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**Extreme storms during the last 500 years from lagoonal sedimentary archives in Languedoc (SE France)**

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Extreme storms during the last 500 years from lagoonal sedimentary archives in Languedoc (SE France)

Tempêtes extrêmes au cours des 500 dernières années dans les lagunes du Languedoc (SE France)

Abstract - A study of sediment cores was undertaken to follow the horizontal extent of washover fans in the Palavasian lagoons (Languedoc, France). These geomorphological structures are associated to intense storm events. Dating of these events shows age ranges that correspond to the second part of the Little Ice Age (LIA). The results also indicate little likelihood of a tsunami origin of these washover fans, although there is historical evidence of tsunamis in the western Mediterranean. Comparison of sediment records with palaeoclimate records indicates that this increase of storm events was probably modulated by atmospheric dynamics. We suggest that extreme storm events are associated with a large cooling of Europe.

Key-words: Paleotempestology, extreme storms, Western Mediterranean coast, Little Ice Age

In the context of current climate change, there is an increasing concern that extreme climatic events may be changing in frequency and intensity. Storms and floods have been for long a threat for the western Mediterranean coast even if their link with climate variability is still misunderstood. This is partly due to the fact that extreme events are inherently rare and difficult to observe in the period of a human life and to the lack of long-term observations or paleo-reconstructions. Understanding causes of their occurrence both in past and present climate, i.e. under different forcings, is an crucial issue for future predictions considering the growing number of people living in the coastal Mediterranean in high-risk areas and therefore enhanced exposure. Natural systems are highly sensitive to intense climate episodes but impact assessment strongly depends on the resiliency and capability for adaptation and mitigation of each system. In order to place such events in the broader context of climate change, it is essential to document their occurrence, both in space and time, over period of several centuries or millennium.

In this study, we focus mainly on the Languedoc-Roussillon (Figure 1), a region of the French Mediterranean coast. This area is particularly sensitive in terms of societal issues for the risks of floods and coastal erosion/submersion during storm events. In this area, the primary forcing of sea-level variations is mostly related to atmospheric variability (TSIMPLIS and JOSEY, 2001), including extra-tropical storms (MORON and ULLMANN, 2005; ULLMANN et al., 2007). Travelling mid-latitude low-pressure systems act to raise the sea level directly below them, but this effect alone is quite weak in semi-enclosed basins such as the Mediterranean Sea. The most important meteorological factors are the associated winds (ULLMANN et al., 2007). For example, sea surges >40 cm in the Camargue recorded between 1974 and 2001 are usually associated with storms moving southeastward across the North Atlantic to the south of 55°N, and strengthening as they approach the Bay of Biscay (MORON and ULLMANN, 2005). During such storms, strong onshore winds cause water to pile up against the north coast of the Gulf of Lions (MORON and ULLMANN, 2005). These storm events can have dramatic actions attacking coastal sand dunes, sometimes breaking the sandy barrier (Pierre Blanche lagoon in 1999), and weakening certain human infrastructure (ports, defense barriers, housing). For the last few decades, the most important storms are those of 1982, 1997 and 1999. From the fifteenth-century to present-day, the analysis of historical documents reveals an increase of flood events particularly during the Little Ice Age (BLANCHEMANCHE, 2010). Over longer periods of time, SABATIER et al., (2012) have studied storm-induced deposits preserved in coastal lagoon sediments to explore the links between climate and storm activity. This study was performed on a single long piston core collected from the Pierre Blanche lagoon (Languedoc, France). Past climatic reconstructions on a single core is always hazardous, particularly in these types...
of environments. The horizontal extent of an overwash deposit can be affected by many complicating factors that are related to storm characteristics, such as the storm 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). 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 storm landfalls. In a previous study (DEZILEAU et al., 2011), a multi-core transects approach was used to follow the horizontal extent of washover fans (2.5 km longitudinal transect). In this study, we expand the study area (16 km longitudinal transect) in order to produce a complete record of past storm landfalls in the Languedoc during the last 500 years.

1 - Study site

Palavasian lagoons are a complex system located in the Gulf of Lion in the South of France (Figure 1). This system consists of nine shallow and brackish water lagoons connected by the Rhone-Sete waterway and...
communicating with the Mediterranean Sea. It is recognized that the system was submitted in the past to sediment accumulation (BARUSSEAU et al., 1992) and morphological evolution (RAYNAL et al., 2003). Ingril, Pierre Blanche, Prevost and Grec lagoons are located in the southern part of the complex system (Figure 1). These polyhaline backbarrier lagoons are separated from the Mediterranean Sea by a wave-produced, sandy barrier between 150-300 m wide and 2-3 m above the mean sea level. These lagoons have a flat bottom with a maximum water depth of approximately 1 m. Modern sediments accumulating at the bottom of this lagoon are made of clay/silt but no sand. Tidal variability is modest (with a mean range of 0.30 m), which minimizes the influence of dynamic tidal currents. The study site is located along the southeastern-facing shoreline, and is extremely vulnerable to intense storms coming from south and southeast.

2 - Materials and methods

2.1 - Core material

Four short cores (ING09B, PB08, EG08 and GR10) and one long core (PB06) were extracted from the four lagoons (Ingril, Pierre Blanche, Prevost and Grec) along a longitudinal transect, (Figure 1). The long core was extracted using the Uwitec platform (University of Chambery and Laboratoire des Sciences du Climat et de l'Environnement). All cores were collected at water depths between 0.5 and 1.5 m. The locations for all coring sites were determined using a handheld GPS unit, which provided a horizontal accuracy of 3 to 6 m.

2.2 - Physical measures

Back at the laboratory, cores were sliced open, photographed and logged. Cores were refrigerated at 5 °C to prevent dessication. Grain-size analysis was conducted on contiguous 2-cm samples using a Beckman-Coulter LS13320 laser diffraction particle-size analyser. Grain-size distribution measurements were made on the less than 0.3 mm sediment fraction without decarbonatation.

2.3 - Geochronology

Dating of sedimentary layers was carried out using the 210Pb method on a centennial time-scale. This nuclide with U, Th, and 226Ra were determined by gamma spectrometry at the Géosciences Montpellier Laboratory (Montpellier, France). The 1-cm-thick sediment layers were washed in deionized water and sieved. The fraction smaller than 1 mm was then finely crushed after drying, and transferred into small gas-tight PETP (polyethylene terephthalate) tubes (internal height and diameter of 38 and 14 mm, respectively), and stored for more than 3 weeks to ensure equilibrium between 226Ra and 228Rn. The activities of the nuclides of interest were determined using a Canberra Ge well detector and compared with the known activities of an in-house standard. Activities of 220Pb were determined by integrating the area of the 46.5-keV photo-peak. 228Ra activities were determined from the average of values derived from the 186.2-keV peak of 226Ra and the peaks of its progeny in secular equilibrium with 210Pb (295 and 352 keV) and 214Bi (609 keV). In each sample, the (210Pb unsupported) excess activities were calculated by subtracting the (226Ra supported) activity from the total (210Pb) activity.

3 - Results

3.1 - Core descriptions

Cores collected from the four lagoons contain organic-rich clay and silt interbedded with coarse-grained layers comprised of a mixture of siliciclastic sand and shell fragments. Logs and high-resolution grain-size analysis for ING09B, PB06, EG08 and GR10 indicate several thin, coarse-grained layers preserved within mud sediments. The more prominent sand layers are typically composed of sand and have often sharp contacts with the organic-rich clay and silt sediments below (Figure 2). These sand layers preserved in the cores are overwash layers, i.e., coming from marine incursions during intense storm events (DEZILEAU et al., 2011).

3.2 - Stratigraphic framework and age model

Since GOLDBERG (1963) first established a method based on 210Pb chronology, this procedure has provided a very useful tool for dating recent sediments. Several 210Pb models were later proposed, allowing a precise calculation of sedimentation rates (e.g., APPLEBY and OLDFIELD, 1992). In the simplest model, the initial (210Pb)ex is assumed constant and thus (210Pb)ex at any time is given by the radioactive decay law. In the CFCS ("constant flux, constant sedimentation rate") model (GOLDBERG, 1963; KRISHNASWAMY et al., 1971), the 210Pb flux and sedimentation rate are assumed to be constant. The sedimentation rate in the different lagoons is clearly variable due to the near-instantaneous sedimentation of sandy storm deposits; however, the CFCS model can be applied when typical lagoonal conditions prevail (SABATIER et al., 2008). Using the CFCS model, the 210Pb data indicate a sedimentation rate of: 1.3 ± 0.8 mm/yr in Ingril (ING09), 2.65 ± 0.2 mm/yr in Pierre Blanche (PB06) and 1.9 ± 0.09 mm/yr in Grec lagoon (GR09, Figure 3).

To allow for a more detailed discussion of the markers and their comparison between records, a chronostratigraphic scale was constructed. Time scales for cores ING09B and GR09 are based on the 210Pb. Time scale for core PB06 was previously estimated on 137Cs, 210Pb and AMS 14C dates (SABATIER et al., 2010). Samples shells were radiocarbon-dated at the Laboratoire de Mesure 14C on ARTEMIS in CEA institute at Saclay. These measurements were obtained from monospecific samples Cerastoderma Glaucum at each level. 14C ages were corrected for reservoir age (see SABATIER et al., 2010 for method) and converted to calendar years using the Calib 5.0.2 calibration program (HUGHEN et al., 2004) at two standard deviations. For the
Fig. 2 – Logs and high-resolution grain-size analysis for ING09B, PB08-3, PB06, EG08 and GR10 indicate several thin, coarse-grained layers preserved within mud sediments.

Fig. 3 – $^{210}\text{Pb}_{\text{ex}}$ activity depth profiles in cores ING09B, PB08-3, PB06, EG08 and GR10. $^{210}\text{Pb}_{\text{ex}}$ activity disappears at around 20 cm for ING09, 40 cm for PB06 and 25 cm for GR09. The deepest $^{210}\text{Pb}_{\text{ex}}$ values of core ING09 were not considered to calculate the sedimentation rate, because of their large associated errors.
other cores, PB08-3 and EG08, we have no absolute age constraints. The proposed age scale for these cores was developed by graphic correlation to cores PB06 and GR09.

4 - Discussion

4.1 - Overwash deposits chronology

In communal archives, intense storm events were mentioned because they caused damage in the vicinity of the studied city. For the last 400 years, eighteen intense storms occurred in the Languedoc. Among all of these, some seem to be more intense (DEZILEAU et al., 2011). The storm of December 4th, 1742, recorded in many city archives around the Aigues-Mortes gulf, is considered as the most catastrophic event in the study area. This storm, probably due to S to SE winds, submerged some local cultivated lands which had been gained at the expense of the older parts of the lagoon. The lagoon was covered with a sand layer over “300 toises”, i.e. 500 m. One of the main consequences was the creation of a large inlet, near Maguelone, which remained open until 1761. The storm of November 23, 1848 associated with strong SSE winds induced the wreckage of a few ships in the Sète Harbour, the biggest port in the region. The sea has completely submerged defense barriers in the harbour. This storm caused the death of numerous people. Certified by many engraved illustrations, the storm of September 21, 1893 also resulted in the devastation of the Sète harbour and the wreckage of a few ships. DEZILEAU et al., (2011) determined which historical events left coarse-grained layers and demonstrated that the sand layers 1, 2 and 3 were consistent with the storm events which occurred in 1742 AD, 1848 AD and 1893 AD, respectively (Figure 4). This new study shows that sand layers 1 (1742 AD) and 2 (1848 AD) are consistent between all cores across the four lagoons, i.e., along a 16 km longitudinal transect, confirming that these storms were of very high intensity. The sand layer 3 (1893 AD) is not consistent across the four lagoons, suggesting that this storm was probably less-intense than the other ones (Figure 4). On the basis of our age model, there is a period of intense storms between 1742 AD and 1893 AD. The interval from 1893 AD to today was relatively quiet. The ages of these intense storms range between 1742 AD and 1893 AD, which corresponds to the second part of the Little Ice Age (LIA).

4.2 - Another origin of these sand layers?

The coarse-grained layers observed in all cores could be also a signature of tsunamis. Data of historical tsunamis in Mediterranean was summarised in the catalogue by SOLOVIEV et al., (2000). There is historical evidence on the French coast of low-intensity events that occurred in 1564, 1818 and 1887, generated probably by submarine landslides on the steep slopes of the Var delta near Nice (JULIAN and ANTHONY, 1996, SHAH-HOSSEINI et al., 2013). Tsunami Fig. 4 – Logs, high-resolution grain-size analysis and age model for ING09B, PB08-3, PB06, EG08 and GR10. $^{210}$Pb chronology in italic. Grey bands are the 3 intense storm events (1742, 1848 and 1893).
waves of the order of 3 m were recorded on the coasts of the Ligurian Sea following a submarine landslide that affected this delta in October 1979 (IOUALALEN et al., 2010). For an earthquake magnitude 6.8 in the Ligurian Sea, PELINOFSKY et al., (2002) show a very local character of the tsunami phenomenon from a numerical simulation. The tsunami propagating from the Ligurian Sea to the west Mediterranean coast (Languedoc) has a lesser amplitude and the tsunami wave height is very low (< 20 cm, PELINOFSKY et al., 2002). Moreover, regarding submarine landslide phenomenon, no such event has ever been reported in the Languedoc area where the shelf is wide and the slope far offshore, conditions that are not propitious to the generation of large submarine landslides. Two events generated by earthquakes occurred in the western Mediterranean over the period from 1665 to 1835AD (www.ngdc.noaa.gov). The earlier one, generated by a strong earthquake in the Alboran Sea, between Spain and Morocco, occurred on October 10, 1680 (SOLOVIEV et al., 2000). This event has been classified as one of magnitude 3 in the Tsunami Intensity Scale. Considering the distance of the epicentre and general features of this event, it is very unlikely that it propagated onto the Languedoc area. This is confirmed by numerical simulations that show tsunami wave height negligible inside the French coast (PELINOFSKY et al., 2002, TINTI et al., 2005). The second event, reported to have occurred on March 24th, 1721, was generated by an earthquake probably associated with a landslide near the Balearic Islands (SOLOVIEV et al., 2000). The certainty of this event has not been authenticated and it is assumed of low intensity. Various lines of evidence presented in this study tend to indicate that the coastal landscape of Languedoc has been affected by a succession of exceptional wave impacts during the second part of the LIA. Considering the available data, tsunami events do not seem to be at the origin of the different sand layers in the four lagoons. In contrast, there is clear evidence that these sand layers are compatible with large storm waves.

4.3 - Paleoclimatological interpretations

Geological data (Figure 4) show an increase in intense storms around 250 years ago lasts to about 1893 AD. This apparent intense meteorological activity seems to return to a quiescent interval after (i.e. during the 20th century AD). Interestingly, the period of most frequent superstorms strikes in the Aigues-Mortes Gulf (AD 1700-1900) coincide with one of the coldest period in Europe during the late Holocene (the latter half of the LIA). Other studies have documented increased intensity and frequency of storms during the LIA in the Mediterranean, as for example in the northern Adriatic Sea (CAMUFFO et al., 2000). Based on an ensemble of six simulations of the LIA using an Ocean-Atmosphere General Circulation Model (OAGCM), RAIBLE et al., (2007) consistently find an increase in cyclone occurrence in the Mediterranean during the LIA compared to present-day. They attribute this signal to a larger cooling in the high latitudes than in the low latitudes (due to polar amplification effect, MASSON-DELMOTTE et al., 2006), leading to enhanced lower tropospheric baroclinicity over a large Central Atlantic-European domain. This result suggests that the cooling observed during the LIA over Europe (GUIOT et al., 2005) may be associated with upstream changes in the large scale dynamics of the atmosphere over the Mediterranean and North Atlantic sectors. It is hypothesized here that such a large-scale flow alteration may have modified the occurrence of extreme wind events along the French Mediterranean coast, thus explaining the local signal found here over the region of Languedoc.

Conclusions

This study shows that reconstructing the overwash history of four backbarrier lagoons can provide a sedimentary record of intense storms. Three distinct, storm deposits are identified in these lagoons along a 16 km longitudinal transect. The ages of these intense storms range between 1742 and 1893, which corresponds to the second part of the LIA. Comparison of sediment records with palaeoclimate records indicates that this increase of storm events was probably modulated by atmospheric dynamics. We suggest that extreme storm events are associated with a large cooling of Europe.

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