Increase of storm events during the Holocene cold events in NW Mediterranean Sea

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Abstract

This paper present a high resolution record of paleostorm events in the French Mediterrannean coast over the past 7000 years based on a long sediment core from lagoonal environment in Gulf of Lions. Using a multi-proxies approach on core associating grain size, faunal analysis, with a chronology derived from radiocarbon dates, we reconstruct Mid to Late Holocene history of backbarrier deposits in relation to landfalling activity. Even if change in lagoon geomorphological setting over the Holocene does not allow to compare storm events in terms of intensity trough time, we have recorded seven periods of increase in storm activity at 6200, 5400, 4600-4200, 3600-3100, 2600, 1900-1500 yr cal B.P. and over the Little Ice Age (450 and 50 yr cal B.P.). Whereas the Medieval Warm Period (1200-700 yr cal B.P.) is characterized by a low storm activity.
These evidences of changes in coastal hydrodynamic are in phase with those observed over the North Atlantic and correspond to Holocene cooling evidenced associated to decreases of SST in the North Atlantic. These periods of low SST observed in North Atlantic can produce a stronger meridional temperature gradient and a southward position of the westerlies during these periods. We hypothesize here that this increase in storm activity during Holocene cold events over the North Atlantic and Mediterranean region was probably due to thermal

gradient increase leading to enhanced lower tropospheric baroclinicity over a large Central Atlantic-European domain. These results demonstrate that North Atlantic region influence the Mediterranean climate at Holocene timescale, in relation to severe storm activity

1. Introduction

The Mediterranean region is one of the world's areas most vulnerable to the climate change (Giorgi, 2006). Regional climate simulations have been used to investigate the variations of precipitation and the cyclonic activity in the Mediterranean region. Gibelin and Déqué (2003) predict, using ARPEGE model, an overall warming and drying in all seasons except in winter over North-Western Mediterranean area with an increase in precipitation. Lionello and Giorgi (2007) show that the reduction of cyclone activity observed in future scenarios would be responsible for the negative change in precipitation on the southern and eastern Mediterranean coast, while positive change occurs in Northern parts in relation to increased strength of mid latitude storm track. In addition, Gaertner et al., (2007) detect for the first time a risk of tropical cyclone development over the Mediterranean Sea under future climate change conditions. However, the effects of climate change on extreme events are difficult to assess because extremes present large variability and consequently, it is more difficult to identify significant trends in relation to the lack of instrumental long time series (Webster et al., 2005; Emanuel 2006a; Landsea et al., 2006). It is therefore, necessary to study the past storm activity in order to better understand the possible regional and local long term trends of these events, associated to past climate conditions.

In this study, we focus mainly on the Gulf of Lions (Figure 1), a region of the French Mediterranean coast. This area is particularly sensitive in terms of societal issues for the risks of flooding (the Mediterranean Heavy Precipitating Events) and the risk of coastal erosion/submersion during storm events. In September 2002, large floods hit this region; there were 23 victims and damage was estimated at over one billion Euros. Linked or not to these rainy episodes, the region is also prone to frequent storms. These events can have dramatic actions when the winds and waves are associated with high sea surges (Ullmann et al., 2008) attacking coastal sand dunes, sometimes breaking the sandy barrier. For the last few decades, the most important storm is that of 1982 with 46m/s of wind (category 2 in Saffir–Simpson scale), this storm caused the deaths of 15 people and economic losses were estimated at 400 million euros. 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 forced by the decline in the intensity of cyclogenesis event (Trigo et al., 2000). Cyclones are the cause of most of the heavy precipitations in the whole Mediterranean region (Trigo et al., 2000; Jansá et al., 2001). Lionello et al., (2006a) find a significant decrease in winter cyclone density over most of the Western Mediterranean during the last 150 years, this tendency is also confirmed by a work on sedimentary archives (Sabatier and Dezileau, in press a). However, there is no evidence that the behaviour of Mediterranean climate extremes on this timescale is inconsistent with natural climate fluctuation as NAO (North Atlantic Oscillation) or EAP (Eastern Atlantic Pattern) during earlier centuries (Quadrelli et al., 2001 ; Sánez et al., 2001 ; Krichak et Alpert, 2005 ; Lionello et al., 2006a ; Luterbacher et al., 2006 ; Trigo et al., 2006; Dezileau et al., submitted).

Reconstruction of the recurrence and intensity of paleostorms in coastal area is necessary due to the recent concentration of resource and population in this zone (Pielke and Landsea 1999; Turner et al., 2006; Lionello et al., 2006a; Dezileau et al., submitted). Therefore, geological data offers opportunities to reconstruct a long term record of intense events and can extend the documented record well beyond the observational record in order to identify how storm activity has responded to past shifts in climate. This study was a part of the ECLICA project, (INSU, ACI-FNS « Aléas et changements gobaux » in 2004, coordinator L. Dezileau) one of the aims of which was to identify regional storm patterns using systematic, historical and paleostorm data. Usually, reconstruction of paleostorm events in coastal environments has been made by identifying the recurrence of overwash coarse grained and associated deposits (Liu and Fearn 1993, 2000; Collins et al., 1999; Donnelly et al., 2001a, 2001b; Nott, 2004; Donnelly, 2005; Donnelly and Woodruff, 2007; Scipelly and Donnelly, 2007; Frappier et al., 2007; Sabatier et al., 2008; Woodruff et al., 2009). In this study we present a high-resolution multi-proxy approach on a long core from the Pierre Blanche lagoon. Part of this record was the subject of a previous work that discussed in detail the link between the sedimentary record of extreme storm events and climate changes of the last 1000 years and the Little Ice Age (Dezileau et al., submitted). Here we extend the record back to the last 7000 years. We then try to assess the most probable mechanisms behind the observed variability of extreme storm events in the area at the millennial scale.

2. Study area

The Gulf of Lions shore line is characterized by many coastal wetlands that are the result of the interaction between a process of shore line regularization by migrations of sandy barriers due to the sediment transfer through littoral hydrodynamics; and a filling of these areas by the fluvial and marine inputs (Certain et al., 2004; Raynal et al., 2009). This study focuses on the Palavasian wetland complex located to the West of the Rhône delta, 10 km south of the city of Montpellier (Figure 1). This area consists of seven small lagoons, with shallow water depth, limited to the South by a narrow sandy barrier, attached from place to place to subdued rocky capes (Aresquier wood or Maguelone Church peninsula, Raynal et al., 2009), and to the North by calcareous Mesozoic hills (Gardiole Mountain). In some places, the barrier is weak and highly sensitive to high energy events, enabling temporary but strong marine influence when the barrier breaks during storm events. This is commonly seen by traces of over-wash fans and ancient temporary inlets (Dezileau et al., 2005; Sabatier et al., 2008). Most of the sediments supplied to the area are carried by the Mosson coastal river. The Mosson average flow is 1.2 m^3/s but can reach the values of 258 m^3/s measured during 3 December 2003 flash flood events. The Mosson drainage basin is mainly constituted by Mesozoic (limestone) and Cenozoic (conglomerate, carbonated sandstone and clay) sedimentary rock with Quaternary deposits. This wetland complex is now crossed by the artificial Rhône-Sète navigation channel constructed in the 17th century. This study focuses on the Pierre Blanche located in the Southern part of this system (Figure 1), with water depths of 60 cm.

This coastal area is characterized by a classical microtidal environment with maximal tide ranges < 50 cm. The annual significant wave height (Hs) and period (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). 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 was around 1% and the return period of a 6m high wave was every 10 yr (Guizien K. personal communication).

3. Material and methods

A piston core of 7.9 meters long (PB06) was collected in the Pierre Blanche lagoon in March 2006 (Figure 1) with the UWITEC© gravity coring platform (University of Chambery). This device consists of a 2 m transparent plastic liner mounted with an “orange-peel” core catcher. No compaction due to the coring system was observed. At the laboratory, cores were split, photographed, radiographed using the Scopix X-ray scanning (EPOC, University of Bordeaux), logged in detail (noting all physical and biogenic sedimentary structures and vertical facies successions), and divided into 1 cm vertical sections prior to analysis.

Grain size and macro-fauna content analyses were performed on 2 cm long sections. To study mollusc shells, samples were sieved at 1mm 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 distribution was determined using a Beckman Coulter© LS 13 320. Only the <150µm fraction was analysed due to the high concentration of shell fragments of a size exceeding 200 µm. Bulk sediments were first suspended in deionized water and gently shaken to achieve desegregation. After introduction of sediment into the fluid module of the granulometer, ultrasounds were 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 runs were performed, following air-drying, ethylene-glycol solvation for 24 hours, and heating at 490ºC for two hours. 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) (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 from the 3.57/3.54 Å peak areas.

Avaatech scanners performed continuous semi-quantitative downcore X-ray fluorescence (XRF) analysis on the surface of split sediment cores. The split core surface has to be covered with a 4 mm thin Ultralene to avoid contamination of the XRF measurement unit and desiccation of the sediment. Core PB06 was run through a non-destructive ITRAX core scanner at the Laboratory EPOC (Université de Bordeaux 1) to obtain subcentimeter-resolution of the sediment's elemental composition, reported as counts per second. In the present study, the selected step size was 0.5 mm with a XRF count time at each step of 30 s. Geochemical data was obtained at different tube voltage, 10 KeV for Al, Si, S, Cl, K, Ca, Ti, Mn, Fe and 30 KeV for Zn, Br, Sr, Rb, Zr (Richter et al., 2006).

Monospecific shell samples (*Cerastoderma glaucum*) were selected for ^{14}C age determinations. ^{14}C analyses were conducted at the Laboratoire de Mesure ^{14}C (LMC14) on the Accelerator Mass Spectrometer (AMS) ARTEMIS in CEA institute at Saclay (Atomic

Energy Commission). ^{14}C ages were converted to calendar years using the Calib 5.0.2 calibration program (Hughen et al., 2004) at two standard deviations.

4. Chronology framework

The chronology of core PB06 has been established using ^{210}Pb and ^{137}Cs chronology associated with Accelerator Mass Spectrometry (AMS) ^{14}C dates on monospecific shell sample (Sabatier et al., in press c). These authors make an estimation of radiocarbon reservoir age which varies in relation to palaeoenvironmental change (see section 5.2). Reservoir age varies between 618 ± 30 ^{14}C yr, local marine reservoir age (Siani et al., 2000) for the deepest part of the core to 943 ± 25 ^{14}C yr, estimated by correlation with ^{210}Pb and ^{137}Cs chronology and historical events, for the last 1.7 m.

In the Pierre Blanche lagoon, Linear Sedimentation Rate (LSR) obtained for the different part of the core PB06 (Figure 2) suggest a low sedimentation rate of 0.33 $mm.yr^{-1}$, at the base of the core (759-710 cm). This rate increases from 0.98 $mm.yr^{-1}$ between 710 and 170 cm to 1.52 $mm.yr^{-1}$ until 40 cm. For the modern part of the core (upper 40 cm), the accumulation rate is estimated through the ^{210}Pb and ^{137}Cs chronology at 2.65 $mm.yr^{-1}$ (Sabatier et al., in press c).

5. Results

The lagoon is mostly filled by grey clay and silt with shell fragments alternating with layers of fine sandy material. Lithological description of PB06 core based on grain size, sedimentary structure and fauna content allows us to identify different facies interpreted in terms of lagoon depositional environments (Sabatier et al., in press b). PB06 is constituted by 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 as lagoonal depositional environment consequent to the Holocene filling of this coastal area. In this study we focus, in the upper unit, on the variations of sediment properties in order to identify paleostorm events.

5.1. Grain size

Grain size data are generally displayed in a spectrum where the percentages of the populations are plotted vs. grain size fraction. They show a combination of different populations of particles, which vary in time describing different deposit mechanisms (Weltje and Prins, 2003). Boulay et al. (2003) used the standard deviation of each grain size interval as a simple method to identify the grain size population with the highest variability. Using this method, we can determine the grain size classes having the most important variation through time. Standard deviation values vs. grain size classes of core PB06 are displayed on Figure 3. Two main grain populations, presenting the highest variability, can be identified. One between 2 and 10 µm (clay to fine silt) and another coarser, between 30 and 100 µm (fine sand). The evolution with depth of these two populations displays eight main changes in PB06 core with a strong anti-correlation between fine and coarse sediment revealed by the grey bands on Figure 4. The main peaks of coarse fraction occur in the upper part of the core at 35, 60, 100 and 225 cm.

5.2. Faunal variations

Macropaleontology analyses are a good indicator of a lagoon paleo-isolation state because fauna develops in different ranges of salinity, temperature and oxygenation. One species develops typically in a lagoon environment (*Hydrobia 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 of Figure 4 show an anti-correlation between species living in lagoon conditions and that representative of the marine environment. The close association of sandy layers, marine species and the disappearance of lagoonal fauna propose that the observed sequences can be interpreted by a succession of marine invasions of the lagoon during storm events, followed by closure of the barrier and return to typical lagoon conditions (Sabatier et al., 2008). Nevertheless, this assumption is valid when lagoonal species are dominant in an isolated lagoonal environment. A main change in mollusc population at around 190-170 cm characterized by an increase of the most typical lagoonal specie *Hydrobia acuta*, whereas the number of marine specie *Bittium recticulatum* decreases. This faunal variation is related to change in environmental conditions (salinity, temperature, nutriments, and oxygenation) from a lagoonal depositional environment, with marine influence to a more isolated lagoonal environment. Such a change could result from local paleo-morphological modifications such as a closure of the communications between the lagoon and the sea (Sabatier et al., in press, b). That 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, numbers of lagoonal and marine species in the two first meters of PB06 can not be compared to the rest of the core in term storm events.

5.3. Clay minerals

Clay minerals display significant differences between (1) the Mosson drainage basin, with high concentration of smectite (73% - 81%) reflecting erosion with reworked processes of ancient formation as Cenozoic conglomerates and (2) the sandy barrier, mostly characterized by high contents of illite (45% - 59%) and chlorite (17% - 26%) related to sediment from the Rhône River (Sabatier et al., submitted). Sediments from PB06 core present mean values for clay minerals included between the Mosson drainage basin and sandy barrier contents. This core consists predominantly of smectite (15% - 70%) and illite (16% - 55%) with less content of chlorite (3% - 25%) and kaolinite (6% - 17%). Theirs average percentages are 44% for smectite, 33% for illite, 12% for chlorite and 11% for kaolinite (Figure 5). In Figure 5 clay minerals can be subdivided into three groups along PB06. Changes of illite and chlorite display similar variations. Smectite general trend is inversely correlated to illite and chlorite, shaded bands. Kaolinite contents seem to vary in time with the same trend as smectite. Therefore, we adopt the ratios of smectite/(illite + chlorite) as mineralogical indicators to reconstruct the history of paleostorm events in the suited system.

5.4. 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 nature of the surface of split-sediment cores due to the effects of sample inhomogeneity and surface roughness. These characteristics are particularly pronounced for sediments containing abundant medium–coarse sand-sized particles such as shell fragments in coastal environments (Richter et al., 2006). Therefore, we have to represent geochemical data, obtained by XRF measurement, in relation to other elements. In this study, we choose to normalize the different elements by the Aluminium, representative to detritic component from the watershed.

The Mosson drainage basin is characterized by Al_2O_3, Fe_2O_3 and Th. Another source is defined by SiO_2 NaO and Zr respectively abundant in quartz, sodium feldspars and heavy minerals present in the sandy barrier (Sabatier et al., submitted). The authigenic productivity is traced in lagoonal sediment by shell abundance with high concentration in CaO and Sr. In Figure 6, we represent on one hand Si/Al and Zr/Al ratios in order to reconstruct the influence of marine component during paleostorm events (high values) and on the other hand Ca/Al and Sr/Al ratios to trace periods of large concentration in mollusk population. Si/Al and Zr/Al ratios are correlated, especially for the first five meters of the core (shaded bands). Ca/Al and Sr/Al ratios display similar variations. High values of this ratio could be due either to a strong biogenic productivity or to the reworking and the transport of shells from the sandy barrier during high energy events. These hypotheses explain how increase of Ca/Al and Sr/Al ratios are not systematically associated with Si/Al and Zr/Al ratios related to paleostorm events (Figure 6).

6. Discussion

6.1. Paleostorms deposits

The multiple deposits identified in PB06 by correlation between grain size, fauna contents, clay minerals and XRF geochemistry suggest that the barrier has been breached numerous times over the last 6500 yrs (Figure 7). The three last events were previously identified in the whole lagoonal system by lateral correspondences on multiple cores transects. These events were dated using ^{210}Pb and ^{137}Cs chronology associated with ^{14}C dates and historical accounts at 1742, 1848 and 1893 A.D (Sabatier et al., 2008; Dezileau et al., submitted). Several peaks (grey band on Figure 7) in grain size, Zr/Al and the number of marine specie related to a decrease in Smectite/(Illte + Chlorite) ratio which may suggest the occurrence of eight high energy events likely reflecting recurrent perturbation of coastal hydrodynamics in relation to paleostorm events. Except for the last three deposits, it is difficult to associate these layers to a specific event or to a short period of increase in landfalling activity. Based on our ^{14}C age model, the strongest evidence for this change in storm activity occurred around 6200, 5400, 4600-4200, 3600-3100, 2600, 1900-1500 and between 450 and 50 cal B.P.

The horizontal extent of the overwash deposit is affected by many complicating factors in relation to storm characteristics such as hurricane intensity, storm surge height, tidal height at time of landfall, angle of storm events and wind direction, timing and duration of landfall (Liu and Fearn, 2000). In this microtidal study area, we may infer that stronger storms tend to result in a higher storm surges and thus producing a thicker and more widespread overwash layer. However, storm landfall conditions as well as timing, duration and angle of approach occur to randomly over time. Liu and Fearn, (2000) present a model, where a coastal lake was subjected to overwash events caused by landfalling hurricanes of various intensities and direction. This study concludes that a suite of cores taken from different sites is vital for producing a complete record of past hurricane landfalls. In this system three multi-cores transects show a clear link between recent overwashes (last 1000 years), due to a catastrophic storm of category 3 intensity or more, and was described and discussed in Dezileau et al., (submitted). 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 are recorded in the whole lagoonal area as supported by correlation over the upper 1.2 m of sedimentary archives.

6.2. Site sensitivity through time

Sea level rise can increase the sensibility of backbarrier study site by moving the shoreline farther inland and narrowing the sandy barrier through time. The Gulf of Lions coast has been free of significant vertical tectonic movements (< 0.02 mm/yr) in Late-Quaternary time (Lambeck and Bard; 2000). The relative sea level curve in the NW Mediterranean Sea, for the last 7000 yr cal B.P. (Figure 8) presents some discrepancies (from observations: Laborel et al., 1994; Vella and Provensal, 2000; Morhange et al., 2001; from glacio-hydro-isostatic model: Lambeck and Bard; 2000). If the relative sea level has remained almost constant for the last 5000 yrs (< 2m), significant changes occurred during the first stand of lagoonal deposit between 6500 (date of the first lagoonal deposit in PB06) and 5000 yrs (1-3 m). The establishment of the sandy barrier has been estimated by Raynal et al., (2009) at around 7500 yrs at 1 km seaward from the present position. Moreover, these authors have dated the actual barrier at 1800 ± 150 yr cal B.P. thanks to a ^{14}C age at the base of the present day sandy barrier. These dates imply a landward movement of the sandy barrier with an average rate of 0.2 m/yr in relation to the decrease of sea level rising rate (Raynal et al., in press). While it is likely that there have been minor sea level fluctuations and shoreline landward movements for the last 1800 yrs, changes were most important before this period. The variation of the sea level before the last 1800 years have probably affected the sensitivity of the site in recording paleostorms and the intensity of the different sedimentary records can not be directly compared.

Fauna content reveals a main palaeoenvironmental change around 1000 yr cal B.P., after this date the sandy barrier was continuous but with temporal inlet formation in relation to storm events (Sabatier et al., in press b). Before this date, the lagoonal system was less isolated from the sea and presents probably a weaker barrier with large permanent channel, which controlled inflow of marine water into the system, typical from a protected lagoon environment. However, the fine organic-rich sediment types appearing throughout the record show that this back barrier area was experiencing quiescent sedimentation during at least the past 6500 yrs. Therefore, this lagoonal system is protected behind the barrier system over that time. This Spatial and temporal variability in barrier beach morphology complicate the sedimentary record of storms, varying the sensitivity of backbarrier locations (Donnelly and Webb, 2004). This morphology can explain why sand material was not clearly found in the deeper identified storm layer deposit (Figure 7).

Sedimentary records of overwash deposit 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., (2006b), show that a decreased of sedimentation rate could induce an apparent drop in landfalling activity during this period of low resolution interval (35% of the apparent decrease). In this study, it is difficult to associate these short periods of high storm activity (between 200 and 400 yrs, Figure 7) to a single event or a succession of events involving punctual records of past landfalling deposit, except for the top of the core. The three last prehistoric overwashs (1742, 1848 and 1893) occur during an interval of relatively high sedimentation rate (around 2 mm/yr). Whereas, during the other periods of increase in storm activity the accumulation rate was lower (less than 1 mm/yr). Therefore, we can suppose that if the accumulation rate was the same all along the core (equal to 2 mm/yr) we would have recorded more storm events during these periods of increase in 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).

In the Pierre Blanche lagoon, many mechanisms can perturb the records of overwash deposits such as level variations, barrier morphodynamics, sediment supply to the system and to the complexity of storm conditions. For the last 1000 years, from a multi cores transects approach Dezileau et al., (submitted) show that the study site appears to be sensitive to only the most severe storm events. However, on Mid to Late Holocene the sensitivity of this environment changes in relation to these mechanisms, therefore we can not compare different paleostorm deposits records in core PB06 in terms of intensity.

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

The Late Holocene sedimentary archive of Palavasian lagoonal system report from the presently available and limited data the occurrence seven periods of increase in storm activity at 6200, 5400, 4600-4200, 3600-3100, 2600, 1900-1500 and 450-50 yr cal B.P., based on our ^{14}C age model (Figure 9c). Although few studies record Mid to Late Holocene storm activity in Mediterranean Sea, these evidences of perturbation in coastal hydrodynamics could be correlated to other events on a regional scale.

Most of the heavy precipitations in the whole Mediterranean region over the last century have had a cyclone in its vicinity (Trigo et al., 2000; Jansá et al., 2001). Moreover, in the Gulf of Lions area severe flooding and intense storm during the last centuries are due to a strong mid-level SW flow over the French Mediterranean coast (Dezileau et al., submitted). Thus, the last period of high storm activity (450-50 yr cal B.P.) are associated to increase of severe flood events during the latter part of the Little Ice Age (LIA), as recorded in municipal archives of township along six coastal rivers located in the Mediterranean Languedoc (Blanchemanche, Accepted). This high hydrological activity is regionally well correlated to the increase of the Vidourle river detritic component (Berger et al., Accepted), to a higher frequency of flood in the Durance river (Miramont et al., 1998), in the Lower Rhône valley (Pichar 1995; Bruneton et al., 2001; Arnaud-Fassetta et al., in press), in the Isère river (Barriendos et al., 2003), in the Upper Rhône valley (Arnaud et al., 2005; Berger et al., 2008) and to high mid-European lake level (Magny, 2004). In the Southern Tyrrhenian Sea (Western Mediterranean Sea) to the East of the studied area, in the shallow marine wedge, Budillon et al. (2005) recognized four event beds related to major storms that occurred in the last 1000 years. These landfalling events associated to historical sources display an important storm activity between the 16th and 19th centuries.

The Medieval Warm Period (MWP) is record in speleothem from Grotte de Clamouse (Southern France) as a relative dry phase (McDermott et al., 1999; McMillan et al., 2005) and is consistent with the last aridification phase identified by Jalut et al., (2000) in a transect covering southeast France and south-west Spain. During this period our record indicates a relative low storm activity (1.2-0.8 kyr cal B.P.).

Each of high storm activity record in Pierre Blanche lagoon is correlated to reduction of progradation of beach ridge systems, in the Alboran Sea (West of the studied area), in relation to 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 kyr cal BP. to present (Goy et al., 2003). These periods are related to cold episodes record in marine Sea Surface Temperatures (SST) in the South of Iberia (Cacho et al., 2001) and to cold events reported in the North Atlantic region (Bond et al., 2001). These erosion 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). Therefore, periods of increase in storm activity recorded in this study are well correlated with Holocene cooling events (5.9, 4.3, 2.8, 1.4 and 0.5-0.1 Kyr, Figure 9a) associated with ice rafted in the North Atlantic (Bond et al., 1997; 2001).

On Holocene timescale some periods of increase in storm activity were described, for example the 8.2 kyr cold event which represents a significant period of abrupt cooling within the early Holocene is associated with coastal sand accretion in Western Europe (resume in Clarke and Rendell, 2009). Moreover, recent studies on the French Atlantic coast, in the Seine estuary and in the Mont-Saint-Michel Bay, show strong evidence of changes in coastal hydrodynamics at 5.6, 4.2, 3, 1.2 kyr cal. B.P. and during LIA in relation to intensification of storm activity (Sorrel et al., 2009, Billeaud et al., 2009, Figure 9d). This present study demonstrates that periods of increase in storm activity in North Atlantic and in North Western Mediterranean Sea are in phase.

6.4. Climate implication on Mid to Late Holocene storm activity

Storm events was related to high flooding activity in South of France over the last 1000 years (Dezileau et al, submitted) but on Mid to Late Holocene it is difficult to confirm this relation, linked to the lack of hydrological data on this time scale, in the studied area. The main result of this study is the connection between high storm activity in North Western Mediterranean Sea and in North Atlantic over the last 7000 yr cal B.P. Moreover, these increases are in phase with cold event record in 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).

Sorrel et al., (2009) suggest that the prevailing climate regime over North-Western France during cold Bond events was probably very similar to the one corresponding to the high phase of the NAO, through an intensification of landfalling activity, suggesting a probable lock on positive NAO values. It has been shown that in positive phase of the NAO storm track cross the Northern part of Europe while, during negative phase of the NAO, westerlies are shifted to the South providing perturbations over the Western Mediterranean area (Hurrel et al., 1995). This present study demonstrates that periods of increase of storm activity in North Atlantic and in North Western Mediterranean Sea during the last 7000 years are in phase (Figure 9c,d). This synchronicity during cold periods provides evidences that the NAO see-saw pattern was probably not the major mechanism forcing the intense storm activity on Holocene timescale. Moreover, Jacobeit et al., (2003) demonstrate that at long-term time scale the climate variability in North Atlantic region must not be restricted to zonal mode and NAO considerations, but has to take account the multiple atmospheric pattern.

This Holocene millennial-scale climate changes have often been associated with solar variability as primary drivers (Bond et al., 1997; 2001, van Geel et al., 1999). Furthermore, precipitation proxies from continental archive in Europe demonstrate that solar variability played a main role in climate change over much of the Holocene (Magny, 1993; 2004; Vaquero, 2004, Holzhauser et al., 2005; Magny et al., 2010). Recent diatom-based Sea Surface Temperature (SST) reconstruction for core LO09-14 from North Atlantic (Berner at al., 2008), show evidences of 18 Holocene cold events (HCEs) associated with drops in SST of 1-3°C (Figure 9e). Periods of high storm activity are well correlated to most important decrease in SST (less than 11°C) in North Atlantic (HCE 8, 9, 11, 12, 14 and 17, dark gray in Figure 9e). Berner et al., (2008) associate this high frequency variation in SST to ^{14}C production rate, implying solar-related changes as an important underlying mechanism for the observed ocean climate variability. Even if strong correlations exist between low solar output and high storm activity (Figure 9b,c) for example at during the LIA and at 2.6, 3.3, 5.4, 6.2 kyr cal B.P., there is no exceptional residual ^{14}C excursions at 1.7 and 4.4 kyr cal B.P. (HCE 17 and 11 for Berner et al., 2008), periods of changes in storminess. Therefore this external forcing is an important 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 been also invoked to play a key role in the observed changes (Bianchi and McCave, 1999, Broecker, 2000, Wanner et al., 2008). Whatever their ultimate cause, millennial-scale Holocene climate variations, the main decreases of SST observed in North Atlantic are in phase with the high storm activity in North Western Mediterranean area.

Raible et al., (2007) using an Ocean-Atmosphere General Circulation Model, comparing the Maunder Minimum (1640 to 1715, early part of the LIA) simulations with the 1990 control simulation and found an increase of cyclone density south of 50°N during this cold period. Across this simulation, extreme wind speed and precipitation are intensified in particular in the Mediterranean region during autumn and winter over this part of the LIA, these results are confirmed by sedimentary archive in this area (Dezileau et al., submitted). Within this low solar activity period, the sea ice was extent southward, particularly in winter over the North Atlantic basin (Lamb, 1995). Raible et al., (2007) hypothesize that this extend implies a thermal gradient increase, leading to enhanced lower tropospheric baroclinicity over a large Central Atlantic-European domain. This mechanism associated to southward displacement of storm track implies an increase of storm activity in NW Mediterranean Sea. Over the Holocene, periods of low SST observed in North Atlantic (Berner et al., 2008) can produce a stronger meridional temperature gradient as simulated during the Maunder Minimum. Moreover, some authors suggest a southward position of the westerlies during Holocene cold event (Magny et al., 2003; Bakke et al;, 2008). We suggest here that this mechanism resulting from a decrease of North Atlantic temperature implies an increase of storm activity in NW Mediterranean region during these cold periods at Holocene timescale.

7. Conclusion

This study provides a 7000 years high resolution record of past storm events using multi-proxy analysis of sedimentary deposits from lagoonal environment in Gulf of Lions in North Western Mediterranean Sea. Lagoon geomorphical setting has clearly changed over the Holocene, we suggest that these modifications altered the sensitivity of the site in recording paleostorms therefore, we can not compare storm events in terms of intensity through time. Nevertheless, from the presently available and limited data, we identify several periods of storm activity increase at 6200, 5400, 4600-4200, 3600-3100, 2600, 1900-1500 yr cal B.P. and over the Little Ice Age (450 and 50 yr cal B.P.), based on our ^{14}C age model.

These evidences of changes in coastal hydrodynamic are in phase with those observed over the North Atlantic (Sorrel et al., 2009; Billeaud et al., 2009) and correspond to Holocene cooling firstly evidenced in the North Atlantic (Bond et al., 1997; 2001) associated to decreases of SST (Berner et al., 2008). These periods of low SST observed in North Atlantic can produce a stronger meridional temperature gradient and a southward position of the westerlies during Holocene cold event. We hypothesize here that this increase in storm activity during Holocene cold events over the North Atlantic and Mediterranean region was probably due to thermal gradient increase leading to enhanced lower tropospheric baroclinicity over a large Central Atlantic-European domain as previously suggested over the LIA (Raible et al., 2007; Dezileau et al., submitted). These results demonstrate that North Atlantic region influence the Mediterranean climate at Holocene timescale, in relation to severe storm activity. In order to confirm these results, it is necessary to realize other studies over the Mediterranean region with the same multi-proxy approach.

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Figure captions:

Figure 1: Map of Pierre Blanche lagoon with localisation of the core PB06.

Figure 2: Age versus depth plot of chronological data for core PB06. Solid horizontal lines denote 2 standard deviations for radiocarbon ages. Linear Sedimentation Rate (LSR) was indicated for the different part of the core. For the modern part of the core (upper 40 cm), the accumulation rate is estimated through the ^{210}Pb and ^{137}Cs chronology at 2.65 mm.yr^{-1} (Sabatier et al., in press c).

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

Figure 4: Core PB06 with from left to right: Photography, X-ray, Grain size population of thin sand (30 – 100 µm) and clay to thin silt (2 – 10 µm), Number of *Bittium recticulatum* (marine specie) and Number of *Hydrobia acuta* (lagoonal specie). Shaded areas mark the main variations.

Figure 5: PB06 clay minerals analyses contents (%) obtained on the carbonated-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.

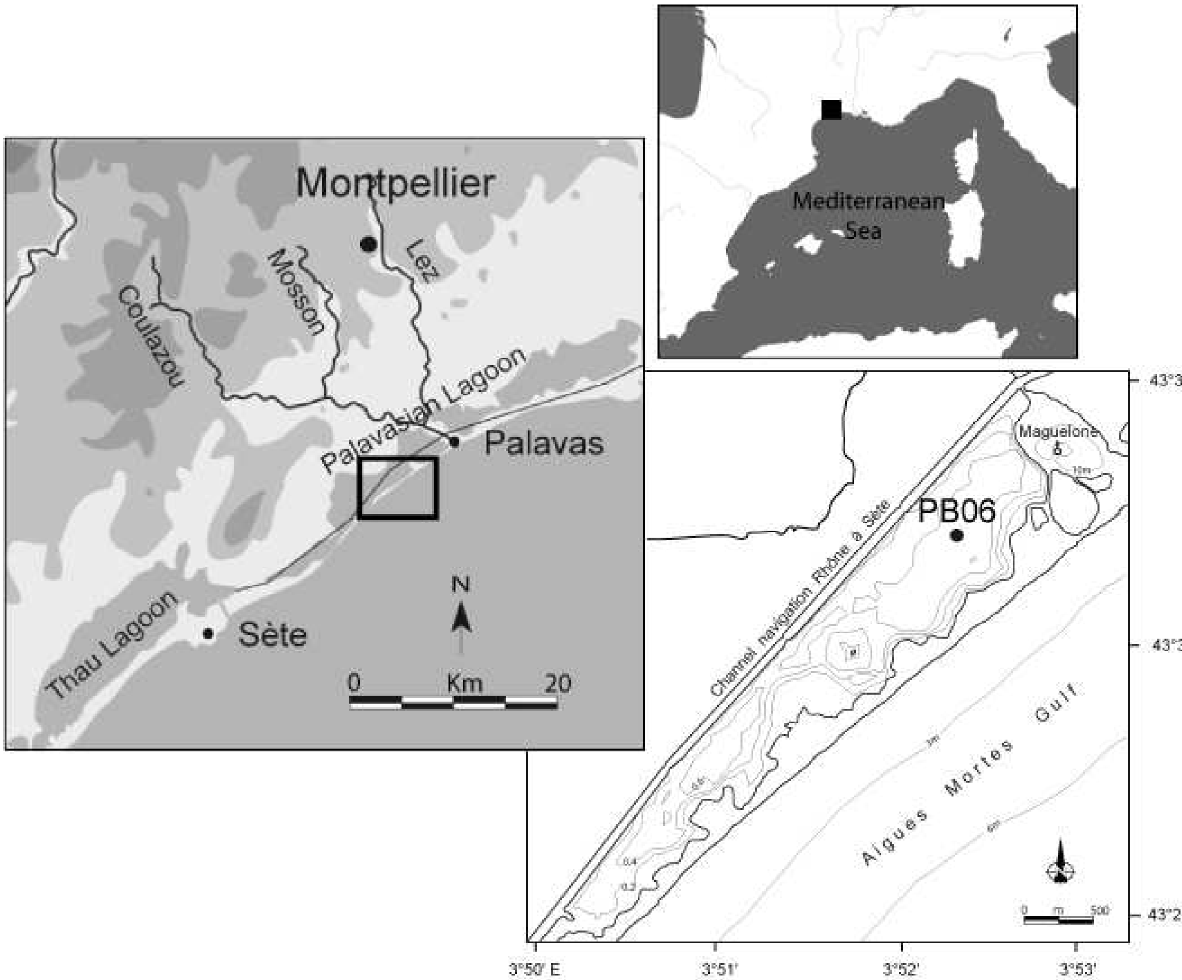
Figure 6: XRF records from core PB06, with down core variations of ratio Si/Al, Zr/Al, Ca/Al and Sr/Al. Shaded areas mark the main variations of Si/Al and Zr/Al ratio.

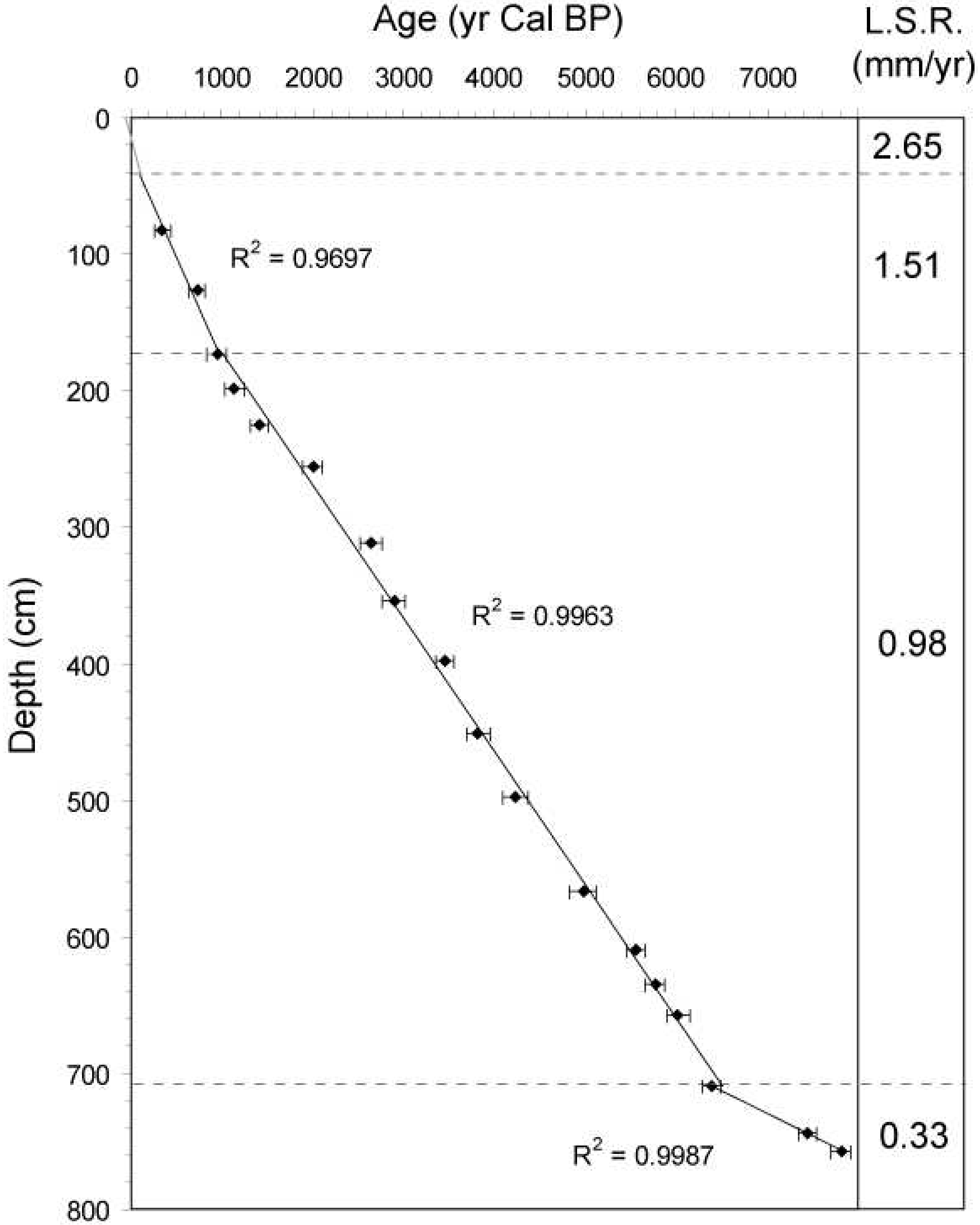
Figure 7: Core PB06 with from left to right: Grain size of 30 to 100 µm population, Zr/Al XRF ratio, Smectite/(illite + chlorite) and Number of *Bittium recticulatum* (marine specie). Grey bands are the high storm activity periods.

Figure 8: Relative sea level curve in the NW Mediterranean Sea for the last 7000 yr cal B.P. from observations in the Rhône delta (Vella and Provensal 2000), La Ciotat (Laborel et al.,

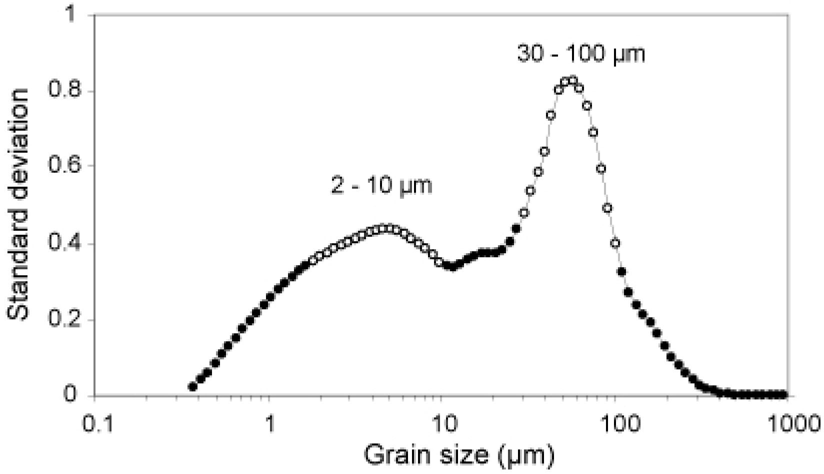
1994) Marseille (Morhange et al., 2001) and from glacio-hydro-isostatic model (Lambeck and Bard; 2000). Shaded area represents the sea level during the first lagoonal deposit.

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 INTCAL04 (Reimer et al., 2004); (c) Smectite/(illite + chlorite) ratio, shaded areas (low value) are interpreted as increase in storm activity in North Western Mediterranean Sea (Palavasian lagoon) based on the multi-proxy correlations defined in Figure 7; (d) Period of high storm activity in North French Atlantic coast (Sorrel et al., 2009; Billaud et al., 2009); (e) Diatom-based Sea Surface Temperature (SST) reconstruction for core LO09-14 from North Atlantic (Berner at al., 2008), the Holocene cold events (HCEs) identified by Berner et al., (2008) are noted as grey shaded areas (18-8).

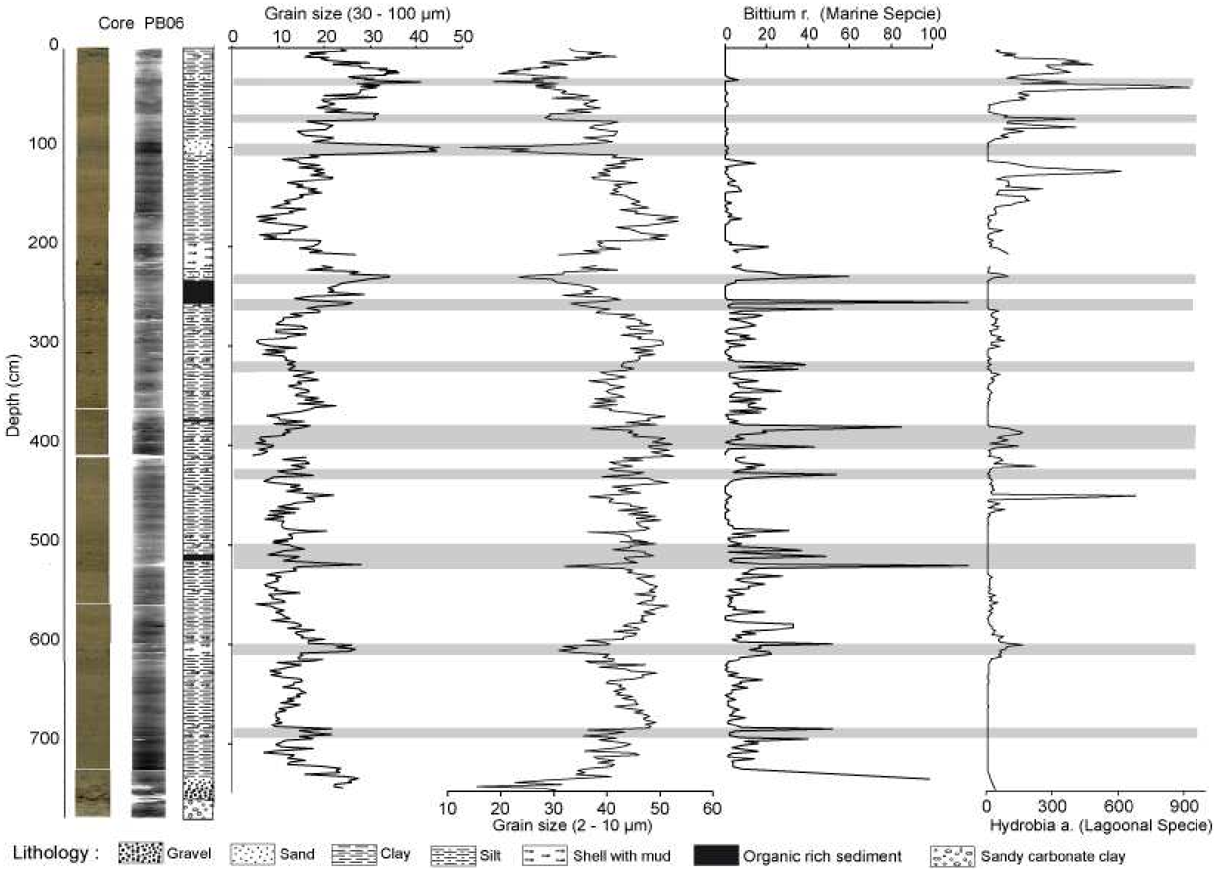

Montpellier
Mosson
Lez
Coulazou
Palavasian Lagoon
Palavas
Thau Lagoon
Sète
N
0
Km
20
Mediterranean
Sea
43°31' N
Maguelone
PB06
Channel navigation Rhône à Sète
43°30'
Aigues Mortes Gulf
43°29'
3°50' E
3°51'
3°52'
3°53'



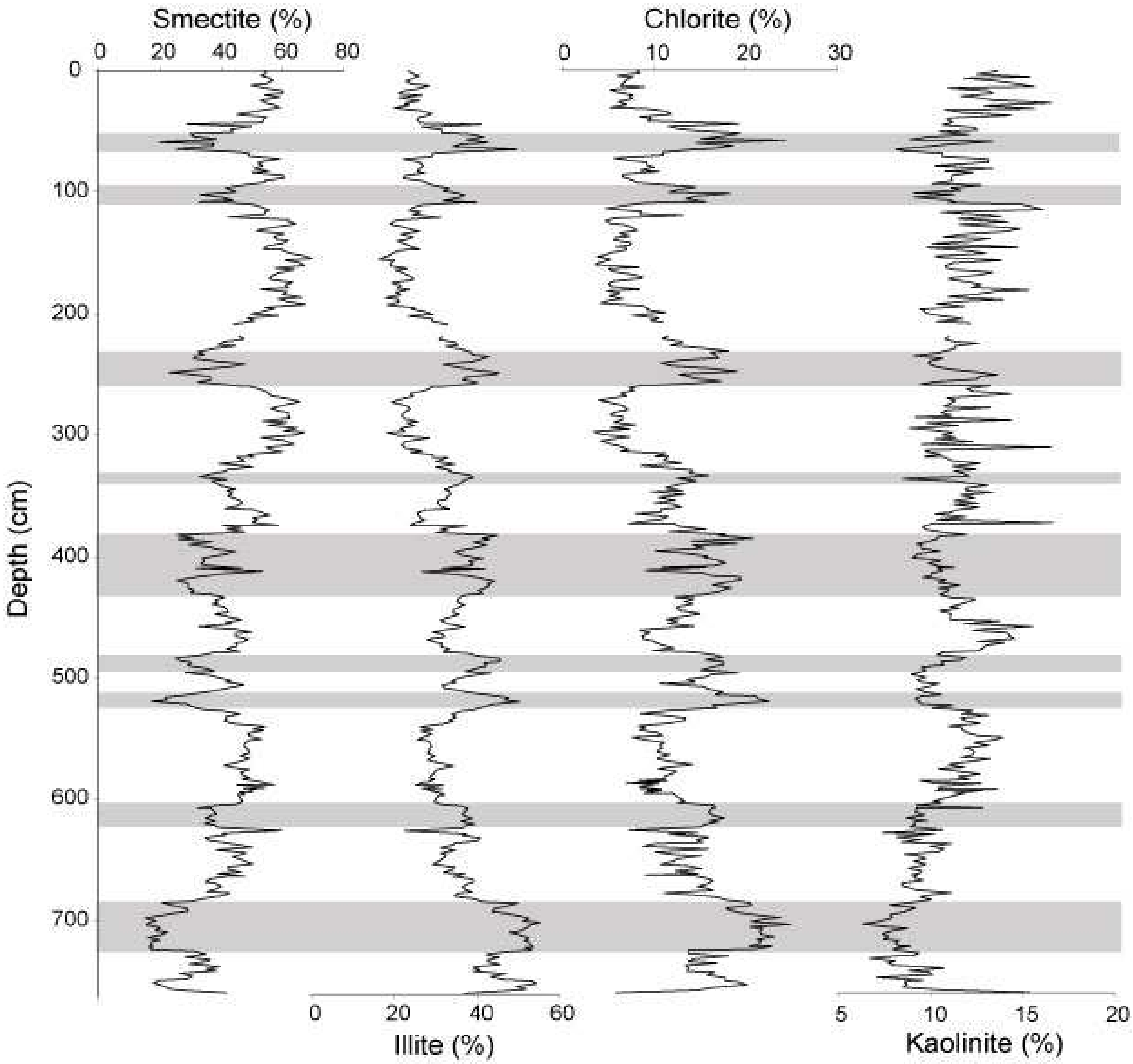
Age (yr Cal BP)
L.S.R. (mm/yr)
0
1000
2000
3000
4000
5000
6000
7000
0
100
200
300
400
500
600
700
800
Depth (cm)
2.65
1.51
0.98
0.33
R2 = 0.9697
R2 = 0.9963
R2 = 0.9987



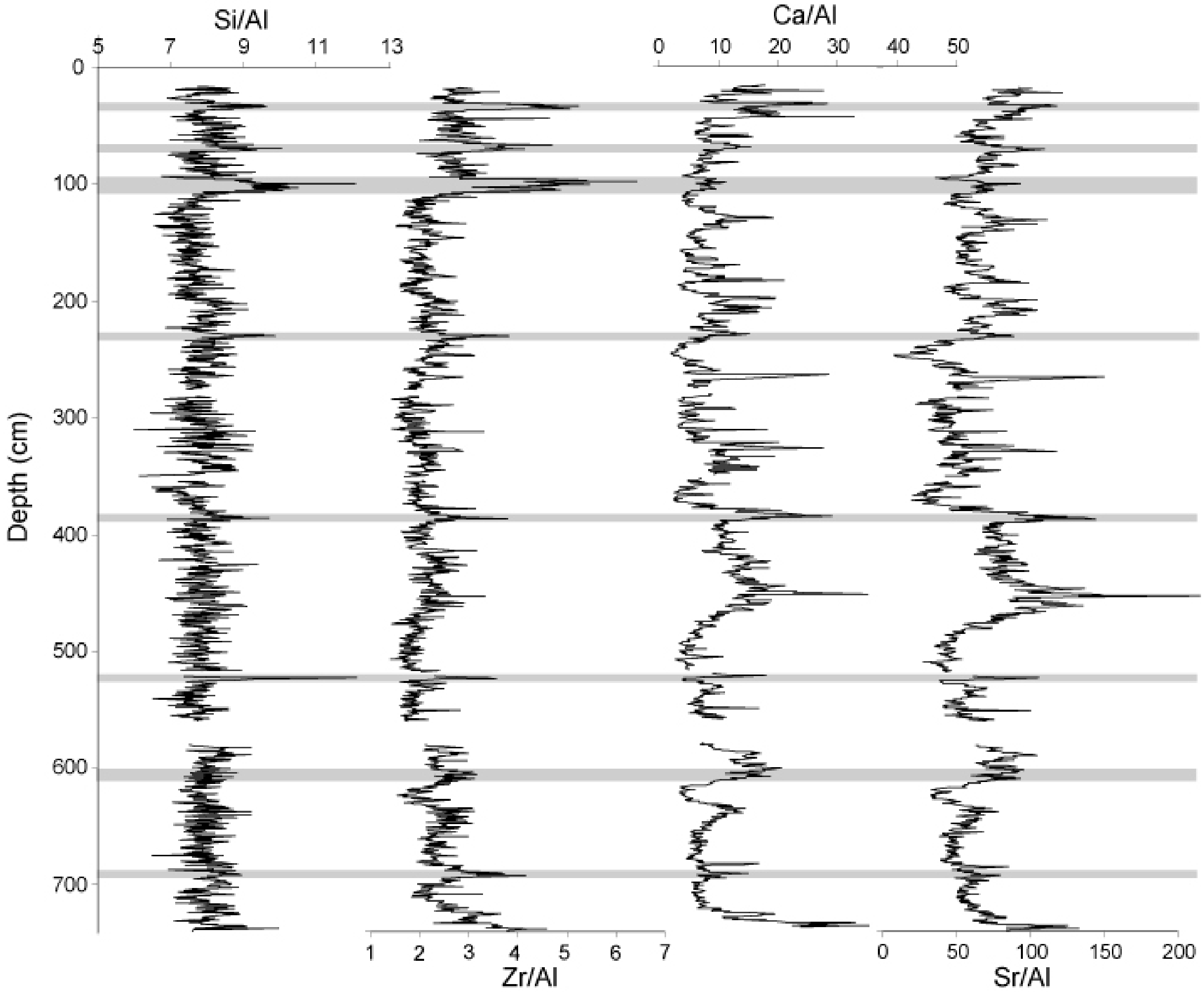
1
0.8
0.6
0.4
0.2
0
Standard deviation
30 - 100 µm
2 - 10 µm
0.1
1
10
100
1000
Grain size (µm)



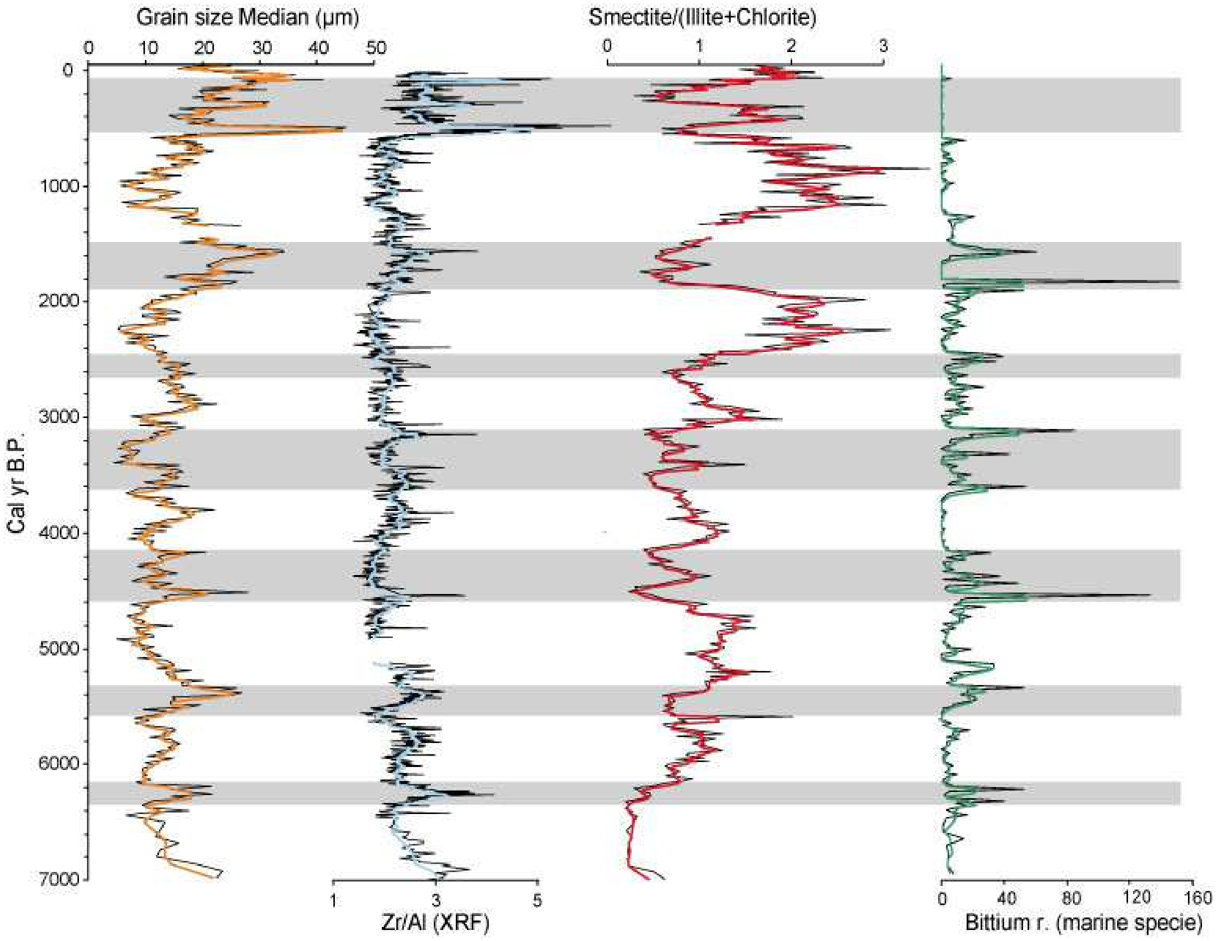
Core PB06
Grain size (30 - 100 µm)
0 10 20 30 40 50
Bittium r. (Marine Sepcie)
0 20 40 60 80 100
Depth (cm)
0
100
200
300
400
500
600
700
10 20 30 40 50 60
Grain size (2 - 10 µm)
0 300 600 900
Hydrobia a. (Lagoonal Specie)
Lithology :
Gravel
Sand
Clay
Silt
Shell with mud
Organic rich sediment
Sandy carbonate clay



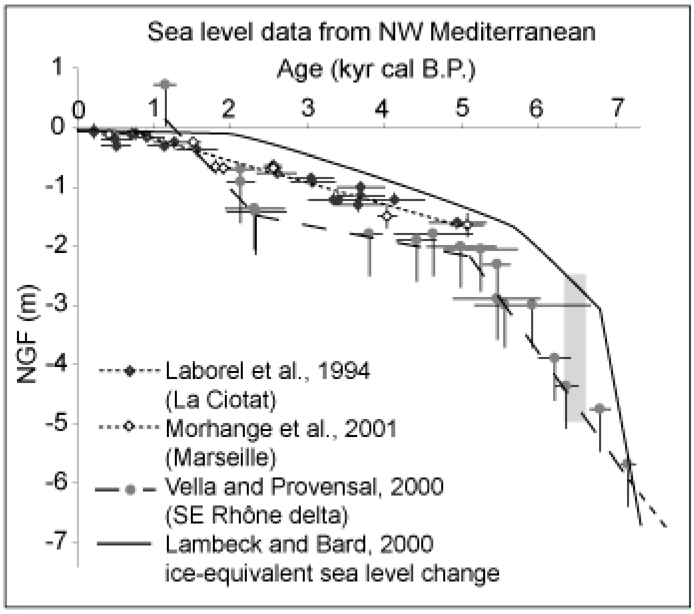
Smectite (%)
0 20 40 60 80
Chlorite (%)
0 10 20 30
Depth (cm)
0 100 200 300 400 500 600 700
0 20 40 60
Illite (%)
5 10 15 20
Kaolinite (%)



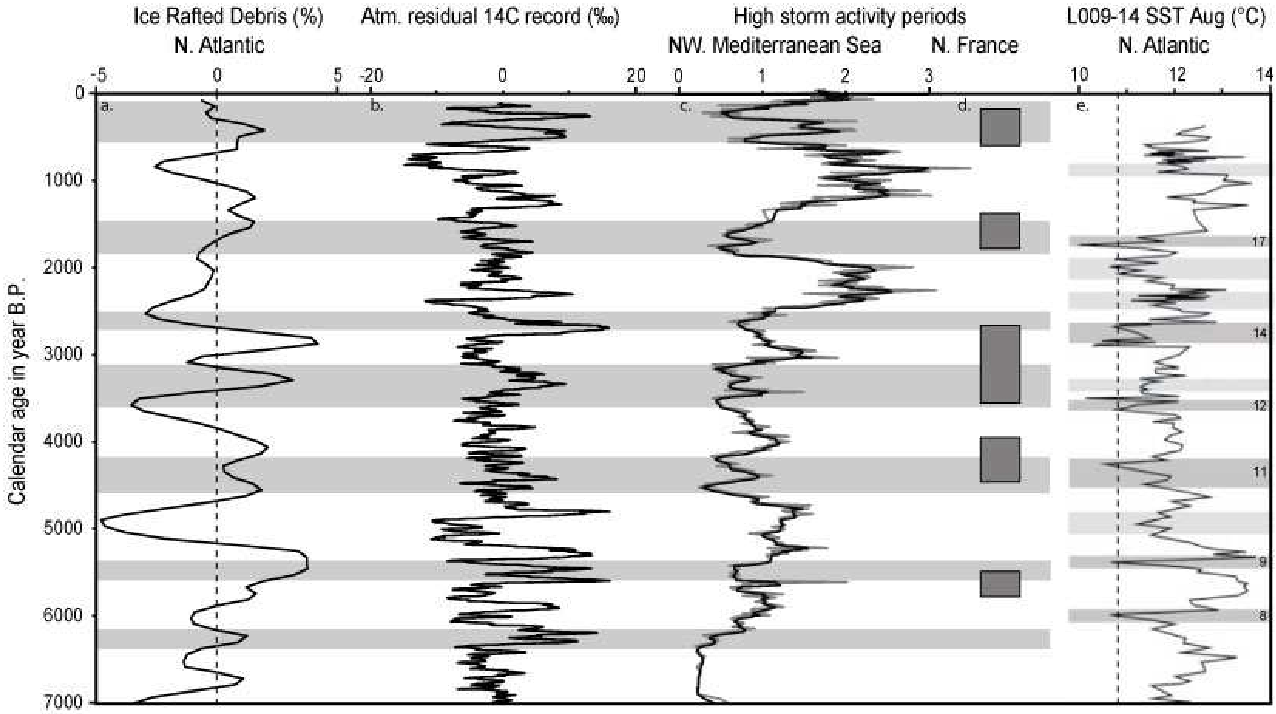
Si/Al
5
7
9
11
13
Ca/Al
0
10
20
30
40
50
0
100
200
300
400
500
600
700
Depth (cm)
1
2
3
4
5
6
7
Zr/Al
0
50
100
150
200
Sr/Al



Grain size Median (µm)
0
10
20
30
40
50
Smectite/(Illite+Chlorite)
0
1
2
3
Cal yr B.P.
0
1000
2000
3000
4000
5000
6000
7000
1
3
5
Zr/Al (XRF)
0
40
80
120
160
Bittium r. (marine specie)



Sea level data from NW Mediterranean
Age (kyr cal B.P.)
0
1
2
3
4
5
6
7
1
0
-1
-2
-3
-4
-5
-6
-7
NGF (m)
Laborel et al., 1994
(La Ciotat)
Morhange et al., 2001
(Marseille)
Vella and Provensal, 2000
(SE Rhône delta)
Lambeck and Bard, 2000
ice-equivalent sea level change



Ice Rafted Debris (%)
N. Atlantic
Atm. residual 14C record (‰)
High storm activity periods
NW. Mediterranean Sea
N. France
L009-14 SST Aug (°C)
N. Atlantic
Calendar age in year B.P.
a.
b.
c.
d.
e.
17
14
12
11
9
8