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Temporal approaches of historical extreme storm events based on sedimentological archives

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Abstract

This paper presents the benefits of multiplying environmental indicators to better understand the impacts of past storm events on the environment. It aims to describe the methodological approaches used to reconstruct past extreme events from washover deposits, at the three main temporal scales used in scientific bibliography: i) the long timescale (Holocene, since 12 000 years BP), ii) the meso timescale (for the last millenary) and iii) the short timescale (Anthropocene, for the last centuries). This methodology is based on a “multiproxy” analysis using sedimentology, geochemistry and various methods of isotope dating. Linking these methods with other disciplines such as history, archaeology and meteorology leads us to confirm with great certainty the existence of these extreme events, and to expose their impacts on the environment and on past coastal societies. These different approaches enable us to enhance and refine our knowledge of coastal hazards, but also to apprehend possible storm influences in the context of climate change.

Keywords

Storm event, climate change, sedimentology, historical archives, washover deposit

Highlights

- Washover detections use various techniques depending on the timescale used.
- Three examples at the long, meso and short timescale are presented.
- Historical data are necessary to attest the stormy origin of a marine deposit.
Marine flooding is nowadays densely studied as its damages are expected to increase in the future (Hinkel et al., 2014). The flooding risk of coastal areas may significantly be enhanced by the meaningful sea level rise expected by the IPCC (Pachauri et al., 2014), crossed with the evolution of meteorological hazards activity (e.g. Paciorek et al., 2002; Page et al., 2010; Ulbrich and Christoph, 1999) and the expected increase of worldwide coastal population (Lutz and Samir, 2010; Neumann et al., 2015). Marine flooding is induced by intense meteorological and oceanological parameters producing a significant morphogenic activity over coastal environments (Figure 1). A “storm surge” is produced when the air pressure falls down and the wind is significant (Doodson, 1924; Doodson and Warburg, 1942; Pugh, 1996), but also when the wave set-up and swash, producing the run-up altogether, are powerful (Cariolet, 2011a, 2011b; Stockdon et al., 2006). A significant storm surge can involve allochthonous deposits, called “washovers”, that come from the marine domain and go to a coastal depositional environment. Three different main mechanisms can produce “washovers” deposits from an “overwash” process (Donnelly et al., 2004):

i) The “overflowing” stays the rarest case because it requires an exceptional water level. The level has to be higher than the protecting barrier or dike (Figure 1). It is probably one of the most dangerous processes because after the retreat of the tide, the water remains blocked by the dike in the coastal low areas (Shimozono and Sato, 2016). ii) The “overtopping” by the action of the waves corresponds to the crossing of waves over dunes or dikes. They propel water over the structure or dune (Figure 1). The water level is not higher than the height of the protecting barrier. The significance of the crossing is mainly determined by the amplitude of the wave swash, but also by the direction and force of the wind influencing water projections (Leroy et al., 2015). iii) The breach of a protecting barrier (dune or dike) is the last marine submersion mechanism (Figure 1). It can be induced by the first two mechanisms presented above, and it is the one that can have the most human damages in coastal areas. It may be punctual, in sections or sometimes characterized by a complete rupture. Even if protective infrastructure serves to protect from the issues of the marine flooding hazards, peoples remains directly exposed during destruction (even partial) of these barriers (Kolen et al., 2002). Breaches also induce a coarser marine deposit than overtopping and overflowing processes, with a grain size distribution from thicker to thinner sediment until the closing of the lagoon. Their standard sedimentological signature is exposed in Figure 2.

To characterize an extreme event by sedimentology and to detect these washovers, three questions arise: i) How to identify a marine layer and differentiate it from traditional lagoon, marsh or lake facies? Thanks to sedimentological analyses, many indicators such as particle size and geochemistry are used to characterize the origin of sediments (Maanan et al., 2015). Marine deposits are then identified and underlined as allochthonous of the marsh (Pouzet et al., 2019). ii) When was the identified marine layer deposited in this coastal depositional
After detecting the marine layers through sedimentological analyses, the sedimentary core is then dated to estimate their dates of deposit periods. This isotopic dating is done either by sediments from surface facies (e.g. Abrantes et al., 2008; Cuellar-Martinez et al., 2017), or by the organic elements present in the core (e.g. Bregy et al., 2018; Feal-Pérez et al., 2014). These methods can be used to estimate the precise age or period when the marine layers settled. iii) *How can we ensure that the marine layer comes from a natural hazard?*

Once the marine layer has been dated, historical data can be used to accurately characterize the hazards that have induced the “overwash” process (Athimon and Maanan, 2018; Garnier et al., 2018; Liu et al., 2001). Direct estimation of return periods can lead to many reserves, especially on macrotidal coasts. Linking this method with a statistical study can, however, offer much stronger conclusions. As with the work of Mann et al. (2009), it can allow an estimation of recurrence intervals on a broader scale. Data on relative sea level and climatic variations are essential to build an accurate estimation of the return periods of extreme events (Goslin et al., 2018).

This paper presents three different methodologies used to detect past storm or phases of high storminess at three different timescales (Pouzet, 2018): the long term (at the Holocene scale), the mesoscale (corresponding to the last millennia), and the short term (the last centuries or decades). At these three timescales, a combination of methods is proposed to answer these three different questions, allowing the link between a marine deposit and a past storm or a phase of high storminess activity. Three distinct methodologies are detailed, including the choice of a relevant coastal depositional environment, of the fieldwork techniques according to the sediment type, the laboratories analyses and the potential discussion that can be set at the three timescales determined. Benefits and limits of each methodology are also exposed. They give a complete display of these three accurate combinations of methods discussed in this paper that scientist may use to detect past extreme storm event from sedimentological archives.

2. State of art of methodological approaches to detect past storm deposits

The first reconstructions of ancient tropical cyclones from the Gulf of Mexico, in a coastal lagoon in Alabama, were published by Liu and Fearn (1993). The sedimentological method was then synthesized in a second study in Florida (Liu and Fearn, 2000). It became widely recognized scientifically from the early 2000s, and was then largely expanded throughout the world. The method is based on the analysis of coastal marine sediment deposition transported by extreme events and deposited in a marsh, lagoon or coastal lake. Liu and Fearn (2000, 1993) also discuss a relationship between the intensity of the past extreme event and its sedimentological signature. They suggest a direct relationship between the deposition structure and the intensity of the hazard. This link is still being discussed nowadays, as the size and extent of these deposits also appear to depend as much on hazard-related
As mentioned in many recent reviews (Clarke and Rendell, 2009; Kaniewski et al., 2016; Oliva et al., 2017; Xiong et al., 2018), this method has grown considerably since the 2000s, and is still widely used worldwide today. The United States, along the North American coasts and the Caribbean Sea (e.g. Donnelly et al., 2001; J. P. Donnelly et al., 2004; Donnelly and Woodruff, 2007; Lambert et al., 2008; Noren et al., 2002; Parris et al., 2009; Scileppi and Donnelly, 2007; Scott et al., 2003) was the first place where this characteristic method significantly developed in the early 21st century. It was then expanded worldwide with some notable examples of works in Oceania (Hayne and Chappell, 2001; May et al., 2016, 2015; Nott et al., 2009; Nott and Hayne, 2001); Asia (Liu et al., 2001; Williams et al., 2015; Woodruff et al., 2009; Yu et al., 2009); Africa (Bozzano et al., 2002; Khalfaoui et al., 2019); in the North Sea (Chang et al., 2006; Jong et al., 2006); or in South America (Oliveira et al., 2014; Ramirez-Herrera et al., 2012). In western Europe, several studies have analyzed “cliff top storm deposits” (e.g. Fichaut and Suanez, 2011; Hall et al., 2006; Hansom et al., 2008; Hansom and Hall, 2009; Suanez et al., 2009; Williams and Hall, 2004), Mediterranean lagoonal sequences (e.g. Abad et al., 2019; Degeai et al., 2015; Kaniewski et al., 2016; Sabatier et al., 2012, 2010) and only few works have been conducted on the French Atlantic coast (Baltzer et al., 2014; Poirier et al., 2017; Sorrel et al., 2009; Van Vliet Lanoe et al., 2014). The British Isles (e.g. Devoy et al., 1996; Kylander et al., 2019; Oldfield et al., 2010; Orme et al., 2015; Wilson et al., 2004), Scandinavia (e.g. Björckl and Clemmensen, 2004; Bondevik et al., 2019; Jong et al., 2006), and Portugal (e.g. Andrade et al., 2004; Dawson et al., 1995; Hindson and Andrade, 1999) have also been deeply studied, mainly from sedimentological deposits.

The first indicators of marine deposition mainly focused on changes in grain sizes. First works compared sandy marine deposits and lagoon continental clays/silts (Liu and Fearn, 1993). The range of indicators available has then grown rapidly over the years and published works (Clarke and Rendell, 2009; Kaniewski et al., 2016; Xiong et al., 2018). Organic matter (OM), geochemistry, radiography, pollen, foraminifera, colorimetry, magnetic susceptibility, clay minerals or several fauna assemblages are commonly used as evidence of a brutal environmental change in the stratigraphy of a coastal marsh.

This method was also extended from the early 2000s to the analysis of tsunami deposits, as mentioned in the works conducted along the Portuguese coasts. The study of tsunami deposits was used there to detect the event of 1755 (e.g. Costa et al., 2012; Cunha et al., 2010; Oliveira et al., 2009). New Zealand’s coasts are also the subject of numerous studies of tsunami deposits from the 2000s onwards (e.g. Chagué-Goff et al., 2002; Goff et al., 2004, 2001). The method then extends across the entire Pacific Ocean coastline (e.g. Goto et al., 2012, 2010, 2007; May et al., 2016; Nanayama et al., 2000; Pinegina and Bourgeois, 2001; Ramirez-
Herrera et al., 2007; Scheffers and Kelletat, 2003). As a result of this extensive work, the geochemistry indicator has been popularized as a reliable indicator in sedimentological research tracing the extreme coastal paleoevents in the world (Chagué-Goff et al., 2017). This indicator is now also widely used in sedimentological studies of past cyclones (e.g. Das et al., 2013; Oliva et al., 2017; Xiong et al., 2018). Distinction between stormy and tsunami deposits is a problem still strongly debated today as these two marine deposits stay similar (Davies and Haslett, 2000; Lario et al., 2010; Xiong et al., 2018). A presentation of the three timescales employed is exposed in the Figure 3.

3. Methodology adapted to different temporal approaches

3.1. Selection of the study sites

The methodology used, detailed into Figure 4, is varied and combines different data collection and analysis techniques. The first step is to select the sampling area. The study areas are chosen according to three criteria: i) they must correspond to lowland coastal areas, as back barrier environment; ii) they mustn’t have been impacted by mankind iii) and these areas have to be located in spaces with tempestuous activities dating back to several centuries, according to local studies.

We first selected several study sites using a century-long diachronic study from Geographic Information Systems (GIS). We were able to retrieve the Cassini’s maps from the end of the XVIIIth century, from the Etat-Major map (XIXth century) and the first aerial photographs taken around 1950. These different data were imported, georeferenced and processed in a GIS according to the method extracted from Pouzet et al. (2015). These data allow us to better understand the recent evolution of the selected sites and to estimate the origin of potential human impacts. The second selection concerns the analysis of topo-bathymetric data. It allows us to analyse the topography and the precise bathymetry, in order to evaluate the current geomorphology of the selected sites. They especially enable us to obtain precisely the altitude of the protective sandy barriers and the protected lowlands cored. We were able to produce a few geomorphological sections to choose the most relevant sites to study extreme events deposits. Finally, we have affined our selection on lands that are regularly impacted by storms (Athimon and Maanan, 2018; Feuillet et al., 2012; Le Roy et al., 2015). After selecting the study areas, sampling stations have to be selected. Coring too close to the protecting barrier can induce a smaller recording of marine deposits. During the deposition process, the sandy barrier usually protects the lowlands located a few meters back according to Liu and Fearn (2000). As the sandy barrier is thicker nowadays than in the past, its protecting action is more important today than before. To detect millenary storms in lowland protected by a barrier which have been thickened, a coring close to the actual barrier may offer the detection of historical storms (Pouzet, 2018).
Two different coastal environments can be studied: i) back barriers lowlands areas and ii) ancient coastal marshes that are sealed today, as peat bog of coastal lakes. Back barriers coastal marshes records past storms that hit the region during the last decades or centuries, depending of their age and the sedimentation rate assessed (e.g. Donnelly et al., 2004; Kenney et al., 2016; May et al., 2015). This first type of coastal environment can be used to study past storms at a short or meso timescale. In sealed ancient coastal marshes, sedimentation rates are lower and can testify of an ancient lowland connected with the sea. They are used to assess Holocene storms or phases of high storm activity and can be used in the long term timescale analyses (e.g. Jong et al., 2006; Liu and Fearn, 1993; Orme et al., 2015; Stewart et al., 2017).

3.2. Sampling methods

Sedimentological cores allow us to study the vertical evolution of the sedimentary facies and to analyse paleoenvironmental dynamics. They can include impacts of land use change (e.g. Cuellar-Martinez et al., 2017; Maanan et al., 2014, 2018, 2015; Ning et al., 2018; Yim et al., 2018), environmental changes such as sea level rise (e.g. Baltzer et al., 2015; Culver et al., 2015; Fruergaard et al., 2015; Lambeck and Bard, 2000) and past storms detection (e.g. Bennington and Farmer, 2014; Parris et al., 2010; Parsons, 1998).

Two coring methods are used depending on the type of environment and the time scale considered: i) The « Beeker » handled corer is used into wet foreshore sediments (e.g. Anderson et al., 1997; Fisher et al., 1992; Giuliani et al., 2015; Glew and Smol, 2016; Kanbar et al., 2017). It can be used for the short term storm analysis of back barrier marshes with high sedimentological dynamics (Figure 4). ii) The « vibracore » corer is used in sealed sediments and can reach more important depths due to the compact sediment (e.g. DeVries-Zimmerman et al., 2014; Francus et al., 2008; McGlue et al., 2015; Thompson and Baedke, 1995; Vance et al., 1992; Yuan et al., 2013). It can be used into back barrier environments which are less dynamics and wetter (natural salt marshes or “schorres”) into the mesoscale methodology. It can also be used in ancient peat bog or sealed marshes for the long term analysis and the detection of Holocene storms or phases of storminess increases (Figure 4).

Cores are then longitudinally opened in the laboratory. The first half is analyzed and the second is archived and stored at 4°C to slow down deposit oxidation. A precise photograph is taken as soon as the cores are opened to preserve the colors of the different facies. A stratigraphic log is then constructed to describe the core (Figure 4). Sediments are characterized by a visual litho-microstratigraphic analysis, to identify major changes in granulometry, color, organic matter and to identify each macrofossil observed.

3.3. Sedimentological analyses for past storm detection
A high-resolution sampling is conducted before sedimentological analyses: a half centimeter sampling is made for the geochemical signature determination and a centimeter sampling for others treatments. Samples from each core will be analyzed by several scientific devices (Figure 4). These analyses permit to characterize the physio-chemical and biological parameters of sediments and to identify their origin (marine, continental or coastal). The dating of the various sedimentary levels of cores is done using $^{210}$Pb and $^{137}$Cs for the last century (e.g. Abrantes et al., 2008; Keen et al., 2004), and radiocarbon ($^{14}$C) for longer time scales (e.g. Liu and Fearn, 2000b; Parris et al., 2010; Sorrel et al., 2009).

X-ray radiography by Scopix is used to provide images of the sedimentary structure of the cores, the bioturbation, density and heterogeneity of the sediments, as well as the general organization of the facies collected. This can also help identify fine sedimentological variations which would be otherwise difficult to pinpoint, or even fine elements located in the center of the core (shells, pebbles, remains of plants, etc.) when analyzing lithostratigraphy (e.g. Coor et al., 2009; Migeon et al., 1998; Scott et al., 2003). Statistical analyses can be used to select relevant indicators to characterize marine deposits made by storms (Pouzet et al., 2019). Marine flooding is identified by a typical sedimentary sequence that alternates between a level of marine sand (the washover fan) and the lagoon layers surrounding composed of vases or silts with continental chemical influence. The marine sand can also be identified by its biology with a significant presence of marine species.

3.3.1. The long scale analysis of Holocene periods of high storm activity

After extracting a core from a sealed coastal marsh with a “vibracore” corer, samples with high carbon concentration or shell or plants remains are dated with the $^{14}$C isotope (Figure 4). The samples are burned at 500°C in a 1 L muffle furnace for four hours, in order to assess the organic matter content by the loss in the ignition process (Santisteban et al., 2004). OM proportion allows us to understand the paleoenvironmental changes of the study site, an important parameter in the long scale analysis. Grain size is measured with a Malvern Mastersizer 2000 © particle size analyzer, after a 5% sodium hexametaphosphate dispersion (Gee and Or, 2002). Sand, silt and clays proportion can be extracted according to the Blott and Pye (2001) classification, and a sand dominated content generally testify of the marine origin of the sediment. Sedimentological high-resolution elemental analyses are evaluated using an Avaatech© X-ray fluorescence (XRF) core scanner. Element intensities are normalized by the total intensity (Bouchard et al., 2011; Martin et al., 2014). Strontium (Sr) and Calcium (Ca) are the two elements which are mostly cited as marine (e.g. Chagué-Goff et al., 2017; Pouzet et al., 2019; Roy et al., 2010). Other possibilities of marine proxy are also mentioned in bibliography, including foraminifera (e.g. Alday et al., 2006; Hippensteel and Martin, 1999), molluscan assemblages, (e.g. Bettinelli et al., 2018), pollens (e.g. Jong et al., 2006), or clay mineral (e.g. Sabatier et al., 2010) analyses.
Marine layers are then extracted after identifying the sediment origins of each facies. To prove that the marine layers have been deposited during a Holocene storm phase, a comparison with other geological works from the scientific bibliography is required (Figure 3). At the Holocene scale, storm phases can be identified from several geological methods, such as other similar back barrier analyses (e.g. Liu and Fearn, 1993; May et al., 2016; Sabatier et al., 2012), “cliff top storm deposits” detection (e.g. Hall et al., 2006; Hansom and Hall, 2009; Williams and Hall, 2004), bay sedimentation (e.g. Baltzer et al., 2014; Poirier et al., 2017; Van Vliet Lanoe et al., 2014), dune evolution (e.g. Clarke and Rendell, 2006; Clemmensen et al., 2009; Jelgersma et al., 1995), beach ridges morphology (e.g. Nott et al., 2009; Scheffers et al., 2012; Thompson and Baedke, 1995), coral distribution (e.g. Gardner et al., 2005; Hongo, 2018; Scoffin, 1993), and speleothems (e.g. Frappier et al., 2007; Zhu et al., 2017), tree-ring (e.g. Cook and Kairiukstis, 2013; Lafon and Speer, 2002; Nicolussi et al., 2005) or diatom (e.g. Nodine and Gaiser, 2015; Stager et al., 2017) production. The crossing of sedimentological deposits with all these methods can be made to assess Holocene storm activity in the same oceanic basin.

The detection of storm phases at a large timescale gives us clues about Holocene storm activity, underlying periods of increasing and decreasing storminess over the last 12 000 years. These phases can be linked to climate change influenced mechanisms, such as atmospheric circulation patterns (e.g. Goslin et al., 2018; Poirier et al., 2017; Stewart et al., 2017), temperature evolution (e.g. Sabatier et al., 2012; Sorrel et al., 2009; Van Vliet Lanoe et al., 2017) or ecstatic sea level variation (e.g. Baltzer et al., 2014; Spencer et al., 1998; Tisdall et al., 2013). As these different drivers can also be reconstructed in long timescales, they can show correlation with Holocene storm phases regionally detected in sedimentology. It may increase our understanding of atmospheric or oceanic storm influences.

3.3.2. The mesoscale analysis of millenary extreme events

A “vibracore” corer can be used to extract a core from less dynamic back barrier environments such as natural salt marshes or “schorres” (Figure 4). Radiocarbon content and upper sediments are then sampled to be dated with $^{14}$C, $^{210}$Pb and $^{137}$Cs. A crossing of the two dating methods gives important dating precision to the entire core. To increase precision of the OM estimation, a LECO © carbon analyzer estimates the CO$_2$ percentage after a 1400°C dioxygen burning and a mineral decarbonizing with sulfuric acid solution (Andrews et al., 2008; Michaelson G. J. et al., 2011). Grain size and elemental analyses are also measured with a Malvern Mastersizer 2000 © particle size analyzer, and a Avaatech© X-ray fluorescence (XRF) core scanner (Bouchard et al., 2011; Gee and Or, 2002; Martin et al., 2014). Marine geochemical ratios, extracted from a statistical study, are used (Pouzet et al., 2019). As a positive correlation between lightness and carbonate content has already been demonstrated (Mix et al., 1995), lightness is estimated by colorimetric analyses with a
Minolta© Cm-2600d spectrometer. The magnetic susceptibility, which has been previously used with success in other paleoenvironmental studies is measured with a MS2E-1© Bartington-type (Bloemendal and deMenocal, 1989; Wassmer et al., 2010).

Once the marine layers are detected, they can be linked to extreme events or precise past storms thanks to historical archives (Figure 3) if the region has a dense historical documentation (Liu et al., 2001). Numerous types of documents, such as ancient maps, narrative sources (chronicles, diaries or memories) and documents preserved in libraries and in regional archives (books of accounts, records of repairs, surveys conducted after a disaster, barometric observations, newspapers for instance) can be used (Athimon and Maanan, 2018; Pouzet et al., 2019). They expose observational and descriptive data on past extreme weather hazards such as the descriptions of the storm and the damage caused, as well as impacts on societies and their reactions and adaptation (Garnier et al., 2018; Sarrazin, 2012; Sauzeau, 2014). Before being used to reconstruct the history of storms and sea flooding over a relatively long period, documents have to be studied, analyzed and criticized (Athimon et al., 2016). A precise date can be assessed from historical archives for storms that hit the region several centuries ago and that have been detected in sedimentology.

Building a precise millennial storm chronology is a relevant tool to understand storm dynamics. Numerous synoptic oceano-climatological patterns such as the North Atlantic Oscillation (NAO) and the El Nino Southern Oscillation (ENSO) are mainly modelled into the last centuries, or in the late Holocene (e.g. Baker et al., 2015; D’Arrigo and Jacoby, 1991; Trouet et al., 2012). To understand the influence of these patterns in storm dynamics, a precise late Holocene storm chronology is required (e.g. Orme et al., 2016; Poirier et al., 2017; Sorrel et al., 2009). In the Atlantic basin, this mesoscale sedimentological and historical coupling may also show storm activity variations between the three climatological main phases: the Medieval Warm Period (WMP), the Little Ice Age (LIA) and the Anthropogenic actual warming (e.g. Degeai et al., 2015; Orme et al., 2016; Van Vliet Lanoe et al., 2014). Understanding these evolutions is necessary to assess future stormy variations in this context of climate change.

3.3.3 The short scale analysis of recent storms

The wet foreshore of a back barrier environment is cored with a “Beeker” type corer, and the top of the core is sampled to be dated with $^{210}$Pb and $^{137}$Cs (Figure 4). As any paleoenvironmental evolution of the study site is assessed at this short timescale study, OM content is not analyzed. Grain size, elemental analyses, lightness and magnetic susceptibility are also measured with a Malvern Mastersizer 2000 © particle size analyzer, a Avaatech© X-ray fluorescence (XRF) core scanner, a Minolta© Cm-2600d spectrometer and an MS2E-1© Bartington-type (Bouchard et al., 2011; Gee and Or, 2002; Mix et al., 1995; Wassmer et al.,
New statistical grain size proxies, as deciles or quartiles, can be tested. Microtextural characteristics of quartz grains can also be used as a proxy (e.g. P. Costa et al., 2012).

To be sure that the observed marine layers are related to a recent storm, numerous historical data can be used (Figure 3). Local diaries offer interesting information about damages made by past extreme events (Athimon and Maanan, 2018). National weather service’s websites can also present dense information about historical marine floodings (Pouzet et al., 2019). In addition, sedimentological archives can also be linked to accurate meteorological data, such as wind speed and direction, air pressure or precipitations (Pouzet et al., 2018b). Meteorological reanalysis offers a dense dataset of meteorological parameters for the XIX\textsuperscript{th} and the XX\textsuperscript{th} centuries (Weisse et al., 2009). As marine inputs testify about past marine flooding in lowland areas, tide parameters can also be estimated in area undergoing a significant tide gauge. It may assure that the past storm induced a temporally sea level rise, and can precisely give the hour when the storm surge occurred during high tides (Kolen et al., 2002). Finally, recent studies showing models of wave parameters during storm surges can also offer additional information about the flooding which brought marine inputs in the coastal marsh (Bertin et al., 2012).

Other biological correlations can be assessed to complement knowledge in recent storms. For instance, Pouzet et al. (2018b) showed that a dendrochronological approach can complement the sedimentological method to understand recent storm dynamics. Independently, sedimentological and dendrochronological data exhibit the dating of some particularly destructive storms in a specified area and their impacts on a back barrier coastal marsh and on trees. The sedimentological study shows some of the strongest marine flooding reported, and the tree-ring analysis offers an overview of the occurrence of the windiest storms at a forest scale. This coupled approach requires the presence of a dune stand near the back barrier environment cored.

4. Three examples of storm detection from sedimentology at the three timescales

4.1. Long timescale series: The stormy period detection at the Yeu island

Stormy phases can be detected in several sites of a same area. The study of Pouzet et al. (2018a) has been conducted in Yeu island, a French island regularly impacted by storms (Athimon and Maanan, 2018). Three old sealed coastal marshes, which are separated from the sea by high dunes, have been cored (Figure 5). The lithostratigraphy of the first core extracted in the Marais de la Guerche is mainly composed of peat. Its main peaty layer is interrupted by a large 40 centimeter wide sandy sheet. A strong event has deeply impacted this lowland, with a marine sandy layer observed from centimeter 10 to 51. The marine occurrence is confirmed by the presence of Bittium Reticulatum marine shells, dated at 1800 cal y BP at centimeter 37,
and the high Ca and Sr values. The sharp contact between the lower peat and the marine layer testifies of the suddenness of the event. It was produced by two consecutive increases in sand, enhancing the mean grain size from 20 to 320 µm and decreasing the OM from 75 to 20% due to the high increase of marine sands (from 15 to 80%) and the disappearance of OM-reach peats. The onset of these two successive increases is estimated at 2070 and 1940 cal y BP. The Marais de La Croix is the second coastal lowland cored. At the bottom of the core, the environment is more energetic, with coarse sediments with low OM levels (10 to 20%), and slight geochemical variations until cm. 55. An important event disturbs the environment near 2100 – 1950 cal y BP (50-55 cm). After this stormy period, there is a change in the environment with a lower energetic depositional marsh with marked increases in OM (30 to 50%), notable mean grain size (20 to 10µm), and Sr (0.7 to 0.5) decreases, until the top of the core. The Coulee Verte is the last environment studied. Several storm incursions are reported in the entire core, including a disturbance starting near centimeter 100, increasing the OM rate from 40 to 60% from centimeter 100 to 90. This disturbance ends at centimeter 80, where a significant grain size increase is estimated from 10 to 30µm, and sandy (from 5 to 45 %) Ca (8 to 10) and Sr (from 1.1 to 1.4) peaks are detected.

In Yeu Island, this significant storm phase which deeply disturbed the three cored marshes is estimated around Anno Domini (Figure 5). It has been assessed around 2100-1950 cal y BP thanks to the $^{14}$C dating results of the three different cores. This storm series may have opened a large breach in the Marais de la Guerche, which functioned as a permanent inlet for 1200 years (Pouzet et al., 2018a). From the crossing with other geological storm-related studies, we can assess that the entire European coast underwent similar impacts near Anno Domini. Degeai et al., 2015 observed a high Mediterranean stormy period in southern France between 2044 and 1993 cal y BP. A storm event was also reported in Brittany at 2060 cal y BP by Van Vliet Lanoe et al. (2014). Peaks of storminess have been reported from 2090 to 1970 cal y BP in western Wales (Orme et al., 2015). Lastly, the start of a transgressive dune building period at 2200 cal y BP is due to strong wind activity with sand invasion in central western Portugal (Clarke and Rendell, 2006). These bibliographic correlations prove the stormy origin of the perturbation observed in the three Yeu island cores.

Overall, nine periods of storminess increases, called Yeu Stormy Periods (YSP), were extracted from the three investigated cores analyzed in Pouzet et al., (2018a). YSP have then been correlated with European paleo-environment studies from the scientific literature, in order to extract five European Atlantic Stormy Events (EASE). EASE are global phases of storm increase period at the scale of the European Atlantic coast, estimated around 600-300, 1700-1100, 2900-2500, 3500-3300, 5500-5100 and 7700-7100 cal y BP. From the correlation with Holocene cold event estimated by Bond et al. (2001, 1997) from an ice rafted debris study (and then extended worldwide by Wanner et al. (2011)), EASE are linked to the Holocene cold climatic phases (Pouzet et al., 2018a). This hypothesis follows previous correlations already established between European storm activity and cold Holocene phases,
which were particularly conducted by Degeai et al. (2015), Sabatier et al. (2010), and Vallve and Martin-Vide (1998). Detection of Holocene storm phases from sedimentology can be a useful tool to apprehend possible climatological influences of historical storm activity.

4.2. Meso-timescale series: an historical extreme event detected in Brittany clarified by ancient archives

The Petite mer de Gâvres (PMG) is a French back barrier lagoon protected from the sea by a high sandy dune in Brittany (Figure 6). The PMG paleoenvironment can be divided into two different stages (Pouzet, 2018). The first one is at the base of the core (between cm. 115 and 280: pre- 768 ±230 AD; section A). It testifies about a calmer environment than the upper centimeters of the core. A silty environment between cm. 180 and 280 is interrupted by several sandy EE. It characterizes the end of the protecting dune construction, with significant grain size and geochemical variations. The dune construction transits until a mudflat environment isolated from the sea once the littoral spit formed, between cm. 115 and 180. This environment is composed of dense clays, rich of continental elements. The second main stage characterizing the construction of this environment corresponds to the upper part of the core (cm. 0-115: post-768 ±230 AD period; section B). This section is more dynamic than section A, with a dominance of marine sediments. Salicornia vegetation testifies about a salt marsh environment undergoing tidal ranges. A succession of important extreme events deposits contributed to the formation of an important marine sandy deposit behind the protecting dune, including a 1445 ± 40 AD impacting event recorded at centimeter 79. It has been dated with the crossing of $^{14}$C and $^{210}$Pb/$^{137}$Cs methods. This extreme event induced a significant mean grain size increase from 59 to 512 µm, a fall of CO$_2$ from 7 to 1% due to the sandy input, and an increase of lightness from 44 to 68% depending on the brighter color of sands compared to clays and silts. As a 3cm wide diameter pebble has been detected in this layer, geochemical analyses and radiography have been interrupted. The pebble is the testament of about a highly impacting extreme event, producing significant oceanic dynamics, which have deeply perturbed this coastal environment.

According to Athimon (2019) data, this significant impact can be linked to the storm that hit the French Atlantic coast during the 27$^{th}$ – 28$^{th}$ January 1469 (n.st) AD, during a high Spring tide assessed on January 28$^{th}$. This storm induced significant damages into dikes and salt marshes of the Bouin town, a former island submerged during the night. After this event, historical records testify about the probable loss of 1 500 tons of salt, inducing major economic losses (Athimon and Maanan, 2018). Important breaches appeared, numerous ridges or roads were destroyed and several fertile lands became sterile (Athimon et al., 2016). The bell tower of Saint-Aubin fell down and numerous trees were uprooted near Angers (Athimon, 2019). Into the Retz region, the seigneurial taxes had to be reduced due to the important impact of the marine flooding (Athimon, 2019; Sarrazin, 2012, 2005). The
information extracted from historical archives offers important details about economical and societal impacts of storm, to complement environmental impacts detected in the sedimentological sequence.

4.3. Short timescale series: a recent storm inducing marine flooding and tree ring disproportions in the Traicts du Croisic

The Traicts du Croisic (TDC) is a French back barrier depositional environment located in Loire-Atlantique, western France (Figure 7). From the analysis of several core extracted from this environment, Pouzet et al. (2019) have identified twelve recent storms producing marine flooding. One of them has been detected in the center of the lagoon at cm. 9 of the core. Mean grain size increased from 80 to 175 µm, with a very slight increase of the tenth decile. Strontium/Iron (Sr/Fe) and Calcium/Titanium (Ca/Ti) respectively increased from 0.08 to 0.15 and from 9 to 22. After the event, lightness started to increase from 40 to 50% and the magnetic susceptibility slightly decreased from 1 to 0. A significant impact is also visible in the radiography. With $^{210}$Pb and $^{237}$Cs dating, this marine layer has been deposited around 1977 AD, with a few years of error margin.

According to the recent historical documents, the two events of 2$^{nd}$ December 1976 AD and 11$^{th}$ January 1978 AD could have caused this marine deposit. However, the 1976 AD storm crossed a very low Neap tide, while a Spring tide occurred during the 1978 AD event. The second date of 11$^{th}$ January 1978 AD is therefore used for this hypothesis. With a dozen reported deaths, this storm crossed a large part of France involving important damages reported from Dunkirk to the Gironde estuary. Numerous shipwrecks and marine flooding are mentioned in French sources (Le Marin 1595, Metmar 101), and English documents for British damages such as Steers et al. (1979). This Britannic source explains that “many houses were swept away by the waves” during the marine flooding that impacted England. Significant windy damages are mentioned in these various sources, including uprooted trees or devastated houses in several parts of the two countries. 130km/h winds are reported in England, and no maximum wind is documented in France (Pouzet, 2018). Precise information can be extracted from these recent data. They attest to the stormy origin of the deposit and to offers further information about the meteorological and oceanological parameters recorded during the storm.

With an Index of Storm Disturbance estimated at 15 % during the 1977 – 1978 AD winter, Pouzet et al. (2018b) showed that this storm has also impacted the dune stand located a few kilometers north of the TDC. Based on tree ring growth disproportions, significant winds have induced the perturbation of 15% of the sampled living trees, attesting the power of the meteorological parameters during this storm. As both the dendrochronological and sedimentological methods underlined storm impacts during the 1977 – 1978 AD winter, it
confirms that this storm has induced significant winds coming from the south west and an
important marine flooding near the TDC area. These hypotheses have also been confirmed by
historical archives. The relation between sedimentological and dendrochronological archives
has yet to be developed with further precision nowadays.

5. Discussion and conclusions

The three methodologies expose three different accurate combinations to detect past storm
impacts from sedimentological archives. However, several choices can be discussed to
improve the reliability of these results. At the Holocene timescale, the $^{14}$C dating of sealed
coastal marshes or peat bogs reaches higher uncertainties than the $^{210}$Pb / $^{137}$Cs method used at
the two other timescales. It remains, however, the most used and accurate dating method
found in bibliography for Holocene sedimentological stratigraphy (e.g. Engel et al., 2012;
May et al., 2016; Page et al., 2010). This higher uncertainty does not allow the detection of a
precise past storm impact estimated to a day or a month. The detection of “storminess
increasing phases” rather than “precise storm impacts” is preferred. For ancient
reconstruction like the Holocene chronology, the only way to be certain of a past storm phase
is the comparison with other storminess found in various environmental studies (Pouzet et al.,
2018a). Unlike the methodology presented for the two other timescales, historical archives
cannot prove old events at a Holocene timescale. Caution must therefore always be applied
when interpreting the paleostorm or paleotsunami marine deposits at this timescale.
Furthermore, if several studies (mainly under a macrotidal regime) suggest a change in the
frequency or intensity of storm events throughout time (e.g. Donnelly and Woodruff, 2007;
Parris et al., 2010), the sedimentological study conducted must take the tide regime into
account. For a macrotidal coast, it remains challenging to discuss storm frequency or intensity
variations since a storm has to be crossed with a Spring tide to impact the coastal area. The
marine deposits detected only prove that storms have more or less impacted the environment
studied at a precise time.

Even if the meso-timescale study reaches high dating precisions, the combination of $^{14}$C with
$^{210}$Pb / $^{137}$Cs dating techniques can be discussed. If the two methods are accurate and give
precise results, the stratigraphical layers that are concerned in the core by the crossing
between the upper $^{210}$Pb / $^{137}$Cs and the lower $^{14}$C dating undergo high dating uncertainties.
Sediment compaction over the time has been proved to interfere with isotope dating. The
accumulation rate found can be different depending on the different dating methods used on a
same core, increasing uncertainties (Brain et al., 2015; Davidson et al., 2004; Edwards, 2006).
To avoid confusion in the determination of precise past storm dates, the crossing of the two
dating techniques has to be conducted on a layer that is not concerned by marine inputs. The
meso-timescale methodology also sets out the primary interest of historical archives. In
addition to confirming ancient sedimentological hypotheses with a low uncertainty, it offers
valuable understanding keys for finely characterizing the damage caused by the past events
detected. The socio-economic impacts of several centuries old storms are fully described and the comparison of several past events can assess the society resiliency evolution across the history (Athimon and Maanan, 2018).

A high resolution of past storm impacts is conducted at the Anthropocene timescale. Meteorological data and recent newspaper articles gives the precise meteorological and oceanological parameters producing these recent storms. Even if geochemical ratios have become a common use into storm and tsunami sedimentological chronologies (Chagué-Goff et al., 2017), these proxies have to be used after a precise analysis of the sediment composition. The geochemical signature depends on the environment studied, and the ratios built can differ depending on the oceanic basin and the continental inputs. A statistical study with a Principal Component Analysis (PCA) and a dendrogram showing the main origin of each element can be conducted (Pouzet et al., 2019). The dendrochronological crossing with sedimentological impacts of storm can still be improved nowadays. These two methods cannot be strictly crossed because their impacts come from distinct parameters (wind activity for the dendrochronology and ocean/oceanological parameters for the sedimentology). Both approaches are however efficient in their own way and their combination helps our understanding of storm impact distribution in a specific area (Pouzet et al., 2018b).

In conclusion, this paper exposes methodologies used at three different timescales to document sedimentological evidence of recent or ancient past storms, and Holocene storm phases. Various coring methods, dating techniques and sedimentological analyses are employed, depending on the main objectives of the paleostorm study conducted. They have been summarized in Figure 8, which illustrates the main points of all the methods exposed in this paper. We underline the necessity of proving the stormy origin of each marine deposit detected and dated in the different cores. To attest to their oceano-atmosphercial origin, historical data study is essential. It proves that marine layers must come from natural coastal hazards. History can be used to date past event accurately, sometimes with a defined day or time. Depending on the timescale used, it can be scientific bibliography, written sources or modern meteorological data such as reanalysis. It provides important information on the impacts identified, characterizing the general magnitude of past events, offering precise complements on societal and economic damages recorded, and the society reaction evolution across the history. Based on these historical data, the three methodologies presented expose accurate combinations of multidisciplinary methods discussed in this paper, used to detect past extreme storm events extracted from sedimentological archives.

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Figure 1. Coastal flooding parameters and the three overwash mechanisms

Figure 2. Presentation of the two marine deposit scenarios in a coastal marsh during an extreme event

Figure 3. Presentation of the three different timescales

Figure 4. Construction of the three methodologies presented at the three different timescales

Figure 5. Presentation of a study conducted with the long timescale method in Yeu island, from Pouzet et al. (2018a), modified

Figure 6. Presentation of a study conducted with the meso timescale method in the Petite mer de Gâvres, from Pouzet (2018), modified

Figure 7. Presentation of a study conducted with the sort timescale method in the Traicts du Croisic, from Pouzet et al. (2019), modified

Figure 8. Synthesis of the method used at the three different timescales for the detection of past storm with sedimentological analyses
A. Overflowing or overtopping scenarios

- Inland
- Marine deposits
- Coastline (dunes, beaches)
- Overwash
- Extreme events
- Marine deposits: sands, clayey sands
- Continental deposits: silts, clays

- Singluar transport of marine sediments by high winds and waves due to intense marine and atmospheric conditions
- Classic continental sedimentary filling
- Core extracted (once the marsh stabilized)

B. Breach scenario

- Inland
- Lake / Lagoon / Marsh
- Marine deposit
- Coastline (dunes, beaches)
- Extreme event
- Marine deposit: coarse sand

- Singluar transport of marine sediments after a breach due to intense marine and atmospheric conditions
- Classic continental sedimentary filling
- Core extracted (once the marsh closed)
Ai. Selection of the study site
GIS: Analysis of ancient maps and photographies
Reliability for washover detection:
- Back barrier environment
- Non anthropised
- Hit by storms

Aii. Analysis of the study site
- Geomorphology of the coast with elevation data
- Sedimentological map of the site
- Study of sea level rise, tidal and wave regimes
- Study of local storm dynamics and tsunami history

Long timescale
Ancient back-barrier environment, sealed coastal/salt marshes, ancient lakes, peat bogs,...

Meso timescale
B. Fieldwork
Back barrier lowland areas
«Schorre» environment of the back barrier lowland area

Short timescale
Wet foreshore environment of the back barrier lowland area
Wet sediments
Beekers corer
One section of 1 - 1.5m depth

C. Sedimentological analyses
q.i: How to identify a marine layer and differentiate it from traditional lagoon, marsh or lake facies?

Basic methods:
- Log and photography,
- Grain-size,
- Geochemistry,
- Radiography

Other possibilities:
- Pollens - Foraminifera - Molluscan assemblages - Clay minerals,...

+ Other precise possibilities:
  e.g. spectrophotometry and Magnetic Susceptibility (MS)

+ Information added for the paleoenvironmental reconstruction:
  Organic Matter (OM) curve steps
  Loss on ignition or Dioxygen Burning (more accurate)

D. Isotopic dating
q.ii: When was the identified marine layer deposited in this coastal depositional environment?

^{14}C: entire core (shell, peat, OM,...)

^{210}Pb / ^{137}Cs: upper clayey centimeters

E. Historical crossing
q.iii: How can we ensure that the marine layer comes from a natural hazard?

Scientific bibliographic sources of other environmental studies
Ancient Historical archives
Newspaper records
Meteorological, oceanological, and reanalysis data