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7000 years of paleostorm activity in the NW Mediterranean Sea in response to Holocene climate events

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ABSTRACT

A high-resolution record of paleostorm events along the French Mediterranean coast over the past 7000 years was established from a lagoonal sediment core in the Gulf of Lions. Integrating grain size, faunal analysis, clay mineralogy and geochemistry data with a chronology derived from radiocarbon dating, we recorded seven periods of increased storm activity at 6300–6100, 5650–5400, 4400–4050, 3650–3200, 2800–2600, 1950–1400 and 400–50 cal yr BP (in the Little Ice Age). In contrast, our results show that the Medieval Climate Anomaly (1150–650 cal yr BP) was characterised by low storm activity.

The evidence for high storm activity in the NW Mediterranean Sea is in agreement with the changes in coastal hydrodynamics observed over the Eastern North Atlantic and seems to correspond to Holocene cooling in the North Atlantic. Periods of low SSTs there may have led to a stronger meridional temperature gradient and a southward migration of the westerlies. We hypothesise that the increase in storm activity during Holocene cold events over the North Atlantic and Mediterranean regions was probably due to an increase in the thermal gradient that led to an enhanced lower tropospheric baroclinicity over a large Central Atlantic–European domain.

Introduction

The Mediterranean region is one of the world's most vulnerable area with respect to the global warming (Giorgi, 2006). Regional climate simulations have been used to investigate variations in precipitation and cyclonic activity in the Mediterranean region. Gibelin and Déqué (2003) have predicted, using the ARPEGE model, overall warming and drying in all seasons, except in the winter over the North-Western Mediterranean area, with an increase in precipitation. Lionello and Giorgi (2007) showed that the reduction of cyclonic activity observed in future scenarios would be responsible for a decrease in precipitation along the southern and eastern Mediterranean coast, whilst an increase occurs in northern areas in relation to the increase in the strength of the mid-latitude storm track. In addition, Gaertner et al. (2007) detected for the first time, a risk of tropical cyclones developing over the Mediterranean Sea under future climate change conditions.

Cyclones cause most of the heavy precipitation events in the entire Mediterranean region (Trigo et al., 2000; Jansá et al., 2001). The interplay between orography and thermal contrast between advected Atlantic air masses and Mediterranean temperatures can produce at the end of the summer season violent extremes of precipitation (Lionello et al., 2006). This wet season (October to March), rainfall over the Northern Mediterranean, which corresponds to the so-called storm season, has decreased over the last four decades, mostly because of the decline in the intensity of cyclogenesis events (Trigo et al., 2000). Lionello et al. (2006) found a significant decrease in winter cyclone frequency over most of the Western Mediterranean during the last 150 yr, and this tendency was also confirmed by research on sedimentary archives (Sabatier and Dezileau, 2010). Trigo et al. (2000) suggest that northward shift of the zonal storm track from the North Atlantic has induced these recent changes in the intensity of Mediterranean cyclones. However, there is no evidence that the behaviour of Mediterranean climate extremes at this time scale is inconsistent with natural fluctuations in climate, such as those due to the NAO (North Atlantic Oscillation) or the EAP (Eastern Atlantic Pattern), during earlier centuries (Quadrelli et al., 2001; Sáenz et al., 2001; Krichak and Alpert, 2005; Lionello et al., 2006; Luterbacher

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et al., 2006; Trigo et al., 2006; Lionello and Galati, 2008; Ullmann et al., 2008).

The effects of modern climate change on the frequency and the intensity of extreme events are difficult to assess because there is large variability in the occurrence of extreme events and consequently, it is more difficult to identify significant trends, especially with the lack of long-term instrumental data (Webster et al., 2005; Emanuel, 2006; Landsea et al., 2006). However, reconstructions of the frequency and the intensity of storms in coastal areas are necessary due to the recent concentration of resources and populations in this zone (Pielke and Landsea, 1999; Lionello et al., 2006; Turner et al., 2006). Geological data offer opportunities to reconstruct long-term records of intense events and allow for the documented record to be extended well beyond the observational record. This enables a better understanding of the possible regional and local long-term trends of storm activity as they relate to past climatic conditions. Usually, reconstructions of paleostorm events in coastal environments have been made by identifying the recurrence of coarse grained overwash and associated deposits (Collins et al., 1999; Liu and Fearn, 1993, 2000; Donnelly et al., 2001a, 2001b; Nott, 2004; Donnelly, 2005; Donnelly and Woodruff, 2007; Frappier et al., 2007; Scileppi and Donnelly, 2007; Sabatier et al., 2008; Woodruff et al., 2009).

This study focuses on the Gulf of Lions (Fig. 1), a region of the French Mediterranean coast. This area is particularly sensitive in terms of environmental and societal issues due to the risks of flooding (the Mediterranean Heavy Precipitation Events) and of coastal erosion/submersion that occur during storm events. These events can have dramatic impacts when the storm winds and waves are associated with high sea surges (Ullmann et al., 2008), attacking coastal sand dunes and sometimes breaking this sandy barrier. Over the last few decades, the most damaging storm was that of 1982; with 46 $m \cdot s^{-1}$ wind speeds (category 2 in Saffir–Simpson scale), this storm caused large human and economic losses (Sabatier et al., 2008). The main objective of this study was to identify regional storm patterns using historical and paleostorm data in a complex lagoonal infill (Sabatier et al., 2010a). Here, we present a high-resolution study, based on previously defined multi-proxy approach (Sabatier et al., 2010b) for examining a well-dated long core from the Pierre Blanche lagoon characterised by environmental and related age-reservoir changes (Sabatier et al., 2010c). In a previous study, we already discussed in detail the link between the sedimentary record of extreme storm events and climate changes over the last 1000 yr and the Little Ice Age (Dezileau et al., 2011). Here, we extend the record back for the last 7000 yr with a continuous high-resolution record of paleostorm events along the Mediterranean area and we try to assess the most probable mechanisms behind the observed variability of extreme storm events in the area at the millennial scale.

Study area

The Gulf of Lions shore line is characterised by many coastal wetlands that are the result of the interaction between a process of shore line regularisation by migrations of sandy barriers due to sediment transfer through littoral hydrodynamics and a filling of these areas by fluvial and marine inputs (Certain et al., 2004; Raynal et al., 2009). This study focuses on the Palavasian wetland complex located west of the Rhône delta (the central part of the Gulf of Lions), 10 km south of the city of Montpellier (Fig. 1). This area consists of seven

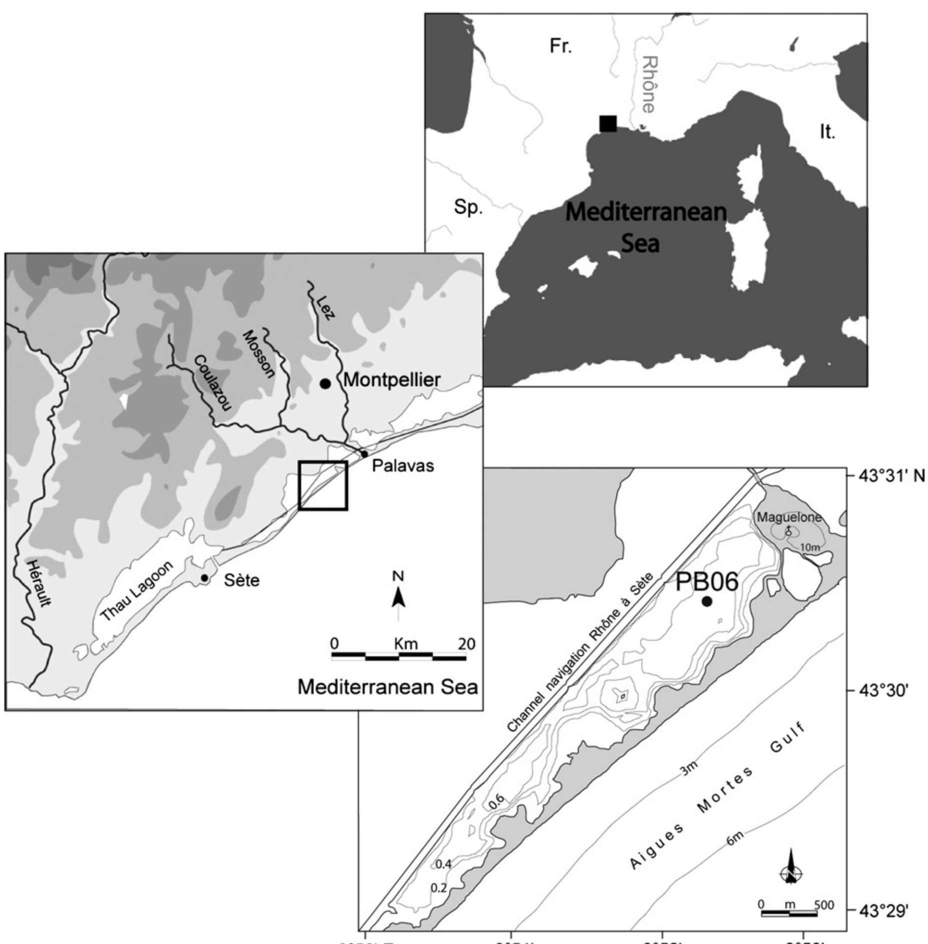

Figure 1. Map of the Pierre Blanche lagoon with localisation of the core PB06. Fr: France, It: Italia, Sp: Spain.

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small lagoons with shallow water depths (<1 m) that are bordered to the south by a narrow sandy barrier that is attached in place to subdued rocky capes (e.g., the Aresquier wood or Maguelone Church peninsula: Raynal et al., 2009) and to the north by calcareous Mesozoic hills (Gardiole Mountain). This wetland complex is now crossed by the artificial Rhône-Sète navigation channel, which was constructed in the 18th century (NW–SE in the lagoonal system, Fig. 1). This study focuses on the Pierre Blanche located in the southern part of this system (Fig. 1), which has water depths of 60 cm.

The sandy barrier has been formed by sediment supply from the Rhône River to the east that is transported by a westward longshore current. The alongshore-oriented sand spits prograding towards the southwest therefore originated exclusively from the Rhône River watershed (Raynal et al., 2009). In some places, the barrier is weak and highly sensitive to high-energy events, enabling a temporary but strong marine influence when the barrier breaks during storm events. This is commonly seen by traces of overwash fans and ancient temporary inlets (Dezileau et al., 2005; Sabatier et al., 2008). Most of the sediment supplied to this lagoonal area is carried by the Mosson coastal river. The average flow of the Mosson River is 1.2 m^3/s, but it has reached values as high as 258 m^3/s (measured during the December 3, 2003 flash-flood events). The Mosson drainage basin is mainly composed of Mesozoic (limestone) and Cenozoic (conglomerate, carbonated sandstone and clay) sedimentary rock with Quaternary deposits.

This coastal area is characterised by a classical microtidal environment with maximal tide ranges of less than 50 cm. The average daily wave heights (Hs) and periods (Tm) measured at the Sète station (located 10 km offshore, at a water depth of 32 m) are fair weather waves during 88% of the year (Hs = 0.84 m; Tm = 4.2 s, Guizien, 2009). However, this fair-weather wave climate is occasionally disturbed by south-western to south-eastern storms, like that of 1982. The annual proportion of waves higher than 4 m is around 1%, and the return period of a 6-m high wave is every 10 yr (Guizien, 2009).

Material and methods

A 7.9-m-long piston core (PB06) was collected from the Pierre Blanche lagoon in March 2006 (Fig. 1) with the UWITEC© coring platform (University of Chambery/LSCE). The record is a composite of two series of consecutive 2-m-long sections taken from two sites within 5 m of each other laterally. The sections of the second series were taken roughly 1 m deeper than those from the first series to provide sufficient overlap for a continuous record. At the laboratory, the cores were split, photographed, radiographed using Scopix X-ray scanning (EPOC, University of Bordeaux 1) and logged in detail (noting all physical and biogenic sedimentary structures and vertical successions of facies). A composite profile was constructed using clearly identifiable marker layers from the overlapping sections of both series. No compaction due to the coring system was observed. The core was divided into 1-cm-long vertical sections prior to analysis.

Grain size and macrofauna content analyses were performed on 2-cm-long sections. To study mollusc shells, samples were sieved at 1 mm, and the number of individuals of all species was counted (every 2 cm). The most representative molluscs of lagoonal environments are *Hydrobia acuta*, *Abra ovata*, *Cerastoderma glaucum* and those of typical marine hard substrate environment are *Bittium recticulatum* and *Rissoa ventricosa* (Dezileau et al., 2005; Sabatier et al., 2008). Grain size distributions were determined using a Beckman Coulter© LS 13 320. Samples were sieved at 150 μm prior to analyses due to the high concentration of shell fragments of a size exceeding 200 μm. Bulk sediments were first suspended in deionised water and then gently shaken to achieve disaggregation. After the introduction of sediment into the fluid module of the granulometer, ultrasound was used to avoid particle flocculation.

Clay minerals were identified by X-ray diffraction (XRD), every 2 cm, using a PANalytical diffractometer at the Laboratoire IDES (Université de Paris XI) on oriented mounts of non-calcareous clay-sized (<2 μm) particles. The oriented mounts were obtained following the methods described in detail by Colin et al. (1999). Three XRD trials were performed, each proceeded by air-drying, ethylene-glycol solvation for 24 hr, and heating at 490°C for 2 h. Identification of clay minerals was made mainly according to the position of the (001) series of basal reflections on the three XRD diagrams. Semi-quantitative estimates of peak areas of the basal reflections for the main clay mineral groups of smectite (including mixed-layers clay) (15–17 Å), illite (10 Å), and kaolinite/chlorite (7 Å) were carried out on the glycolated curve using the MacDiff software (Petschick, 2000). Relative proportions of kaolinite and chlorite were determined based on the ratio of the 3.57/3.54 Å peak areas.

X-ray fluorescence (XRF) analysis was performed on the surfaces of the split sediment core PB06 every 0.5 cm using a non-destructive Avaatech core-scanner (EPOC, Université Bordeaux 1). The split core surface was first covered with a 4-μm-thick Ultralene to avoid contamination of the XRF measurement unit and desiccation of the sediment. Geochemical data was obtained at different tube voltages, 10 kV for Al, Si, S, Cl, K, Ca, Ti, Mn, Fe and 30 kV for Zn, Br, Sr, Rb, Zr (Richter et al., 2006).

Monospecific shell samples (*C. glaucum*) were selected for ^{14}C age determinations. The ^{14}C analyses were conducted at the Laboratoire de Mesure ^{14}C (LMC14) on the Accelerator Mass Spectrometer (AMS) ARTEMIS at the CEA institute at Saclay (Atomic Energy Commission). The ^{14}C ages were converted to "calendar" years with the R-code package "clam" developed by Blaauw (2010) using the Intcal09 calibration curve (Reimer et al., 2009) with the reservoir age defined by Sabatier et al. (2010c). Two-sigma ages are reported in text.

Chronological framework

The chronology of core PB06 was established using ^{210}Pb and ^{137}Cs measurements associated with Accelerator Mass Spectrometry (AMS) ^{14}C dates on monospecific shell samples (Sabatier et al., 2010c). These authors made an estimation of radiocarbon reservoir ages which vary in relation to palaeoenvironmental changes (see Faunal variations). The local marine reservoir age varies between 618 ± 30 ^{14}C yr (Siani et al., 2000) for the deepest part of the core, and 943 ± 25 ^{14}C yr, estimated by correlation with the ^{210}Pb and ^{137}Cs chronologies and historical events, for the last 1.7 m.

The age model of PB06 core was realised by fitting a smooth spline curve using the "clam" R-code package (Blaauw, 2010) on ^{14}C ages and historical storm (Sabatier et al., 2010b). The main changes observed in PB06 suggest a low sedimentation rate around 0.4 $mm \cdot yr^{-1}$, which occurred at the base of the core (759–710 cm). This rate increased from around 1 $mm \cdot yr^{-1}$ between 710 and 110 cm to 2.3 $mm \cdot yr^{-1}$ for the upper part. For the modern part of the core (the upper 40 cm), the accumulation rate was estimated through the ^{210}Pb and ^{137}Cs chronologies at 2.65 $mm \cdot yr^{-1}$ (Sabatier et al., 2010c).

Results

The lagoon is mostly filled by grey clay and silt, with shell fragments alternating with layers of fine sandy material (Fig. 2). A lithological description of the PB06 core based on its grain size, sedimentary structure and faunal content allowed for the identification of different facies interpreted in terms of their lagoon depositional environments (Sabatier et al., 2010a). The core PB06 consists of two main sedimentary units above Pliocene deposits. The first one is a complex basal polygenic surface consisting of the ravinement surface and above conglomerate. This unit is from subaerial erosion during times of relative sea-level low stand and subsequent reworking during the ensuing transgression. The second one is constituted by clay and silt with shell fragments interpreted to be from a lagoonal

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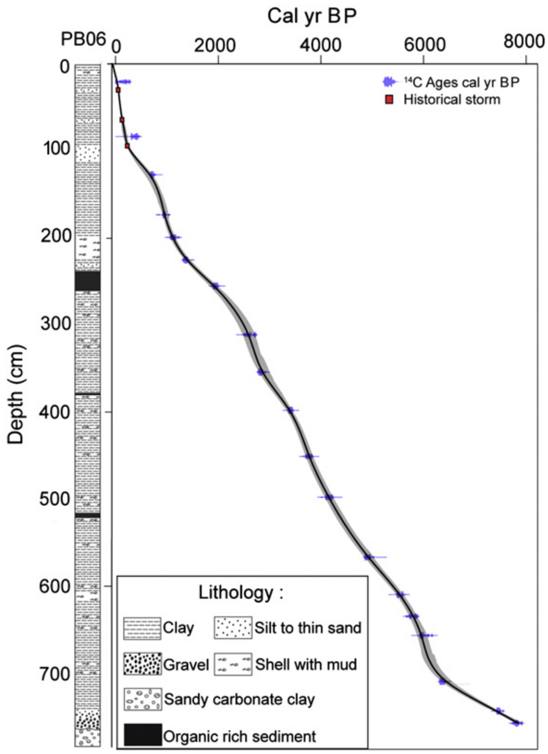

Figure 2. Lithological description and age versus depth plot of chronological data for the core PB06 (modified from Sabatier et al., 2010c). The Age model was calculated by fitting a smooth spline curve using the "clam" R-code package (Blaauw, 2010).

depositional environment due to the Holocene filling of this coastal area. In this study, we focus on the variations of sediment properties in the upper unit in order to identify paleostorm events.

Grain size

Boulay et al. (2003) used the standard deviation of each grain size interval as a simple method for identifying the grain size population with the highest variability. Using this method, it is possible to determine the grain size classes that had the most significant variation through time. Standard deviation values versus grain size classes of core PB06 are displayed in Figure 3. Two main grain populations, representing those with the highest variability, can be identified. One occurs between 2 and 10 µm (clay to fine silt), and another coarser one occurs between 30 and 100 µm (silt to fine sand). The evolution with depth of these two populations displays eight main changes in core PB06 with a strong negative correlation between the fine and coarse sediment sizes revealed by the grey bands in Figure 4a. The main peaks in the coarse fraction occur in the upper part of the core around 35, 60, 100 and 225 cm.

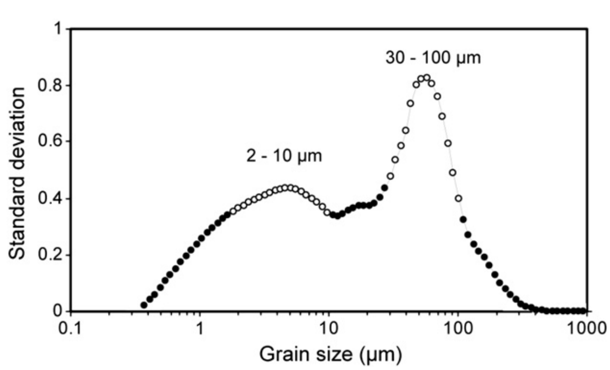

Figure 3. Standard deviation values versus grain size class diagram of the whole PB06 core. Open circles are the most significant granulometric populations, with one (clay to thin silt) between 2 and 10 µm, and the other (thin sand) between 30 and 100 µm.

Faunal variations

Macrofaunal analyses are good indicators of a lagoon's palaeo-isolation state (with no permanent connection with the sea) because species develop in different ranges of salinity, temperature and oxygenation. One species typically develops in a lagoon environment (*H. acuta*), whereas another is typical of a marine environment (*Bittium reticulatum*). The presence of marine species within the lagoon indicates either their transport during a storm event or a change in environmental conditions. Data in Figure 4b shows a large change in the mollusc population at around 190–170 cm is characterised by an increase in the most typical lagoonal species *H. acuta*, whereas the abundance of the marine species *B. recticulatum* decreases (Fig. 4b). In details, for this upper part the main decreases of *H. acuta* correspond to a small increase of *B. recticulatum*, and for the lower part of PB06 cores these two species do not present a systematic negative correlation, but several major peaks of *B. recticulatum* appeared (around 250, 320, 400, 520, 600 and 700 cm).

Clay mineralogy

There were significant differences in clay minerals between (1) the Mosson drainage basin, with a high concentration of smectite (73–81%) reflecting erosion and reworking processes of ancient formations, such as Cenozoic conglomerates, and (2) the sandy barrier, mostly characterised by high contents of illite (45–59%) and chlorite (17–26%) related to sedimentation from the Rhône River (Sabatier et al., 2010b). Sediments from core PB06 had mean values for clay minerals between those of the Mosson drainage basin and sandy barrier. The core predominantly consisted of smectite (15–70%) and illite (16–55%) with lower contents of chlorite (3–25%) and kaolinite (6–17%). The average percentages of these clays were as follows: 44% for smectite, 33% for illite, 12% for chlorite and 11% for kaolinite (Fig. 5). In Figure 5, the clay minerals can be subdivided into three groups along PB06. The changes in the illite and chlorite contents displayed similar variations. Generally, the smectite content was inversely correlated with the illite and chlorite contents (shaded bands in Fig. 5). Kaolinite contents seemed to vary in time with the same trend as smectite.

Geochemistry

X-ray fluorescence core scanning provides high-resolution palaeoenvironmental information in a variety of sedimentary settings. These results are inherently semi-quantitative due to the effects of sample inhomogeneity and surface roughness. These characteristics are particularly pronounced for sediments containing abundant medium to coarse sand-sized particles, such as shell fragments in coastal environments (Richter et al., 2006). Geochemical results on the lithogenous fraction are often reported as ratios of a given element to a conservative element; aluminium is generally used because of its similar concentration in a large variety of rocks. This provides qualitative information on the enrichment or depletion of a given element, as well as allowing for the correction of the dilution effect.

The Mosson drainage basin is mainly characterised by Al, Fe and Th (Sabatier et al., 2010b). Another source is the sandy barrier defined by Si, Na and Zr, respectively abundant in quartz, sodium feldspars and heavy minerals (Sabatier et al., 2010b). In Figure 6, we present the Si/Al and Zr/Al ratios to reconstruct the influence of marine components (high values). The Si/Al and Zr/Al ratios are correlated, especially for the upper 5 m of the core (shaded bands).

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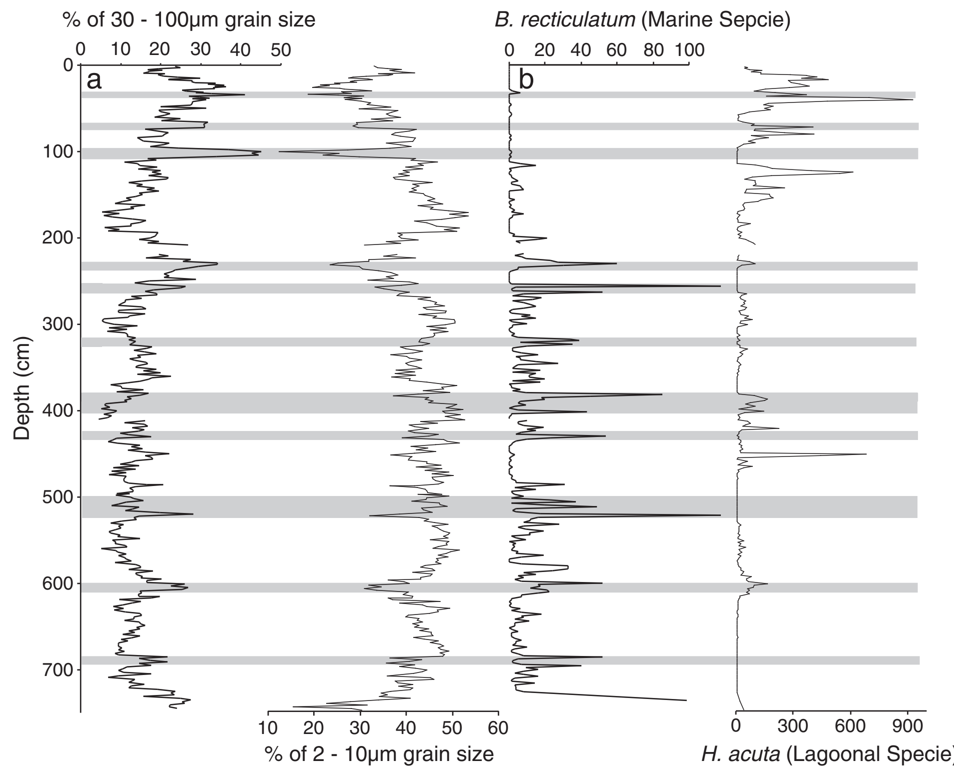

Figure 4. The core PB06 with: a. Grain size population of thin sand (30–100 µm) and clay to thin silt (2–10 µm); b. Number of *B. recticulatum* (marine specie) and Number of *H. acuta* (lagoonal specie). Shaded areas mark the main variations.

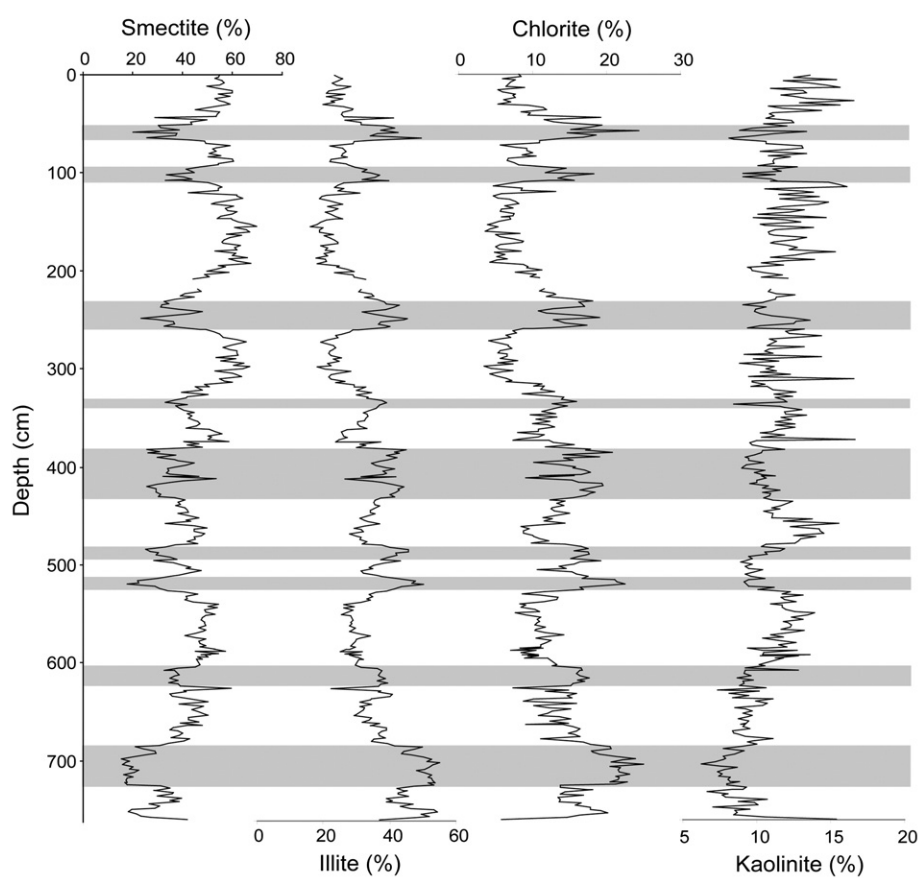

Figure 5. PB06 clay mineral analysis contents (%) obtained on the carbonate-free <2 µm size fraction. Smectite and illite are dominant (up to 75% of the total clay minerals). Illite and chlorite co-vary opposed to that of smectite. Kaolinite contents do not vary significantly with time. Shaded areas mark the main variations.

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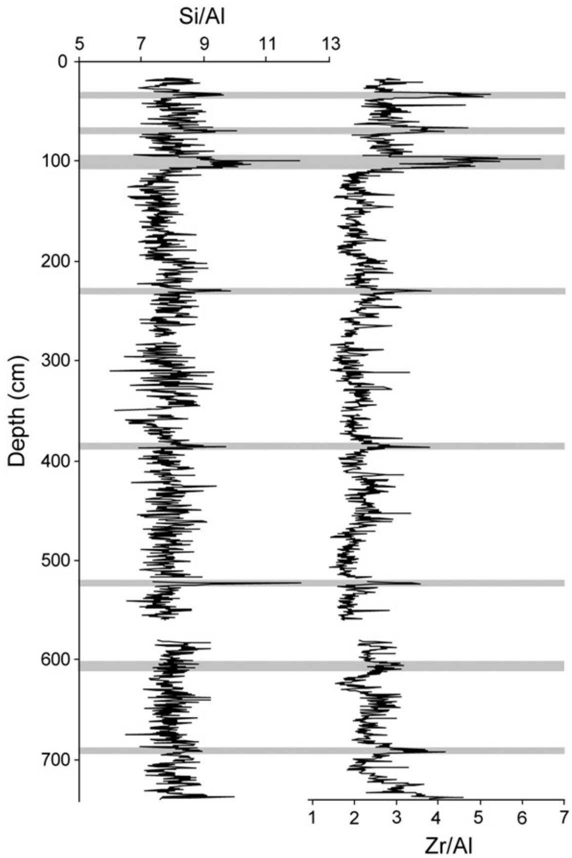

Figure 6. XRF records from the core PB06, with down-core variations of ratio Si/Al, Zr/Al. Shaded areas mark the main variations of Si/Al and Zr/Al ratio.

Discussion

In studying the last 1000 yr, using multi-core transects approach in the Pierre Blanche lagoon, Dezileau et al. (2011) showed that the study site appears to only be sensitive to the most severe storm events. However, for the mid to late Holocene, many mechanisms could have perturbed the records of overwash deposits, such as sea-level variation, barrier morphodynamics, sediment supply to the system and the complexity of storm conditions. Thus these mechanisms have to be discussed in detail before paleostorm reconstruction.

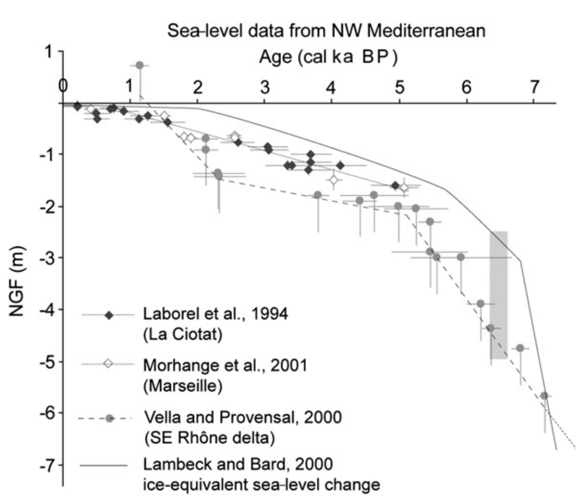

Figure 7. Relative sea level curve in the NW Mediterranean Sea for the last 7000 cal yr BP. from observations in the Rhône delta (Vella and Provansal, 2000), La Ciotat (Laborel et al., 1994), Marseille (Morhange et al., 2001) and from glacio-hydro-isostatic model (Lambeck and Bard, 2000). Shaded area represents the sea level during the first lagoonal deposit.

Barrier morphodynamics

Sea-level rise can increase the sensitivity of a back-barrier study site by moving the shoreline farther inland and narrowing the sandy barrier through time. The Gulf of Lions coast was free of significant vertical tectonic movements ($<0.02\ mm \cdot yr^{-1}$) in the Late-Quaternary time period (Lambeck and Bard, 2000). The relative sea-level curve for the NW Mediterranean Sea for the last 7000 cal yr BP (Fig. 7) presents some discrepancies (from observations: Laborel et al., 1994; Vella and Provansal, 2000; from a glacio-hydro-isostatic model: Lambeck and Bard, 2000; Morhange et al., 2001). If the relative sea level has remained almost constant for the last 5000 yr (<2 m), significant changes occurred during the first stand of lagoonal deposits between 6500 cal yr BP (the date of the first lagoonal deposit in PB06) and 5000 cal yr BP (1–3 m). The establishment of the sandy barrier was estimated by Raynal et al. (2009) to be around 7500 cal yr BP at 1 km seaward from the present position. Moreover, these authors dated the actual barrier at 1800 ± 150 cal yr BP thanks to a ^{14}C age at the base of the present day sandy barrier. These dates imply the landward movement of the sandy barrier with an average rate of 0.2 m/yr in relation to the decrease in the rate of sea-level rise rate (Raynal et al., 2010) until 1800 cal yr BP. Over the last 300 yr, no change in barrier morphology has occurred, as demonstrated by Dezileau et al.'s (2011) examination of historical geographical maps. Even though it is likely that there have been minor sea level fluctuations and shoreline landward movements for the last 1800 yr, the largest changes occurred before this period. The sea-level variation before 1.8 ka and landward movement of the barrier since this date probably affected the sensitivity of the site in recording paleostorms, and thus the intensity of the different sedimentary records cannot be directly compared after and before this date.

The faunal content revealed a major palaeoenvironmental change around 190–170 cm (i.e. 1000 cal yr BP, Fig. 4b). This faunal variation was related to change in environmental conditions (salinity, temperature, nutriments, and oxygenation) from a lagoonal depositional environment with a marine influence to a more isolated lagoonal environment. Such a change could have resulted from a local palaeomorphological modification such as a closure of communications between the lagoon and the sea (Sabatier et al., 2010a). This implies a shift from a protected lagoon to an isolated lagoon environment in relation to the final closure of the sandy barrier by coastal hydrodynamics. Therefore, after this date, the sandy barrier was continuous, but temporary inlets were formed in relation to storm events. Before this date, the lagoonal system was less isolated from the sea and probably presented a weaker barrier with large permanent channels, which controlled the inflow of marine water into the system, typical for a protected lagoon environment. However, the fine organic-rich sediment types appearing throughout the record show that this backbarrier area experienced quiescent sedimentation during at least the past 6500 yr. Therefore, this lagoonal system was protected behind the barrier system over that time. This spatial and temporal variability in barrier beach morphology complicates the sedimentary record of storms due to the varying sensitivity of backbarrier locations (Donnelly and Webb, 2004). Thus, the numbers of lagoonal and marine species in the first 2 m of core PB06 cannot be compared to the rest of the core in terms of storm event intensities. This morphology can also explain why sandy material was not found in the deeper storm layer deposits identified (Fig. 4a).

Paleostorm deposits

The close association of sandy layers, marine species and the disappearance of lagoonal fauna indicates that the observed sequences

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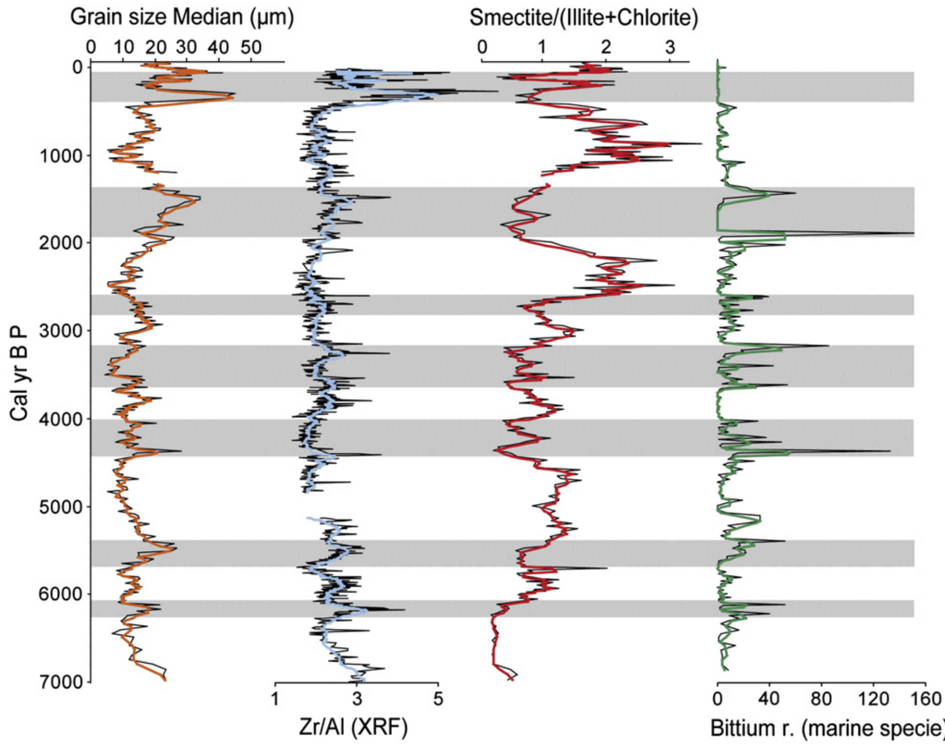

Figure 8. Core PB06 with from left to right: Grain size of 30 to 100 µm population, Zr/Al XRF ratio, smectite/(illite + chlorite) and number of *Bittium recticulatum* (marine specie). Grey bands are the high storm activity periods.

can be interpreted as a succession of marine invasions of the lagoon during storm events (Sabatier et al., 2008). Moreover, the ratios of smectite/(illite + chlorite), Si/Al and Zr/Al were used as indicators to reconstruct changes in the sedimentation sources from the Mosson drainage basin versus the marine environment. Therefore, variations in these mineralogical and geochemical ratios have been shown to be strongly linked to paleostorm events (Sabatier et al., 2010b).

In the PB06 core, the correlations between the grain size, Zr/Al ratio and number of marine species with the decrease in the smectite/(illite + chlorite) ratio suggest that the barrier was breached numerous times over the last 6500 yr (Fig. 8). The last three events were previously identified in the whole lagoonal system by lateral correspondences between multiple core transects. These events were dated using ^{210}Pb and ^{137}Cs chronologies associated with ^{14}C dates and historical accounts as occurring at 1742, 1848 and 1893 AD (Sabatier et al., 2008). Except for the last three deposits, it was difficult to associate storm layers with a specific event or with a short period of increase in landfall activity. Indeed, sedimentary records of overwash deposits through time could be influenced by sediment supply, especially during periods when accumulation rates are low. Woodruff et al. (2008), using a model developed by Emanuel et al. (2006), have shown that a decrease in sedimentation rate can result in an apparent drop in landfall activity during this low-resolution interval (35% of the apparent decrease). In this study, it was difficult to associate these short periods of high storm activity (between 200 and 400 yr, Fig. 8) with a single event or to a succession of events involving punctual records of past landfall deposits, except for the upper part of the core. The three last historic overwash deposits (1742, 1848 and 1893 AD) occurred during an interval of relatively high sedimentation rate (more than 2 $mm \cdot yr^{-1}$), whereas during the other periods of increased storm activity, the accumulation rate was lower (less than 1 $mm \cdot yr^{-1}$). Therefore, we can suppose that if the accumulation rate was the same all along the core (equal to 2 $mm \cdot yr^{-1}$), more storm events would be recorded during periods of increased storm activity. In general, if two back-barrier storm deposits are not separated by enough time in relation to the sedimentation rate, these two overwash layers can appear as a single unit (Scileppi and Donnelly, 2007).

This multi-proxy approach suggests the occurrence of seven high-energy events likely reflecting recurrent perturbations of coastal hydrodynamics that occurred in relation to paleostorm events (grey bands on Fig. 8). Based on our ^{14}C age model, the strongest evidence for these changes in storm activity occurred at 6300–6100, 5650–5400, 4400–4050, 3650–3200, 2800–2600, 1950–1400 and 400–50 cal yr BP.

The horizontal extent of an overwash deposit is affected by many complicating factors that are related to storm characteristics, such as the hurricane intensity, storm surge height, tidal height at the time of landfall, angle of storm events and wind direction, timing and the duration of landfall (Liu and Fearn, 2000). In this microtidal study area, we may infer that stronger storms tend to result in higher storm surges, thus producing a thicker and more widespread overwash layer. However, storm landfall conditions as well as the timing, duration and angle of approach occur randomly over time. Liu and Fearn (2000) presented a model where a coastal lake was subjected to overwash events caused by landfalling hurricanes of various intensities and directions. This study concluded that a suite of cores taken from different sites is vital for producing a complete record of past hurricane landfalls. In the system studied here, multi-core transects show a clear link between recent overwash events (during the last 1000 yr), due to catastrophic storms of category 3 intensity or more that were described and discussed in Sabatier and Dezileau (2010). Just one long core was sampled thus, the oldest paleostorm layers were not correlated with other deposits, but we suggest that the most powerful events were recorded in the whole lagoonal area, as supported by correlations over the upper 1.2 m of sedimentary archives.

Storm activity: region-wide comparison and Holocene climate changes.

The mid to late Holocene sedimentary archive of the Palavasian lagoonal system recorded the occurrence of seven periods of increased storm activity at 6300–6100, 5650–5400, 4400–4050, 3650–3200, 2800–2600, 1950–1400 and 400–50 cal yr BP, based on our ^{14}C age model (Fig. 9c). Although few studies have recorded Holocene storm

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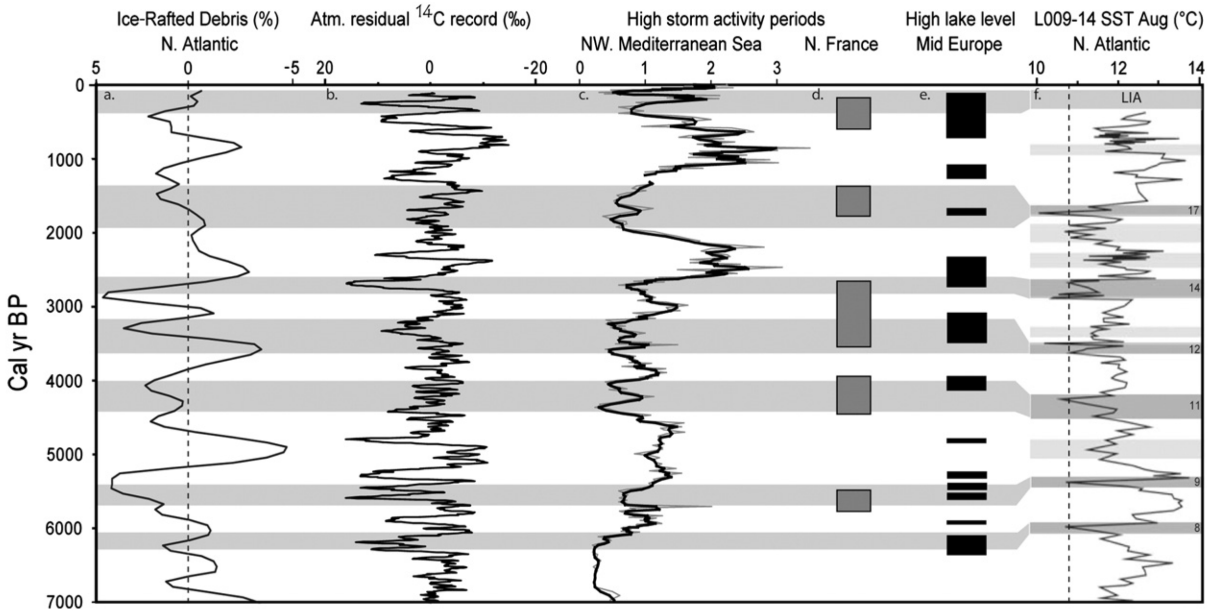

Figure 9. Comparison between (a) Ice Rafted Debris events (IRD) in the North Atlantic (Bond et al., 1997, 2001); (b) residual ^{14}C as an indicator of solar variability from INTCAL09 (Reimer et al., 2009); (c) smectite/(illite + chlorite) ratio, dark grey shaded areas (low value) are interpreted as increase in storm activity in the NW Mediterranean Sea (Palavasian lagoon) based on the multi-proxy correlations defined in Figure 8; (d) period of high storm activity in the North French Atlantic coast (Billeaud et al., 2009; Sorrel et al., 2009); (e) high lake level in Mid Europe (Magny, 2004); (f) diatom-based sea surface temperature (SST) reconstruction for the core LO09-14 from the North Atlantic (Berner et al., 2008), the Holocene cold events (HCEs) identified by Berner et al. (2008) are noted as grey shaded areas (18–8, defined by these authors), darker bands correspond to the coldest events, less than 11°C (dotted line).

activity in the Mediterranean Sea, the evidence for perturbation in coastal hydrodynamics could be correlated with other events that occurred on a regional scale.

In the Southern Tyrrhenian Sea (Western Mediterranean Sea) to the east of the studied area, in a shallow marine wedge, Budillon et al. (2005) recognised four event beds related to major storms that occurred in the last 1000 yr. These landfall events were associated with historical sources and represented important storm activity that occurred between the 16th and 19th centuries. Severe flooding and intense storms during the last centuries in the Gulf of Lions area were due to a strong mid-level SW flow over the French Mediterranean coast (Sabatier et al., 2008). Blanchemanche (2009) found an increase in severe flood events between the 17th and end of the 19th centuries (the latter part of the Little Ice Age) that were recorded in the historical archives of townships along six coastal rivers located in the Mediterranean Languedoc. This high level of hydrological activity was well correlated regionally with an increase in the Vidourle River detritic component (Berger et al., 2010); a higher frequency of floods in the Durance River (Miramont et al., 1998), the Lower Rhône valley (Pichard, 1995; Bruneton et al., 2001; Anraud-Fassetta et al., 2010), the Isère River (Barriendos et al., 2003), the Upper Rhône valley (Arnaud et al., 2005; Berger et al., 2008); and a high mid-European lake level (Magny, 2004; Fig. 9e).

Before this period of high storm and hydrological activities, a relatively dry phase was recorded in the Medieval Climate Anomaly (MCA) in a speleothem from the Cave of Clamouse, 30 km north of the studied area (McDermott et al., 1999; McMillan et al., 2005). This period was correlated regionally with the last aridification phase identified by Jalut et al. (2000) in a transect covering southeast France and southwest Spain. During this period our record indicates a relatively low storm activity (1.2–0.8 cal ka BP).

During the Holocene, each period of high storm activity recorded in the Pierre Blanche lagoon is, taking into account chronological uncertainty, correlated with a reduction of progradation of beach ridge systems in the Alboran Sea (west of the studied area) and intense erosion produced by storm waves generated by winds from the SW at 6–5.4, 4.2, 3–2.7, 1.9 and 0.5 cal ka BP to the present (Goy et al., 2003). These periods were related to cold episodes recorded by sea surface temperatures (SST) in the Alboran Sea (Cacho et al., 2001) and to cold events reported in the North Atlantic region (Bond et al., 2001). These erosive phases recorded in coastal regions are interpreted as arid episodes, marked by reduced rainfall and/or increased wind velocity and intensity (Goy et al., 2003; Zazo et al., 2008). In addition, the periods of increased storm activity recorded in this study seem to be correlated with Holocene cooling events (Fig. 9a) associated with rafted ice in the North Atlantic (Bond et al., 1997, 2001).

In the eastern Atlantic, periods of increased storm activity have also been described, for example, the 8.2 ka cold event, which represented a significant period of abrupt cooling within the early Holocene, that was associated with coastal sand accretion in Western Europe (Clarke and Rendell, 2009). Moreover, recent studies on the French Atlantic coast, in the Seine estuary and in the Mont-Saint-Michel Bay, have shown strong evidence of changes in coastal hydrodynamics at 5.6, 4.2, 3, 1.2 cal ka BP and the latter half of the Little Ice Age (LIA) that were related to intensification storm activity (Sorrel et al., 2009; Billeaud et al., 2009, Fig. 9d). The present study demonstrates that periods of increased storm activity in the Eastern North Atlantic and in the North Western Mediterranean Sea were in phase over the last 6000 yr. (Figs. 9c,d), as previously demonstrated for the LIA period (Dezileau et al., 2011). These periods probably corresponded to large climatic perturbations over the mid European domain as attested by the correlation of high lake level in this area (Magny, 2004; Fig. 9e).

Climate implications for Mid to Late Holocene storm activity

The main result of this study is the connection between high storm activity in the North-Western Mediterranean Sea and high storm activity in the Eastern North Atlantic over the last 7000 cal yr BP. Moreover, these periods of increased storm activity seem to be in phase with cold events recorded in the North Atlantic (Bond et al., 1997, 2001), even if the origins of these events over the Holocene are not straightforward (Mayewski et al., 2004; Debret et al., 2007; Wanner et al., 2008; Charman, 2010).

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Hurrell (1995) showed that in positive phases of the NAO, storm tracks cross the northern part of Europe, and during negative phase of the NAO, westerlies are shifted to the south and cause perturbations over the Western Mediterranean area. This region is located at the southern limit of the North Atlantic storm tracks, so that shifts in storm tracks can influence cyclogenesis in the Mediterranean. Trigo et al. (2000) demonstrated that, over the last four decades, the reduction in strength of the most intense cyclones has been driven by trends observed in the coupled ocean-atmospheric circulation over the Northern Atlantic, in particular by the northward migration of the main Atlantic storm tracks. Sorrel et al. (2009) have suggested that the prevailing climate regime over northwestern France during cold Bond events was probably very similar to the positive phases of the NAO, with an intensification of landfalling activity, suggesting a probable lock on the preferred high phase of the NAO. However, a recent study by Trouet et al. (2009), using a proxy-based reconstruction of the NAO index over the last millennium, find a persistent long-term phase of positive (negative) NAO conditions during the MCA (LIA). Therefore the lock on the preferred high phase of the NAO invoked by Sorrel et al. (2009) cannot explain the increased storm activity in northwestern France. Moreover, the present study demonstrates that periods of increased storm activity in the eastern North Atlantic and in the NW Mediterranean Sea during the last 7000 yr were in phase (Figs. 9c,d). This synchronicity during cold periods also provides evidence that the NAO seesaw pattern was probably not the major mechanism forcing the intense storm activity at the Holocene time scale. Moreover, Jacobeit et al. (2003) demonstrated that at a long-term time scale, the climate variability in the North Atlantic region must not be restricted to zonal mode and NAO considerations but must take into account multiple atmospheric patterns.

Holocene millennial-scale climate changes have often been associated with solar variability as a primary driver (van Geel et al., 1999; Bond et al., 1997, 2001). Furthermore, precipitation proxies from continental archives in Europe demonstrate that solar variability played a main role in climate change over most of the Holocene (Magny, 1993, 2004; Vaquero, 2004; Holzhauser et al., 2005; Magny et al., 2010). A recent diatom-based SST reconstruction for core LO09-14 from the southern part of the Reykjanes Ridge in the North Atlantic, (Berner et al., 2008) found evidence for 18 Holocene cold events (HCEs) associated with drops in SSTs of 1–3°C (Fig. 9f). Periods of high storm activity seem to correspond with most of the main decreases in SST, less than 11°C (dotted line), in the North Atlantic (HCEs 8, 9, 11, 12, 14 and 17, in dark grey in Fig. 9f, defined by Berner et al., 2008). These authors associated this high frequency variation in SST with ^{14}C production rates, implying that solar-related changes are an important underlying mechanism for the observed ocean climate variability. Even if strong correlations exist between low solar output and high storm activity (Figs. 9b,c), for example, during the LIA and at 2.7, 3.4, 5.5 and 6.2 cal ka BP, there were no exceptional residual ^{14}C excursions at the 1.7 and 4.2 cal ka BP (HCE 17 and 11 for Berner et al., 2008) periods of changes in storminess. Therefore, this external forcing was a significant mechanism for the observed storm variability, but it cannot explain all the observed changes in storm activity during the Holocene. Internal oscillations in both the ocean circulation system and atmospheric processes have also been suggested to play a key role in the observed climate changes (Bianchi and McCave, 1999; Broecker, 2000; Wanner et al., 2008). Whatever the ultimate cause of these millennial-scale Holocene climate variations, the main decreases of SST observed in the North Atlantic seem to be an important mechanism to explain high storm activity in the NW Mediterranean area.

Raible et al. (2007) using an Ocean–atmosphere General Circulation Model compared Maunder Minimum (1640 to 1715, during the LIA) simulations with a 1990 control simulation and found an increase in cyclone density south of 50°N during this low solar-activity period. Within this cold period, the sea ice extended further southward, particularly in winter over the North Atlantic basin (Lamb, 1995). Throughout this simulation time period, extreme wind speeds and precipitation events were intensified, in particular in the Mediterranean region during the autumn and winter over this part of the LIA. These results were confirmed by Dezileau et al. (2011), who hypothesised that this extended sea ice implies that a thermal gradient increase leads to enhanced lower tropospheric baroclinicity over a large Central Atlantic–European domain. This mechanism, which is associated with southward displacement of storm tracks, implies an increase in storm activity in the NW Mediterranean Sea (Raible et al., 2007). Moreover, based on instrumental data (1950–1992), Betts et al. (2004) showed that the strengthening of the NS thermal gradient across the Atlantic transfers the upper westerlies and cyclonic activity to more southerly tracks. During the Holocene, the periods of low SSTs observed in the North Atlantic (Bond et al., 2001; Berner et al., 2008) could have produced a stronger meridional temperature gradient, as simulated during the Maunder Minimum, and thus a southward position of the westerlies during the Holocene cold events, as previously suggested (Magny et al., 2003; Bakke et al., 2008). We propose here that this mechanism, which results from a decrease in the North Atlantic temperature, causes an increase in storm activity in the NW Mediterranean region during these cold periods of the Holocene.

Conclusion

This study provides a 7000-yr high-resolution record of past storm events using a multi-proxy analysis of sedimentary deposits from a lagoonal environment in the Gulf of Lions in the North-Western Mediterranean Sea. The lagoon's geomorphological setting has clearly changed over the Holocene. We suggest that these modifications altered the sensitivity of the site in recording paleostorm. Therefore, we cannot compare storm events in terms of intensity through time. Nevertheless, from the presently available data, seven periods of increased storm activity were identified at 6300–6100; 5650–5400; 4400–4050; 3650–3200; 2800–2600; 1950–1400 cal yr BP and over the Little Ice Age (from 400–50 cal yr BP) based on our ^{14}C age model.

The evidence suggests that these changes in coastal hydrodynamics were in phase with those observed over the Eastern North Atlantic (Billeaud et al., 2009; Sorrel et al., 2009) and seem to correspond to Holocene cooling first shown in the North Atlantic (Bond et al., 1997, 2001) and associated with decreases in SST (Berner et al., 2008). These periods of low SST observed in the North Atlantic may have produced a stronger meridional temperature gradient and a southward position of the westerlies during the Holocene cold events. We hypothesise here that this increase in storm activity during Holocene over the Eastern North Atlantic and the Mediterranean region was probably due to an increase in the thermal gradient that led to enhanced lower tropospheric baroclinicity over a large Central Atlantic–European domain, as previously suggested over the LIA (Raible et al., 2007). These results demonstrate that the North Atlantic region has influenced the Mediterranean climate at the Holocene time scale in relation to severe storm activity.

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