at St. Mary's, southwestern UK (Haigh et al. 2009). The long tide gauge data series for Brest, located within the northern part of the Bay of Biscay (Fig. 1a), has also revealed that SLR is accelerating (an SLR of 1.3 ± 0.5 mm yr^{-1} between 1890–1980, and of 3.0 ± 0.5 mm yr^{-1} during 1980–2004; Wöppelmann et al. 2006). Such acceleration is in agreement with the rates obtained in the open waters of the Bay of Biscay since 1993, when operational satellite altimetry commenced, by Marcos et al. (2007) (3.09 mm yr^{-1} during 1993–2002) and Caballero et al. (2008) (2.7 mm yr^{-1} during 1993–2005). Along the Basque coast, indirect approaches, such as foraminifera-based transfer functions (Pascual & Rodríguez-Lázaro 2006), have identified a rate of rise of 2 mm yr^{-1} during the 20th century (Leorri et al. 2008, Leorri & Cearreta 2009). These results are consistent with the tide gauge records over that area according to the periods of time (St. Jean de Luz: 2.09 mm yr^{-1} from 1942–2006; Bilbao: 2.98 mm yr^{-1} from 1993–2005; Chust et al. 2009; Fig. 5).

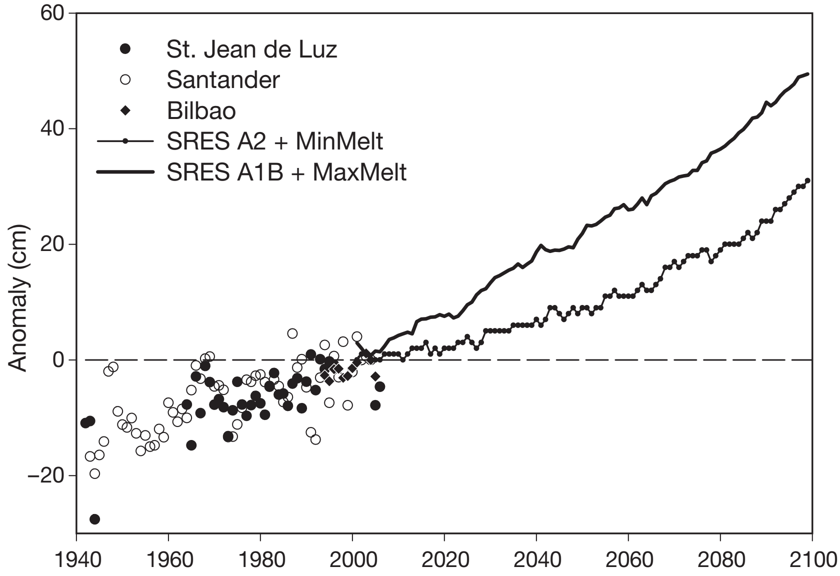


Fig. 5. Observed annual mean sea level series (large circles and diamonds) for the tide gauges of Santander, St. Jean de Luz and Bilbao, and projected levels (lines) for the 21st century under 2 Intergovernmental Panel on Climate Change (IPCC) climate scenarios. Mean sea levels are given as anomalies with respect to the level at Santander in 2004. Expected global sea level rise from the melting of ice sheets and glaciers is between 4 cm (MinMelt) and 20 cm (MaxMelt) by the end of the 21st century (Meehl et al. 2007). The mean sea level of all data sets is with reference to the level in 2004. Modified from Chust et al. (2009, 2010)

2.4.2. Projections for the 21st century

In the Bay of Biscay, Chust et al. (2010) computed thermosteric sea level variations for the 21st century from temperature outputs of the AOGCM projections within the area for 2 climate scenarios. Salinity changes were excluded in that study since the averaged salinity over the upper 100 m of the water column is not expected to change throughout the 21st century. The results of the study have shown that from 2001–2099, the SLR within the Bay of Biscay is estimated at between 28.5 and 48.7 cm (Fig. 5), as a result of regional thermal expansion and global ice melting (4–20 cm), under scenarios A1B and A2 of the IPCC AR4. These regionally projected SLRs are similar to global estimates under the same scenarios (A1B: 21–48 cm, A2: 23–51 cm; Meehl et al. 2007). However, the accelerated decline of polar ice sheet mass indicates that global SLR could be significantly larger (Nicholls & Cazenave 2010) than those projected by the IPCC AR4, with estimated rises of 0.8 m (Pfeffer et al. 2008) and 0.5 to 1.4 m (Rahmstorf 2007).

2.5. Hydroclimatic variability and anomaly patterns: observations in the 20th century

The annual cycle of the shelf waters within the southeastern Bay of Biscay is characterised by changes in the relative prevalence of downwelling and upwelling mechanisms (Valencia et al. 2004). Hence, within this area and during the period 1958–1976, there was weak mean annual downwelling (–200 m^3 s^{-1} km^{-1}), or even low upwelling (130 m^3 s^{-1} km^{-1}; Fig. 6). However, after 1977, the mean annual downwelling values were established at around –300 m^3 s^{-1} km^{-1}, with the lowest values (–500 to –600) occurring within the period 1998–2002. These high downwelling value periods coincide with high turbulence (>400 m^3 s^{-3}). After 2003, there is less downwelling and a decrease in turbulence (Fig. 6).

The relief of the southeastern part of the Bay of Biscay results in a strong continental influence over the Basque coast. Comparatively, the southern Bay of Biscay has marked thermal zoning, from a cold southwestern part (Galicia) where the oceanic influence is greater, towards the inner part where continental influence is stronger. The intensity and frequency of upwelling events decreases southeastward as temperature and stratification increase (Valencia et al. 2004). On a seasonal basis, the cycle in SST varies from the southwest towards the southeast (Lavín et al. 2006). In Galicia, the temperature range from summer to winter is reduced more, as upwelling cools the water in summer. In the southeastern part of the bay, in contrast, there is more influence from the land climate and the shelf waters are less saline, colder in winter, and warmer in summer (Valencia et al. 2003, 2004, Alvarez et al. 2010).

In terms of atmosphere–ocean interaction, coupling mechanisms between climate and water mass properties and circulation have been documented for the region (Pérez et al. 2000, García-Soto et al. 2002, Pingree 2005). Although the NAO greatly influences the circulation in the north Atlantic, its influence is less significant in the northeastern Atlantic, especially in the intergyre zone and the inner Bay of Biscay (Trigo et al. 2002). The most influential atmospheric pattern seems to be the East Atlantic (EA) pattern, particularly for the southeastern Bay of Biscay, by means of the influence of a low pressure centre to the west of the British Isles. Several studies have demonstrated that over the area adjacent to the Bay of Biscay, the EA pattern is related to (inter alia) the variability of precipitation related the position of the Atlantic storm track (Rogers 1997), winter land temperature through heat fluxes (Sáenz et al. 2001b), anchovy recruitment (Borja et al. 2008), autumn-winter temperature, evaporation and moisture transport (Valencia et al. 2009), and upwelling patterns (Borja et al. 2008, Alvarez et al. 2010). Hence, the positive phase of the EA index after 1997 can explain the trend in the upwelling–downwelling pattern in the southeastern Bay of Biscay (Borja et al. 2008).

In terms of atmosphere–sea interaction, significant coupling between oceanographic and meteorological data is observed for the southeastern part of the Bay of Biscay, showing that the atmospheric temperature

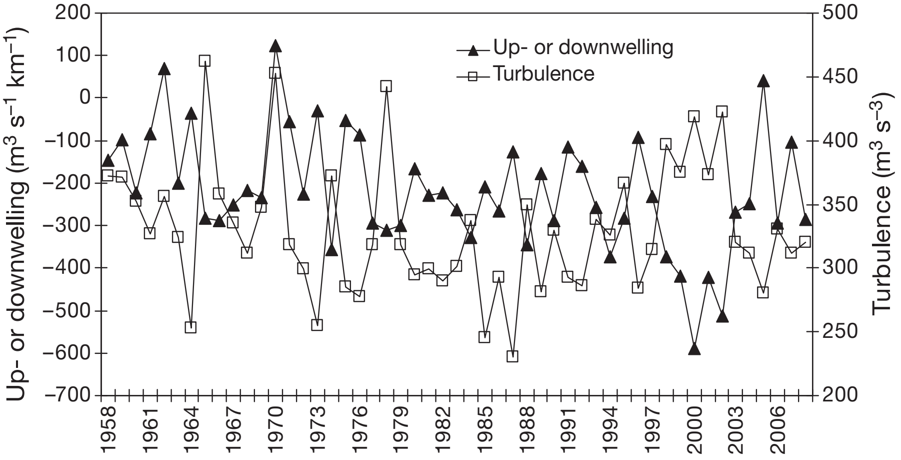


Fig. 6. Up- and downwelling and turbulence annual mean time series for the southeast area of the Bay of Biscay (data updated from Valencia et al. 2004)

significantly influences the variability in SST and, to a lesser degree, the thermal bulk of the water column (Fontán et al. 2008, Goikoetxea et al. 2009).

Within the last decade, frequent seasonal anomaly patterns of oceano-meteorological variables have been observed in the southeastern Bay of Biscay (Fontán et al. 2008, Goikoetxea et al. 2009). These authors concluded that the duality of cold winters and long warm summers prevails in comparison with the seasonal cycle of the temperate Atlantic areas. Moreover, the period 2003–2005 was characterised by the prevalence of warm spring and summer seasons, with cold autumn and winter periods. Exceptional events such as those during the last decade (González-Pola et al. 2005, Somavilla et al. 2009) are explained not only by air temperature fluctuations, but also by other meteorological and physical parameters such as irradiance, turbulence and upwelling events (Borja et al. 2000, Goikoetxea et al. 2009).

In addition to the thermal anomaly patterns, other variables also indicate shifts with respect to the average seasonal patterns. For instance, although the Basque coast is characterised by downwelling conditions in autumn, upwelling conditions prevailed in the autumn of 2005. Similar results were obtained by Borja et al. (2008) and deCastro et al. (2008a,b), who noted that the positive phase of the EA was directly related to ufavourable upwelling conditions along the eastern (Borja et al. 2008) and northwestern (deCastro et al. 2008) coasts of the Bay of Biscay.

Although frequent seasonal anomalies are evident, few anomalies in terms of annual average values can be identified (Fontán et al. 2008). Hence, despite several regime shifts and anomaly patterns for different ocean–meteorological indices (e.g. ENSO, NAO, EA) throughout the last decades, only limited consolidated trends can be reported for the southeastern Bay of Biscay; this is probably related to the counteracting effect of some extreme conditions, i.e. the very warm summer in 2003 compared to the very cold winter in 2005 (González-Pola et al. 2005, Fontán et al. 2008, Somavilla et al. 2009). Although the observed rise in SST can result in an increase in thermal stratification, the storm events and wave climate prevailing during recent decades have produced turbulent mixing and thermal homogeneity.

2.6. Wave climate

2.6.1. Observations in the 20th century

Waves are generated directly by wind forcing; as such, global climate change can affect regional wave climates. In the North Atlantic, for example, the interannual evolution of wave heights is related, at least partially, to climatic factors, such as the NAO index (The WASA Group 1998, Wolf & Woolf 2005). Woolf et al. (2003) found that most of the interannual variability of winter wave climate around the British Isles can be related to the NAO. According to Lionello & Galati (2008), the EA pattern (Wallace & Gutzler 1981) has a greater influence on the variability of waves than the NAO over the western Mediterranean. Dupuis et al. (2006) reported that the wave height recorded at a station located in the southern Bay of Biscay (Biscarosse) did not show any significant correlation with the NAO, whilst wave periods were positively correlated.

Several studies have investigated the evolution of wave climate in the northern part of the North Atlantic Ocean (e.g. Grevemeyer et al. 2000). Most of these studies, based on observations, indicated a general upward trend in wave heights (e.g. Dupuis et al. 2006, Debernard & Røed 2008). In contrast, numerical models based upon reanalysis (The WASA Group 1998), have suggested that wave height over most of the northeast Atlantic and in the North Sea has decreased from 1955–1994. However, the present intensity of storms and wave climate seems to be similar to that observed over the last 100 yr (The WASA Group 1998).

The analysis of the period 1980–1998 within the eastern Bay of Biscay (off Biscarosse, France) has shown that wave heights tend to decrease (Dupuis et al. 2006). In turn, an analysis of the longest time series (40 yr) for the area, on storm surges and wave heights in Santander, has suggested that these extreme events have intensified over the last decade (F. Méndez pers. comm.).

2.6.2. Projections for the 21st century

Empirical 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). In particular, significant wave heights exceeding 12 h yr^{-1} (H_{s12}) are expected to increase from 0.26 to 0.30 cm yr^{-1} along the Basque coast. Extreme events with wave heights H_{ST50} (significant wave heights with a 50 yr return period) will increase only slightly. The prevailing direction of the waves is also expected to change and to be more westerly. The potential intensification of storms will affect Basque coastal areas that are more exposed to the prevailing wind and wave directions (NW) (González et al. 2004), i.e. the east part of Gipuzkoa and the western part of Bizkaia. Although these new wave climate regimes may affect the morphology of the coasts, the reliability of these projections is still uncertain (Cendrero et al. 2005).

3. IMPACTS ON COASTAL AREAS AND BIODIVERSITY

3.1. Coastal flooding

SLR and the intensification of extreme wave climate events during the 21st century are considered to be among the major threats to coastal ecosystems (Nicholls et al. 2007, FitzGerald et al. 2008, Defeo et al. 2009). An increase in mean sea level induces a higher risk of the 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 & Chappell 1996, Morris et al. 2002, Crooks 2004, Pascual & Rodríguez-Lázaro 2006, FitzGerald et al. 2008, Kirwan & Murray 2008a, Kirwan et al. 2008, Poulter & Halpin 2008, Gesch 2009). These climate-change-driven threats will probably exacerbate several existing pressures along the coastal regions such as the concentration of population (McGranahan et al. 2007) and the increasing rate of urbanisation (European Environment Agency 2006), causing degradation, fragmentation and habitat loss (Fahrig 2003, Halpern et al. 2008).

Evidence of the impacts of SLR throughout the 20th century is relatively scarce (Williams et al. 1999, 2003, Denslow & Battaglia 2002, Jokiel & Brown 2004, De Santis et al. 2007), compared with the future threats expected for the next 100 yr (see reviews by Nicholls et al. 2007 and FitzGerald et al. 2008). To establish clear evidence of SLR effects at the habitat level is difficult in most cases because of the overwhelming anthropogenic changes, and because of the difficulty of differentiating between natural processes (such as wave action) and the effect of SLR on the beach retreat (FitzGerald et al. 2008). For instance, a loss of 3 ha of sandy beaches and saltmarshes within the eastern Basque coast has been detected using historical data and attributed to 10 cm SLR from 1954–2004, whilst the simulated effect was 11 ha over the 50 yr period (Chust et al. 2009).

Concerning future threats, efforts have been concentrated upon large low-lying areas and deltas (e.g. Ericson et al. 2006, McGranahan et al. 2007). However, on steep coasts, such as the Basque and the remainder of the Cantabrian coast, the sea cliffs and hilly relief limit the extent of the sandy beaches, saltmarshes, urban settlements and industrial zones along the coast. Therefore, these confined habitats and infrastructures are vulnerable to small variations in sea level and wave climate (Michael 2007, Vinchon et al. 2009). Within this context, Chust et al. (2010) used a high-resolution digital terrain model to assess the potential impact of the estimated SLR by 2099 (49 cm, see section 2.4.) on natural and artificial coastal habitats in this area. Similar approaches were applied previously by Webster et al. (2004, 2006) along the coast of New Brunswick (Canada). The flood risk map generated for the Gipuzkoa coast indicates that 111 ha of the supralittoral area may be affected by the end of the 21st century (Fig. 7). Whilst the effects of SLR are concentrated in low-lying areas within the inner estuaries, extreme waves predicted with a 50 yr return period will affect mainly sandy beaches, harbours and urban areas exposed to high energy waves (author's unpubl. data, see Fig. 7).

The regime of flood events in the Basque Country will change also due to the expected decrease in mean precipitation and the increase of extreme rainfall for the 21st century (see section 2.2.). The rivers draining to the Basque coast are torrential in character, with very short time lags between the precipitation and resulting river discharge. Thus, lower river flow and higher intensity floods are expected, as well as changes in the water properties of the estuarine waters. Since the major concentrations of suspended matter take

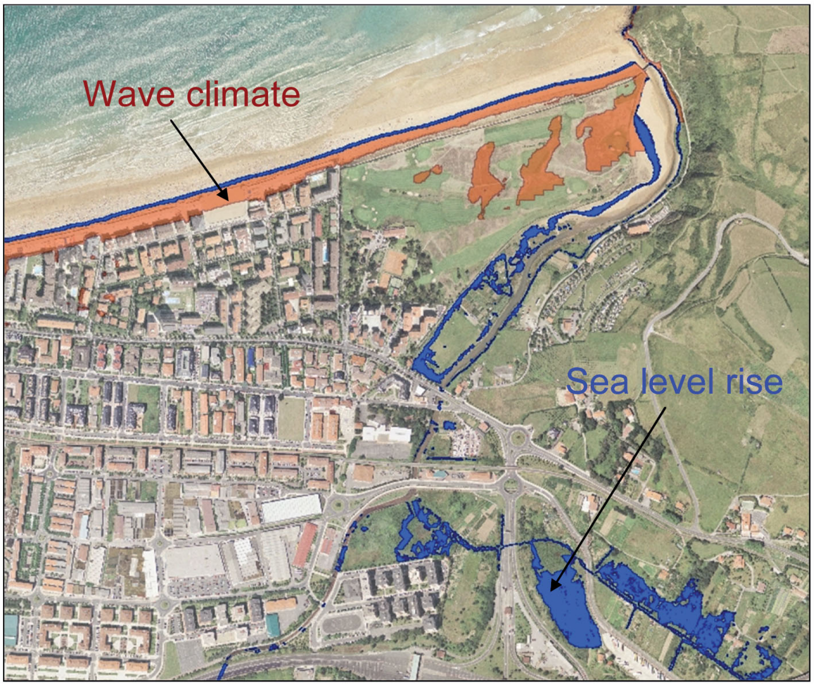


Fig. 7. Flood-risk map expected for a 49 cm sea level rise in 2100 (blue) and extreme wave climate for a 50 yr return period (orange), in Zarautz (Basque coast, Spain; authors' unpubl. data)

place during intense rainfall, following dry periods (Uriarte et al. 2004), the new expected precipitation regime will induce intensification of these conditions. As a consequence, the estuarine ecosystems will be subjected to more contrasting periods of lower river flow waters to higher hydrodynamic, turbid waters. If these expected rainfall regimes and temperature increases also take place in adjacent areas, nearby rivers such as the Adour (France), which can affect the Basque coastal waters during large freshwater discharges (Ferrer et al. 2009, Petus et al. 2010), could shift from a nival regime to a nival-pluvial regime.

3.2. Retreat of sandy beaches and dunes

A direct consequence of SLR is the displacement of the high-water mark landward, causing beaches to migrate slowly inland (Defeo et al. 2009), together with the permanent or long-term loss of sand from the beaches (FitzGerald et al. 2008). Low-gradient dissipative shores are most at risk, compared with steep coarse-grained beaches; this is due to their erosive nature and the much greater run-up of swashes on gentle gradients (Defeo et al. 2009). Confinement of the sand beaches through the construction of coastal structures also makes them more prone to erosion (FitzGerald et al. 2008). Because the effects of global SLR on coasts will vary spatially and at the habitat level, the prediction of coastal changes should be approached on regional to local scales and be map based. Studies undertaken in Aquitaine (France), for example, indicate that climate change will induce a significant increase of erosion hazard for most of the sandy coast (Vinchon et al. 2009); on the cliff-lined coast, small and narrow beaches are likely to retreat drastically, if not disappear altogether, because of limited sediment storage.

Along the Basque coast, 2 approaches were adopted to assess the beach erosion expected by an SLR of 49 cm in Chust et al. (2010). The first approach, based on geographic information system (GIS) analysis, evaluates the retreat of beach habitats using extensive high-resolution height data. In particular, the area between the coastline defined by the maximum high tide and the coastline generated by adding the estimated future SLR was delimited using GIS. The second approach took into account the redistribution of sediment along the sandy beaches, according to the Bruun Rule, i.e. the ‘equilibrium profile’ (Bruun 1988, FitzGerald et al. 2008), of each beach analysed, from a set of 15 main beaches selected. Although criticisms and modifications to the Bruun Rule have been suggested (Cooper & 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. According to the study, sandy beaches on the Basque coast are expected to suffer shoreline retreats of between 25% of the average beach width (GIS-based approach) and 40% (Bruun approach). In both the map-based and the Bruun approaches, the number of beaches in which the supralittoral zone is expected to disappear is lower (2 to 3 of the 15 analysed beaches) than the previous estimates given by Cendrero et al. (2005), i.e. 12 out of 19 beaches. Cendrero et al. (2005) applied the Bruun Rule on a single beach profile assuming erosion of 1 m for every 1 cm of SLR. On the other hand, 17 out of the 19 beaches of Gipuzkoa are already at present naturally or artificially confined (Chust et al. 2009); this makes them more likely to disappear (FitzGerald et al. 2008). As a consequence of the migration of the entire beach profile landward under the SLR scenario, some vegetated dune patches may disappear because of the presence of the artificial rigid seafronts.

The new estimates of beach retreat may have impacts on different goods and services that sandy shores provide, such as biodiversity and recreational activities. Coastal vegetated dunes, especially grey dunes, hold highly specialised floristic diversity and are included as priority habitat in the Natura 2000 network (Habitats Directive 1992). Although the threat to dune habitat is less than for the supralittoral sandy beaches, historical loss, degradation and squeezing by urbanisation makes them more vulnerable. In terms of services, tourism is an important sector in the Basque Country, contributing from 4.7 to 5.3% of the gross domestic product (from 2000 to 2004, www.eustat.es). The success of this industry depends, at least partially, on the quality of the sandy beaches and the ebb tidal deltas (Liria et al. 2009). Within a scenario of beach retreat, either tourism may decline, or alternatively the pressure of recreational seashore activities will overwhelm the sandy beaches.

The joint effect of accelerating SLR and ongoing coastal urbanisation processes in the area (Chust et al. 2007) is of particular concern for beach erosion, especially for vegetated dunes (Defeo et al. 2009) and within the context of higher global SLR projections by 2100, which were recently reported to be between 0.5 and 1.4 m (Rahmstorf 2007, Pfeffer et al. 2008). Sandy beaches are identified as one of the most threatened coastal habitats of the Basque coast. Adaptation strategies to face SLR-induced beach erosion should include measures to promote coastal resilience, including protection, stabilisation and regeneration of dune plants, the maintenance of sediment supply, and the provision of buffer zones by providing setback zones which would allow the beach to migrate landward (Defeo et al. 2009).

3.3. Estuaries, saltmarshes and wetlands

3.3.1. Relationship between climate and estuarine species

Long-term series of estuarine biological data from the Basque Country are scarce, starting in 1989 for the Nervión and Barbadún estuaries (see Fig. 1b for locations) (Borja et al. 2006) and in 1995 for the remainder (Borja et al. 2004b). Using these data, Pérez et al. (2009) studied the temporal trends in Basque estuarine soft-bottom macrofaunal communities, explained by anthropogenic, climatic and sedimentological factors. As these estuaries have been polluted historically (Cearreta et al. 2004), this has affected of benthic communities in recent years (Borja et al. 2009). Overall, sediments are the most relevant factor, explaining 17.2% of benthic variability in the species density, whilst anthropogenic variables (pollutants) explain 16.9% and climatic variables represent only 15.4% of the variability (Fig. 8). Hence, substratum and pollution explain most of the variability of these altered systems, with climate factors being less relevant for the Basque benthic estuarine communities.

On the other hand, in the case of plankton communities, climatic variables seem to play an important role, even in historically-polluted estuaries, such as that of Nervión. Hence, Villate et al. (2008) described for the Oka estuary a chain of effects from the NAO to chlorophyll: air temperature inversely followed the NAO index, water temperature followed air temperature, and chlorophyll *a* (chl *a*) followed water temperature. Aravena et al. (2009a) described similar relationships in both the Oka and Nervión estuaries, including river discharge and rainfall. Related to zooplankton, Aravena et al. (2009b) recorded several species of *Acartia* copepods in the Nervión estuary between 1998 and 2005. *A. clausi* dominated the euhaline stretch of the estuary until 2003, when it was displaced from the inner part by *A. tonsa*, due to environmental changes. The decrease in *A. clausi* abundance in low-salinity waters was related to a significant decrease of dissolved oxygen saturation levels, whereas the increase in temperature was linked to a significant increase of *A. tonsa*. *A. margalefi* and *A. discaudata* were scarce over the entire period, but they were valuable indicators of hydrological changes associated with climate factors.

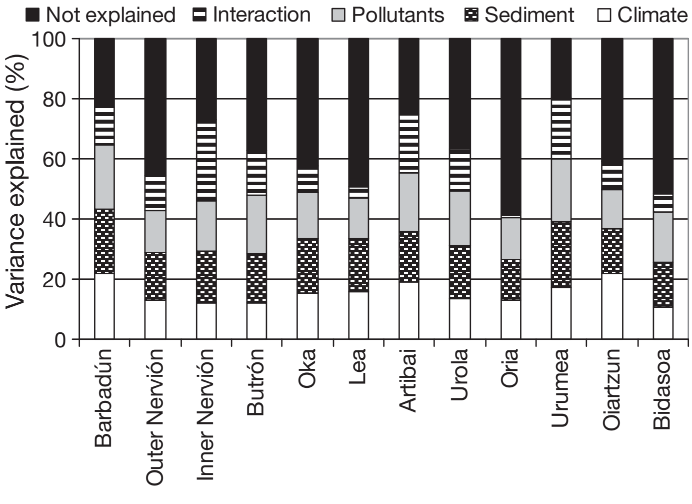


Fig. 8. Partition of the variance explained by different natural (climate, sediment) and anthropogenic (pollutants) factors, together with the interactions of those factors, in soft-bottom benthic communities in Basque estuaries (data from Pérez et al. 2009)

3.3.2. Sea level rise and estuarine habitats

The impacts of SLR in estuaries could lead to changes in the extent of the low-lying areas, the migration of saltmarshes landward, salinisation of aquifers and changes in sediment and nutrient transport (Crooks 2004, FitzGerald et al. 2008). Elevation relative to mean sea level is a critical variable for the establishment and maintenance of biotic coastal communities and a threat to biodiversity (Kirwan & Murray 2008b, Kirwan et al. 2008), as has been detected in the past for the Basque Country (Pascual & Rodríguez-Lázaro 2006). In tidal areas, this elevation determines the duration and frequency at which coastal habitats are submerged, this being one of the factors controlling the productivity of macrophyte communities (Morris et al. 2002). The SLR is already causing the retreat of coastal forests (Williams et al. 1999, 2003, DeSantis et al. 2007), the loss of saltmarshes (Denslow & Battaglia 2002, Chust et al. 2009), coral reef bleaching (Jokiel & Brown 2004) and the loss of goods and services (Costanza et al. 1997, Schröter et al. 2005, Michael 2007).

Along the Basque coast, a study of the impacts of 49 cm in SLR on the Gipuzkoa estuaries was undertaken by Chust et al. (2010). This study revealed that 3.9 ha of wetlands and saltmarshes (i.e. 6.5% of the surface) may be affected (Fig. 7). The impact assessment of such an approach is useful in assessing relatively large areas at high resolution and is reliable for hard substrata. However, marshes are dynamic systems which respond to SLR according to a balance between accretion and subsidence, bioproductivity and decomposition, erosion and vegetative stabilisation, and tidal prism and drainage efficiency (Morris et al. 2002, FitzGerald et al. 2008, Reeve & Karunarathna 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

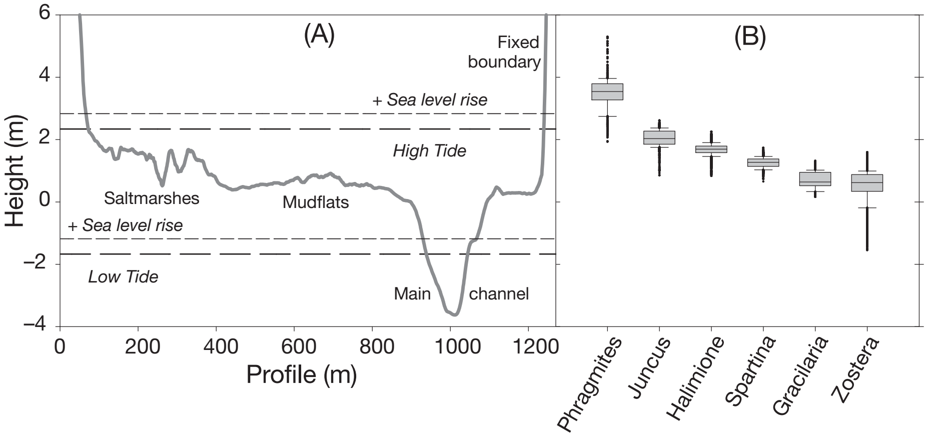


Fig. 9. (A) Height profile derived from bathymetric data of intertidal habitats in the inner Oka estuary (Basque coast). High tide and low tide are the observed mean spring tide values for the Bilbao I tide gauge station. (B) Height distribution of main intertidal flora of the innermost Oka estuary (*Phragmites australis*, *Juncus maritimus*, salt marshes dominated by *Halimione portulacoides* and *Salicornia* sp., *Spartina maritima*, *Gracilaria* sp., *Zostera noltii*). Plots show the median, 10th, 25th, 75th and 90th percentiles as vertical boxes with error bars, and outliers (crosses). Height data were extracted from bathymetric LiDAR system acquired in June 2007

matter; this, in turn, determines the future evolution of the marsh in response to SLR (Morris et al. 2002). Saltmarshes are capable of being near equilibrium in relation to rates of SLR (Friedrichs & Perry 2001), whilst under specific conditions, they could lag by several decades (Kirwan & Murray 2008b). An average accretion rate of 3.7 mm yr^{-1}, as calculated for the Basque marshes in the 20th century by Leorri et al. (2008), suggests that these marshes are potentially able to adjust to the projected SLR rates.

On the other hand, when the accretion is below the rate of SLR, which can take place within mudflats, the habitat suitable for vegetation can be reduced in some cases — e.g. where the coastal margin is squeezed between the fixed landward boundary (artificial or natural) and the SLR, i.e. the so-called 'coastal squeeze' effect (Schleupner 2008). To test the case of a natural fixed boundary, a species-specific habitat model was developed for the intertidal seagrass *Zostera noltii* in the Oka estuary (Basque coast, see Fig. 1b), using ecological niche factor analysis (Valle et al. 2010). The dependence of this seagrass on the inundation frequency of tides (Fig. 9), together with a high-resolution bathymetry generated by an airborne LiDAR system, enabled these authors to map the present habitat suitability and estimate the future scenarios. The area of suitable habitat (with a probability of presence >50%) for *Z. noltii* in the Oka estuary is expected to be reduced by 40% by the end of the 21st century, as a consequence of the future SLR (author's unpubl. data, Fig. 10). This result suggests that migration of the seagrass landward, following the SLR, can be limited by the estuarine profile (Fig. 9). The habitat distribution of this seagrass also depends upon the hydrodynamic conditions and grain size features. Thus, ongoing research in numerical modelling on future sediment redistribution should enhance the reliability of habitat loss estimates.

The projected rise in air temperature in the Basque Country (section 2.1) and sea temperatures within the Bay of Biscay (section 2.3) might also interact negatively with SLR, having implications in terms of the loss of coastline biodiversity. On the one hand, the warming of marine waters may cause the migration of

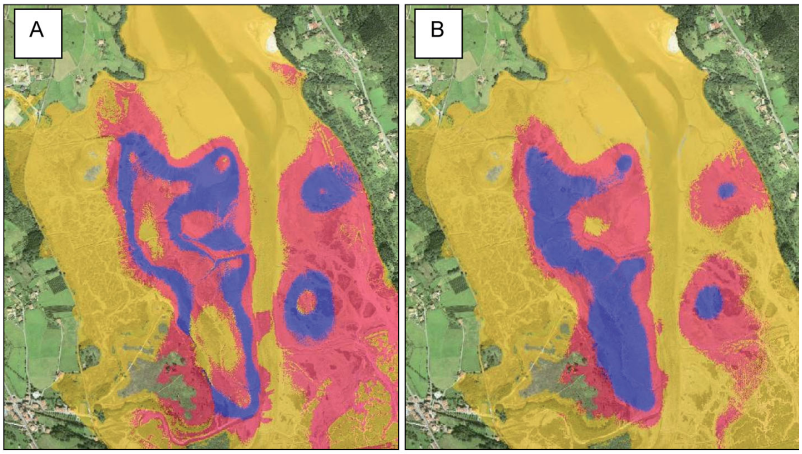


Fig. 10. Habitat suitability for *Zostera noltii* in the Oka estuary (Basque coast) (A) at present (2008) and (B) expected by the end of the 21st century as a consequence of future sea level rise. Habitat suitability is classified into 3 probability ranges of occurrence: 0 to 33% (yellow), 34 to 66% (red) and 67 to 100% (blue) (authors' unpubl. data)

intertidal species with a narrow niche to higher latitudes. On the other hand, the eventual loss of small saltmarshes leads to fragmentation of the estuarine habitat patches along the coast, thereby reducing the potential connectivity between local populations (Fahrig 2003). Thus, similar to the contraction of alpine species distribution, estuarine species populations with narrow niches, with limited dispersal potential (Defeo et al. 2009) and with fragmented habitat by historical urbanisation in a particular area, may be at local extinction risk under climate change.

Wetlands and marshes in the Basque estuaries are also squeezed by croplands and pastures that lie within the original upper intertidal zone. In the area, these croplands are protected by walls and drained to be used for agriculture purposes, since they lie below the present maximum astronomic high tide level. Hence, these human activities are vulnerable to the SLR expected by 2100, especially when extreme events, such as high tides and river floods, occur simultaneously. Likewise, if agriculture activity continues to decline, as throughout the 20th century (Cearreta et al. 2004), these areas may be abandoned and may be susceptible to recolonisation by marsh communities (Garbutt et al. 2006, Marquiegui & Aguirrezabalaga 2009). On the basis of these latter socio-economic and climate change scenarios, saltmarshes and wetlands might increase, as predicted for other areas (Titus et al. 2009).

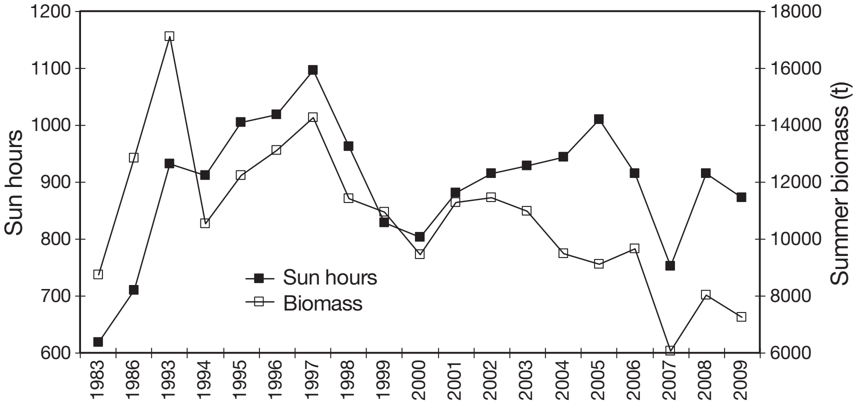


Fig. 11. *Gelidium corneum.* Evolution of biomass between Orio and Hondarribia in summer, and sunlight hours in winter-spring (January–June), for the period 1983–2009 (updated data from Borja et al. 2004a)

3.4. Coastal benthic communities

3.4.1. Relationships between climate and benthos

The macroalga *Gelidium corneum* plays an important role along the Basque coast, as it is one of the most important structuring species in subtidal waters and is important as an exploited resource for agar-agar production (Borja et al. 2004a). The long-term time series of biomass of this macroalga, within this coast, started in 1983 (Borja 1987). The most important environmental factors driving *G. corneum* biomass are irradiance, temperature and wind (as wave energy; Borja 1994). Hence, the summer standing stock evolution, in the area from Orio to Hondarribia (see Fig. 1b), from 1983–2002, is significantly correlated ($r = 0.55$, $p < 0.05$) with sunlight hours in the preceding winter and spring periods (Borja et al. 2004a). This time series has been updated up to 2009, when the relationship continued to be significant (Fig. 11). Moreover, the extremely low biomass of the period 2007–2009 coincides not only with low levels of irradiance, but also with a high number of waves >6 m in significant height, which can be considered as being able to detach algae from the bottom (Borja 1994). Hence, from 2002–2006, for the period of January–June, the number of cases in which waves were >6 m ranged between 0 and 6, whereas they ranged between 10 and 14 for the period 2007–2009. Some of the last cases were in April–June, close to the biomass assessment period, at the end of June (authors' unpubl. data). This factor produces an early detachment of algae, and, together with a low level of production due to low irradiance, results in a low summer biomass.

In other subtidal macroalgae species, such as *Saccorhiza polyschides*, temperature appears to be the most important factor in their distribution along the Basque coast throughout the 20th century (Borja & Gorostiaga 1990). *S. polyschides*, a cold-water species, decreased in abundance and retreated in its range along the Basque coast during periods of warming (i.e. 1950s); the reverse occurred during periods of cooling (e.g. 1970s). This is probably why this species has disappeared from the Basque coast since the end of the 1990s and in the 2000s, coinciding with the warmest period since 1946 (section 2.3.). Similar patterns of expansion and retreat have been detected in intertidal hard-bottom fauna and flora (e.g. limpets, barnacles, *Littorina, Laminaria, Fucus, Bifurcaria*) throughout the Bay of Biscay through the 20th century (Southward et al. 1995, 2004, Alcock 2003).

In the case of soft-bottom benthic communities, the dataset commenced in 1995 (Borja et al. 2004b). Using this information (19 subtidal coastal stations, 12 yr, and 275 species), Garmendia et al. (2008) showed that sediment variables explained 11.1% of the total community inertia, whereas anthropogenic variables (pollutants) explained only 4.8% of the variability. Climatic variables were the most important, explaining

17 % of the total variability. Of the latter, the most important variables were river flow (explaining 49.2 % of the variability), precipitation (7.3 %), winter NAO (6.9 %), sunshine (6.6 %) and EA (5.9 %). Hence, it seems that although in Basque estuaries, sedimentological and anthropogenic factors determine benthic abundance (see above), in coastal waters climatic variables generally explain most of the variability of such abundance. Only in areas more affected by pollution (e.g. near wastewater discharges), are anthropogenic factors determining the evolution of benthic abundance.

3.4.2. Predictions in benthos changes

Investigations into the prediction of the effects of climate change on coastal benthos, within the Bay of Biscay, are concentrated within the northern part of the bay (Southward et al. 1995, 2005). Southward et al. (1995) predicted a general shift of warm water species to the north, together with a retreat of the cold water species. Additionally, they predicted the definitive decline in some species, such as the native oyster *Ostrea edulis*, which is already under threat from pollution and introduced pathogens, and will likely be replaced by warmer water species from the genus *Crassostrea*, as has already been detected in the Basque Country.

Using a graphical model (with the summer and winter limits of temperature for benthic species), Alcock (2003) predicted changes in 18 intertidal species until 2050. In general, for those warm water species (e.g. *Patella rustica, Pollicipes pollicipes*) with a present geographical limit on the Basque or French coasts, expansion to the north of the British Isles and to the south of the North Sea is predicted. Species presently extending to the south of the British Isles (e.g. *Osilinus lineatus, Gibbula umbilicalis, Balanus perforatus, Patella depressa*) will expand to southern Norway. In turn, cold water species (e.g. *Patella vulgata, Nucella lapillus, Semibalanus balanoides, Pelvetia canaliculata, Fucus vesiculosus, F. serratus, Laminaria hyperborea*), which are present only in the western and northern parts of the Bay of Biscay, will disappear completely from the bay by 2025. In some cases, such as *N. lapillus*, this has already been detected. This species was identified in the 1980s off the Barbadun estuary (Borja et al. 1982), and began disappearing from the Basque coast in the 1990s, with the increase in sea temperature.

On the other hand, using robust supervised classification methods, as applied to fish recruitment (Fernandes et al. 2010), prediction of the summer *Gelidium corneum* biomass was attempted, taking into account sun hours, waves, winds, NAO and EA. Data from 1993–2009 showed that EA and sun hours are the factors which best explain the variability in the summer biomass. Hence, scenarios considering low sun hours (<929) in winter and spring, together with mean EA values (0 to 0.7), predicted 80 % of probability of having low *Gelidium* biomass (<7000 t) and 20 % of probability of moderate biomass (7000–8000 t).

3.5. Urban coastal environment

The main climate drivers that could affect urban environments are the increase (decrease) of heat (cold) stress in summer (winter), a change in precipitation patterns, SLR and increasing extreme weather events, such as storms and flooding (Wilbanks et al. 2007). The impacts of global climate change on urban environments depend markedly on the geographical location and the industrial development of human settlements. In Europe, the main climate drivers that could affect coastal urban environments are wind-driven waves and storms, together with the SLR (Alcamo et al. 2007). The main impacts of these drivers on urban areas are flooding, coastal defence failures and the damaging of infrastructures; likewise, rising water tables could impede the drainage and cause salinisation of groundwater (Nicholls et al. 2007, Devoy 2008).

Along the Basque coast, urban areas are located mostly within the estuaries; of the 45 % of the estuarine areas lost following the post-Flandrian retreat, 90 % was due to land reclamation (Rivas & Cendrero 1994). The purposes of the landfill of estuarine areas, which began in the 17th century, were socioeconomic, viz. agriculture, industrial installations, residential areas and transport infrastructure, amongst others (Díez et al. 2000). Although the coastal municipalities occupy 14.6 % of the total surface of the Basque Country, 60.4 % of the total housing is concentrated within such areas. The population density at the coast is 4 times higher than that of the Basque Country as a whole. With regard to the infrastructure, there are 17 ports, an airport, several roads and rail links and around 30 sewage treatment plant within this region. Thus, climate drivers, mainly the frequency of the storms and the SLR (Cendrero et al. 2005), could affect the socioeconomic activities of the Basque coast.

Assuming a scenario of 49 cm in SLR for 2099 (section 2.4.), the artificial area in the Gipuzkoan coast that could be flooded is 35.2 ha (Chust et al. 2010). A greater part of these areas are those which have been reclaimed since the 17th century, including industrial, residential, harbour and transport infrastructure, such as roads and an airport. Their vulnerability will be higher at high tides and during sea storms (Fig. 7). Amongst the affected areas, those located within estuaries will be even more vulnerable, since besides SLR and high tides, they will also be exposed to river floods.

At present, the predicted flooded areas are protected by defences against flooding; these will not be overtopped with the projected SLR, providing that the defences do not fail. Nevertheless, the flood defences will support a higher water volume and consequently may suffer more erosion.

Harbour infrastructures and external dykes are also thought to be affected by climate change. The combined action of sea level and wave height rise will increase the overtopping of the piers located along the Cantabrian coast; in some cases their stability will diminish. Assuming a standard dyke, the overtopping (water volume exceeding the height of the dyke above sea level) over the main external dykes of the Basque coast will increase by at least 30 % from the beginning to the end of the 21st century (authors' unpubl. data). This result was obtained under a scenario of sea level and significant wave height (exceeding 12 h yr^{-1}) rise. In the case of the main harbours of the Basque coast, the sole impact of SLR will imply a smaller distance between the levels of the highest astronomical tide and that of their piers, towards the end of the 21st century (Chust et al. 2010); in time, this may diminish the functionality of the piers. If the geometry of the navigation channel is modified, this could also affect navigation into the harbours (Acinas 2002). The rising seawater tables would also increase salt water intrusion; hence, it could threaten drainage systems and the groundwater such as those of Gernika, which are occasionally contaminated by salt water (B. G. Bikuña, M. Moso, J. Arrate, S. Lujan unpubl. data).

4. IMPACTS ON THE PELAGIC ENVIRONMENT

4.1. Chlorophyll and primary production

4.1.1. Long-term trends

Most of the time-series measurements of phytoplankton in the Bay of Biscay are coastal or estuarine. Furthermore, all of them cover <25 yr, which makes it difficult to extract long-term trends. The results from coastal time series differ locally. Off Gijon, a decrease in primary production has been observed over the last 10 yr (Valdés et al. 2007, Llope et al. 2007), whereas an increase has been observed off La Coruña, around the area of the Galician upwelling (Valdés et al. 2007). In turn, regarding long-term trends in chl *a*, Bode et al. (2009) did not identify any evidence for significant change at 2 locations, in Galicia and the central Cantabrian Sea, over the past 10 to 20 yr. Along the Basque coast, a significant ($p < 0.05$) slight decrease in surface chl *a* was observed from 1986–2008 (Revilla et al. 2010; Fig. 12). This decrease is consistent with the conceptual model of Richardson & Schoeman (2004) that describes the effect of increasing temperature in marine waters with seasonal stratification and limited nutrient concentrations, such as that within the southeastern part of the Bay of Biscay. In turn, when studying the water column (0 to 100 m water depth), a significant chl *a* increase was found for the period 1986–2009, especially in the photic layer (0 to 50 m) with values of 6.2×10^{-3} µg l^{-1} yr^{-1} (M. Revilla pers. comm.). In this period, the deepening of the subsurface maximum of chlorophyll was from 10 m in 1986 to 30 m in the years 2000–2009, explaining this incoherency between the decrease in surface and the increase in subsurface layers (M. Revilla pers. comm.).

Offshore in the Bay of Biscay, a 10 yr study of the optical properties derived from the SeaWIFS sensor has suggested a significant increase in chl *a* within this area (Vantrepotte & Mélin 2010). Actually, the longest time series (from 1957) covering oceanic waters is the continuous plankton recorder (CPR) survey line, linking the UK to Galicia. The phytoplankton colour index indicates a clear increase in primary productivity in the areas that encompass offshore waters in the Bay of Biscay (Edwards et al. 2009). This increase in primary productivity does not appear to have been transferred to the higher trophic levels, as CPR data suggest that zooplankton concentration is stable or has declined, as also observed in coastal time series (Valdés et al. 2007).

4.1.2. Predictions in plankton changes

Global models are in agreement in forecasting a long-term decrease of primary production in the North Atlantic, including the Bay of Biscay (Steinacher et al. 2009). However, such global models generally do not perform well in coastal areas such as those of the Bay of Biscay (Steinacher et al. 2009). On the other hand, higher-resolution regional models also predict an increase in the total annual stratified days for the bay (Lowe et al. 2009), which would result in a decrease in nutrients and net primary production. Such forecasts must be considered with caution, since in the Bay of Biscay, nutrient concentration is also heavily dependent upon river discharges, and at present no regional models on variation in river discharges for the overall area are available.

4.2. Fish stocks

4.2.1. Relationships between climate and fishes

The population dynamics of practically all species of commercial interest within the Bay of Biscay are influ-

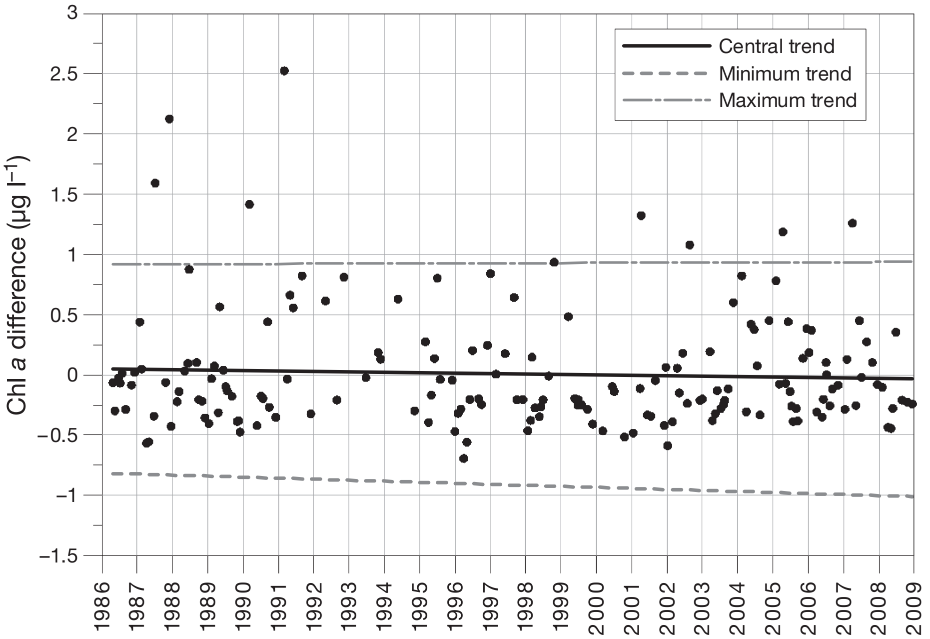


Fig. 12. Temporal trend of sea surface chlorophyll *a* at Station D2 (43° 27′ N, 1° 55′ W; offshore waters from the Basque Country, southeastern part of the Bay of Biscay), from 1986–2008. Values presented are the difference between the measured data and the data estimated for an average year (for details, see Revilla et al. 2010)

enced by climate. Factors such as the NAO (albacore, Arregui et al. 2006; sardine, Alheit & Hagen 1997; several fish stocks, mammals and seabirds, Hemery et al. 2008), EA pattern (anchovy, Borja et al. 2008); temperature anomaly (hake, Fernandes et al. 2010), upwelling strength (anchovy, Borja et al. 2008), turbulence (anchovy, mackerel and hake, Borja et al. 1998, 2002, Allain et al. 2007, Fernandes et al. 2010), river discharge (anchovy, Planque & Buffaz 2008) and Ekman transport (anchovy, Irigoien et al. 2008) have been shown to have significant effects on the recruitment or abundance of these species.

From bottom survey time series, Poulard & Blanchard (2005) found that the abundance of fish species with a wide latitudinal distribution (mainly subtropical) has increased in the Bay of Biscay, whereas the abundance of temperate and least widely distributed species has decreased. In a study focusing on flatfish in the area of Bay of Villaine, Désaunay et al. (2006) found a decrease in northern spawners such as plaice and dab, whereas southern spawners, such as wedge sole, increased.

One of the best examples showing the links between climate, oceanography and fish recruitment within the Bay of Biscay is that of anchovy (Borja et al. 2008). These authors demonstrated that 55% of the recruitment variability of this species can be explained by upwelling over the spawning area (southeastern part of the bay), with the upwelling intensity related to the EA pattern (Fig. 13). The conceptual understanding of the relationship suggests that negative EA periods are associated with northeasterly wind circulation, which produces weak upwelling over the continental shelf. This pattern results in hydrodynamic stability over the area, probably leading to adequate food availability. In turn, positive EA periods are associated with southwesterly winds and downwelling over the continental shelf; this leads to the dispersion of anchovy food and larvae, together with increasing mortality.

Recently, data mining techniques have been used to extract the combinations of climatic factors that influence the recruitment of anchovy and hake (Fernandes et al. 2010). Anchovy recruitment is influenced mainly by the upwelling index, wind direction and turbulence; for hake, temperature anomaly and turbulence are the factors emerging from the analysis. Understanding how climate change will influence local variations in upwelling strength, wind direction or turbulence will require further development of the regional climate models. On the other hand, it could be assumed that a temperature increase should generally benefit hake recruitment. However, we must be aware of the risks of linear extrapolations, as both the analysis of past data and the extrapolations are influenced by abrupt regime shifts (Reid et al. 2001, Beaugrand 2004). Such regime shifts have an influence on fish distribution, even those with wide migrations (Dufour et al. 2010). Furthermore, the benefit of the temperature increase for hake would not be linear, because, as for any other species, there is a maximum temperature over which further increases are detrimental (Mantzouni & MacKenzie 2010).

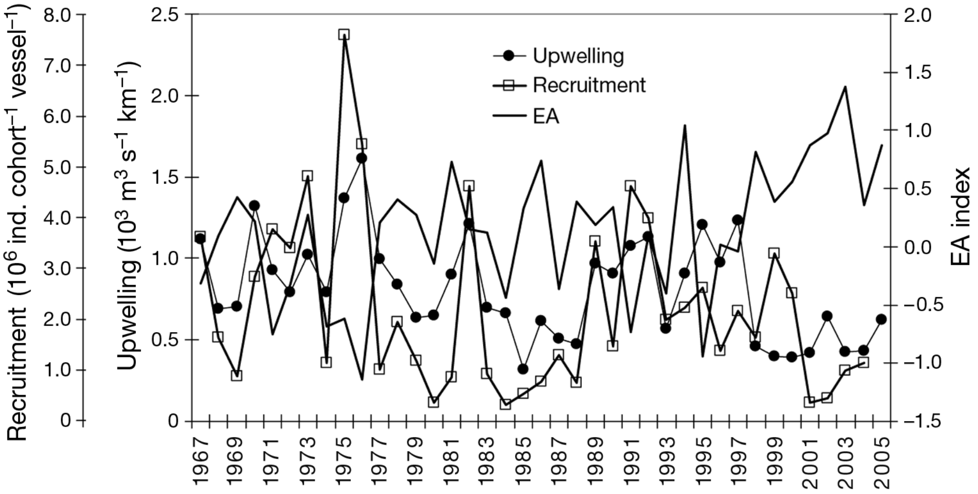


Fig. 13. Comparison between the total annual upwelling (March to July), Eastern Atlantic (EA) index (March to July) and the Bay of Biscay anchovy recruitment index, between 1967 and 2005 (modified from Borja et al. 2008)

4.2.2. Predictions on fish changes

The projected increase in sea temperature over the Bay of Biscay (section 2.3.), a weakening in the Atlantic thermohaline circulation and an increase in stratification, together with other changes described in previous sections, will change the geographical distribution of species (Clemmesen et al. 2007). These changes will result in: (1) shifts of fish populations, with the invasion of alien species and disappearance of native species; and (2) direct influence on survivorship, reproduction, dispersal, fertility and the behaviour of individuals and, thus, on abundance and distribution, as also stated for other marine areas (Drinkwater et al. 2010).

Studies focusing on diadromous fish species (Lassalle & Rochard 2009) have predicted that river basins in the Bay of Biscay may no longer be suitable for a number of species (e.g. *Petromyzon marinus, Salmo salar, Lampetra fluviatilis, Alosa alosa, Platichthys flesus*). Although it is very difficult to judge at a global level who the main losers and winners will be from changes in fish and fisheries as a result of climate change, Brander (2010) provided some recommendations on short-, medium- and long-term management for fisheries. These can be summarised in an adaptation to changing climate, future monitoring and research, all of which must be linked closely to responsive, flexible and reflexive management systems.

5. CONCLUDING REMARKS

The trend in annual air temperature throughout the 20th century (1901–2005) in the northern region of the Iberian Peninsula was, within a 95 % interval, between 0.09 and 0.16°C dec^{-1}. This trend was much higher during the period 1973–2005, with an estimated increase of 0.51°C dec^{-1}. Projections from regional climate models for the 21st century, under GHG emission scenarios, indicate warming of surface air over the Basque Country. In particular, heat wave episodes will increase in duration, and the 90th percentile of daily maximum temperature is expected to increase during summer by 3 ± 0.9°C. Air surface warming will increase the temperature of the upper sea surface layers, especially in the coastal areas. According to the projections, the temperature of the upper 100 m of the water column in the Bay of Biscay will increase by between 1.5 and 2.05°C during the 21st century; this is in agreement with the SST warming trend since the 1970s. The consequence of such warming is thermal expansion of the ocean and, hence, SLR. In particular, the projections (A1B and A2 scenarios) of SLR in the bay indicate an increase of between 29 and 49 cm from 2001–2099, as a result of regional thermal expansion and global ice melt. This is in agreement with the long-term tide gauge records and satellite-derived measurements in the Bay of Biscay, consistently showing an SLR throughout the 20th century.

SLR is predicted to flood 111 ha of the supralittoral area of the Gipuzkoan coast, concentrated within low-lying areas within the inner estuaries, whilst extreme waves predicted with a 50 yr return period will mainly affect sandy beaches, harbours and some urban areas. Wetlands and saltmarshes are expected to be affected to a lesser degree, since their dynamic response in terms of accretion may balance the future rate of SLR. Future research should focus on modelling the estuarine sediment morphodynamics according to the expected sea level by the end this century. Sandy beaches, which are expected to undergo mean shoreline retreats of between 25 and 40 % of their width, are identified as one of the main vulnerable littoral elements. For artificial surfaces, the expected main impacts are erosion or failure of coastal defences, flooding of urban areas in estuaries, damage to drainage systems and the salinisation of groundwater. The projected warming of the air and sea along the Basque coast might also interact negatively with SLR, e.g. through loss of coastal biodiversity, especially for those estuarine populations of species with narrow niches, with limited dispersal potential and with artificially fragmented habitat.

The future impacts of ocean warming on pelagic and coastal water ecosystems are subjected to different positive and negative feedbacks. The distribution and dynamics of most of the biological elements reviewed (i.e. chl *a*, plankton and benthic species communities and populations, natural habitats, fisheries) are affected by ocean-climatic variability. Observations of biological indicators within the study area are somewhat short term (<25 yr) or 'snapshots', which makes it difficult to extract any long-term trends. However, if the Atlantic thermohaline circulation is weakened and stratification is increased during the 21st century, as expected by some projections, these changes will result in shifts of fish populations, invasion by alien species, disappearance of some native species, and direct influence on survivorship, reproduction, dispersal, fertility and behaviour of individuals and, thus, on abundance and distribution. The projections for the 21st century over this area indicate a slight decrease in the mean precipitation ($-0.7 \pm 0.3\%$ dec^{-1}) and a slight increase in extreme daily rainfall (10%). This pattern may have implications for those marine species dwelling or spawning in estuarine waters. In particular, the regime of flood events in the coast of the area studied is expected to change slightly and the estuarine ecosystems will be subjected to more extremes, e.g. from lower streamflow (during dry spells), to higher hydrodynamic, turbid (suspended matter charged) waters (during heavy rainfall events). Future research should focus on projecting changes on current circulation, upwelling/downwelling, climatic indices (i.e. EA, NAO), wave climate and acidification within the bay, in order to better assess the future potential impacts on pelagic and coastal water ecosystems.

Acknowledgements. This study was supported by the Department of Environment, Regional Planning, Agriculture and Fisheries (DERPAF) of the Basque Government (K-Egokitzen and EKLIMA21 projects, *Etortek* Funding Program); likewise, by the Ministry of Environment and Rural and Marine Environment of the Spanish Government (Project Ref.: 0.39/SGTB/2007/4.1), and the Ministry of Science and Innovation (Project Ref.: CGL2008-03321). We acknowledge the contribution of M. Collins (School of Ocean and Earth Science, University of Southampton and AZTI-Tecnalia), A. Fontán and M. González (AZTI-Tecnalia) for providing useful comments; I. Galparsoro and J. M. Garmendia (AZTI-Tecnalia) for providing data for generating the *Z. noltii* habitat model; and F. J. Méndez (Universidad de Cantabria) for providing wave height scenarios. This is contribution 529 from AZTI-Tecnalia Marine Research Division.

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Submitted: April 12, 2010; Accepted: July 31, 2010

Proofs received from author(s): August 22, 2011