Fluvial response to the last Holocene rapid climate change in the Northwestern Mediterranean coastlands


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A B S T R A C T
The variability of fluvial activity in the Northwestern Mediterranean coastal lowlands and its relationship with modes of climate change were analysed from the late 9th to the 18th centuries CE. Geochemical analyses were undertaken from a lagoonal sequence and surrounding sediments in order to track the fluvial inputs into the lagoon. An index based on the K/S and Rb/S ratios was used to evidence the main periods of fluvial activity. This index reveals that the Medieval Climate Anomaly (MCA) was a drier period characterized by a lower fluvial activity, while the Little Ice Age (LIA) was a wetter period with an increase of the river dynamics. Three periods of higher than average fluvial activity were evidenced at the end of the first millennium CE (ca. 900–950 cal yr CE), in the first half of the second millennium CE (ca. 1150–1550 cal yr CE), and during the 1600s–1700s CE (ca. 1650–1800 cal yr CE). The comparison of these fluvial periods with other records of riverine or lacustrine floods in Spain, Italy, and South of France seems to indicate a general increase in fluvial and flood patterns in the Northwestern Mediterranean in response to the climate change from the MCA to the LIA, although some episodes of flooding are not found in all records. Besides, the phases of higher than average fluvial dynamics are in good agreement with the North Atlantic cold events evidenced from records of ice-rafted debris. The evolution of fluvial activity in the Northwestern Mediterranean coastlands during the last millennium could have been driven by atmospheric and oceanic circulation patterns.

1. Introduction

The last cooling transition from the Medieval Climate Anomaly (MCA), or Medieval Warm Period (MWP), to the Little Ice Age (LIA), is referred as a rapid climate change (RCC) (Mayewski et al., 2004; Fletcher and Zielhofer, 2013; Goudeau et al., 2015). It was particularly well studied in the North Atlantic realm (e.g. Mayewski et al., 1997; Grove, 2001; Meeker and Mayewski, 2002; Dawson et al., 2003, 2007; Mann et al., 2009; Trouet et al., 2009, 2012), although the existence of the LIA as a coherently and globally defined climatic period has been questioned (Goosse et al., 2005). This climate change took place in the context of millennial-scale oscillations characterized by the occurrence of cold events in the Northern Hemisphere (Bond et al., 1997, 2001; Wanner et al., 2008, 2011). However, the mechanisms at the origin of this millennial-scale pattern such as variations in atmospheric and oceanic circulation or in solar irradiance have differed from the Early to the Late Holocene (Debret et al., 2007, 2009; Fletcher et al., 2013; Wassenburg et al., 2016; Zielhofer et al., 2017).

In the Western and Central Mediterranean, the MCA and LIA chronology based on oxygen and carbon isotopic records of foraminifera or speleothems can show some age discrepancies, but there is a common point to start the MCA between ca. 600 and 900 cal yr CE, to demarcate the MCA from the LIA between ca. 1200 and 1400 cal yr CE, and to end the LIA in the late 1800s CE (Desprat et al., 2003; Frisia et al., 2005; Lебreiro et al., 2006; Martin-Chivelet et al., 2011; Grauel et al., 2013). In these areas, the hydroclimate change that occurred from the MCA to the LIA was characterized by a decrease of temperature and an increase of humidity patterns (Mayewski et al., 2004; Frisia et al., 2005; Grauel et al., 2013; Goudeau et al., 2015; Mensing et al., 2016; Sanchez-Lopez et al., 2016), as well as by an increase of storm-induced coastal flooding (Dezileau et al., 2011, 2016; Sabatier et al., 2012; Degeai et al., 2015) and runoff or fluvial flood frequency (Moreno et al., 2008, 2012; Wilhelm et al., 2012, 2016; Vannière et al., 2013; Benito et al., 2015a, 2015b). Besides, the reconstruction of the Northern Hemisphere hydroclimate variability over the past millennium shows that the

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hydrological activity was more intense during the colder periods in the NW Mediterranean (Ljungqvist et al., 2016).

In the Western Mediterranean and surrounding areas, elemental analyses were often used to detect the sedimentary layers deposited during fluvial flood or rainfall runoff events (Moreno et al., 2008, 2012; Martin-Puertas et al., 2010, 2011; Wilhelm et al., 2012, 2013, 2016; Vannière et al., 2013; Wirth et al., 2013a, 2013b; Dezileau et al., 2014; Gonzalez-Lemos et al., 2015; Bajard et al., 2016; Sanchez-Lopez et al., 2016). Furthermore, the age model of the sedimentary sequences used to track the fluvial activity can be validated by the compilation of historical texts describing flood events, as applied to the reconstruction of past Mediterranean riverine and storm-induced flooding from fluvial or lagoonal archives (Sabatier et al., 2008; Blanchemanche, 2009; Berger et al., 2010; Dezileau et al., 2011; Degeai et al., 2015).

In this paper, we focus on the study of the evolution of fluvial activity in coastal wetlands during the MCA and the LIA from a lagoonal sedimentary sequence in the NW Mediterranean. The results are compared with sedimentary records or historical written sources of flood and runoff events in order to assess the reliability of our data. A statistical-based comparison with regional and global climate proxy records is then undertaken in order to evidence the climatic mechanisms at the origin of the variability of the fluvial activity in the NW Mediterranean coastlands.

2. Geological setting

The study area is located in the region of Languedoc along the continental shelf of the Gulf of Lions, which extends in the Northwestern

![Image of location maps](https://example.com/figure1.png)

**Fig. 1.** Location maps of the studied area in the Northwestern Mediterranean. (A) Topographical map of the lagoons along the Gulf of Lions; (B) Geological map of the Bagnas pond and the floodplain of the Hérault River in Languedoc.
The catchment of the Bagnas Lagoon is about 10 km sub-elliptical surface exhibits a length of 2 km and a width of 1.5 km.

Amongst the lagoons in Languedoc, the Bagnas pond is located to the south of the Thau Lagoon between the municipalities of Agde and Marseillan (Fig. 1B). It contains a continuous lagoonal sequence of ca. 5 m thick for approximately the last millennium (Fig. 2A). This very shallow lagoon is <1 m-depth and evolves into a maritime marsh. Its sub-elliptical surface exhibits a length of 2 km and a width of 1.5 km. The catchment of the Bagnas Lagoon is about 10 km² and surrounded by the 4 km wide floodplain of the Hérault River to the west and the Thau Lagoon to the east. The maximal elevation is found at 114 m in the south of the Bagnas catchment where is located the Pleistocene scoria cone of the Mont Saint-Loup.

Field observations and geological map show that the catchment is mainly covered with Pleistocene alluvial deposits composed of quartz and basalt gravel and pebbles in a brownish to reddish silty clayey matrix (Berger et al., 1978). Holocene deposits outcrop in the channel of the Bragues River, which drains the Bagnas catchment (Fig. 1B). The sedimentation in the Bagnas Lagoon is supplied by the fluvial inputs from the Bragues River and the Hérault River.

The Hérault’s riverine flux into the Bagnas occurs during flood events by a narrow corridor between the basaltic lava flow of Agde and the western hillside of the Bagnas catchment. The minimum elevation of this corridor is at 0.9 m above sea level and its mean width is of the order of 250 m. The different flooding simulations in the Hérault River valley and surrounding areas reveal that the Bagnas is very sensitive to the Hérault River flood events (Fig. S1). In all tested scenarios (decadal, centennial, and millennial probability of flood), the height of inundation in the Bagnas basin exceeds 2 m. A total of 23 floods with a height of water column higher than or equal to 2 m were recorded on the stream gauge at Agde since the mid-1800s (Table S1). The maximum flood height of 3.65 m was measured in September of 1875 and in December of 1997 (DIREN, 2007; DDTM, 2014).

Besides, the Bagnas pond may have been affected by brief episodes of marine submersion during extreme sea storm surge events, which can lead to reworking of materials from the coastal barrier into the lagoon (Degeai et al., 2015). The Bagnas lagoonal sequence recorded one storm episode during the MCA and five storm episodes during the LIA (Degeai et al., 2015).

3. Material and methods

3.1. Sampling

The lagoonal sedimentary sequence of the Bagnas pond was sampled on a levee in the central part of the lagoon (B1 core, Fig. 1B) with a one-meter long thin wall tube equipped with a 80-mm diameter cutting shoe and mounted on a hydraulic piston corer. The MCA-LIA period is represented on the five upper meters of the Bagnas sequence (Fig. 2A). Additional samples were taken in the catchment of the Bagnas pond, on the coastal sandbars and in the Hérault River floodplain in order to find geochemical tracers of detrital material deposited in the Bagnas basin (Fig. 1B).

3.2. Geochronology

The age-depth model was established from Accelerator Mass Spectrometry (AMS) 14C radiocarbon ages (CDRC Lyon) on terrestrial material (charcoal, fragment of wood) and mollusc shells (Fig. 2, Table 1). To minimize the risk of sampling reworked shells, we have selected only monospecific bivalve lagoonal species (Parvicardium exiguum) in fine sediments with the two valves connected. The calibration of the radiocarbon ages of mollusc shells was achieved by using a reservoir age R(t) determined for the Bagnas Lagoon for the last 3 kyr (Fig. 2B). This reservoir age includes the regional reservoir age offset ΔR from the world ocean 14C age (Stuiver and Braziunas, 1993; Siani et al., 2000; Hughen et al., 2004). It was calculated by the use of five control points (CP1–CP5, Fig. 2B). Thus the evolution of the reservoir age of the B1 sequence is one of the best characterized in the Mediterranean basin for the Late Holocene.

The control points CP1 and CP2 correspond to the 14C ages at respectively 0.6 m depth (or −0.1 m asl) and 0.75 m depth (or −0.25 m asl) (Table 1). The R(t) of CP1 and CP2 was obtained from the comparison of the conventional 14C age of shells at these control points with the 14C age at 0 m asl in the B1 core. This level corresponds to the land emergence of the drilling site that occurred
between 1774 and 1821 CE from the historical maps of the Royal Canal of Languedoc and the Napoleonic cadastre, i.e. between 168 ± 7 and 102 ± 6 14C yr BP from the IntCal13 calibration curve (Reimer et al., 2013). The R(t) of CP3 and CP4 was determined by comparing the conventional 14C age of shells at 2.75 and 3.825 m depth with the respective atmospheric 14C age of wood and charcoal at 2.65 and 3.65 m depth (Table 1). The control point CP5 corresponds to the reservoir age of 600 ± 49 yr BP at the 14C age of 2935 ± 35 BP found for the adjacent lagoon of Thau by Court-Picon et al. (2010). The reservoir age of the lowermost shell at 4.80 m depth was calculated by using a linear regression between the conventional 14C age and the reservoir age of CP4 and CP5 (Fig. 2B).

Finally, the atmospheric 14C age of shells was obtained by subtracting the reservoir age R(t) from the conventional 14C age of shells (Stuiver and Braziunas, 1993; Reimer and McCormac, 2002; Sabatier et al., 2010a). The atmospheric 14C ages of shells, charcoals, and woods were then calibrated using Calib 7.04 and the IntCal13 calibration curve (Reimer et al., 2013). Besides, the most recent intervals of the 2-o confidence level for the six uppermost calibrated ages were not taken into account in the age model, given that all the dated material from the B1 sequence was sampled in lagoonal sediments, while the above-mentioned historical maps show that the drilling site emerged from the lagoon and evolved in an aerial environment from the late 17th/early 18th centuries CE.

### Table 1

<table>
<thead>
<tr>
<th>Laboratory code</th>
<th>Material description</th>
<th>Depth (cm)</th>
<th>14C age (BP)</th>
<th>Reservoir age R(t) in year BP</th>
<th>1-σ ranges of calibrated age and relative probability</th>
<th>2-σ ranges of calibrated age and relative probability</th>
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</thead>
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<tr>
<td>Lyon-11166</td>
<td>Charcoal</td>
<td>365</td>
<td>555 ± 35</td>
<td>0</td>
<td>1322–1347, 1392–1419 cal CE</td>
<td>1306–1363, 1385–1433 cal CE</td>
</tr>
<tr>
<td>Lyon-11178</td>
<td>Parvicardium exiguum</td>
<td>382.5</td>
<td>1350 ± 35</td>
<td>728 ± 49</td>
<td>1298–1323, 1347–1373, 1376–1393 cal CE</td>
<td>1290–1401 cal CE</td>
</tr>
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### 4. Results and discussion

#### 4.1. Geochemical proxies

The age-depth model from the Bagnas lagoon sediments shows that the five upper meters of the B1 sequence encompass the MCA (or MWP) and the IA (Fig. 2). These five upper meters are mainly composed of red to reddish brown clay to silty clay. The mean accumulation rates varied from 1.8 to 3.5 mm yr−1 during the 18th century CE. A multivariate analysis of the geochemistry of detrital sources from the Bagnas catchment, the coastal sandbars, and the floodplain of the Hérault River shows that the fluvial sedimentary inputs deposited in the Bagnas lagoon from the Bragues River and the Hérault River are characterized by relative high contents of K, Rb, Ba, Zn, Zr, As, and Pb (Fig. 3). The origin of these seven elements in the sedimentary sequences from the Western Mediterranean are discussed below in order to select the most suitable elements to track the fluvial activity in the Bagnas lagoon.

The riverine detrital supplies in the Late Holocene marine sediments from the Western Mediterranean are characterized by high values of K and Rb, which are associated with common host mineral phases such as illite, chlorite, K-feldspars, fibrous clays, or smectites (Frigola et al., 2007; Martin-Puertas et al., 2010; Nieto-Moreno et al., 2011; Rodrigo-Gamiz et al., 2011, 2014; Moreno et al., 2012; Martinez-Ruiz et al., 2015). The illite mineral dominates the clay assemblage of the Last Glacial and Holocene sediments from the Gulf of Lions (Bout-Roumazeilles et al., 2007, 2013). On the continent, Sabatier et al. (2010b) evidenced that the clay minerals from the sedimentary sources around the lagoons in northern Languedoc are mainly composed of smectite for the riverine supply and illite for the coastal sandbars.

The K-enriched sediments from the Zonar Lake in southern Spain correspond to erosion in the catchment area (Martin-Puertas et al., 2011). For the same Spanish lake, Rb was considered as an allochthonous component of the lacustrine sediments and was proposed as a possible proxy for erosion in the catchment area (Martin-Puertas et al., 2010). Thus, the Rb/Al ratio was interpreted as a runoffprecipitation proxy reflecting the rainfall variability (Martin-Puertas et al., 2010). Besides, an increase of the K content was evidenced during the Holocene flood events from the lacustrine sequence of the Lake Ledro in the Southern Alps in Italy (Wirth et al., 2013a).
The zirconium present in the Late Holocene marine or lacustrine sediments from the Western Mediterranean is usually hosted in zircon minerals transported by aeolian processes (Martin-Puertas et al., 2010; Nieto-Moreno et al., 2011, 2013a; Rodrigo-Gamiz et al., 2011, 2014; Moreno et al., 2012; Martinez-Ruiz et al., 2015). The zinc is a redox-sensitive element possibly deriving from sulphides in oxygen-poor bottom waters (Moreno et al., 2004; Nieto-Moreno et al., 2011; Rodrigo-Gamiz et al., 2011, 2014; Martinez-Ruiz et al., 2000, 2015). Excess of barium was reported as an indicator of either marine paleoproductivity (Martinez-Ruiz et al., 2000, 2015; Jimenez-Espejo

Fig. 3. Principal component analysis of the geochemistry of detrital sources around the Bagnas lagoon. Each dataset was transformed into a standardized and mean normalized distribution.

Fig. 4. Content of K, Rb, and S, and K/S and Rb/S elemental ratios from the Bagnas B1 sequence with error bars.
et al., 2008; Rodrigo-Gamiz et al., 2011, 2014), endogenic carbonate formation in lacustrine ecosystems (Martin-Puertas et al., 2011), or riverine input (Nieto-Moreno et al., 2011). Besides, arsenic and lead were detected in the Western Mediterranean anthropogenic environmental palaeopollutions during the last millennia (Martin-Puertas et al., 2010; Elbaz-Poulichet et al., 2011; Serrano et al., 2011). From the above considerations, only K and Rb were used in order to evidence the fluvial inputs into the Bagnas Lagoon (Fig. 4). The other elements were discarded because they cannot unambiguously record the fluvial input owing to their potential aeolian, authigenic, or anthropogenic origin in the Western Mediterranean. The elemental concentrations in marine sediments are generally Al-normalized in order to minimize the effects of dilution by calcium carbonate (Thomson et al., 1999; Moreno et al., 2004; Martinez-Ruiz et al., 2015), although some cautions have to be taken when using this common divisor in such normalizations (Van der Weijden, 2002). In coastal lagoons, the sulphur content of sediments was included in elemental ratios used as paleosalinity proxies (Lopez-Buendia et al., 1999; Chagué-Goff et al., 2002). An increase to high S-values can indicate change from freshwater to brackish or saltwater in the lagoonal sequences (Chagué-Goff et al., 2002; Haenssler et al., 2013). Besides, Martin-Puertas et al. (2011) showed that the S-rich sediments in a lacustrine sequence from southern Spain were deposited in a saline lake with gypsum, while sediments enriched in elements associated with alumina-silicates such as K reflect freshwater conditions. Consequently, the high values of the K/S and Rb/S ratios from the Western Mediterranean lagoonal sequences are thought to be representative of freshwater inputs into the lagoon during periods of higher fluvial activity.

4.2. Comparison with historical floods

The K/S and Rb/S elemental ratios are highly correlated ($r = 0.98$) and show similar patterns (Fig. 4). Both ratios were used to calculate the Bagnas fluvial index (BFI) (Fig. 5). The BFI corresponds to the standard scores of the average of the K/S and Rb/S ratios. A positive BFI indicates a higher than average fluvial activity. Major fluvial periods can be demarcated when there is no overlap of the 2-$\sigma$ range of the calibrated radiocarbon age model associated with the positive values of the BFI. The BFI were compared with historical flood events for rivers in Languedoc in order to validate the radiocarbon age model of the B1 sequence (Fig. 5). The riverine flooding in Languedoc was documented for the last centuries from historical written sources (Blanchemanche, 2009; Berger et al., 2010; Larguier, 2011). Amongst these historical archives, the financial cost of flood damage can be considered as an indicator of the occurrence of flood events for the period of 1300–1600 CE, but not of the intensity of floods, given that the value of currency may have changed during this period (Larguier, 2011).

The period of high fluvial activity evidenced from the Bagnas lagoonal sequence between 1660 and 1780 cal yr CE approximately matches the major phase of riverine flooding in Languedoc between 1680 and 1770 CE. The minor peaks of the BFI between 1590 and 1630 cal yr CE are supposed to be related with the peaks of flood frequency and cost of flood damage around 1600 CE. The short episode of high fluvial activity recorded in the Bagnas lagoonal sequence at ca. 1510–1525 cal yr CE could be linked to the brief period of high cost of flood damage between 1530 and 1540 CE. Finally, although the historical data are incomplete for the second half of the 14th century CE (Larguier, 2011), we suggest that the period with a positive BFI between 1350 and 1430 cal yr CE is tied to the period of increase in flood damage between 1350 and 1450 CE.

This comparative analysis with historical floods shows a maximum lag of 20 years between the radiocarbon age model and the calendar years. Hence, the robustness of the age model used for the BFI record would be sufficient to identify the multi-centennial variability of fluvial activity in the Bagnas basin, at least for the five centuries from 1300 to 1800 CE.

4.3. Regional comparison

The fluvial activity recorded in the Bagnas lagoonal sequence (Fig. 6a) was compared with other records in South of France (Fig. 6b–c), northern Italy (Fig. 6d), and Spain (Fig. 6e–g).

Overall, the fluvial activity in the Bagnas pond seems to have been higher during the LIA than during the MWP (Fig. 6a). In the meantime, an increase of riverine input in the marine sediments from the western-most Mediterranean was evidenced during the LIA, while drier environmental conditions with low flood frequency and decreasing fluvial input to marine basins were recognized in the Iberian Peninsula during the MWP (Martin-Puertas et al., 2010; Nieto-Moreno et al., 2011, 2013a; Moreno et al., 2012).

The longest fluvial flood records in South of France (Fig. 6a and c) and northern Italy (Fig. 6d) show a dominant period of low fluvial activity during the MWP from the 9th to the 12th centuries CE. The short
period of higher than average fluvial activity in the Bagnas basin at the end of the first millennium CE (FP3) seems to be concomitant with a slight increase of the flood frequency and runoff events in the Southern Alps and northern Spain (Fig. 6c–e).

The major fluvial period FP2 began in the late MWP and ended in the mid-1500s CE. During this period, multidecadal to centennial periods of increased flooding occurred at ca. 1150, 1350–1400, and 1450–1500 cal yr CE in the southern French Alps (Fig. 6c), at 1250 and
1500 cal yr CE in Northern Italy (Fig. 6f), and at 1200 cal yr CE in central Spain (Fig. 6f). In northern Spain, a general increase in runoff events started from 1300 cal yr CE (Fig. 6e).

The fluvial dynamics show a spatial variability in the NW Mediterranean around 1600 cal yr CE, with a high flood frequency in the southern French Alps (Fig. 6c) and central and northern Spain (Fig. 6f–g), but a low flood frequency and fluvial activity in Languedoc (Fig. 6a), the lower Rhône (Fig. 6b), and northern Italy (Fig. 6d). During the fluvial period FP1 (ca. 1650–1800 cal yr CE), most flooding records from the NW Mediterranean show an increase in flood events, except for the southern French Alps (Fig. 6c) and the northeastern Spanish coast (Fig. 6g).

Besides, the Ca/Ti and K/Ti ratios of fluvial-derived sediments deposited on the inner shelf of the Gulf of Lions recorded two episodes of increased riverine flux from the Rhone River during the last millennium at 935–950 and 1230–1305 cal yr CE (Bassetti et al., 2016). These hydrological events occurred respectively during the fluvial period FP3 and in the first half of FP2.

4.4. Climate vs. anthropogenic forcing

The Late Holocene lacustrine sequences in southwestern Europe show that the variability of the runoff or fluvial activity and the consequent soil erosion was potentially caused by climate and vegetation change or by anthropogenic forcing (Macaire et al., 1997; Degeari and Pastre, 2009; Simonneau et al., 2013; Vannière et al., 2013; Wirth et al., 2013b; Joannin et al., 2014; Schwörer et al., 2014; Beffa et al., 2016; Wilhelm et al., 2016). In the case of the Bagas lagoon, these forcing mechanisms have been tentatively deciphered from paleobotanical and geochemical data (Fig. S2). In Languedoc, the variations in the seed concentration of grassland or cultivated plants can reflect vegetation change and human impact on the environment (Bouby et al., 2013; Figeurial et al., 2015). The content of these plants is very low in the Bagas B1 sequence, except for the samples at the turn of the 17th and 18th centuries CE, which occurred, however, during years of low or moderated fluvial activity (Fig. S2). Besides, the lead anomalies recorded in the lagoonal sequences from Languedoc during the last millennia could be related to anthropogenic pollutions caused by human activities (Elbaz-Poulitich et al., 2011). The curve of lead concentration in the B1 sequence shows sharp peaks at 1250, 1450–1500, and 1600 cal yr CE. These Pb anomalies also arose during years of low or moderated fluvial activity.

Consequently, the fluvial activity recorded from the Bagas lagoonal sequence would result mainly from climate change and variability of precipitation patterns rather than anthropogenic forcing and vegetation change due to human land use, which probably plays a secondary role in this case.

4.5. Climate mechanisms

Most modern rivers from Languedoc have a typical Mediterranean regime characterized by flash flood events due to large amounts of precipitation that can accumulate over several days (Dezieuleau et al., 2014). The atmospheric disturbances created by warm air from the Mediterranean Sea and cold air from the Atlantic or northern Europe are reinforced by the relief of the Massif Central (Fig. 1A).

The main periods of high fluvial activity in the NW Mediterranean coastlands were generally synchronous with the periods of high production of ice-rafted debris (IRD) in the North Atlantic (Fig. 6h–i), which signal the occurrence of cooling events in the Northern hemisphere (Bond et al., 1997, 2001). Frigola et al. (2007) suggested that a rapid response of the Mediterranean thermohaline circulation to climate change in the North Atlantic could be confirmed by the synchronism between the abrupt events recorded from the Minorca sediment drift in the Western Mediterranean and the Holocene cooling events in the North Atlantic. In particular, the last Minorca abrupt event M0 occurred during the LIA synchronously with the last Holocene cold event evidenced by the North Atlantic drift-ice record from Bond et al. (1997, 2001).

In parallel to the evolution toward higher fluvial dynamics during the LIA, the NW Mediterranean lagoonal sequences recorded a lower (higher) storminess activity during the MCA (LIA) (Dezieuleau et al., 2011; Sabatier et al., 2012; Degeari et al., 2015). In the central Mediterranean, the LIA was a relatively humid and cool period with humid summers and winters (Goudeau et al., 2015), while periods with high flood frequency coincided with cool summer temperature in the European Alps over the last 2500 years (Glur et al., 2013). The consecutive cold winters in Europe during the LIA seem to be related to an anomalous high SLP system in the eastern North Atlantic, which corresponds to a negative phase of the East Atlantic (EA) pattern (Moffa-Sanchez et al., 2014; Sanchez-Lopez et al., 2016). These frequent and persistent atmospheric blocking events modified the flow of the westerly winds (Moffa-Sanchez et al., 2014).

The negative state of the EA mode enhances the heat loss across the Mediterranean basin and generates a cold and dry northerly airflow from continental Europe, which leads to a mean air temperature cooling of around 1 °C close to the NW Mediterranean coastal area (Josey et al., 2011). In the Gulf of Lions, a northerly cold and dry wind, the so-called Mistral (Fig. 1A), blows at all seasons and causes an intense surface water cooling (Sicre et al., 2016). The Mistral is favoured by anticyclonic blocking over the northeastern Atlantic, i.e. a synoptic configuration described by a negative EA pattern (Najac et al., 2009; Sicre et al., 2016).

Sicre et al. (2016) and Jalali et al. (2016) evidenced that the sea surface temperature (SST) in the Gulf of Lions were on average warmer during the MCA than fluctuated strongly during the LIA from cold extremes to abrupt warming (Fig. 6j). Sicre et al. (2016) suggested that the coldest decades of the LIA were likely caused by phases of prevailing negative EA mode associated with atmospheric blocking over the North Atlantic leading to an intensified and cold Mistral wind to blow over the NW Mediterranean.

The study of instrumental data for the last decades evidenced that the EA pattern has a dominant influence on the heat budget of the Western Mediterranean Sea while the NAO plays only a secondary role (Josey et al., 2011). Moreover, the relationship between the δ18O precipitation and the NAO was affected by the concomitant state of the EA pattern (Comas-Bru et al., 2016). In the Western Mediterranean, previous studies evidently evidenced that drier (wetter) periods during the MCA (LIA) were synchronous with positive (negative) phases of the NAO (Nieto-Moreno...
et al., 2011, 2013a, 2013b; Moreno et al., 2012; Wassenburg et al., 2013; Mensing et al., 2016; Sanchez-Lopez et al., 2016), based on the NAO proxies from Trouet et al. (2009), Olsen et al. (2012), and Baker et al. (2015). The Bagas record shows a general increase in fluvial activity from the MCA to the LIA, which agrees with the above relationship between humid climatic conditions in the Western Mediterranean and a predominant negative phase of the NAO during the LIA. However, the period of high fluvial activity between ca. 1200 and 1400 cal yr CE appears to be associated with positive values of NAO indexes (Fig. 6k-m), which could support the hypothesis of a complex interplay between the EA and NAO climate modes.

5. Conclusion

Environmental change can impact the variability and intensity of river flood events, and it is challenging to assess the origin of fluvial dynamics in order to evidence the respective role of external forcing and internal mode of climate variability driving the continental hydrological activity. The multi-centennial oscillation of fluvial activity in the NW Mediterranean coastallands during the last millennium was studied from the sediments deposited in the Bagas lagoon in Languedoc. The investigated period highlights the variation in fluvial activity during the transition from the Medieval Climate Anomaly to the Little Ice Age, also known as the last Holocene rapid climate change.

A principal component analysis of the detrital sources in the Bagas catchment was used to decipher the riverine and marine inputs into the lagoon. Geochemical analyses of the Bagas lagoonal deposits was then undertaken in order to determine the episodes of strengthened fluvial inputs into the lagoon. A fluvial index was calculated from the K/S and Rb/S ratios. The sedimentary sources around the Bagas lagoon, as well as the marine or lacustrine sequences in the NW Mediterranean, show that the high values of K and Rb are associated with terrigenous supply from fluvial fluxes, while the variation of the S content may be representative of the water salinity in the lagoon. Consequently, the high values of the Bagas fluvial index (BFI) are indicative of an increase of the fluvial fluxes in the Bagas catchment, which led to freshwater supplies in the lagoon.

The BFI reveals three periods of higher than average fluvial activity at ca. 900–950, 1150–1150, and 1650–1800 cal yr CE. The comparison with other records in Spain, Italy, and South of France suggests that there was a general increase in floods in the NW Mediterranean from the Medieval Climate Anomaly to the Little Ice Age. This evolution is in agreement with the good correspondence between the periods of high fluvial activity evidenced from the BFI and the phases of high production of ice-raftered debris during cooling events in the North Atlantic.

Besides, the variability of the fluvial activity in the NW Mediterranean during the last Holocene rapid climate change may have been driven by internal modes of atmospheric and oceanic changes such as the East Atlantic pattern, the North Atlantic Oscillation, and the thermohaline circulation. Nevertheless, further studies of these patterns such as the East Atlantic pattern, the North Atlantic Oscillation, and the thermohaline circulation. Nevertheless, further studies of these patterns as well as the variability of the Bagas fluvial index might evidence from the BFI and the phases of high production of ice-raftered debris during cooling events in the North Atlantic. Other records in Spain, Italy, and South of France suggest that there was a general increase in floods in the NW Mediterranean from the Medieval Climate Anomaly to the Little Ice Age. This evolution is in agreement with the good correspondence between the periods of high fluvial activity evidenced from the BFI and the phases of high production of ice-raftered debris during cooling events in the North Atlantic.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gloplacha.2017.03.008.

References


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