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ORIGINAL ARTICLE

Climatic drivers of potential hazards in Mediterranean coasts

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Abstract This paper studies climatic drivers (air and water temperature, precipitation rates, river discharge, sea level and storm patterns) in four Mediterranean regions: the Catalan-Valencia Coast (Spain), the Oran (Algeria) and Gabès (Tunisia) Gulfs and the western Nile Delta (Egypt). The paper also considers the potential hazards that these drivers can induce. It first analyses climatic trends in the drivers, taking into account the available time series of recorded and simulated meteo-oceanographic data from different sources. Next, it presents the general framework to assess biogeophysical hazards (flooding, erosion, droughts and water quality), followed by a simple and yet robust evaluation of those hazards for the four studied coastal sites. Assuming climate change projections under different scenarios and considering the observed trends in drivers, the resulting erosion rates due to sea-level rise and wave storm effects have been estimated. The Nile and Ebro Deltas, together with the Oran Gulf, are more vulnerable than the Gulfs of Valencia and Gabès. Regarding water quality in terms of (a) precipitation and dissolved oxygen in the water column and (b) sea surface temperature, the results show that the most vulnerable zones for the projected conditions (a) are the Gulfs of Oran, Valencia and Gabès, while the Nile Delta is the region where the decrease in water quality will be less pronounced. For the projected conditions (b), the most vulnerable zone is the Ebro Delta, while the impact in the other three cases will be smaller and of comparable magnitude. Finally, the overall future impact of these hazards (associated to climatic change) in the four sites is discussed in comparative terms, deriving some conclusions.

Keywords Mediterranean · Coastal hazards · Climatic drivers · Erosion · Flooding · Water quality

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Introduction

During this century, society will increasingly be confronted with impacts of global change, such as pollution and land uses (Metzeger and Schröter 2006). A "robust" illustration for the driving climatic terms is provided by the global average surface temperature, projected to increase by 1.1–6.4°C by 2100 (Bates et al. 2008).

There is a general agreement that impacts of climate change are more likely to result from altered climate

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variability and extremes than from changes in mean trends (Goubanova and Li 2007). Any intensification and/or increase in the number of extreme events are likely to have disastrous socioeconomic implications on developed and developing countries (Changnon 2003). Indeed, global climate modelling experiments suggest that climate extremes may become more severe under increased greenhouse concentrations in most regions of the globe (Kharim and Zwiers 2000; Voss et al. 2002).

It is also expected that global warming will aggravate disease and pest transmission. Stronger or more frequent extremes (storms, floods, etc.) associated with climate change would cause physical damage, population displacement and adverse effects on food production, freshwater availability and quality. The combination of these elements would also increase the risks of infectious and vector-borne diseases, particularly in developing countries such as those of the southern Mediterranean shores (Moreno 2006). Primary sectors, such as agriculture and forestry, will be more sensitive to climate change than secondary and tertiary sectors, such as manufacturing and retailing. Nevertheless, some tertiary sectors can also be affected. For example, climate is a crucial resource for tourism, so climate variations would have a profound impact on tourism producing shifts in the pattern of demand (Hamilton and Tol 2007), with direct implications on tourist areas such as Mediterranean shores.

Climate change also has the potential to significantly alter the conditions for crop production due to changes in the precipitation regime that would affect the yield distribution considerably (Torriani et al. 2007). Climate change is expected to have positive impacts only in northern countries, implying that areas of crop suitability may expand northwards (Olesen et al. 2007). Southern areas (such as Mediterranean coastal countries) will probably have to face increasing water shortage and incidence of extreme adverse events, reducing crop yields and the area for cropping. Moreover, the higher temperatures are likely to increase crop water requirements and more irrigation water will be needed per hectare (Rodríguez-Díaz et al. 2007). Different studies on the impacts of climate change on crop yields have been performed at different levels (Iglesias et al. 2000; Saarikko 2000; Chen et al. 2004; Parry et al. 2004; Trnka et al. 2004; Reidsma et al. 2009), but the overall conclusion does not vary with scale, although there is a sharp spatial variability across the Mediterranean basin.

Low-lying coastal regions, such as deltas or bays, are subject to a series of driving factors that dynamically interact with the active (as a function of the considered time-scale) geo and ecosystems. These areas are specially sensitive to changes in climatic drivers. In particular, deltaic systems show the consequences of many kinds of human-induced changes such as variations in river liquid discharge (flow regulation) or in river solid discharge (erosion control in the catchment basin or barrier effect of dams). Affected by changes in relative sea-level rise (SLR) and in atmospheric and marine factors (precipitation, wind, storminess), deltaic systems are, thus, highly sensitive ecosystems subject to the interactions of river, sea, land and atmospheric factors (Sánchez-Arcilla and Jiménez 1997). Coastal bays are also influenced by meteo-oceanographic factors as well as natural or man-made boundaries, which can act as a barrier constraining water circulation and, thus, affecting water quality (Sánchez-Arcilla et al. 2007). The associated changes in land use have become a major driver and indicator of environmental change. This can be illustrated by conflicts between past and present land uses or between economic and ecologic priorities (Hill et al. 2008) and also by the large areas of the European Mediterranean that are affected by land degradation or desertification.

In coastal zones, flooding occurs due to storm surges generated by meteorological forcing, mainly due to the tangential surface wind stress on the ocean surface and the atmospheric pressure gradients associated with the weather systems (Kurian et al. 2009). This, combined with anthropogenic global warming, is expected to contribute to an increase in flooding frequencies during this century and beyond. Sea-level rise will increase the vulnerability of coastal populations and ecosystems, via permanent inundation of low-lying regions, inland extension of episodic flooding, increased beach erosion and saline intrusion of aquifers (Cooper et al. 2008). Finally, wind waves are another component of Mediterranean coastal systems, and changes in their characteristics can have important consequences on off-shore activities such as ship traffic and, even more critical, on coastal uses and resources (Lionello et al. 2008a).

In this paper, the main climatic drivers affecting coastal areas in the Mediterranean basin and their potential hazards have been analysed. The study focuses on four areas of the Mediterranean region, which represent a variety of features and coastal environments that can be found in this region. The diversity of environments is also reflected in the available data sets, limited in time, restricted in spatial coverage and showing important gaps that shall be highlighted in the paper.

Study area

The aim of this work is to characterize drivers and hazards for typical Mediterranean conditions. Because of that, four areas (representative of the Mediterranean coastal environment and particularly sensitive to climate change) have been selected. They all fulfil some minimum requirements for observational evidence to allow performing an initial analysis at climatic scales. The four areas in a west-east direction are as follows: the Spanish NW Mediterranean Coast (Spain), the Gulf of Oran (Algeria), the Gulf of Gabès (Tunisia) and the Alexandria and West Nile Delta area (Egypt). Their locations are shown in Fig. 1.

The four cases present a typical Mediterranean climate, but each area has some distinctive features. The studied part of the Spanish Coast, in the north-western Mediterranean, is located in front of the Balearic Islands, stretching from the Creus Cape in the north to La Nao Cape in the south, with a coastal length of about 750 km. Its location, together with the local topography, exert a significant control over the wind climate, which is characterized by low to medium average winds, although some synoptic events are responsible for strong winds in this region (Sánchez-Arcilla et al. 2008a). Moreover, this area also presents some special features that determine the wave climate, being the most important the short fetches (due to the presence of the Balearic Islands), the high wind variability in time and space (Mösso et al. 2007) and the wave calms during the summer and energetic storms from October to May. This wave climate has a very defined seasonal structure with yearly averaged significant wave heights lower than 1 m (Garcia et al. 1993; Sierra et al. 2002). As a result of the oblique wave approach for the more energetic E-NE storms, long shore sediment transport shows a net S-SW component (Sánchez-Arcilla et al. 2005).

As most of the Mediterranean coast, this is a microtidal environment and, according to different tide gauges located in the area, the maximum spring tide range observed is of about 40 cm. Storm surges are also common, with intensities up to 1.0 m for typical storm conditions (Sánchez-Arcilla et al. 2008b). In some areas, there is also subsidence, as for instance in the Ebro Delta, where the average rate is between 1.5 and 3.0 mm per year (Sánchez-Arcilla et al. 1996; Somoza et al. 1998).

The second analysed case, the Gulf of Oran, located in western Algeria, is delimited by the Aiguille Cape in the east and the Falcon Cape in the west, and it is about 50 km wide. This gulf encompasses, in its western part, from the port of Oran to the Mers El Kebir, and it is characterized by high and escarped cliffs, going from 10 to almost 30 m in height. In the eastern part, the coast presents smaller cliffs, interrupted by small and narrow beaches.

This area has a semi-arid Mediterranean climate, with mild and wet winters and hot and dry summers. The average rainfall is of about 390 mm/year (varying from 2 mm in July to 120 mm in December). This sunny region, with more than 3,300 h of sunshine per year, has monthly average temperatures ranging from 12°C in January to 29°C in August (Chegaar and Chibani 2001). The wind regime features 6% of calm periods and an average wind velocity of 3.6 m/s (Merzouk 2000), with monthly average wind speeds between 3 m/s (December) and 4.6 m/s (April) (Mahmoudi et al. 2009).

Due to the prevailing currents in the area, the Gulf of Oran receives waters of Atlantic origin (Millot 1987). The circulation seems to be turbulent along the Algerian Coast, and these turbulences favour the dispersion of eventual pollution sources and allow a relative important primary productivity (Millot et al. 1997).

The third studied zone, the Gulf of Gabès, is a shallow eastward-facing embayment area located in the Tunisia Coast. It is 100 km long and 100 km wide, with depths typically ranging from 20 to 50 m (Sammari et al. 2006). It is bordered by a subdued topography formed mainly by low plateaus (20–70 m) and plains (1–5 m), and it is characterized by an arid Mediterranean climate, with an average rainfall varying from 250 mm/year in the north to 100–150 mm/year in the south, although the rainfall rate is highly irregular (Oueslati 1992).

The Gulf of Gabès is one of the few Mediterranean regions where astronomic tides are relatively important, with a semi-diurnal pattern and spring tidal range of

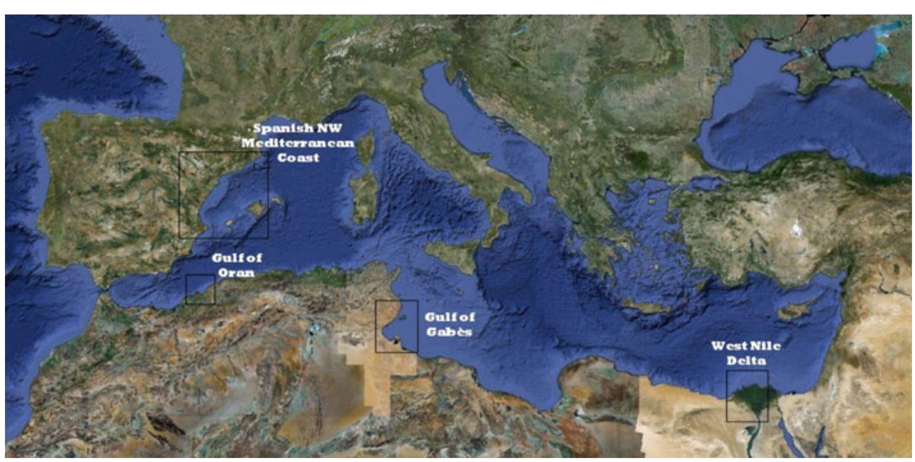

Fig. 1 The Mediterranean basin showing the four case studies selected for this work

2.0–2.3 m (Morhange and Pirazzoli 2005). This is because of resonance phenomena in the area which act to amplify tidal levels (Sammari et al. 2006). On the other hand, wave storms in the Gulf of Gabès are generally low energy events, because of the shallowness of the broad continental shelf and the important meadows of phanerogams. The wave energy is also bounded by the low wind velocities and, in some positions, the limited fetch (Oueslati 1992), which restricts the effect of the stronger easterly winds. This area is also characterized by weak currents, with high temperature (13.2–26.5°C) and high salinity in summer (37.5–39.25‰) (Pérez-Domingo et al. 2008), although lower salinities (37.3–37.5‰) have been detected in the region in other seasons and have been attributed to the presence of Modified Atlantic Water (Béranger et al. 2004; Pelegrí et al. 2005; Poulain and Zambianchi 2007; Drira et al. 2008; Bel Hassen et al. 2009).

In the last years, this area has suffered high anthropic pressures due to urban and industrial activities (Drira et al. 2008), experiencing a substantial proliferation of microalgae and, particularly, toxic dinoflagellates (Turki et al. 2006). As a consequence, fish resources in the Gulf of Gabès (which represent 65% of the national fish production in Tunisia) have declined, associated to the degradation of seagrass meadows.

Finally, the fourth studied environment, the West Nile Delta, is located in Egypt, in the eastern Mediterranean and at the mouth of one of the world's longest rivers (6,690 km). The annual average water discharge averaged 84 billion m^3 during the twentieth century. More than 80% of the Nile River total discharge occurs from August to October, while about 20% is distributed during the remaining 9 months (Stanley and Warne 1998).

This delta is located in a hyperarid region, with temperatures over 30°C in July and mean annual precipitation ranging from 100 to 200 mm. The deltaic plain encompasses about 22,000 km^2, and its coast is about 225 km long. It is characterized by a very low tidal range (spring tides average 30–40 cm), N-NW offshore winds that are active during most of the year, and a large-scale counterclockwise circulation pattern that drives water masses eastward. The offshore surface (geostrophic) eddy velocities can exceed 0.25 m/s (Stanley and Warne 1998). Predominant waves feature an oblique approach, generating longshore currents with velocities from 20 to 50 cm/s and occasionally exceeding 100 cm/s. Storm waves with heights of 1.5–3 m approach the coast from the northern quadrant (commonly from the north-west), eroding and displacing sediment eastwards (Stanley 1989; Stanley et al. 1998).

The Nile Delta is also experiencing relative sea-level rise due to land subsidence. In the northern delta, this happens at a rate between 1 and 5 mm per year (Emery et al. 1988; Stanley 1988, 1990; Stanley and Goodfriend 1997). Moreover, since the construction of the High Dam at Aswan in 1964, less than 2% of sediment bypasses this dam, and about 100 million tons of sediments per year accumulate in the southern part of Lake Nasser reservoir. As a consequence, less than 10% of the former Nile River potential sediment load is now delivered to the Mediterranean coast (Stanley and Warne 1998).

Drivers

General framework

One of the most robust indicators of climate change is air temperature. Most of Europe has revealed increases in surface air temperatures during the twentieth century. This warming has been largest over north-western Russia and the Iberian Peninsula (Nicholls et al. 1996), suggesting that in Europe the balance (in terms of implications) of climate change will be more negative in southern and eastern countries (Maracchi et al. 2005).

In the last decades, extreme events registered in the Mediterranean basin have shown an increase in heavy precipitations and a raise of extreme temperatures (Sánchez et al. 2004; Giorgi et al. 2004). Present climate models indicate a decrease in precipitation levels during the twenty-first century (Gibelin and Déqué 2003), mainly during the summer months (Rowell 2005), with the central and south Mediterranean being one of the regions most affected by the precipitation decrease. This will exacerbate drought episodes, land degradation and desertification, particularly for the East-Mediterranean (Körner et al. 2005; Vicente-Serrano 2007). A pronounced warming is also projected, being maximum in the summer season with a greater occurrence of high temperature events (Giorgi and Lionello 2008).

Global low-frequency sea-level trends are dominated by the steric component, and the associated ocean volume increase (Levitius et al. 2000; Calafat and Gomis 2009). However, at a regional scale, atmospheric pressure and wind effects can also play a key role (e.g. Gomis et al. 2008) such as it happens for the Mediterranean region.

Wind-generated waves are the more energetic driving term among all meteo-oceanographic factors, given the limited tidal range in the Mediterranean. The available observational series span less than three decades, which suggests the use of numerically generated series. However, the hindcast fields should be used with care since the accuracy of predicted waves is significantly smaller than for open sea conditions (Béranger et al. 2004; Cavaleri and Bertotti 2006).

Some analyses suggest a milder future wave storm climate, being the significant wave height reduction linked to the diminished ocean surface winds and storm activity. A reduction in low-pressure centre intensity is consistent with the overall decrease in precipitation and northward displacement of storm tracks, which most models indicate for the Mediterranean area (Lionello et al. 2008a). Nevertheless, within the last decades, the NW Mediterranean has experienced some of the most severe storm events ever recorded in the area (Sánchez-Arcilla et al. 2008a).

Sea level

Sea level rise is an important indicator of climate change, with great relevance in squeezed coastal regions, such as those of the Mediterranean, for flooding, coastal erosion and the loss of low-lying areas. Relative sea-level rise increases the likelihood of storm surges, enforces landward intrusion of salt water and endangers coastal ecosystems and wetlands. Apart from natural ecosystems, coastal areas often feature important managed ecosystems, economic sectors and major urban centres. Thus, a higher flood risk increases the threat of loss of life and property as well as of damage to protection measures and infrastructures. This, in turn, should result in a degradation of coastal functions such as recreation, transport.

A change in relative mean sea level (MSL) at the coast may have various origins. It can be caused by the vertical movement of the land itself. This applies to the Mediterranean basin, which is located on the boundary of an active geological plate, so that any global sea-level rise induced by climate change may be locally accentuated or minimized by tectonic movements. Relative MSL can also arise from local sea-level changes due to variations in prevailing winds and ocean currents or from by a change in the volume of the world's oceans, mainly controlled by temperature.

It is generally accepted that the global sea level has increased between 10 and 25 cm over the past 100 years (e.g. Raper et al. 2001), and it is expected that the rise will not only continue in the near future, but it will probably also accelerate, although the range of predictions and models is so large that precise forecasting is not possible. Nicholls and Hoozemaans (1996) point out that the sea level might rise between 0.2 and 0.9 m by the year 2100, being the best estimates in the order of 0.5 m. In the past 100 years, European and global average sea level has risen by 10–20 cm with a central value of 15 cm (IPCC 2001). Currently, the sea level at Mediterranean coasts is rising at a rate of 1.0 mm/year (Marseille), 1.3 mm/year (Genova or Trieste), to 2.6 mm/year (Venice), which is close to the global average (Liebsch et al. 2002). It is likely that the observed trend in sea-level rise over the past 100 years is mainly attributable to an increase in the volume of ocean water as a consequence of global warming. The local variations could be explained by some of the other processes mentioned above. In what follows, we shall discuss the trends in the Catalan (Spain) Coast and Gabès Gulf. There is no conclusive evidence for Oran and the case of the Nile Delta will be discussed at the end of this section.

The relative sea level in the Spanish Mediterranean Coast and Gulf of Gabès do not present a common or well-defined pattern. The available data in the Spanish Coast case consist of hindcasted storm surge data (HIPOCAS) from 1958 to 2001 (Ratsimandresy et al. 2008) and observations of the residual tide within the ports of Barcelona and Valencia from 1992 to date. For the Gulf of Gabès case, there are only observed series since 1999.

For the Spanish coastal case, storm surge simulations (Fig. 2a) suggest that the relative sea level is slightly decreasing during the considered time span. The average decrease in surge intensity is of about −0.54 m per decade. The observations also suggest a fall in mean sea level of −0.04 m per year, although the registered time series are too short to allow any final conclusion. In both cases, it is assumed that the land remains at a steady level since that is the conclusion obtained from recent geological studies (Somoza et al. 1998). The trend in mean sea level derived from observations is, however, so small dependent on the considered time-scale (due to the shortness of the series) that the more robust conclusion is that it is almost steady.

In the case of the Gulf of Gabès, the observed data, provided by the Tunisia Hydrographic and Oceanographic Center, suggest that the relative sea level is rising at a rate of 2.6 cm per decade (Fig. 2b). These results are consistent with altimetry data that show an increase in sea level of 2.1 cm per decade. Notably, for the Spanish case, if only modelled data from 1992 to 2001 are considered (coinciding temporarily with some of the observed data), they suggest an increase in storm surge of 1.75 cm per decade. This suggests an increase in mean sea level at both locations and illustrates the sensitivity of the relative sea-level values to the selected time and space intervals.

Precipitation rates

Changes in average precipitation can have potentially far-reaching impacts on ecosystems and biodiversity, agriculture (food production), water resources and river flows. Global climate model simulations indicate that there shall be a decrease in yearly averaged values but that the return period for heavy rainfall events may decrease (Lionello et al. 2002). This change in precipitation patterns, associated to a decreasing mean and an increasing variance in the corresponding probability function, should lead to an intensification of flooding during the rainy period, particularly for low-lying coastal areas. This will be accompanied by more frequent and severe drought periods, more

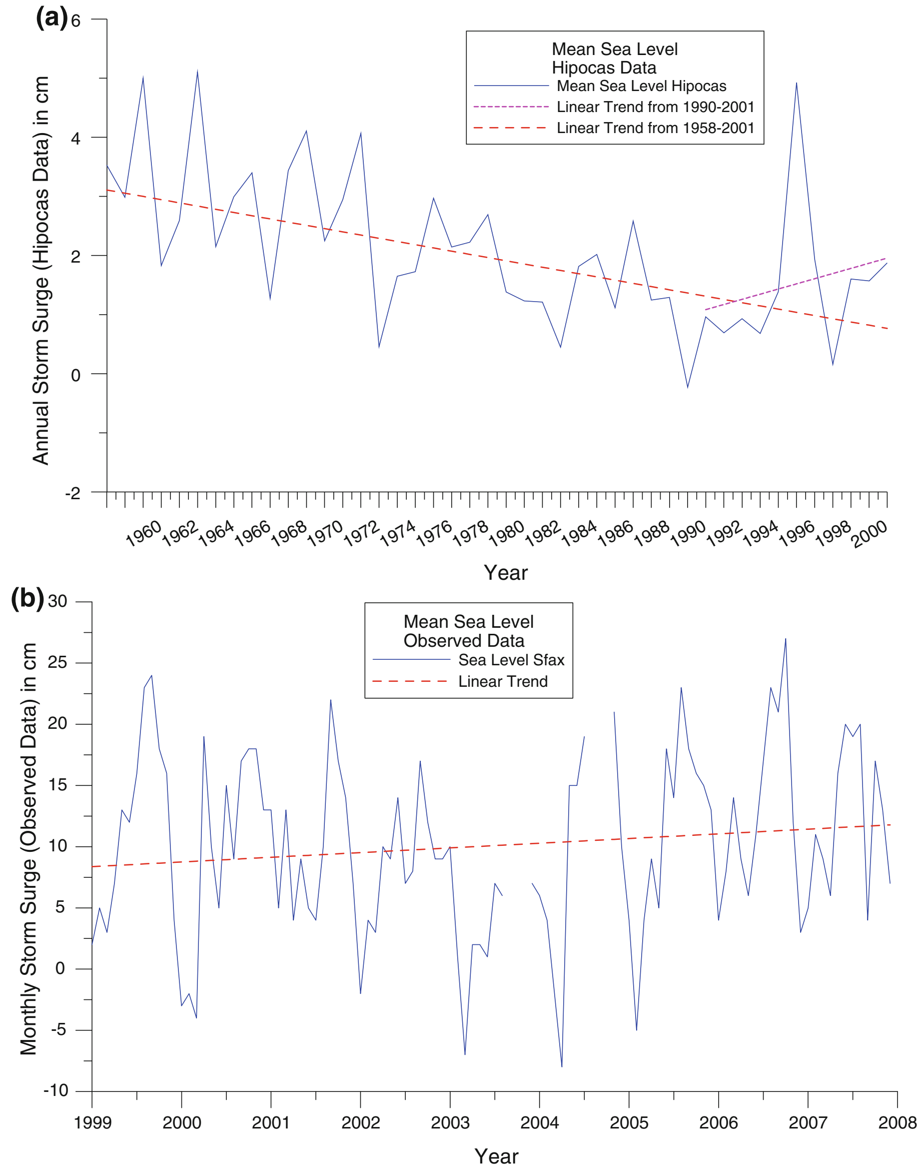

Fig. 2 Storm surge at the Ebro Coast in Spain (hindcasted data) and at the Gabès Gulf (observed data). Considering the hindcast time series (1954–2001), there is a slight decreasing trend at Ebro, while if we only look at the last decade of data, there is an increasing trend, consistent with the observations of mean sea level from Gabès

frequent land slides and increased soil erosion. Floods and droughts can even occur in the same region in different seasons of the same year (e.g. a region may be exposed to drought in spring and summer and be flooded in autumn). Brunet et al. (2007) have studied the changes in precipitation extremes within Spain (from the beginning of the twentieth century) indicating that there is a tendency towards more intense rainy days and increases in heavy precipitation during the twentieth century, a behaviour consistent with a warmer planet.

Decreasing precipitation trends will mean reductions in water quality and availability over the four regions. Drought periods are likely to become more frequent as the probability of dry days and the length of dry spells increase. The more frequent extreme precipitation events will intensify the hydrological cycle and the risk of extreme flooding and erosion. Most scenarios suggest an increase in the frequency of extreme events and, in particular, of droughts and flooding in the western Mediterranean. The potential coastal impact of modified precipitation rates is largely associated to the supply of riverine sediment to counter the enhanced land loss and erosion induced by the sea-level rise and increased storminess. Therefore, and taking into account that river sediment transport takes place only when the river flow exceeds a given threshold, it is the time distribution of extreme precipitation events that is of interest, rather than a mean (e.g. yearly) precipitation trend. Nevertheless, the real influence on the coast of larger rainfall rates is limited due to the effective decoupling of riverine systems from the coastal environment, because of the intensive regulation of river flows by dams. In recent works, it has been estimated that more than 90% of the sediment transported by, e.g., the Ebro River became trapped in the numerous reservoirs built along its course. The reduction is nearly complete for bed load (the only one providing beach sized material) but is also affects suspended and wash loads (Mariño 1992; Ibáñez et al. 1996; Jiménez 2005). The same applies to the Nile, as mentioned in the previous section.

Precipitation data coverage in the Mediterranean is quite heterogeneous, and the derived trends are uncertain, because measurement techniques have changed during the twentieth century. However, it is clear from the recorded data that precipitation, in terms of standardized anomalies (e.g. the case of the Catalan Coast), shows a large variability typical of the Mediterranean climate, preventing a clear identification of sub-periods with differential behaviour (Fig. 3).

Precipitation patterns in the four studied sites (Fig. 3) show the characteristic variability of the Mediterranean, with negative or positive trends depending on location. There are inverse trends between Barcelona and Ebro Delta (200 km apart) in the Spanish case or between Gabès and Oran and important decadal shifts in the West Nile Delta. Despite the great variability, any changes in precipitation patterns will have a direct influence on the studied coasts. Precipitation rates in the 4 cases show a large variance and no significant commonalities. In the Spanish case, the studied stations (Fabra in Barcelona from 1914 to 2008 and Ebro Delta, from 1906 to 2008) show an opposite trend, the yearly mean decreasing in Fabra and increasing in Ebro Delta through the observed period, and without similarities in the annual distribution of rainfall. Table 1 summarizes the different dry and wet periods recorded at the analysed stations.

The registered series show some commonalities among sites, such as the dry period around 1925 in the Catalan Coast and Gulf of Gabès or the rainy interval around 1970–1975 in the Catalan Coast, the Gulf of Oran and Gabès. There are no clear and statistically significant trends, nor any common sustained patterns, for the 4 studied sites. Moreover, the Gabès plot (where data provided by the Ministery of Agriculture and Water Resources of Tunisia from other stations are included) illustrates the high-level variability at a local scale (less that 200 km) typical of Mediterranean shores.

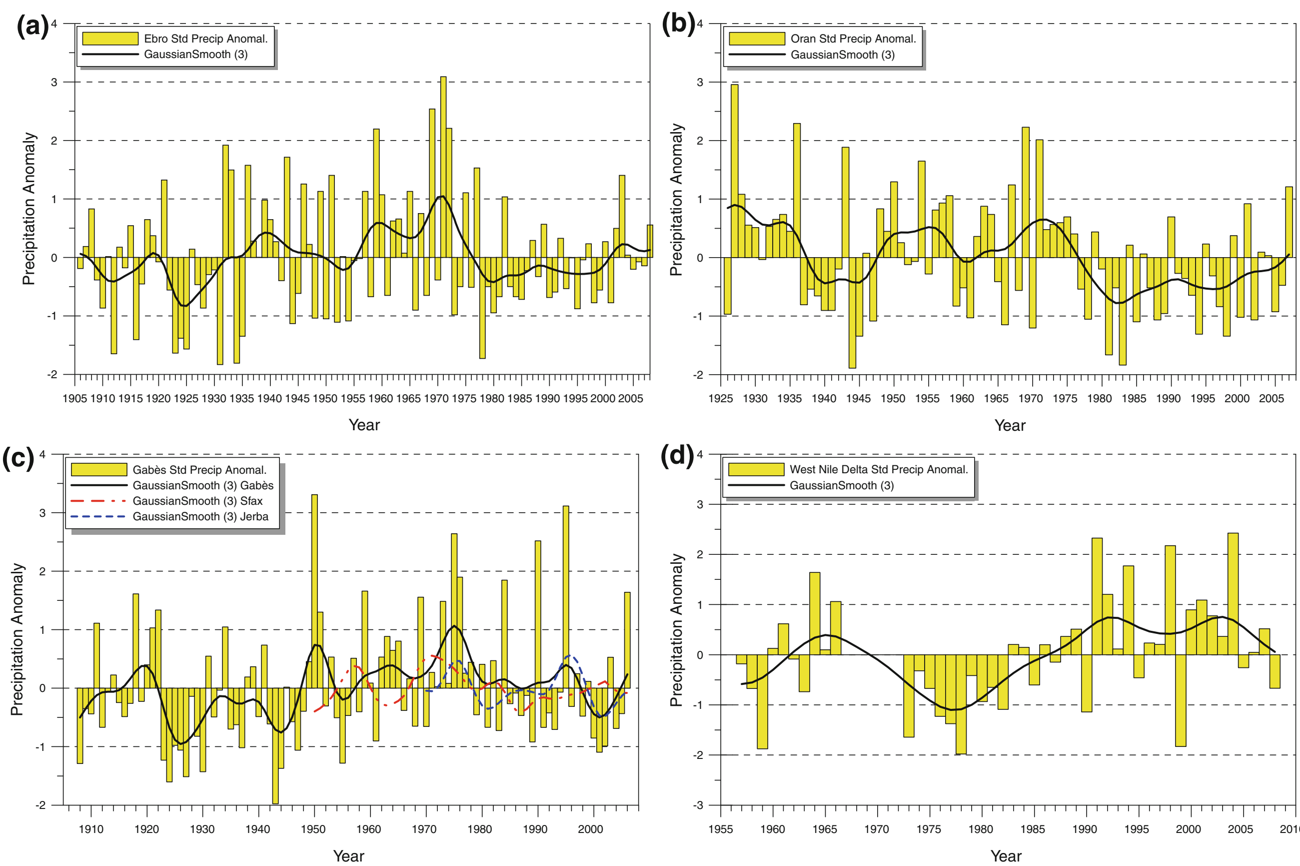

Fig. 3 Precipitation rates, expressed as anomaly over standard deviation, at the Spanish NW Mediterranean Coast (**a**), Gulf of Oran (**b**), Gulf of Gabès (**c**) and West Nile Delta (**d**). The Gulf of Gabès plot includes time series from www.tutiemp.net and from the Tunisian Ministry of Agriculture and Water Resources, illustrating the high level of local variability

Table 1 Summary of rainy and drought periods in the four study cases

Site	Rainy period	Drought period
Spanish Coast (Barcelona)	(1970–1993)	(1994–2008)
Spanish Coast (Ebro)	(1936–1949) (1956–1976) (2001–2008)	(1907–1932) (1976–2000)
Gabès	(1917–1922) (1948–1997)	(1907–1916) (1923–1948) (1998–2005)
Oran	(1926–1926) (1948–1976)	(1937–1947) (1997–2007)
West Nile Delta	(1962–1969) (1988–2009)	(1970–1987)

This observational evidence agrees with predicted regional changes (Lionello et al. 2008b), which suggest a decrease in average precipitation together with an increase in rainy events during fall/winter. These trends may be different for the northern Mediterranean shore, particularly in the region of Alpine influence, which may even experience an increase in precipitation.

Storms

Even assuming that the frequency and intensity of storms do not vary due to climate change, the return period of extreme water levels induced by storm surges at the coast will be reduced because of relative sea-level rise (Sánchez-Arcilla et al. 2008b). This will eventually lead to a larger frequency of flooding events in coastal low-lying areas. Particularly vulnerable to this effect will be deltaic areas and coastal lagoons (Sánchez-Arcilla and Jiménez 1994), where the combined effects of subsidence plus low topography will induce flooding and enhanced erosion (Fig. 4).

Any variations in wave and storm characteristics will play a critical role in determining the coastal impact of climate change, since the present shoreline configuration is in dynamic equilibrium with today's meteo-oceanographic patterns. Incident waves with larger average heights will result in stronger longitudinal and return currents, which will eventually lead to enhanced coastal sediment transport and erosion rates. A further contribution to coastline erosion can result from the increased frequency of moderate storms, since the coast will not have enough recovering time between storm events.

However, the exact response of the coast to these storms depends not only on the energy of the event, but also on the particular features of the storm, such as duration, wave period or steepness (Sánchez-Arcilla et al. 2008a). Related flooding (due to storm surge and wave-breaking) is the single most destructive type of natural disaster that strikes humans and their livelihoods around the world (Ismail-Zadeh and Takeuchi 2007), and this also holds true for Mediterranean coasts.

The storms considered in this study have been defined by two different criteria, in terms of meteorological conditions for the Gulf of Oran and in terms of wave

Fig. 4 Storm impact in the Ebro region and, in particular, in the Trabucador Beach (*top-left*). Breaching after the impact of the October 1990 storm (*top-right*). Breaching after the November 2001 storm (*bottom*)

conditions for the Spanish Mediterranean Coast (Bolaños et al. 2004). This provides the widest possible coverage of meteo-oceanographic conditions for the available observations. The main result is the large variability, in time and space, characteristic of Mediterranean conditions, which are essentially torrential. The average number of observed meteorological storms in the Gulf of Oran from 1950 to 2007 does not present significant changes throughout the observation period, though there are more extremes since 1970. More specifically, autumn storms have increased their frequency by about 10% since 1975. This increase is related to recent floods in the north-western region of Algeria.

In the Spanish case (Fig. 5), the annual number of moderate and severe wave storms throughout the observation period (1990–2006) presents an opposite trend: a decrease in the number of severe storms, while there is an increase in the number of moderate storms.

Regarding the actual Hs magnitude, the observed data series are too short (Fig. 6) to provide any definite conclusion. The hind-cast values, on the other hand, suggest an increase at most stations, as illustrated in Fig. 6 for the Gabès and Catalan Coasts. The Spanish data come from the HIPOCAS project and have been supplied by Puertos del Estado (Ministry of Public Works). The Tunisian data come from the Direction Générale des services Aeriens et Maritimes, Ministère de l'Equipement et l'Habitat.

The average duration of the studied moderate storms is fairly constant, while the corresponding value for severe storms has shown an increasing trend during the last decade (Fig. 5). The directional distribution of incident waves shows also large variations, as expected for the irregular topo-bathymetric characteristics of Mediterranean coasts. This is illustrated with data from the Spanish coast (Fig. 7). In the sector around Barcelona, the more energetic waves come from the East, corresponding to the longest fetch, since this part of the coast is sheltered from Northern wave components. The Ebro Delta Coast, in the middle of the Spanish case, shows frequent wave events from the East and North-West. The East corresponds to the same storms as for the Barcelona sector, while the NW (Mistral) waves are associated to winds from that direction blowing down the valley of the Ebro River. The most southern Spanish location (Cullera Bay) shows a predominance of NE waves since this corresponds to the longest available fetch, with other directional sectors being limited in occurrence and energetic content, due to the coast orientation and the presence of the Balearic Islands.

In the particular case of the Ebro region, eastern wave storms tend to occur simultaneously with surged water levels, related to the passage of low-pressure systems off the delta (Sánchez-Arcilla and Jiménez 1994; Jiménez et al. 1997). In this case, the most important effects are related to the inundation of agricultural zones plus the affectation of natural values due to wave exposure and flooding. All these effects result in a large "impulsive" coastal erosion (see Fig. 4 for a sample illustration).

Sea surface temperature

The oceans have a large capacity for storing and redistributing heat. By storing heat, they delay global temperature increases, but this goes together with an increase in evaporation and, thus, precipitation. Overall ocean temperatures show a rising trend consistent with the observed increase in air temperatures (Levitius et al. 2000). The western Mediterranean and North Atlantic react in a manner similar to that of global oceans. In the 1990s, these seas warmed by about 0.5°C (Rixen et al. 2005; Vargas-Yáñez et al. 2009).

More specifically, the annual mean, maximum and minimum values of sea surface temperature (SST) show a clear increasing trend (Fig. 8a). However, the intra-annual viability is so pronounced that it tends to mask this longer term trend, which is about 0.77°C/decade in the Ebro station (Fig. 8b). The increasing trend of SST is linked to a similar behaviour in air temperature evolution (Fig. 9a for the Catalan Coast). This pattern is also observed (Fig. 9b–d) for the rest of coastal sites. In particular, the

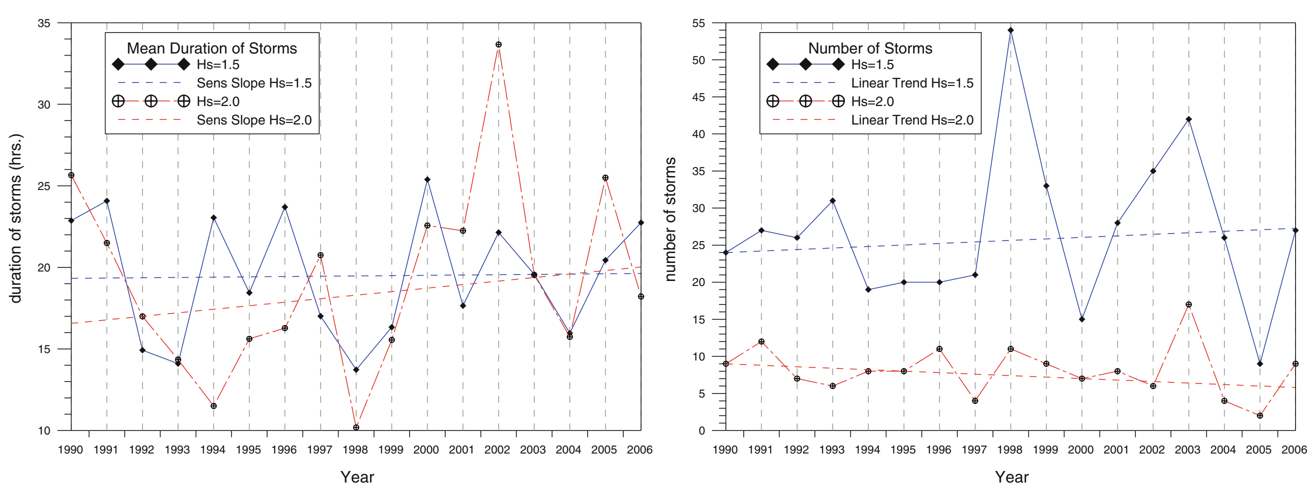

Fig. 5 Mean duration of moderate (above an Hs threshold of 1.5 m) and severe (above an Hs threshold of 2.0 m) storms (*left*) and number of occurrences (*right*) for the same two storm types. Both panels correspond to the observed wave data series off the Ebro Delta, in the Spanish NW Mediterranean coast

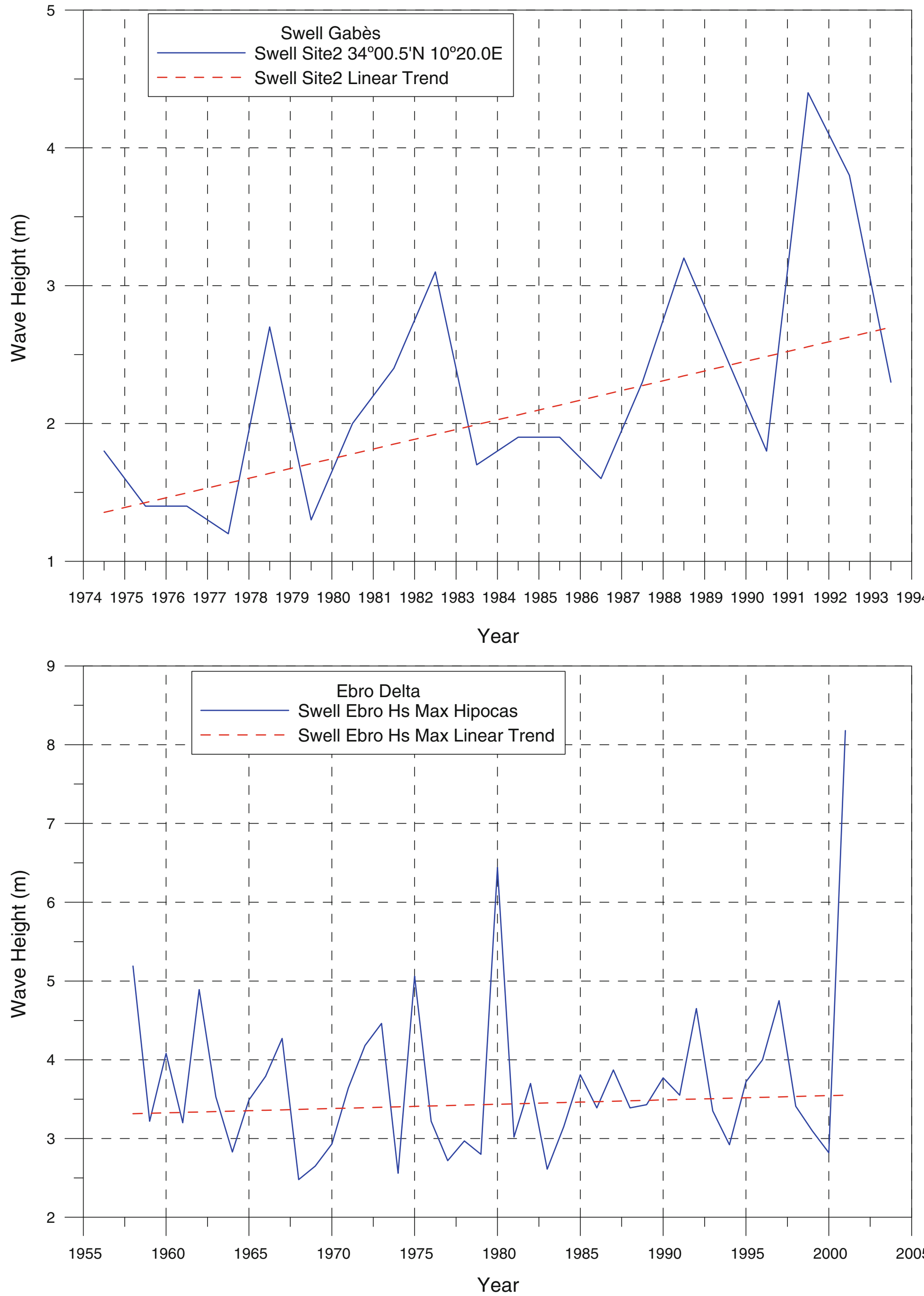

Fig. 6 Yearly mean hind-cast Hs values for the Gabès (*top*) and Catalan (*bottom*) coasts. The data have been provided by the Ministère de l'Equipement et l'Habitat for Tunisia and by Puertos del Estado, Ministry of Public Works for Spain (see text)

Gabès mean-maximum temperature data from 1950 to 2005 (provided by the Tunisia National Meteorological Centre) show a 0.29°C/decade increase with a clear acceleration during the last 30 years. This means that, although no instrumental records are available, there should be a general SST increase in all coastal stations.

Among the extreme natural events that struck the Earth and our coastal societies in recent times, some of the most violent (e.g. hurricane Charley (category 4 on the Saffir-Simpson scale, in August 2004), Ivan (category 3, in September 2004), Katrina (category 4, August 2005), etc.) have been related to this increase in sea surface temperatures (SST). Several studies suggest that global warming will likely result in SST increase, which will enhance the intensity of extreme storms (Sun et al. 2007) and mean sea levels. This also applies regionally, where the largest, ever recorded, significant wave height in the Catalan coast occurred in the Costa Brava region—near the border between Spain and France—in December 2008. Therefore, it is a matter of when rather than if such extreme natural events will occur.

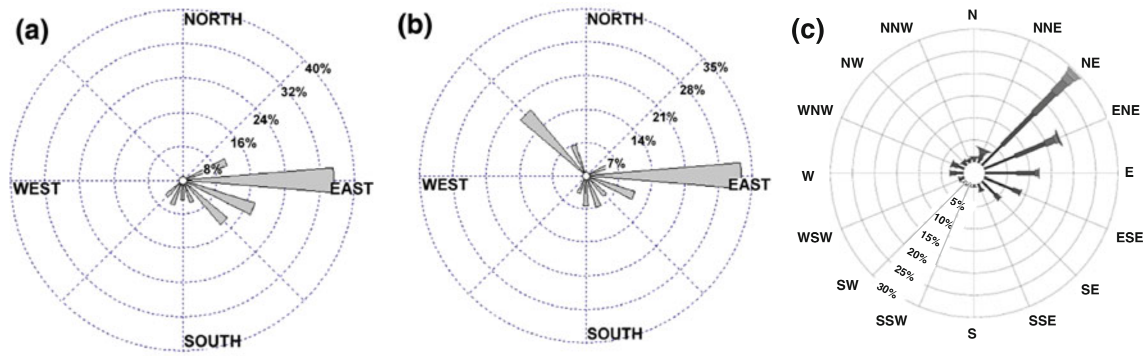

Fig. 7 Directional wave distribution along the Spanish Coast. The radial axis indicates frequencies of occurrence. **a** Llobregat wave buoy that corresponds to the Barcelona coast, **b** Cap Tortosa buoy that corresponds to the Ebro Delta cost and **c** Cullera Bay that corresponds to the central/south Valencia Gulf (*sources*: Sánchez-Arcilla et al. 2008a **a**, **b** and Mösso et al. 2007 **c**)

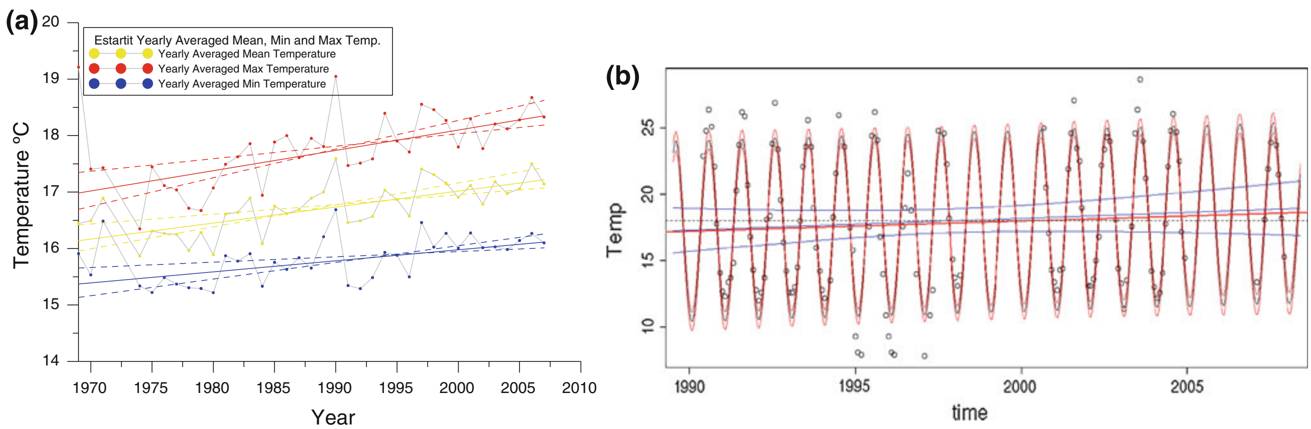

Fig. 8 **a** Annual mean (*middle curve*), maximum (*upper curve*) and minimum (*lower curve*) sea surface temperature (*SST*) at the Northern Catalan Coast (Estartit station), for the period 1969–2008 (*left*) and **b** monthly SST in front of the Ebro Delta, for the period 1990–2008 (*right*). *Data sources*: SMC (Servei Meteorologic de Catalunya) and Josep Pascual

Hazards

General framework

In this section, we present the implications of climatic variability on erosion and water quality [both bio-geo-physical hazards (Adger 2006)], driven by changes in physical parameters. The assessment should be in terms of the average trend and the estimated changes in variance. However, in order to be consistent with the paucity of available data, we shall only perform the exercise for the medium trend.

Even with this simplified approach, there remain a large number of uncertainties. They can be classified in seven large blocks, of which the first four are the normally accepted sources of uncertainty in climatic scenarios (Somot et al. 2006, 2008; Terray and Braconnot 2007). They can be summarized as follows:

– Green house gas emissions, related to the socioeconomic behaviour and technological developments.
– Modelling performance, related to the employed equations and parameterizations.
– Type of downscaling (physical or statistical) and selected boundary conditions, plus the considered feedbacks.
– The inherent limits of predictability, which vary depending on the nonlinearity of the sub-system property considered (for instance, about 1 year for features such as the North Atlantic oscillation or the ENSO).

It is also important to include three additional sources of uncertainty, which may become even dominant in terms of the resulting hazards. They are related to:

– The response function that links climatic drivers to the desired "property" of the coastal system and that is normally poorly known. For instance, computations of sediment transport rates may present errors of up to 100% (see e.g. Cáceres et al. 2009).
– The threshold needed to calculate hazards, which is also an open question mark for many practical applications related to erosion, flooding or water quality.

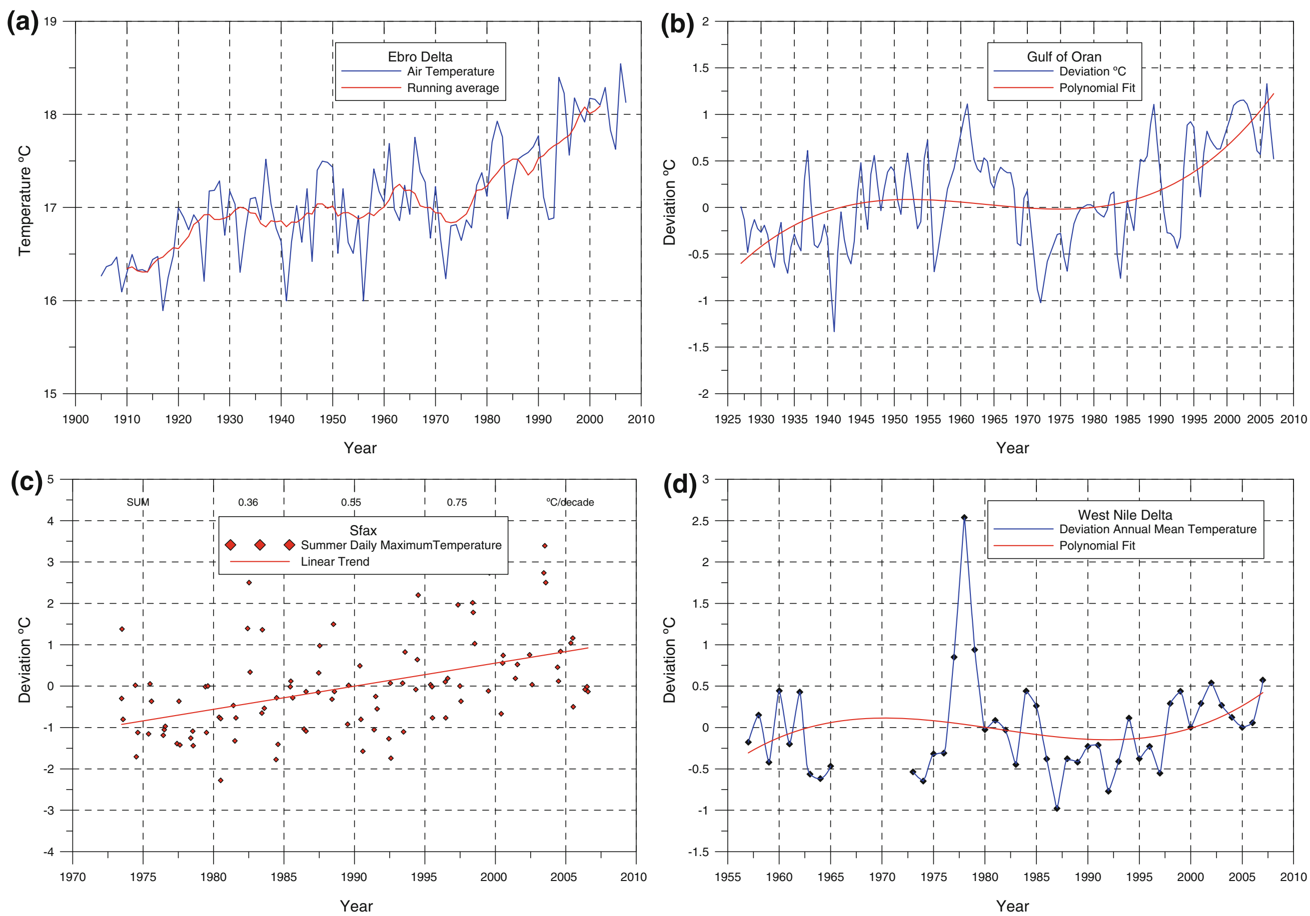

Fig. 9 Air temperature evolution at **a** Catalan Coast, **b** Gulf of Oran, **c** Gulf of Gabès and **d** West Nile Delta. In all four cases, disregarding the type of statistical analyses or whether they refer to absolute temperature data or temperature deviation, there is an increasing trend over the observation period

– The probability distribution functions of drivers and responses which is seldom known and is introduced in terms of a mean, or, at most a mean plus a standard deviation. This presents particular problems, especially for extremes since the tail of the distributions are sensitive to all previous hypotheses.

Such a wide fan of uncertainties also applies to the four studied field sites, which are characteristic examples of Northern and Southern Mediterranean coasts (Fig. 1). They have been analysed covering a wide range of physical drivers with some Esocioeconomic implications. Uncertainties begin with the fact that the Mediterranean is a particularly vulnerable region to climate changes (Goubanova and Li 2007) and has shown large climatic shifts in the past, being identified as one of the most prominent "hot-spots" in future climatic change projections (Giorgi 2006). Given that the Mediterranean is a transition area between the temperate climate of central Europe and the arid climate of northern Africa, changes have the potential to deeply modify the climatic characteristics of the Mediterranean. The population density plus these effects could result in devastating impacts on water resources, natural ecosystems (both terrestrial and marine), human activities (e.g. agriculture, recreation, tourism) and health (Giorgi and Lionello 2008).

Flooding is the most common of these environmental hazards, and the number of people vulnerable to it is increasing as populations rise and the alternative settlement sites decrease. In particular, floods are the most common kind of natural hazard in the Western Mediterranean region (Milelli et al. 2006), either in river basins by intense rainfalls over small catchments (flash floods) or by energetic sea storm events, acting on low-lying coastal areas.

Because of this torrential character of the climate, droughts are one of the main climatic hazards affecting Mediterranean regions. In Spain, they have become a frequent phenomenon due to the high spatial and temporal variability of precipitation. They are controlled by atmospheric circulation patterns in the North Atlantic (Barriendos and Llasat 2003; Vicente-Serrano and Cuadrat 2007) and also by local cyclo-genesis. Drought periods can result in significant loses for crop yields (Quiring and Papakryiakou 2003), increasing the risk of forest fires (Pausas 2004), gradual reduction in tree growth (Körner et al. 2005) and triggering processes of land degradation and desertification (Schlesinger et al. 1990).

Sea temperatures control atmosphere–ocean exchanges and are, thus, linked to evaporation and precipitation rates. The associated hazards come, mainly, from coastal flooding due to continental run-off. Water temperature also controls the solubility of certain substances—among them dissolved oxygen—and primary production (Manasrah et al. 2006; Markfort and Hondzo 2009). This results in a factor affecting water quality, as described below.

Water temperature regulates ecosystem functioning both directly, through physiological effects on organisms, and indirectly, as a consequence of habitat loss. Photosynthesis and aerobic respiration and the growth, reproduction, metabolism and mobility of organisms are all affected by changes in water temperature. Indeed, the rates of biochemical reactions usually double when temperature is increased by 10°C within the given tolerance interval of an organism, and this also applies to microbial processes such as nitrogen fixation, nitrification and denitrification.

Aquatic organisms can only survive within a particular temperature range. If temperature goes too far above or below (positive or negative temperature anomalies of only a few degrees can induce mortality), the tolerance for a given species (e.g. fish, insects, benthic invertebrates, zooplankton, phytoplankton & microbes) and its ability to survive may be compromised. Unnatural changes in water temperature impact indirectly upon biota through loss of supporting habitat, by changing the solubility of oxygen and calcium carbonate (calcite or aragonite) in water or by influencing the extent to which metal contaminants and other toxicants are assimilated by physiological processes. Water temperature is also, probably, the most important factor influencing viral persistence in estuarine environments, since it affects the density, conductivity and pH of the water column.

In addition, the solubility of gases (e.g. dissolved oxygen and carbon dioxide) decreases with increasing temperature (solubility being the maximum amount of gas that can be dissolved in a given volume of water). Water is more likely to become anoxic or hypoxic under warmer conditions, because of increased bacterial respiration and a decreased ability of water to hold dissolved oxygen.

If SST warming continues, the solubility of CO_2 and thus the net uptake of it by the oceans will decrease. On the other hand, ocean warming can activate zoo- and phytoplankton, the so-called "biological pump", which is responsible for the oceans' biological uptake of CO_2. However, the decreasing physical solubility of CO_2 in warmer seas could override the positive effect of the biological pump, in terms of global average and also for regional scales, such as in the case of the Mediterranean (Westby et al. 2002).

Physical hazards based on sediment balance: forcing terms

Within the framework just presented, there is a variety of physical hazards that can be considered. We shall focus on erosion and water quality at climatic scales. Coastal erosion will be addressed in terms of the corresponding sediment balance, whose main drivers are analysed in what follows.

The first obvious climatic driver is sea-level rise which, as mentioned in previous sections, has experienced during the twentieth century in the Mediterranean an average rise of about 10 cm. By 2100, all SRES scenarios (Nakicenovic et al. 2000) predict an average rise of 18–59 cm. No better estimation is presently available for the Mediterranean, far less distinguishing between the Eastern and Western sides or Northern vs. Southern shores. Based on the available time series, the short-term rates of SLR for the four studied sites, excluding subsidence, are found to be smaller than 5 mm per year for Spain (Catalan Coast), Oran and Gabès and between 5 and 10 mm per year for the Nile Delta. More specifically, there appears to be a relatively steady sea level in the Spanish case (less than 1 mm per year of change), while mean sea level appears to be increasing in the southern shore (e.g. Gabès) since 1992, at a rate of about 2 mm per year.

The subsidence rates have been taken as close to 0 for Gabès and Oran, as 2.5 mm per year for sinking areas in the Catalan coast such as the Ebro Delta and of about 4 mm per year for the Nile Delta. These values correspond to the last decades, being representative of some "contemporary" interval in the last century. They are in agreement with the present state-of-art (Emery et al. 1988; Sánchez-Arcilla et al. 1998; Somoza et al. 1998; Ericson et al. 2006) but should be considered as the best possible educated guess at this time, due to the lack of more solid geophysical evidence. However, they are considered to be suitable for the vulnerability analysis to be performed in next section.

A more accurate estimation is, however, urgently required in the near future, since even small increases or variations in these parameters can produce a large impact. As an example, 1 cm of sea-level rise increases the flooded area by various metres in the low-lying areas along the Mediterranean coast, and a sea-level rise of 1 m has been estimated to produce a loss of 10% of the available emerged plain in the Nile Delta (Dasgupta et al. 2007). This justifies the need for an enhanced monitoring effort in the coming future.

These same limitations apply to other climatic variables such as river discharge or wave storminess. In the case of river discharge, there should be a distinction between liquid and solid transport, and this latter variable should be split into bed, suspended and wash loads. Bed-load transport, which is mostly sand, has been significantly reduced in all regulated rivers (see e.g. Sánchez-Arcilla et al. 1996). However, wash-load and suspended fluxes are not so sharply reduced, although they only provide fine material such as silt or clay, which is not suitable for building a stable shoreline. The same fate applies to nutrient discharges, important for the biological productivity of the coastal sea, which is also dependent on the liquid discharge. In the case of regulated rivers, the experience from Northern Mediterranean shores of the European Union (e.g. the Deltas of the Ebro, Rhone or Po) is that river regulation exerts a stronger control than climatic variability (Sánchez-Arcilla et al. 1996; Sierra et al. 2004).

Physical hazards: erosion

We shall now estimate coastal erosion due to relative sea-level rise, without considering any further reductions in river sedimentary supplies with respect to the present situation, because of the stronger effects of river regulation when compared to climate variability. The corresponding erosion rates appear in Table 2. In this table, the "recent past" corresponds to the last century, while the "present" estimates have been obtained assuming a 1 mm sea-level rise per year as an average figure for the whole domain. The "near future" rates correspond to the interval 2050–2100 and have been obtained assuming an increase in sea level by 2100 of about 50 cm. The displayed figures correspond to an average estimate, assuming a "solid" response of the shoreline to sea-level rise based on a simplified version on Bruun's rule. However, it should be explicitly stated that the actual response will vary from beach to beach, depending on sediment and profile features and the availability of space for the required beach erosion. Because of that these numbers, expressed in horizontal metres of erosion, should be considered as rough estimates to illustrate the variability across Mediterranean coasts. The numbers can nevertheless be used to perform a regional scale analysis.

Regarding storm events, there appears to be a slight increase in the number of moderate storms during the fall period, based, as it was described in previous sections, on the thunderstorms for the Oran Gulf and on the wave storms for the Catalan region. However, the number of more energetic events appears to be decreasing, while there is an increase in storm duration (based on a limited set of data from the Catalan case).

Table 2 Shoreline erosion rates in horizontal metres, due to SLR for the last century (recent past), present conditions (present) and by the year 2100 (near future)

Site	Recent past		Present		Near future	
	No sub	Sub	No Sub	Sub	No sub	Sub
Valencia	0		10		50	
Ebro Delta		25		35		75
Oran	25		35		75	
Gabès	25		35		75	
Nile		40		50		90

A distinction is made between the sites without subsidence (no sub) and those with subsidence (sub). The uncertainty in the estimates should be always considered

The beach profile erosion associated to wave storms depends on both intensity and duration (see e.g. Sánchez-Arcilla et al. 2008b). If, as justified in previous sections, we assume an increase in duration of 2 h per decade, then we can estimate the corresponding increase in eroded volume as approximately 2 m^3/m (for the extra 2 storm hours) based on the previous reference. This results in an erosion increase of 2 m per decade, using a berm height of between 1.0 and 2.0 m, since we are including also part of the submerged beach profile to calculate the balance. This would result in 20 m of extra erosion by 2100 for the Catalan, Nile and Oran cases, while the Gabès case, more sheltered, has not been considered to be subject to this effect. The increase in number of storms reported from the Oran case has been considered to be included in the 2 h per decade increase in duration (in terms of resulting erosion) since these 2 h per decade may come from either a longer duration or an increase in the number of storms.

Adding this enhanced erosion due to wave storminess to the previously calculated figures, resulting from relative sea-level rise, we end up with the estimates presented in Table 3, which again correspond to the horizontal average erosion expected for 2100.

The combined erosion for the year 2100 is, therefore, around 70 m for the most favourable cases of the Spanish NW Mediterranean Coast (excluding deltas) and Gabès Gulf, while it goes up to 95 m or even 110 m for subsiding areas (Nile and Ebro Deltas) or the Oran case. This illustrates the high vulnerability of many of the beaches located in our four sites which, for the urban beaches, seldom have widths in excess of 100 m.

It is also possible to estimate the "coping capability" of a given beach, based on the minimum beach width needed to perform the protection function associated to a given sandy stretch (Valdemoro et al. 2007). Defining that the minimum reserve width for protection should be similar to the erosion produced by two consecutive storms (Bolaños et al. 2007), we can estimate the storm induced erosion as

Table 3 Shoreline erosion rates in horizontal metres due to SLR + storm effects for the last century (recent past), present conditions (present) and by the year 2100 (near future)

Site	Recent past		Present		Near future	
	No sub	Sub	No sub	Sub	No sub	Sub
Valencia	0		10		70	
Ebro Delta		25		35		95
Oran	25		35		95	
Gabès	25		35		75	
Nile		40		50		110

A distinction is made between the sites without subsidence (no sub) and those with subsidence (sub)

The uncertainty in the estimates should be always considered

30 m^3/m (Sánchez-Arcilla et al. 2008b). This results in erosion, approximately, 30 m of horizontal retreat, using again a berm height between 1 and 2 metres and considering also part of the active submerged beach profile. The effect of these 2 consecutive storms would, therefore, require a width of about 60 m, which would be the minimum sub-aerial beach required to cope with present meteo-oceanographic conditions. For the corresponding climatic-scale assessment, it is necessary to add the margin due to the worsening of climatic conditions, which are shown in Tables 2 and 3. The end result of all that is that an average width of 150 metres should be prescribed throughout Mediterranean coasts to ensure the survival for many of our beaches.

Physicochemical hazards: water quality

Looking now at coastal water quality, we can relate it to climate dynamics in terms of precipitation and dissolved oxygen in the water column. Precipitation affects water quality, in the sense that it determines the concentration of pollutants coming from river discharges or from the distributed continental run-off. If we assume that concentration is inversely proportional to the discharged volume and, therefore, for a constant drainage area, inversely proportional to the precipitation rate, this results in water quality being directly proportional to precipitation rate (assuming that the amount of pollutants remains constant). Intuitively, this simply means that higher precipitation rates produce a higher dilution and therefore should improve water quality.

Of course this is a crude simplifying hypothesis, since impulsive rain events (at least the first of a series) would have to "cleanse" the drainage system and, thus, contribute a higher concentration of pollutants. However, the extra momentum of torrential discharges favour river plumes that are able to cross the continental shelf (Sánchez-Arcilla and Simpson 2002) and, thus, reduce the local pollutant load. All things considered, we have opted for a robust, simple analysis to achieve some regional order of magnitude estimates as presented below.

Yearly average precipitation has experienced a reduction from about 400 mm in the interval 1927–1997 to around 300 mm in the interval 1978–2007 (for the Oran case). This supposes a decrease in precipitation, and thus water quality, of about 20%. Future scenarios, although less robust for precipitation than for variables such as temperature, predict a reduction in precipitation of about 5% for the Northern Mediterranean Coast and of about 20–25% for the Southern Mediterranean Coast (rounded estimates after Christensen et al. 2007). This corresponds to A1B scenarios, where the rapid economic growth goes accompanied by more efficient technologies.

Based on these numbers and the work performed within the CIRCE project, we are assuming that, under present conditions, the precipitation in the Spanish case has remained reasonable steady, while there has been an increase in the Gabès case in winter and a decrease in the Oran case starting in 1970 (this includes the 30-year severe drought experienced by Oran from 1977 to 2007). The Nile case has shown a decrease in precipitation in the 1970 and 1980 s and a further decrease in the 1990 and 2000s. The associated changes in water quality (expressed as percentages) for the four studied cases appear in Table 4.

These numbers should be considered as representative of the trend, since they constitute a rough estimate of the variation in water quality due to precipitation changes. They also fail to consider the local scale differences in climatic variability. Moreover, the distinction between summer and winter periods should be also handled with care since it represents the forecast variation in precipitation, depending on the season within the year. Regarding water quality, we should also consider that the expected change towards more pulsed river discharges, linked to more torrential precipitations concentrated in time, should also increase the amount of pollutants discharged to the coastal sea. This effect is nearly impossible to assess with the present level of information and has not, therefore, been included in the analysis.

Table 4 Water quality percentual variations driven by precipitation

	Present (%)	Near future		
		Average (%)	Summer (%)	Winter (%)
Oran	−20	−40	−50	−40
Spanish coast	0	−5	−30	0
Gabès	0	−20	−25	−20
Nile	0	−20	−5	−20

Present conditions are indicated by "present", while the estimates for the year 2100 appear as "near future"

The uncertainty in the estimates should be always considered

Water quality can also be assessed from the amount of dissolved oxygen (DO) in a water "parcel". The DO will change within the water column and as a function of the spatial hydrodynamic pattern. It will also depend on the water temperature and several other physicochemical parameters. In this work, we have considered only the relation to water temperature to infer the impact of future climatic scenarios.

Based on previous campaigns and analyses, we have found out that the DO range in the Mediterranean is roughly between 5 and 12 mg/l. Below 5 mg/l, the aquatic system becomes stressed and the WQ degrades sharply (Benson and Krause 1984; Boyd 2000). Assuming a linear relation of DO with temperature, it is obtained that DO decreases by about 2% (0.15 mg/l) for each Celsius degree of temperature increase. In terms of water quality, considering that we would need about 15°C of temperature increase to reach the 5 mg/l threshold, this means a WQ decrease of about 7% for each Celsius degree of temperature increase. This means that we would need an increase in temperature of 5° for the dissolved oxygen to get below the 5 mg per litre for deep water and an increase of 17° for dissolved oxygen to go below this threshold for surface water.

Water quality is, therefore, inversely related to the temperature via the level of dissolved oxygen. This means that the sea surface temperature (SST) range included in climatic projections can be translated into percentual decreases in water quality via the dissolved oxygen rate proposed above. This relationship amounts to about a 7% decrease per Celsius degree. If we apply that to the projected scenarios, we end up with the numbers presented in Table 5.

The obtained variations in water quality correspond to the forecast changes in air and water temperatures in the Mediterranean, which are higher than the world average (Somot et al. 2008). These numbers have been obtained based on the A2 scenario. The expected increase in the warm period or summer season, estimated in about 10 days per decade for the Gabès case, should also lead to a deterioration of the corresponding water quality since the water volume and the contained aquatic ecosystem would be exposed to the forecast increases for a longer period of time.

The performed analyses illustrate the possible range of effects of climatic variability in a given coastal region. These effects will be linked to socioeconomic impacts originated by an increase in mean sea level, storminess and/or water/air temperatures. We have seen how these increases vary for the four studied sites and the uncertainties in the quantifications. The resulting erosion, flooding, water quality degradation and salinization will require, as schematized in Fig. 10, further energy

Table 5 Percentual variation in water quality driven by temperature changes for present conditions and by the year 2100 (denoted as near future)

	Present rates	Near future	
Spanish Coast	+3.3°C	+5.0°C	
	−20%	−40%	
Oran Gulf	+4°C	+2°C	+6°C
	−30%	−10%	−50%
Gabès Gulf	+4°C	+2°C	+6°C
	−30%	−10%	−50%
Nile Coast	+4°C	+2°C	+6°C
	−30%	−10%	−50%
		Winter	Summer
	Present	Near future	

Values of average variation in SST (sea surface temperature) and WQ (water quality) are shown simultaneously (SST/WQ) for the present conditions and the accelerated rate due to climate change. The uncertainty in the estimates should be always considered

consumption and they are, thus, likely to enhance human-induced climatic change.

Conclusions

From the presented analysis, it is concluded that the more direct and robust climatic indicators for the state of coastal zones are mean sea level and wave storminess for erosion and flooding and water temperature and precipitation for water quality. Erosion due to increases in relative mean-sea-level appears due to the incident waves being able to reach higher parts of the Coastal Winter-land, normally not expressed directly to wave action without that rise in sea level. Erosion also appears due to enhanced wave storms due to offshorewards directed transport and, in general, a reshaping of the shore to get in equilibrium with the new wave conditions. Erosion is, thus, related to (1) relative level between land and sea, (2) energy of storms and (3) other storm features such as duration, wave steepness (ratio of wave height to wave length), wave orientation with a respect to the coast and repetition of energetic events (i.e. frequency of occurrence).

Water quality on the other hand is related to (1) water temperature and (2) precipitation features such as volume, duration and repetition or frequency of occurrence. Increased precipitation favours dilution, and this leads to improved water quality, although the amount of discharged pollutants may also become larger. The raise in water temperature decrease the amount of dissolved oxygen in the water and should, therefore, lead to a worsening of ecosystem conditions, which may reach anoxia for certain semi-enclosed bodies of water such as the Mediterranean lagoons found in our study sites.

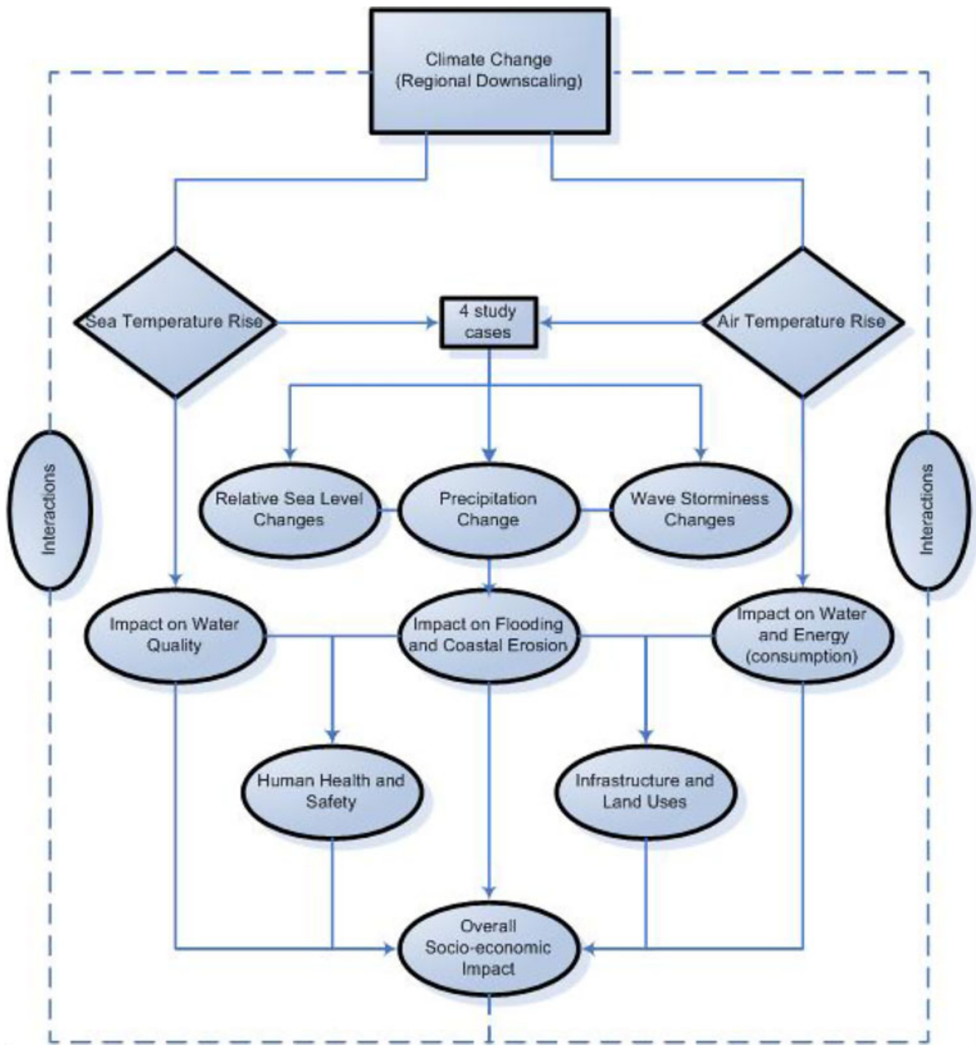

Fig. 10 Schematization of the conceptual relation between climate hazards and cross-sectorial socioeconomic impacts, for the coastal cases studied in this paper

Sea surface temperature appears to be increasing in all studied sites, with a clear upward trend for the annual mean. This should lead to lower values of dissolved oxygen which, together with the decrease in average precipitation plus a concentration into more torrential events, will result in water quality degradation.

Although the available level of instrumental information and the errors in simulated fields preclude any final conclusion, there are a number of commonalities and differences to be observed. Precipitation interannual variability is so large that it hampers deriving any common pattern for all studied sites. There appears, however, to be a slight increasing trend in the number of moderate storms. This could support the incipient evidence towards a higher number of impulsive events (wave storms, precipitation, etc.) in the area. The resulting impact, for a squeezed coast such as the Mediterranean, subject to storms from more than one direction, would be enhanced erosion and flooding. The human response should, accordingly, be an "ordered" retreat from the immediate coastline, in what is nowadays called managed realignment. Alternatively, for selected stretches of the coast where this realignment is not possible (e.g. coastal cities), there should be a reenforcement of defence structures, including if at all possible a wide enough beach (natural or, more likely, artificial) in front. The human response should, thus, be a careful design of sea-outfalls, avoiding semi-enclosed bodies of water and periods of abnormally high temperature and/or low water renovation. This implies managing coastal waters using the available knowledge on oceanographic variables and the corresponding wave and current operational predictions. This information could also be used to achieve safer bathing water conditions, regulating access and preferential areas as a function of the prevailing meteo-oceanographic conditions.

The associated impacts will be cross-sectorial and with feedbacks at multiple scales, some of which may, in turn, require higher energy consumption and an enhancement of climatic change. This illustrates the importance to act in an anticipatory manner, invoking in case of doubt the precautionary principle, so that we can preserve an environment as valuable and unique as the Mediterranean coastal fringe.

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