Temporal approaches of historical extreme storm events based on sedimentological archives

Pierre Pouzet, Mohamed Maanan

► To cite this version:

Pierre Pouzet, Mohamed Maanan. Temporal approaches of historical extreme storm events based on sedimentological archives. *Journal of African Earth Sciences*, 2020, 162, pp.103710. 10.1016/j.jafrearsci.2019.103710 . hal-02422247

HAL Id: hal-02422247

<https://hal.science/hal-02422247>

Submitted on 9 Jul 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Temporal approaches of historical extreme storm events based on sedimentological archives

Pierre Pouzet^{1,2*} and Mohamed Maanan²

¹ Université de Nantes, OSUNA – UMS 3281, Nantes, France.

² Université de Nantes, LETG – UMR CNRS 6554, Nantes, France.

* Corresponding author. E-mail: pierre.pouzet@univ-nantes.fr

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.

1. Introduction: from the coastal flooding to the washover 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*

environment? 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

meteorological parameters as on the geomorphological characteristics of the cored environment (Morton, 2002; Otvos, 2002; Sallenger, 2000).

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; Ramírez-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.,

2010). 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 XIXth and the XXth 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-rich 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 10 μm), 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 30 μm , 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 $\pm$ 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 $\pm$ 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 $\pm$ 40 AD impacting event recorded at centimeter 79. It has been dated with the crossing of ^{14}C and $^{210}\text{Pb}/^{137}\text{Cs}$ 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 27th – 28th January 1469 (n.st) AD, during a high Spring tide assessed on January 28th. 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 2th December 1976 AD and 11th 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 11th 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 oceano/meteorological 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-atmospherical 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.

6. Acknowledgements

The authors gratefully acknowledge Cassandra Carnet for English corrections. Analyses, operating costs and field measurements were funded by the DREAL-Pays de Loire and the

OSUNA through the research program OR2C-AXE3 (History of coastal risk). We also thank editor-in-chief Dr. Mohamed Abdelsalam and two anonymous reviewers for their useful comments, which helped us to greatly improve this article.

7. References

- Abad, M., Muñoz, A.F., González-Regalado, M.L., Ruiz, F., Rodríguez-Vidal, J., Cáceres, L.M., Carretero, M.I., Monge, G., Pozo, M., Prudencio, M.I., Dias, M.I., Marques, R., Izquierdo, T., Tosquella, J., Romero, V., 2019. Evolución paleoambiental de una turbera finiholocena en el sector suroccidental del Parque Nacional de Doñana (S.O. España). *Estudios Geológicos* 75, 087. <https://doi.org/10.3989/egeol.43417.514>
- Abrantes, F., Alt-Epping, U., Lebreiro, S., Voelker, A., Schneider, R., 2008. Sedimentological record of tsunamis on shallow-shelf areas: The case of the 1969 AD and 1755 AD tsunamis on the Portuguese Shelf off Lisbon. *Marine Geology* 249, 283–293. <https://doi.org/10.1016/j.margeo.2007.12.004>
- Alday, M., Cearreta, A., Cachão, M., Freitas, M.C., Andrade, C., Gama, C., 2006. Micropalaeontological record of Holocene estuarine and marine stages in the Corgo do Porto rivulet (Mira River, SW Portugal). *Estuarine, Coastal and Shelf Science* 66, 532–543. <https://doi.org/10.1016/j.ecss.2005.10.010>
- Anderson, W.T., Mullins, H.T., Ito, E., 1997. Stable isotope record from Seneca Lake, New York: Evidence for a cold paleoclimate following the Younger Dryas. *Geology* 25, 135–138. [https://doi.org/10.1130/0091-7613\(1997\)025<0135:SIRFSL>2.3.CO;2](https://doi.org/10.1130/0091-7613(1997)025<0135:SIRFSL>2.3.CO;2)
- Andrade, C., Freitas, M.C., Moreno, J., Craveiro, S.C., 2004. Stratigraphical evidence of Late Holocene barrier breaching and extreme storms in lagoonal sediments of Ria Formosa, Algarve, Portugal. *Marine Geology, Storms and their significance in coastal morpho-sedimentary dynamics* 210, 339–362. <https://doi.org/10.1016/j.margeo.2004.05.016>
- Andrews, J.E., Samways, G., Shimmield, G.B., 2008. Historical storage budgets of organic carbon, nutrient and contaminant elements in saltmarsh sediments: Biogeochemical context for managed realignment, Humber Estuary, UK. *Science of The Total Environment* 405, 1–13. <https://doi.org/10.1016/j.scitotenv.2008.07.044>
- Athimon, E., 2019. “Vimers de mer” et sociétés dans les provinces de la facade atlantique du royaume de France (XIVe-XVIIIe siècle) (phdthesis). Université de Nantes.
- Athimon, E., Maanan, M., 2018. Vulnerability, resilience and adaptation of societies during major extreme storms during the Little Ice Age. *Climate of the Past Discussions* 2018, 1–28. <https://doi.org/10.5194/cp-2018-62>
- Athimon, E., Maanan, M., Sauzeau, T., Sarrazin, J.-L., 2016. Vulnérabilité et adaptation des sociétés littorales aux aléas météo-marins entre Guérande et l’île de Ré, France (XIVe - XVIIIe siècle). *Vertigo - la revue électronique en sciences de l’environnement* 16. <https://doi.org/10.4000/vertigo.17927>
- Baker, A., Hellstrom, J.C., Kelly, B.F.J., Mariethoz, G., Trouet, V., 2015. A composite annual-resolution stalagmite record of North Atlantic climate over the last three millennia. *Scientific Reports* 5. <https://doi.org/10.1038/srep10307>
- Baltzer, A., Cassen, S., Walter-Simonnet, A.-V., Clouet, H., Lorin, A., Tessier, B., 2015. Variations du niveau marin Holocène en Baie de Quiberon (Bretagne sud) : marqueurs archéologiques et sédimentologiques. *Quaternaire. Revue de l’Association française pour l’étude du Quaternaire* 26, 105–115. <https://doi.org/10.4000/quaternaire.7201>
- Baltzer, A., Walter-Simonnet, A.-V., Mokeddem, Z., Tessier, B., Goubert, E., Cassen, S., Diffio, A., 2014. Climatically-driven impacts on sedimentation processes in the Bay of Quiberon (south Brittany, France) over the last 10,000 years. *The Holocene* 24, 679–688. <https://doi.org/10.1177/0959683614526933>

- Bennington, J.B., Farmer, E.C., 2014. Recognizing Past Storm Events in Sediment Cores Based on Comparison to Recent Overwash Sediments Deposited by Superstorm Sandy, in: *Learning from the Impacts of Superstorm Sandy*. Academic Press, Cambridge, pp. 89–106.
- Bertin, X., Bruneau, N., Breilh, J.-F., Fortunato, A.B., Karpytchev, M., 2012. Importance of wave age and resonance in storm surges: The case Xynthia, Bay of Biscay. *Ocean Modelling* 42, 16–30. <https://doi.org/10.1016/j.ocemod.2011.11.001>
- Bettinelli, M., Dillenburg, S.R., Lopes, R.P., Caron, F., 2018. Pleistocene molluscan assemblage in the southern Coastal Plain of Rio Grande do Sul, Brazil: Implications in the evolution of a Barrier-Lagoon System. *Journal of South American Earth Sciences* 86, 200–215. <https://doi.org/10.1016/j.jsames.2018.06.014>
- Björck, S., Clemmensen, L.B., 2004. Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record of Holocene winter storminess variation in southern Scandinavia? *The Holocene* 14, 677–688. <https://doi.org/10.1191/0959683604hl746rp>
- Bloemendal, J., deMenocal, P., 1989. Evidence for a change in the periodicity of tropical climate cycles at 2.4 Myr from whole-core magnetic susceptibility measurements. *Nature* 342, 897–900. <https://doi.org/10.1038/342897a0>
- Blott, S.J., Pye, K., 2001. Gradistat : a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms* 26, 1237–1248. <https://doi.org/10.1002/esp.261>
- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent Solar Influence on North Atlantic Climate During the Holocene. *Science* 294, 2130–2136. <https://doi.org/10.1126/science.1065680>
- Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A Pervasive Millennial-Scale Cycle in North Atlantic Holocene and Glacial Climates. *Science* 278, 1257–1266. <https://doi.org/10.1126/science.278.5341.1257>
- Bondevik, S., Lødøen, T.K., Tøssebro, C., Årskog, H., Hjelle, K.L., Mehl, I.K., 2019. Between winter storm surges – Human occupation on a growing Mid-Holocene transgression maximum (Tapes) beach ridge at Longva, Western Norway. *Quaternary Science Reviews* 215, 116–131. <https://doi.org/10.1016/j.quascirev.2019.05.006>
- Bouchard, F., Francus, P., Pienitz, R., Laurion, I., 2011. Sedimentology and geochemistry of thermokarst ponds in discontinuous permafrost, subarctic Quebec, Canada. *Journal of Geophysical Research: Biogeosciences* 116, 14. <https://doi.org/10.1029/2011JG001675>
- Bozzano, G., Kuhlmann, H., Alonso, B., 2002. Storminess control over African dust input to the Moroccan Atlantic margin (NW Africa) at the time of maxima boreal summer insolation: a record of the last 220 kyr. *Palaeogeography, Palaeoclimatology, Palaeoecology* 183, 155–168. [https://doi.org/10.1016/S0031-0182\(01\)00466-7](https://doi.org/10.1016/S0031-0182(01)00466-7)
- Brain, M.J., Kemp, A.C., Horton, B.P., Culver, S.J., Parnell, A.C., Cahill, N., 2015. Quantifying the Contribution of Sediment Compaction to late Holocene Salt-Marsh Sea-Level Reconstructions, North Carolina, USA. *Quaternary Research* 83, 41–51. <https://doi.org/10.1016/j.yqres.2014.08.003>
- Bregy, J.C., Wallace, D.J., Minzoni, R.T., Cruz, V.J., 2018. 2500-year paleotempestological record of intense storms for the northern Gulf of Mexico, United States. *Marine Geology, Geological Records of Extreme Wave Events* 396, 26–42. <https://doi.org/10.1016/j.margeo.2017.09.009>
- Cariolet, J.-M., 2011a. Inondation des côtes basses et risques associés en Bretagne : vers une redéfinition des processus hydrodynamiques liés aux conditions météo-océaniques et des paramètres morpho-sédimentaires (phdthesis). Université de Bretagne occidentale - Brest.
- Cariolet, J.-M., 2011b. Quantification du runup sur une plage macrotidale à partir des conditions morphologiques et hydrodynamiques. *Géomorphologie : relief, processus, environnement* 17, 95–109. <https://doi.org/10.4000/geomorphologie.9315>
- Chagué-Goff, C., Dawson, S., Goff, J.R., Zachariasen, J., Berryman, K.R., Garnett, D.L., Waldron, H.M., Mildenhall, D.C., 2002. A tsunami (ca. 6300 years BP) and other Holocene environmental changes, northern Hawke's Bay, New Zealand. *Sedimentary Geology, Coastal Environment*

- Change During Sea-Level Highstands 150, 89–102. [https://doi.org/10.1016/S0037-0738\(01\)00269-X](https://doi.org/10.1016/S0037-0738(01)00269-X)
- Chagué-Goff, C., Szczuciński, W., Shinozaki, T., 2017. Applications of geochemistry in tsunami research: A review. *Earth-Science Reviews* 165, 203–244. <https://doi.org/10.1016/j.earscirev.2016.12.003>
- Chang, T.S., Flemming, B.W., Tilch, E., Bartholomä, A., Wöstmann, R., 2006. Late Holocene stratigraphic evolution of a back-barrier tidal basin in the East Frisian Wadden Sea, southern North Sea: transgressive deposition and its preservation potential. *Facies* 52, 329–340. <https://doi.org/10.1007/s10347-006-0080-2>
- Clarke, M.L., Rendell, H.M., 2009. The impact of North Atlantic storminess on western European coasts: A review. *Quaternary International, Hurricanes and Typhoons: From the Field Records to the Forecast* 195, 31–41. <https://doi.org/10.1016/j.quaint.2008.02.007>
- Clarke, M.L., Rendell, H.M., 2006. Effects of storminess, sand supply and the North Atlantic Oscillation on sand invasion and coastal dune accretion in western Portugal. *The Holocene* 16, 341–355. <https://doi.org/10.1191/0959683606hl932rp>
- Clemmensen, L.B., Murray, A., Heinemeier, J., de Jong, R., 2009. The evolution of Holocene coastal dunefields, Jutland, Denmark: A record of climate change over the past 5000 years. *Geomorphology* 105, 303–313. <https://doi.org/10.1016/j.geomorph.2008.10.003>
- Cook, E.R., Kairiukstis, L.A., 2013. *Methods of Dendrochronology: Applications in the Environmental Sciences*. Springer Science & Business Media, Netherlands.
- Coor, J.L., Donoghue, J., Wang, Y., Das, O., Kish, S., Elsner, J., Hu, X.B., Niedoroda, A.W., Ye, M., 2009. Development of a Long-Term Storm History for the Northwest Florida Coast Using Multiple Proxies. *AGU Fall Meeting Abstracts* 11.
- Costa, P., Andrade, C., Dawson, A.G., Mahaney, W.C., Freitas, M.C., Paris, R., Taborda, R., 2012. Microtextural characteristics of quartz grains transported and deposited by tsunamis and storms. *Sedimentary Geology* 275–276, 55–69. <https://doi.org/10.1016/j.sedgeo.2012.07.013>
- Costa, P.J.M., Andrade, C., Freitas, M., Oliveira, M., Lopes, V., Dawson, A., Moreno, J., Fatela, F., Jouanneau, J.-M., 2012. A tsunami record in the sedimentary archive of the central Algarve coast, Portugal: Characterizing sediment, reconstructing sources and inundation paths. *The Holocene* 22, 899–914. <https://doi.org/10.1177/0959683611434227>
- Cuellar-Martinez, T., Ruiz-Fernández, A.C., Sanchez-Cabeza, J.-A., Alonso-Rodríguez, R., 2017. Sedimentary record of recent climate impacts on an insular coastal lagoon in the Gulf of California. *Quaternary Science Reviews* 160, 138–149. <https://doi.org/10.1016/j.quascirev.2017.01.002>
- Culver, S.J., Leorri, E., Mallinson, D.J., Corbett, D.R., Shazili, N.A.M., 2015. Recent coastal evolution and sea-level rise, Setiu Wetland, Peninsular Malaysia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 417, 406–421. <https://doi.org/10.1016/j.palaeo.2014.10.001>
- Cunha, P.P., Buylaert, J.P., Murray, A.S., Andrade, C., Freitas, M.C., Fatela, F., Munhá, J.M., Martins, A.A., Sugisaki, S., 2010. Optical dating of clastic deposits generated by an extreme marine coastal flood: The 1755 tsunami deposits in the Algarve (Portugal). *Quaternary Geochronology, 12th International Conference on Luminescence and Electron Spin Resonance Dating (LED 2008)* 5, 329–335. <https://doi.org/10.1016/j.quageo.2009.09.004>
- D'Arrigo, R.D., Jacoby, G.C., 1991. A 1000-year record of winter precipitation from northwestern New Mexico, USA: a reconstruction from tree-rings and its relation to El Niño and the Southern Oscillation. *The Holocene* 1, 95–101. <https://doi.org/10.1177/095968369100100201>
- Das, O., Wang, Y., Donoghue, J., Xu, X., Coor, J., Elsner, J., Xu, Y., 2013. Reconstruction of paleostorms and paleoenvironment using geochemical proxies archived in the sediments of two coastal lakes in northwest Florida. *Quaternary Science Reviews* 68, 142–153. <https://doi.org/10.1016/j.quascirev.2013.02.014>
- Davidson, G.R., Carnley, M., Lange, T., Galicki, S.J., Douglas, A., 2004. Changes in Sediment Accumulation Rate in An Oxbow Lake Following Late 19Th Century Clearing of Land for

- Agricultural Use: A ^{210}Pb , ^{137}Cs , and ^{14}C Study in Mississippi, USA. *Radiocarbon* 46, 755–764. <https://doi.org/10.1017/S0033822200035797>
- Davies, P., Haslett, S.K., 2000. Identifying storm or tsunami events in coastal basin sediments. *Area* 32, 335–336. <https://doi.org/10.1111/j.1475-4762.2000.tb00146.x>
- Dawson, A.G., Hindson, R., Andrade, C., Freitas, C., Parish, R., Bateman, M., 1995. Tsunami sedimentation associated with the Lisbon earthquake of 1 November AD 1755: Boca do Rio, Algarve, Portugal. *The Holocene* 5, 209–215. <https://doi.org/10.1177/095968369500500208>
- Degeai, J.-P., Devillers, B., Dezileau, L., Oueslati, H., Bony, G., 2015. Major storm periods and climate forcing in the Western Mediterranean during the Late Holocene. *Quaternary Science Reviews* 129, 37–56. <https://doi.org/10.1016/j.quascirev.2015.10.009>
- Devoy, R.J.N., Delaney, C., Carter, R.W.G., Jennings, S.C., 1996. Coastal Stratigraphies as Indicators of Environmental Changes upon European Atlantic Coasts in the Late Holocene. *Journal of Coastal Research* 12, 564–588.
- DeVries-Zimmerman, S., Fisher, T.G., Hansen, E.C., Dean, S., 2014. Sand in lakes and bogs in Allegan County, Michigan, as a proxy for eolian sand transport. *Geological Society of America. Special Papers* 508, 111–131.
- Donnelly, J.P., Butler, J., Roll, S., Wengren, M., Webb, T., 2004. A backbarrier overwash record of intense storms from Brigantine, New Jersey. *Marine Geology, Storms and their significance in coastal morpho-sedimentary dynamics* 210, 107–121. <https://doi.org/10.1016/j.margeo.2004.05.005>
- Donnelly, J.P., Roll, S., Wengren, M., Butler, J., Lederer, R., Webb, T., 2001. Sedimentary evidence of intense hurricane strikes from New Jersey. *Geology* 29, 615–618. [https://doi.org/10.1130/0091-7613\(2001\)029<0615:SEOIHS>2.0.CO;2](https://doi.org/10.1130/0091-7613(2001)029<0615:SEOIHS>2.0.CO;2)
- Donnelly, J.P., Woodruff, J.D., 2007. Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African monsoon. *Nature* 447, 465–468. <https://doi.org/10.1038/nature05834>
- Doodson, A.T., 1924. Meteorological Perturbations of Sea-Level and Tides. *Geophysical Journal International* 1, 124–147. <https://doi.org/10.1111/j.1365-246X.1924.tb05363.x>
- Doodson, A.T., Warburg, H.D., 1942. Admiralty Manual of Tides. H. M. Stationary Office, London.
- Edwards, R.J., 2006. Mid-to late-Holocene relative sea-level change in southwest Britain and the influence of sediment compaction. *The Holocene* 16, 575–587. <https://doi.org/10.1191/0959683606hi941rp>
- Engel, M., Brückner, H., Pint, A., Wellbrock, K., Ginau, A., Voss, P., Grottker, M., Klasen, N., Frenzel, P., 2012. The early Holocene humid period in NW Saudi Arabia – Sediments, microfossils and palaeo-hydrological modelling. *Quaternary International, Geoarchaeology of Egypt and the Mediterranean: reconstructing Holocene landscapes and human occupation history* 266, 131–141. <https://doi.org/10.1016/j.quaint.2011.04.028>
- Feal-Pérez, A., Blanco-Chao, R., Ferro-Vázquez, C., Martínez-Cortizas, A., Costa-Casais, M., 2014. Late-Holocene storm imprint in a coastal sedimentary sequence (Northwest Iberian coast). *The Holocene* 24, 477–488. <https://doi.org/10.1177/0959683613520257>
- Feuillet, T., Chauveau, É., Pourinet, L., 2012. Xynthia est-elle exceptionnelle ? Réflexions sur l'évolution et les temps de retour des tempêtes, des marées de tempête, et des risques de surcotes associés sur la façade atlantique française. *Noréis* n° 222, 27–44.
- Fichaut, B., Suanez, S.S., 2011. Quarrying, transport and deposition of cliff-top storm deposits during extreme events: Banneg Island, Brittany. *Marine Geology* 283, 36–55. <https://doi.org/10.1016/j.margeo.2010.11.003>
- Fisher, M.M., Brenner, M., Reddy, K.R., 1992. A simple, inexpensive piston corer for collecting undisturbed sediment/water interface profiles. *Journal of Paleolimnology* 7, 157–161. <https://doi.org/10.1007/BF00196870>
- Francus, P., Bradley, R.S., Lewis, T., Abbott, M., Retelle, M., Stoner, J.S., 2008. Limnological and sedimentary processes at Sawtooth Lake, Canadian High Arctic, and their influence on varve

- formation. *Journal of Paleolimnology* 40, 963–985. <https://doi.org/10.1007/s10933-008-9210-x>
- Frappier, A.B., Sahagian, D., Carpenter, S.J., González, L.A., Frappier, B.R., 2007. Stalagmite stable isotope record of recent tropical cyclone events. *Geology* 35, 111–114. <https://doi.org/10.1130/G23145A.1>
- Fruergaard, M., Andersen, T.J., Nielsen, L.H., Johannessen, P.N., Aagaard, T., Pejrup, M., 2015. High-resolution reconstruction of a coastal barrier system: impact of Holocene sea-level change. *Sedimentology* 62, 928–969. <https://doi.org/10.1111/sed.12167>
- Gardner, T.A., Côté, I.M., Gill, J.A., Grant, A., Watkinson, A.R., 2005. Hurricanes and Caribbean Coral Reefs: Impacts, Recovery Patterns, and Role in Long-Term Decline. *Ecology* 86, 174–184. <https://doi.org/10.1890/04-0141>
- Garnier, E., Ciavola, P., Spencer, T., Ferreira, O., Armaroli, C., McIvor, A., 2018. Historical analysis of storm events: Case studies in France, England, Portugal and Italy. *Coastal Engineering* 134, 10–23. <https://doi.org/10.1016/j.coastaleng.2017.06.014>
- Gee, G.W., Or, D., 2002. 2.4 Particle-Size Analysis, in: Dane, J.H., Topp, C.G. (Eds.), *SSSA Book Series*. Soil Science Society of America, San Diego, pp. 255–293. <https://doi.org/10.2136/sssabookser5.4.c12>
- Giuliani, S., Bellucci, L.G., Romano, S., Piazza, R., Turetta, C., Vecchiato, M., Nhon, D.H., Frignani, M., 2015. Exploring the possibility to detect recent temporal changes in highly disturbed sedimentary records through sampling repetitions and core comparisons of porosity and sand content. *Environmental Monitoring and Assessment* 187, 480. <https://doi.org/10.1007/s10661-015-4702-4>
- Glew, J.R., Smol, J.P., 2016. A push corer developed for retrieving high-resolution sediment cores from shallow waters. *Journal of Paleolimnology* 56, 67–71. <https://doi.org/10.1007/s10933-015-9873-z>
- Goff, J., Chagué-Goff, C., Nichol, S., 2001. Palaeotsunami deposits: a New Zealand perspective. *Sedimentary Geology* 143, 1–6. [https://doi.org/10.1016/S0037-0738\(01\)00121-X](https://doi.org/10.1016/S0037-0738(01)00121-X)
- Goff, J., McFadgen, B.G., Chagué-Goff, C., 2004. Sedimentary differences between the 2002 Easter storm and the 15th-century Okoropunga tsunami, southeastern North Island, New Zealand. *Marine Geology* 204, 235–250. [https://doi.org/10.1016/S0025-3227\(03\)00352-9](https://doi.org/10.1016/S0025-3227(03)00352-9)
- Goslin, J., Fruergaard, M., Sander, L., Galka, M., Menviel, L., Monkenbusch, J., Thibault, N., Clemmensen, L.B., 2018. Holocene centennial to millennial shifts in North-Atlantic storminess and ocean dynamics. *Scientific Reports* 8, 12778. <https://doi.org/10.1038/s41598-018-29949-8>
- Goto, K., Chagué-Goff, C., Goff, J., Jaffe, B., 2012. The future of tsunami research following the 2011 Tohoku-oki event. *Sedimentary Geology*, The 2011 Tohoku-oki tsunami 282, 1–13. <https://doi.org/10.1016/j.sedgeo.2012.08.003>
- Goto, K., Chavanich, S.A., Imamura, F., Kunthasap, P., Matsui, T., Minoura, K., Sugawara, D., Yanagisawa, H., 2007. Distribution, origin and transport process of boulders deposited by the 2004 Indian Ocean tsunami at Pakarang Cape, Thailand. *Sedimentary Geology* 202, 821–837. <https://doi.org/10.1016/j.sedgeo.2007.09.004>
- Goto, K., Miyagi, K., Kawamata, H., Imamura, F., 2010. Discrimination of boulders deposited by tsunamis and storm waves at Ishigaki Island, Japan. *Marine Geology* 269, 34–45. <https://doi.org/10.1016/j.margeo.2009.12.004>
- Hall, A.M., Hansom, J.D., Williams, D.M., Jarvis, J., 2006. Distribution, geomorphology and lithofacies of cliff-top storm deposits: Examples from the high-energy coasts of Scotland and Ireland. *Marine Geology* 232, 131–155. <https://doi.org/10.1016/j.margeo.2006.06.008>
- Hansom, J.D., Barltrop, N.D.P., Hall, A.M., 2008. Modelling the processes of cliff-top erosion and deposition under extreme storm waves. *Marine Geology* 253, 36–50. <https://doi.org/10.1016/j.margeo.2008.02.015>
- Hansom, J.D., Hall, A.M., 2009. Magnitude and frequency of extra-tropical North Atlantic cyclones: A chronology from cliff-top storm deposits. *Quaternary International*, Hurricanes and

798 Typhoons: From the Field Records to the Forecast 195, 42–52.
799 <https://doi.org/10.1016/j.quaint.2007.11.010>

800 Hayne, M., Chappell, J., 2001. Cyclone frequency during the last 5000 years at Curacao Island, north
801 Queensland, Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 168, 207–219.
802 [https://doi.org/10.1016/S0031-0182\(00\)00217-0](https://doi.org/10.1016/S0031-0182(00)00217-0)

803 Hindson, R.A., Andrade, C., 1999. Sedimentation and hydrodynamic processes associated with the
804 tsunami generated by the 1755 Lisbon earthquake. *Quaternary International* 56, 27–38.
805 [https://doi.org/10.1016/S1040-6182\(98\)00014-7](https://doi.org/10.1016/S1040-6182(98)00014-7)

806 Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X.,
807 Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation costs under 21st
808 century sea-level rise. *PNAS* 111, 3292–3297. <https://doi.org/10.1073/pnas.1222469111>

809 Hippensteel, S.P., Martin, R.E., 1999. Foraminifera as an indicator of overwash deposits, Barrier
810 Island sediment supply, and Barrier Island evolution: Folly Island, South Carolina.
811 *Palaeogeography, Palaeoclimatology, Palaeoecology* 149, 115–125.
812 [https://doi.org/10.1016/S0031-0182\(98\)00196-5](https://doi.org/10.1016/S0031-0182(98)00196-5)

813 Hongo, C., 2018. The Hydrodynamic Impacts of Tropical Cyclones on Coral Reefs of Japan: Key Points
814 and Future Perspectives, in: *Coral Reef Studies of Japan, Coral Reefs of the World*. Springer,
815 Singapore, pp. 163–173. https://doi.org/10.1007/978-981-10-6473-9_11

816 Jelgersma, S., Stive, M.J.F., van der Valk, L., 1995. Holocene storm surge signatures in the coastal
817 dunes of the western Netherlands. *Marine Geology* 125, 95–110.
818 [https://doi.org/10.1016/0025-3227\(95\)00061-3](https://doi.org/10.1016/0025-3227(95)00061-3)

819 Jong, R. de, Björck, S., Björkman, L., Clemmensen, L.B., 2006. Storminess variation during the last
820 6500 years as reconstructed from an ombrotrophic peat bog in Halland, southwest Sweden.
821 *Journal of Quaternary Science* 21, 905–919. <https://doi.org/10.1002/jqs.1011>

822 Kanbar, H.J., Montargès-Pelletier, E., Losson, B., Bihannic, I., Gley, R., Bauer, A., Villiéras, F., Manceau,
823 L., Samrani, A.G.E., Kazpard, V., Mansuy-Huault, L., 2017. Iron mineralogy as a fingerprint of
824 former steelmaking activities in river sediments. *Science of the Total Environment* 599–600,
825 540–553. <https://doi.org/10.1016/j.scitotenv.2017.04.156>

826 Kaniewski, D., Marriner, N., Morhange, C., Faivre, S., Otto, T., Campo, E.V., 2016. Solar pacing of
827 storm surges, coastal flooding and agricultural losses in the Central Mediterranean. *Scientific*
828 *Reports* 6. <https://doi.org/10.1038/srep25197>

829 Keen, T.R., Bentley, S.J., Chad Vaughan, W., Blain, C.A., 2004. The generation and preservation of
830 multiple hurricane beds in the northern Gulf of Mexico. *Marine Geology, Storms and their*
831 *significance in coastal morpho-sedimentary dynamics* 210, 79–105.
832 <https://doi.org/10.1016/j.margeo.2004.05.022>

833 Kenney, W.F., Brenner, M., Arnold, T.E., Curtis, J.H., Schelske, C.L., 2016. Sediment cores from
834 shallow lakes preserve reliable, informative paleoenvironmental archives despite hurricane-
835 force winds. *Ecological Indicators* 60, 963–969.
836 <https://doi.org/10.1016/j.ecolind.2015.08.046>

837 Khalfaoui, O., Dezileau, L., Degeai, J.-P., Snoussi, M., 2019. Reconstruction of past marine submersion
838 events (storms and tsunamis) on the North Atlantic coast of Morocco. *Natural Hazards and*
839 *Earth System Sciences Discussions* 1–14. <https://doi.org/10.5194/nhess-2019-130>

840 Kolen, B., Slomp, R., Jonkman, S.N., 2002. The impacts of storm Xynthia February 27–28, 2010 in
841 France: lessons for flood risk management. *Journal of Flood Risk Management* 6, 261–278.
842 <https://doi.org/10.1111/jfr3.12011>

843 Kylander, M.E., Söderlindh, J., Schenk, F., Gyllencreutz, R., Rydberg, J., Bindler, R., Cortizas, A.M.,
844 Skelton, A., 2019. It's in your glass: a history of sea level and storminess from the Laphroaig
845 bog, Islay (southwestern Scotland). *Boreas*. <https://doi.org/10.1111/bor.12409>

846 Lafon, C.W., Speer, J.H., 2002. Using dendrochronology to identify major ice storm events in oak
847 forests of southwestern Virginia. *Climate Research* 20, 41–54.

- Lambeck, K., Bard, E., 2000. Sea-level change along the French Mediterranean coast for the past 30 000 years. *Earth and Planetary Science Letters* 175, 203–222. [https://doi.org/10.1016/S0012-821X\(99\)00289-7](https://doi.org/10.1016/S0012-821X(99)00289-7)
- Lambert, W.J., Aharon, P., Rodriguez, A.B., 2008. Catastrophic hurricane history revealed by organic geochemical proxies in coastal lake sediments: a case study of Lake Shelby, Alabama (USA). *Journal of Paleolimnology* 39, 117–131. <https://doi.org/10.1007/s10933-007-9101-6>
- Lario, J., Luque, L., Zazo, C., Goy, J.L., Spencer, C., Cabero, A., Bardají, T., Borja, F., Dabrio, C.J., Civis, J., González-Delgado, J.Á., Borja, C., Alonso-Azcárate, J., 2010. Tsunami vs. storm surge deposits: a review of the sedimentological and geomorphological records of extreme wave events (EWE) during the Holocene in the Gulf of Cadiz, Spain. *Zeitschrift für Geomorphologie* 54, 301–316.
- Le Roy, S., Pedreros, R., André, C., Paris, F., Lecacheux, S., Marche, F., Vinchon, C., 2015. Coastal flooding of urban areas by overtopping: dynamic modelling application to the Johanna storm (2008) in Gâvres (France). *Natural Hazards and Earth System Sciences* 15, 2497–2510. <https://doi.org/10.5194/nhess-15-2497-2015>
- Leroy, S., Pedreros, R., André, C., Paris, F., Lecacheux, S., Marche, F., Vinchon, C., 2015. Coastal flooding of urban areas by overtopping: dynamic modelling application to the Johanna storm (2008) in Gâvres (France). *Natural Hazards and Earth System Science* 15, 2497–2510. <https://doi.org/10.5194/nhess-15-2497-2015>
- Liu, K., Fearn, M.L., 2000a. Reconstruction of Prehistoric Landfall Frequencies of Catastrophic Hurricanes in Northwestern Florida from Lake Sediment Records. *Quaternary Research* 54, 238–245. <https://doi.org/10.1006/qres.2000.2166>
- Liu, K., Fearn, M.L., 2000b. Holocene history of catastrophic hurricane landfalls along the Gulf of Mexico coast reconstructed from coastal lake and marsh sediments, in: Zhu, H., Kamran, K. (Eds.), *Current Stresses and Potential Vulnerabilities: Implications of Global Change for the Gulf Coast Region of the United States*. Franklin Press, Plymouth, pp. 38–47.
- Liu, K., Fearn, M.L., 1993. Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology* 21, 793–796. [https://doi.org/10.1130/0091-7613\(1993\)021<0793:LSROLH>2.3.CO;2](https://doi.org/10.1130/0091-7613(1993)021<0793:LSROLH>2.3.CO;2)
- Liu, K., Shen, C., Louie, K., 2001. A 1,000-Year History of Typhoon Landfalls in Guangdong, Southern China, Reconstructed from Chinese Historical Documentary Records. *Annals of the Association of American Geographers* 91, 453–464. <https://doi.org/10.1111/0004-5608.00253>
- Lutz, W., Samir, K., 2010. Dimensions of global population projections: what do we know about future population trends and structures? *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 365, 2779–2791. <https://doi.org/10.1098/rstb.2010.0133>
- Maanan, Mehdi, Maanan, Mohamed, Rueff, H., Adouk, N., Zourarah, B., Rhinane, H., 2018. Assess the human and environmental vulnerability for coastal hazard by using a multi-criteria decision analysis. *Human and Ecological Risk Assessment: An International Journal* 24, 1642–1658. <https://doi.org/10.1080/10807039.2017.1421452>
- Maanan, Mehdi, Ruiz-Fernández, A.-C., Maanan, Mohamed, Fattal, P., Zourarah, B., Sahabi, M., 2014. A long-term record of land use change impacts on sediments in Oualidia lagoon, Morocco. *International Journal of Sediment Research* 29, 1–10.
- Maanan, Mohamed, Saddik, M., Maanan, Mehdi, Chaibi, M., Assobhei, O., Zourarah, B., 2015. Environmental and ecological risk assessment of heavy metals in sediments of Nador lagoon, Morocco. *Ecological Indicators* 48, 616–626. <https://doi.org/10.1016/j.ecolind.2014.09.034>
- Mann, M.E., Woodruff, J.D., Donnelly, J.P., Zhang, Z., 2009. Atlantic hurricanes and climate over the past 1,500 years. *Nature* 460, 880–883. <https://doi.org/10.1038/nature08219>
- Martin, L., Mooney, S., Goff, J., 2014. Coastal wetlands reveal a non-synchronous island response to sea-level change and a palaeostorm record from 5.5 kyr to present. *The Holocene* 24, 569–580. <https://doi.org/10.1177/0959683614522306>

- May, S.M., Brill, D., Engel, M., Scheffers, A., Pint, A., Opitz, S., Wennrich, V., Squire, P., Kelletat, D., Brückner, H., 2015. Traces of historical tropical cyclones and tsunamis in the Ashburton Delta (north-west Australia). *Sedimentology* 62, 1546–1572. <https://doi.org/10.1111/sed.12192>
- May, S.M., Falvard, S., Norpoth, M., Pint, A., Brill, D., Engel, M., Scheffers, A., Dierick, M., Paris, R., Squire, P., Brückner, H., 2016. A mid-Holocene candidate tsunami deposit from the NW Cape (Western Australia). *Sedimentary Geology* 332, 40–50. <https://doi.org/10.1016/j.sedgeo.2015.11.010>
- McGlue, M.M., Silva, A., Assine, M.L., Stevaux, J.C., Pupim, F. do N., 2015. Paleolimnology in the Pantanal: Using Lake Sediments to Track Quaternary Environmental Change in the World's Largest Tropical Wetland, in: *Dynamics of the Pantanal Wetland in South America, The Handbook of Environmental Chemistry*. Springer, Cham, pp. 51–81. https://doi.org/10.1007/698_2015_350
- Michaelson G. J., Ping C. L., Jorgenson M. T., 2011. Methane and carbon dioxide content in eroding permafrost soils along the Beaufort Sea coast, Alaska. *Journal of Geophysical Research: Biogeosciences* 116, 10. <https://doi.org/10.1029/2010JG001387>
- Migeon, S., Weber, O., Faugeres, J.-C., Saint-Paul, J., 1998. SCOPIX: A new X-ray imaging system for core analysis. *Geo-Marine Letters* 18, 251–255. <https://doi.org/10.1007/s003670050076>
- Mix, A.C., Harris, S.E., Janecek, T.R., 1995. Estimating lithology from nonintrusive reflectance spectra : Leg 138. *Proceedings of the Ocean Drilling Program, Scientific Results* 138, 413–428.
- Morton, R.A., 2002. Factors Controlling Storm Impacts on Coastal Barriers and Beaches: A Preliminary Basis for near Real-Time Forecasting. *Journal of Coastal Research* 18, 486–501.
- Nanayama, F., Shigeno, K., Satake, K., Shimokawa, K., Koitabashi, S., Miyasaka, S., Ishii, M., 2000. Sedimentary differences between the 1993 Hokkaido-nansei-oki tsunami and the 1959 Miyakojima typhoon at Taisei, southwestern Hokkaido, northern Japan. *Sedimentary Geology* 135, 255–264. [https://doi.org/10.1016/S0037-0738\(00\)00076-2](https://doi.org/10.1016/S0037-0738(00)00076-2)
- Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. *PLOS ONE* 10, 34. <https://doi.org/10.1371/journal.pone.0118571>
- Nicolussi, K., Kaufmann, M., Patzelt, G., Der, J.P. van, Thurner, A., 2005. Holocene tree-line variability in the Kauner Valley, Central Eastern Alps, indicated by dendrochronological analysis of living trees and subfossil logs. *Vegetation History and Archaeobotany* 14, 221–234. <https://doi.org/10.1007/s00334-005-0013-y>
- Ning, W., Nielsen, A.B., Ivarsson, L.N., Jilbert, T., Åkesson, C.M., Slomp, C.P., Andrén, E., Broström, A., Filipsson, H.L., 2018. Anthropogenic and climatic impacts on a coastal environment in the Baltic Sea over the last 1000 years. *Anthropocene* 21, 66–79. <https://doi.org/10.1016/j.ancene.2018.02.003>
- Nodine, E.R., Gaiser, E.E., 2015. Seasonal differences and response to a tropical storm reflected in diatom assemblage changes in a southwest Florida watershed. *Ecological Indicators* 57, 139–148. <https://doi.org/10.1016/j.ecolind.2015.04.035>
- Noren, A.J., Bierman, P.R., Steig, E.J., Lini, A., Southon, J., 2002. Millennial-scale storminess variability in the northeastern United States during the Holocene epoch. *Nature* 419, 821–824. <https://doi.org/10.1038/nature01132>
- Nott, J., Hayne, M., 2001. High frequency of 'super-cyclones' along the Great Barrier Reef over the past 5,000 years. *Nature* 413, 508–512. <https://doi.org/10.1038/35097055>
- Nott, J., Smithers, S., Walsh, K., Rhodes, E., 2009. Sand beach ridges record 6000 year history of extreme tropical cyclone activity in northeastern Australia. *Quaternary Science Reviews* 28, 1511–1520. <https://doi.org/10.1016/j.quascirev.2009.02.014>
- Oldfield, F., Battarbee, R.W., Boyle, J.F., Cameron, N.G., Davis, B., Evershed, R.P., McGovern, A.D., Jones, V., Thompson, R., Walker (née Wake), R., 2010. Terrestrial and aquatic ecosystem responses to late Holocene climate change recorded in the sediments of Lochan Uaine, Cairngorms, Scotland. *Quaternary Science Reviews* 29, 1040–1054. <https://doi.org/10.1016/j.quascirev.2010.01.007>

- Oliva, F., Peros, M., Viau, A., 2017. A review of the spatial distribution of and analytical techniques used in paleotempestological studies in the western North Atlantic Basin: Progress in Physical Geography: Earth and Environment 41, 171–190.
<https://doi.org/10.1177/0309133316683899>
- Oliveira, F.M., Macario, K.D., Simonassi, J.C., Gomes, P.R.S., Anjos, R.M., Carvalho, C., Linares, R., Alves, E.Q., Castro, M.D., Souza, R.C.C.L., Marques Jr., A.N., 2014. Evidence of strong storm events possibly related to the little Ice Age in sediments on the southern coast of Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology, Continental and Coastal Marine Records of Centennial to Millennial Changes in South American Climate since the Last Glacial Maximum 415, 233–239. <https://doi.org/10.1016/j.palaeo.2014.03.018>
- Oliveira, M.A., Andrade, C., Freitas, M.C., Costa, P.J., 2009. Modeling Volume Transfer between Beach-Foredune and the Backshore by the 1755 Lisbon Tsunami at Boca Do Rio Lowland, Algarve (Portugal). Journal of Coastal Research 2, 1547–1551.
- Orme, L.C., Davies, S.J., Duller, G. a. T., 2015. Reconstructed centennial variability of Late Holocene storminess from Cors Fochno, Wales, UK. Journal of Quaternary Science 30, 478–488.
<https://doi.org/10.1002/jqs.2792>
- Orme, L.C., Reinhardt, L., Jones, R.T., Charman, D.J., Barkwith, A., Ellis, M.A., 2016. Aeolian sediment reconstructions from the Scottish Outer Hebrides: Late Holocene storminess and the role of the North Atlantic Oscillation. Quaternary Science Reviews 132, 15–25.
<https://doi.org/10.1016/j.quascirev.2015.10.045>
- Otvos, E.G., 2002. Discussion of “Prehistoric Landfall Frequencies of Catastrophic Hurricanes...” (Liu and Fearn, 2000). Quaternary Research 57, 425–428.
<https://doi.org/10.1006/qres.2002.2333>
- Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N.K., Edenhofer, O., Elgizouli, I., Field, C.B., Forster, P., Friedlingstein, P., Fuglestad, J., Gomez-Echeverri, L., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Jimenez Cisneros, B., Kattsov, V., Lee, H., Mach, K.J., Marotzke, J., Mastrandrea, M.D., Meyer, L., Minx, J., Mulugetta, Y., O’Brien, K., Oppenheimer, M., Pereira, J.J., Pichs-Madruga, R., Plattner, G.-K., Pörtner, H.-O., Power, S.B., Preston, B., Ravindranath, N.H., Reisinger, A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T.F., Tschakert, P., van Vuuren, D., van Ypersele, J.-P., 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.
- Paciorek, C.J., Risbey, J.S., Ventura, V., Rosen, R.D., 2002. Multiple Indices of Northern Hemisphere Cyclone Activity, Winters 1949–99. Journal of Climate 15, 1573–1590.
[https://doi.org/10.1175/1520-0442\(2002\)015<1573:MIONHC>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<1573:MIONHC>2.0.CO;2)
- Page, M.J., Trustrum, N.A., Orpin, A.R., Carter, L., Gomez, B., Cochran, U.A., Mildenhall, D.C., Rogers, K.M., Brackley, H.L., Palmer, A.S., Northcote, L., 2010. Storm frequency and magnitude in response to Holocene climate variability, Lake Tutira, North-Eastern New Zealand. Marine Geology, From mountain source to ocean sink – the passage of sediment across an active margin, Waipaoa Sedimentary System, New Zealand 270, 30–44.
<https://doi.org/10.1016/j.margeo.2009.10.019>
- Parris, A.S., Bierman, P.R., Noren, A.J., Prins, M.A., Lini, A., 2010. Holocene paleostorms identified by particle size signatures in lake sediments from the northeastern United States. Journal of Paleolimnology 43, 29–49. <https://doi.org/10.1007/s10933-009-9311-1>
- Parris, A.S., Bierman, P.R., Noren, A.J., Prins, M.A., Lini, A., 2009. Holocene paleostorms identified by particle size signatures in lake sediments from the northeastern United States. J Paleolimnol 43, 29–49. <https://doi.org/10.1007/s10933-009-9311-1>
- Parsons, M.L., 1998. Salt Marsh Sedimentary Record of the Landfall of Hurricane Andrew on the Louisiana Coast: Diatoms and Other Paleoindicators. Journal of Coastal Research 14, 939–950. <https://doi.org/10.2307/4298846>

- Pinegina, T.K., Bourgeois, J., 2001. Historical and paleo-tsunami deposits on Kamchatka, Russia: long-term chronologies and long-distance correlations. *Natural Hazards and Earth System Sciences* 1, 177–185. <https://doi.org/10.5194/nhess-1-177-2001>
- Poirier, C., Tessier, B., Chaumillon, E., 2017. Climate control on late Holocene high-energy sedimentation along coasts of the northeastern Atlantic Ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology* 485, 784–797. <https://doi.org/10.1016/j.palaeo.2017.07.037>
- Pouzet, P., 2018. Étude des paléoévénements extrêmes le long de la côte atlantique française : Approches sédimentologiques, dendrochronologiques et historiques (phdthesis). Université de Nantes. NNT : 2018NANT2035
- Pouzet, P., Creach, A., Godet, L., 2015. Dynamique de la démographie et du bâti dans l'ouest du Marais poitevin depuis 1705. *Noréis* 234, 83–96. <https://doi.org/10.4000/noréis.5589>
- Pouzet, P., Maanan, M., Piotrowska, N., Baltzer, A., Stéphan, P., Robin, M., 2018a. Chronology of Holocene storm events along the European Atlantic coast: New data from the Island of Yeu, France. *Progress in Physical Geography: Earth and Environment* 42, 431–450. <https://doi.org/10.1177/0309133318776500>
- Pouzet, P., Maanan, M., Schmidt, S., Athimon, E., Robin, M., 2019. Correlating three centuries of historical and geological data for the marine deposit reconstruction of two depositional environments of the French Atlantic coast. *Marine Geology* 407, 181–191. <https://doi.org/10.1016/j.margeo.2018.10.014>
- Pouzet, P., Robin, M., Decaulne, A., Gruchet, B., Maanan, M., 2018b. Sedimentological and dendrochronological indicators of coastal storm risk in western France. *Ecological Indicators* 90, 401–415. <https://doi.org/10.1016/j.ecolind.2018.03.022>
- Pugh, D.T., 1996. Tides, surges and mean sea-level. John Wiley & Sons Ltd, New Jersey.
- Ramirez-Herrera, M.T., Cundy, A., Kostoglodov, V., Carranza-Edwards, A., Morales, E., Metcalfe, S., 2007. Sedimentary record of late-Holocene relative sea-level change and tectonic deformation from the Guerrero Seismic Gap, Mexican Pacific Coast. *The Holocene* 17, 1211–1220. <https://doi.org/10.1177/0959683607085127>
- Ramírez-Herrera, M.-T., Lagos, M., Hutchinson, I., Kostoglodov, V., Machain, M.L., Caballero, M., Goguitchaichvili, A., Aguilar, B., Chagué-Goff, C., Goff, J., Ruiz-Fernández, A.-C., Ortiz, M., Nava, H., Bautista, F., Lopez, G.I., Quintana, P., 2012. Extreme wave deposits on the Pacific coast of Mexico: Tsunamis or storms? — A multi-proxy approach. *Geomorphology* 139–140, 360–371. <https://doi.org/10.1016/j.geomorph.2011.11.002>
- Roy, P.D., Caballero, M., Lozano, R., Ortega, B., Lozano, S., Pi, T., Israde, I., Morton, O., 2010. Geochemical record of Late Quaternary paleoclimate from lacustrine sediments of paleo-lake San Felipe, western Sonora Desert, Mexico. *Journal of South American Earth Sciences* 29, 586–596. <https://doi.org/10.1016/j.jsames.2009.11.009>
- Sabatier, P., Dezileau, L., Briquieu, L., Colin, C., Siani, G., 2010. Paleostorm events revealed by clay minerals and geochemistry in coastal lagoon: a study case of Pierre Blanche (NW Mediterranean Sea). *Sedimentary Geology* 228, 205–217.
- Sabatier, P., Dezileau, L., Colin, C., Briquieu, L., Bouchette, F., Martinez, P., Siani, G., Raynal, O., Von Grafenstein, U., 2012. 7000 years of paleostorm activity in the NW Mediterranean Sea in response to Holocene climate events. *Quaternary Research* 77, 1–11. <https://doi.org/10.1016/j.yqres.2011.09.002>
- Sallenger, A.H., 2000. Storm Impact Scale for Barrier Islands. *Journal of Coastal Research* 16, 890–895.
- Santisteban, J.I., Mediavilla, R., López-Pamo, E., Dabrio, C.J., Zapata, M.B.R., García, M.J.G., Castaño, S., Martínez-Alfaro, P.E., 2004. Loss on ignition: a qualitative or quantitative method for organic matter and carbonate mineral content in sediments? *Journal of Paleolimnology* 32, 287–299. <https://doi.org/10.1023/B:JOPL.0000042999.30131.5b>
- Sarrazin, J.-L., 2012. « Vimers de mer » et sociétés littorales entre Loire et Gironde (XIVe-XVIe siècle). *Noréis* n° 222, 91–102.

1054 Sarrazin, J.-L., 2005. Le paysage salicole de l'île de Bouin à la fin du Moyen Âge, in: Chauvaud, F.,
1055 Péret, J. (Eds.), *Terres Marines, Histoire*. Presses universitaires de Rennes, Rennes, pp. 57–67.

1056 Sauzeau, T., 2014. L'histoire, les tempêtes et la prospective littorale face aux changements
1057 climatiques, in: Laget, F., Vignion, A. (Eds.), *S'adapter à La Mer : L'homme, La Mer et Le*
1058 *Littoral Du Moyen Âge à Nos Jours, Enquêtes et Documents*. Presses universitaires de
1059 Rennes, Rennes, pp. 71–86.

1060 Scheffers, A., Engel, M., Scheffers, S., Squire, P., Kelletat, D., 2012. Beach ridge systems – archives for
1061 Holocene coastal events? *Progress in Physical Geography: Earth and Environment* 36, 5–37.
1062 <https://doi.org/10.1177/0309133311419549>

1063 Scheffers, A., Kelletat, D., 2003. Sedimentologic and geomorphologic tsunami imprints worldwide—a
1064 review. *Earth-Science Reviews* 63, 83–92. [https://doi.org/10.1016/S0012-8252\(03\)00018-7](https://doi.org/10.1016/S0012-8252(03)00018-7)

1065 Scileppi, E., Donnelly, J.P., 2007. Sedimentary evidence of hurricane strikes in western Long Island,
1066 New York. *Geochemistry, Geophysics, Geosystems* 8, 25.
1067 <https://doi.org/10.1029/2006GC001463>

1068 Scoffin, T.P., 1993. The geological effects of hurricanes on coral reefs and the interpretation of storm
1069 deposits. *Coral Reefs* 12, 203–221. <https://doi.org/10.1007/BF00334480>

1070 Scott, D.B., Collins, E.S., Gayes, P.T., Wright, E., 2003. Records of prehistoric hurricanes on the South
1071 Carolina coast based on micropaleontological and sedimentological evidence, with
1072 comparison to other Atlantic Coast records. *GSA Bulletin* 115, 1027–1039.
1073 <https://doi.org/10.1130/B25011.1>

1074 Shimozone, T., Sato, S., 2016. Coastal vulnerability analysis during tsunami-induced levee overflow
1075 and breaching by a high-resolution flood model. *Coastal Engineering* 107, 116–126.
1076 <https://doi.org/10.1016/j.coastaleng.2015.10.007>

1077 Sorrel, P., Tessier, B., Demory, F., Delsinne, N., Mouazé, D., 2009. Evidence for millennial-scale
1078 climatic events in the sedimentary infilling of a macrotidal estuarine system, the Seine
1079 estuary (NW France). *Quaternary Science Reviews* 28, 499–516.
1080 <https://doi.org/10.1016/j.quascirev.2008.11.009>

1081 Spencer, C.D., Plater, A.J., Long, A.J., 1998. Rapid coastal change during the mid- to late Holocene:
1082 the record of barrier estuary sedimentation in the Romney Marsh region, southeast
1083 England. *The Holocene* 8, 143–163. <https://doi.org/10.1191/095968398673197622>

1084 Stager, J.C., Cumming, B.F., Laird, K.R., Garrigan-Piela, A., Pederson, N., Wiltse, B., Lane, C.S., Nester,
1085 J., Ruzmaikin, A., 2017. A 1600-year diatom record of hydroclimate variability from Wolf
1086 Lake, New York. *The Holocene* 27, 246–257. <https://doi.org/10.1177/0959683616658527>

1087 Steers, J.A., Stoddart, D.R., Bayliss-Smith, T.P., Spencer, T., Durbidge, P.M., 1979. The Storm Surge of
1088 11 January 1978 on the East Coast of England. *The Geographical Journal* 145, 192–205.
1089 <https://doi.org/10.2307/634386>

1090 Stewart, H., Bradwell, T., Bullard, J., Davies, S.J., Gollidge, N., McCulloch, R.D., 2017. 8000 years of
1091 North Atlantic storminess reconstructed from a Scottish peat record: implications for
1092 Holocene atmospheric circulation patterns in Western Europe. *Journal of Quaternary Science*
1093 32, 1075–1084. <https://doi.org/10.1002/jqs.2983>

1094 Stockdon, H.F., Holman, R.A., Howd, P.A., Sallenger, A.H., 2006. Empirical parameterization of setup,
1095 swash, and runup. *Coastal Engineering* 53, 573–588.
1096 <https://doi.org/10.1016/j.coastaleng.2005.12.005>

1097 Suanez, S., Fichaut, B., Magne, R., 2009. Cliff-top storm deposits on Banneg Island, Brittany, France:
1098 Effects of giant waves in the Eastern Atlantic Ocean. *Sedimentary Geology* 220, 12–28.
1099 <https://doi.org/10.1016/j.sedgeo.2009.06.004>

1100 Thompson, T.A., Baedke, S.J., 1995. Beach-ridge development in Lake Michigan: shoreline behavior in
1101 response to quasi-periodic lake-level events. *Marine Geology* 129, 163–174.
1102 [https://doi.org/10.1016/0025-3227\(95\)00110-7](https://doi.org/10.1016/0025-3227(95)00110-7)

1103 Tisdall, E.W., McCulloch, R.D., Sanderson, D.C.W., Simpson, I.A., Woodward, N.L., 2013. Living with
1104 sand: A record of landscape change and storminess during the Bronze and Iron Ages Orkney,
1105 Scotland. *Quaternary International, Geoarchaeology: a toolbox of approaches applied in a*

1106 multidisciplinary research discipline 308–309, 205–215.
 1107 <https://doi.org/10.1016/j.quaint.2013.05.016>
 1108 Trouet, V., Scourse, J.D., Raible, C.C., 2012. North Atlantic storminess and Atlantic Meridional
 1109 Overturning Circulation during the last Millennium: Reconciling contradictory proxy records
 1110 of NAO variability. *Global and Planetary Change* 84–85, 48–55.
 1111 <https://doi.org/10.1016/j.gloplacha.2011.10.003>
 1112 Ulbrich, U., Christoph, M., 1999. A shift of the NAO and increasing storm track activity over Europe
 1113 due to anthropogenic greenhouse gas forcing. *Climate Dynamics* 15, 551–559.
 1114 <https://doi.org/10.1007/s003820050299>
 1115 Vallve, M.B., Martin-Vide, J., 1998. Secular Climatic Oscillations as Indicated by Catastrophic Floods in
 1116 the Spanish Mediterranean Coastal Area (14th–19th Centuries). *Climatic Change* 38, 473–
 1117 491. <https://doi.org/10.1023/A:1005343828552>
 1118 Van Vliet Lanoe, B., Goslin, J., Hallégouet, B., Hénaff, A., Delacourt, C., Fernane, A., Franzetti, M., Le
 1119 Cornec, E., Le Roy, P., Pénaud, A., 2014. Middle- to late-Holocene storminess in Brittany (NW
 1120 France): Part I - morphological impact and stratigraphical record. *Holocene* 24, 413–433.
 1121 <https://doi.org/10.1177/0959683613519687>
 1122 Van Vliet Lanoe, B., Lauer, T., Meurisse-Fort, M., Gosselin, G., Frechen, M., 2017. Late Holocene
 1123 coastal dune activity along the Dover Strait, Northern France – Insights into Middle Ages and
 1124 Little Ice Age coastal dynamics constrained by optically stimulated luminescence dating.
 1125 *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* 168, 53–66.
 1126 <https://doi.org/10.1127/zdgg/2016/0043>
 1127 Vance, R.E., Mathewes, R.W., Clague, J.J., 1992. 7000 year record of lake-level change on the
 1128 northern Great Plains: A high-resolution proxy of past climate. *Geology* 20, 879–882.
 1129 [https://doi.org/10.1130/0091-7613\(1992\)020<0879:YRQLLC>2.3.CO;2](https://doi.org/10.1130/0091-7613(1992)020<0879:YRQLLC>2.3.CO;2)
 1130 Wanner, H., Solomina, O., Grosjean, M., Ritz, S.P., Jetel, M., 2011. Structure and origin of Holocene
 1131 cold events. *Quaternary Science Reviews* 30, 3109–3123.
 1132 <https://doi.org/10.1016/j.quascirev.2011.07.010>
 1133 Wassmer, P., Schneider, J.-L., Fonfrère, A.-V., Lavigne, F., Paris, R., Gomez, C., 2010. Use of
 1134 anisotropy of magnetic susceptibility (AMS) in the study of tsunami deposits: Application to
 1135 the 2004 deposits on the eastern coast of Banda Aceh, North Sumatra, Indonesia. *Marine*
 1136 *Geology* 275, 255–272. <https://doi.org/10.1016/j.margeo.2010.06.007>
 1137 Weisse, R., von Storch, H., Callies, U., Chrastansky, A., Feser, F., Grabemann, I., Günther, H., Pluess,
 1138 A., Stoye, T., Tellkamp, J., Winterfeldt, J., Woth, K., 2009. Regional Meteorological–Marine
 1139 Reanalyses and Climate Change Projections. *Bulletin of the American Meteorological Society*
 1140 90, 849–860. <https://doi.org/10.1175/2008BAMS2713.1>
 1141 Williams, D.M., Hall, A.M., 2004. Cliff-top megaclast deposits of Ireland, a record of extreme waves in
 1142 the North Atlantic—storms or tsunamis? *Marine Geology* 206, 101–117.
 1143 <https://doi.org/10.1016/j.margeo.2004.02.002>
 1144 Williams, H., Choowong, M., Phantuwongraj, S., Surakietchai, P., Thongkhao, T., Kongsan, S., Simon,
 1145 E., 2015. Geologic Records of Holocene Typhoon Strikes on the Gulf of Thailand Coast.
 1146 *Marine Geology* 372, 66–78. <https://doi.org/10.1016/j.margeo.2015.12.014>
 1147 Wilson, P., McGourty, J., Bateman, M.D., 2004. Mid-to late-Holocene coastal dune event stratigraphy
 1148 for the north coast of Northern Ireland. *The Holocene* 14, 406–416.
 1149 <https://doi.org/10.1191/0959683604hl716rp>
 1150 Woodruff, J.D., Donnelly, J.P., Okusu, A., 2009. Exploring typhoon variability over the mid-to-late
 1151 Holocene: evidence of extreme coastal flooding from Kamikoshiki, Japan. *Quaternary Science*
 1152 *Reviews, Quaternary Ice Sheet–Ocean Interactions and Landscape Responses* 28, 1774–1785.
 1153 <https://doi.org/10.1016/j.quascirev.2009.02.005>
 1154 Xiong, H., Huang, G., Fu, S., Qian, P., 2018. Progress in the Study of Coastal Storm Deposits. *Ocean*
 1155 *Science Journal* 53, 149–164. <https://doi.org/10.1007/s12601-018-0019-x>
 1156 Yim, J., Kwon, B.-O., Nam, J., Hwang, J.H., Choi, K., Khim, J.S., 2018. Analysis of forty years long
 1157 changes in coastal land use and land cover of the Yellow Sea: The gains or losses in

1158 ecosystem services. *Environmental Pollution* 241, 74–84.
1159 <https://doi.org/10.1016/j.envpol.2018.05.058>
1160 Yu, K.-F., Zhao, J.-X., Shi, Q., Meng, Q.-S., 2009. Reconstruction of storm/tsunami records over the
1161 last 4000 years using transported coral blocks and lagoon sediments in the southern South
1162 China Sea. *Quaternary International* 195, 128–137.
1163 <https://doi.org/10.1016/j.quaint.2008.05.004>
1164 Yuan, F., Koran, M.R., Valdez, A., 2013. Late Glacial and Holocene record of climatic change in the
1165 southern Rocky Mountains from sediments in San Luis Lake, Colorado, USA.
1166 *Palaeogeography, Palaeoclimatology, Palaeoecology* 392, 146–160.
1167 <https://doi.org/10.1016/j.palaeo.2013.09.016>
1168 Zhu, Z., Feinberg, J.M., Xie, S., Bourne, M.D., Huang, C., Hu, C., Cheng, H., 2017. Holocene ENSO-
1169 related cyclic storms recorded by magnetic minerals in speleothems of central China.
1170 *Proceedings of the National Academy of Sciences* 114, 852–857.
1171 <https://doi.org/10.1073/pnas.1610930114>
1172

1173 Figure 1. Coastal flooding parameters and the three overwash mechanisms

1174 Figure 2. Presentation of the two marine deposit scenarios in a coastal marsh during an
1175 extreme event

1176 Figure 3. Presentation of the three different timescales

1177 Figure 4. Construction of the three methodologies presented at the three different timescales

1178 Figure 5. Presentation of a study conducted with the long timescale method in Yeu island,
1179 from Pouzet et al. (2018a), modified

1180 Figure 6. Presentation of a study conducted with the meso timescale method in the Petite mer
1181 de Gâvres, from Pouzet (2018), modified

1182 Figure 7. Presentation of a study conducted with the sort timescale method in the Traicts du
1183 Croisic, from Pouzet et al. (2019), modified

1184 Figure 8. Synthesis of the method used at the three different timescales for the detection of
1185 past storm with sedimentological analyses

1186

1187

1188

1189

1190

1191

1192

A - Overflowing

B - Overtopping

C - Breach

A. Overflowing or overtopping scenarios

B. Breach scenario

Ai. Selection of the study site

GIS : Analysis of ancient maps and photographs

Reliability for washover detection :

- Back barrier environment
- Non anthropised
- Hit by storms

Aii. Analyse 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

«Wet foreshore» environment of the back barrier lowland area

Compact sediments
Vibracore corer
Higher depths

Wet sediments
Beeker 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

Map of the Brittany region in France, showing the coastline and major cities. The map includes labels for Quimper, Lorient, Vannes, Redon, Saint-Nazaire, Nantes, and Rennes. It also shows the Bay of Bourgneuf, the Bay of Quiberon, and the Vilaine river. A scale bar indicates 20 and 40 km. An inset map shows the location of the study area within France.

name of sample and measured Carbon-14 date

Bittium reticulatum shell dated, datation not preserved for age depth modelling

date cal y BP of disturbance estimated with age depth modeling

Location of the study :