Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

Climate of the Past Discussions
Open Access
EGU

Extreme storms during the last 6,500 years from lagoonal sedimentary archives in Mar Menor (SE SPAIN)

Dezileau L. *[,1], Pérez-Ruzafa A.[2], Blanchemanche P.[3], Degeai J.P.[3], Raji O.[1,4], Martinez P.[5], Marcos C.[2] and Von Grafenstein U.[6]

[1]{Université de Montpellier, Geosciences Montpellier, CNRS, UMR 5243}

[2]{Universidad de Murcia, Departamento de Ecologia e Hidrologia, Regional Campus of International Excellence Campus Mare Nostrum, Murcia 30100, Spain}

[3]{Université Montpellier 3, Laboratoire d'Archéologie des Sociétés Méditerranéennes, CNRS, UMR 5140}

[4]{Department of Earth Sciences, Université MohammedV-Agdal, Rabat, Morocco}

[5]{Université Bordeaux 1, EPOC, CNRS, UMR 5805}

[6]{Laboratoire des Sciences du Climat et de l'Environnement, CNRS/CEA, Saclay}

* Correspondence to : laurent.dezileau@gm.univ-montp2.fr

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

Climate of the Past Discussions
Open Access
EGU

21

22 Abstract

23 Amongst the most devastating marine catastrophes that can occur in coastal areas, are storms and
24 tsunamis, which may seriously endanger human society. Many such events are known and have
25 been reported for the Mediterranean, a region where high-frequency occurrences of these extreme
26 events coincides with some of the most densely populated coastal areas in the world. In a
27 sediment core from Mar Menor Lagoon (SE Spain), we discovered eight coarse grained layers
28 which document marine incursions during periods of intense storm activity or tsunami events.
29 Based on radiocarbon dating, these extreme events occurred around 5250, 4000, 3600, 3010,
30 2300, 1350, 650 and 80 years cal B.P.. No comparable events have been observed during the 20th
31 and 21th centuries. The results indicate little likehood of a tsunami origin for these coarse grained
32 layers, although historical tsunami events are recorded in this region. These periods of surge
33 events seem to coincide with the coldest periods in Europe during the late Holocene, suggesting a
34 control by a climatic mechanism for periods of increased storm activity. Spectral analyses
35 performed on the sand % revealed four major periodicities of 1228 ±327, 732 ±80, 562 ±58, and
36 319 ±16 yr. Amongst the well-known proxies that have revealed a millennial-scale climate
37 variability during the Holocene, the ice-rafted debris (IRD) indices in North Atlantic developed
38 by Bond et al. (1997, 2001) present a cyclicity of 1470 ±500 yr, which matches the 1228 ±327 yr
39 periodicity evidenced in the Mar Menor lagoon, considering the respective uncertainties on the
40 periodicities. Thus, an in-phase storm activity in Western Mediterranean is found with the coldest
41 periods in Europe and to the North Atlantic thermohaline circulation. However, further
42 investigations, such as additional coring, high-resolution coastal imagery, are needed to better

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

43 constrain the main cause of these multiple-events.

44

45

46

47 Keywords: coastal lagoons, storm, tsunami, Mediterranean Sea, Late Holocene.

48

49

50 1. Introduction

51 In the last century the Mediterranean coastal zones have undergone a considerable development
52 and the coastal hazards incidence has significantly increased. The coastal zones are exposed to
53 flooding and coastal erosion processes, and are highly vulnerable to extreme events, such as
54 storms, cyclones or tsunamis, that can cause significant losses (Seisdedos et al., 2013).
55 Mediterranean intense storms and cyclones are rare meteorological phenomena observed in the
56 Mediterranean Sea. Different climatological and meteorological works in the western
57 Mediterranean area show that extreme storms and cyclones show a complex variability in the
58 sense of non-uniform spatial and temporal patterns (Trigo et al., 2000; Lionello et al., 2006;
59 Gaertner et al., 2007). This is in partly due to the lack of a clear large scale pattern which may be
60 expeted when dealing with intense events, as the number of events is low with irregular intensity
61 and intervals. More long-term observations or paleo-reconstructions in different area of the
62 western Mediterranea are needed. Tsunamis are known to occur in the Mediterranean Sea where
63 all types of sources-earthquakes, volcanic eruptions and landslides from the continental margins
64 are active. There are evidences of intense tsunamis during the historical and pre-historical period,
65 especially in the tectonically more active eastern Mediterranean (e.g., Kelletat and Schellmann,

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

66 2002 ; Morhange et al., 2006). The western part of the basin has also been reported as tsunami-
67 exposed. Historic events have been reported from the Algerian coast and tsunami propagation has
68 been modelled (Alvarez-Gomez et al., 2011). Geomorphic evidence of ancient tsunami impacts
69 has also been documented (Maouche et al., 2009). A long-term record of tsunami and storm
70 activity on time scales of centuries to millennia is especially important in understanding the
71 temporal variability of these extreme events.
72
73 This study focuses mainly on the Murcia province in Spain (Figure 1). This
74 Mediterranean coast is sensitive for the risks of submersion during extreme events. We propose
75 to use a high-resolution geochemical and sedimentogical approach to reconstruct past surge
76 events in the Mar Menor lagoon, and then confront our results with extreme historical coastal
77 events in the western Mediterranean.
78

79 2. Study site

80
81 The Mar Menor lagoon is the largest lagoon of the Spanish Mediterranean coast, located at the
82 SE of the Iberian Peninsula, in the region of Murcia in the area called Campo de Cartagena basin
83 (Lat. 37.786129, Lon. 0.810450, Figure 1). This coastal lagoon occupies an area of
84 approximately 135 km^2 with an average depth of 3.6 m. This lagoon is separated from the
85 Mediterranean sea by La Manga, which is a sandy barrier of 20 km long, between 30 and 500 m
86 wide and less than 3 m above sea level. This sandy barrier is crossed by five, more or less
87 functional, channels or "golas". The Campo de Cartagena Basin represent 1,440 km^2, with an
88 elevations ranging from the sea level to 1065 m, surrounded by the Mediterranean sea to the East,

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

89 the anticline of Torrevieja to the North and the Cartagena-La Unión mountain range to the south.
90 This basin is filled by sediments from early Miocene to quaternary. The major lithologies are
91 sand, silt, clay conglomerate, caliche and sandstone (Quaternary); marl, conglomerate and
92 gypsum (Miocene, Pliocene) (Jiménez-Martinez et al, 2012). The lagoon and the northern salt
93 marshes of San Pedro are protected for their ecological importance (Special Protected Area of
94 Mediterranean Interest, Natura 2000 network and Ramsar). The area is impacted by residual past
95 mining activity, agricultural activities (intensive fruits and vegetable production), and urban
96 growth coupled with touristic development since 1956 (Pérez-Ruzafa et al., 1987; 1991; 2005).
97 Most of La Manga area is urbanized, a population of 10,000 inhabitants live here all year long,
98 and growing to ~ 200,000 habitants during summer. High population density and low level
99 topography makes the area very sensitive to the impact of climate change and sea level rise. Mar
100 Menor lagoon is considered as one of the Spanish coast most threatened site by the mean sea
101 level rise and possible increase of extreme climatic events.
102
103

104 3. Materials and methods

105

106 3.1 Core material

107

108 A 4-m-long piston core (MM2) was collected in the Mar Menor lagoon in September 2011
109 (Figure 1) with the UWITEC© gravity coring platform (Laboratoire des Sciences du Climat et de
110 l'Environnement and University of Chambery) using a simplified piston corer of 2 m length and
111 83 mm inner diameter. Two consecutive sections (0m to 2 m and 2m to 4m sediment depth,

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

112 respectively, were cored from a first position followed by a third section (1m to 3m) from a
113 position ca. 1 m apart to cover the technical hiatus between the first two sections. MM2 core was
114 collected at 4 m below sea level.
115
116 3.2 Physical measures
117
118 Back to the laboratory, the structure of the sediment was studied using the Scopix X-ray scanning
119 (EPOC, University of Bordeaux 1) and photographed. This was complemented by granulometric
120 analyses on contiguous 1-cm samples using a Beckman-Coulter LS13320 laser diffraction
121 particle-size analyser (Géosciences Montpellier). XRF analysis were performed on the surface of
122 split sediment core MM2 every 0.5 cm using a non-destructive Avaatech core-scanners (EPOC,
123 Université Bordeaux 1). The split core was covered with a 4 μm thin Ultralene to avoid
124 contamination. Geochemical data was obtained at different tube voltage, 10 kV for Al, Si, S, Cl,
125 K, Ca, Ti, Mn, Fe and 30 kV for Zn, Br, Sr, Rb, Zr (Richter et al., 2006).
126
127
128 3.3 Macro-fauna
129
130 To study mollusc shells, samples were taken every 2 cm and sieved at 1mm. Individuals were
131 determined to the lower taxonomic level possible (species or genera) and counted. Assemblage
132 structure was estimated by mean of species richness (S), taxon abundance (n_i) and total
133 abundance (N).
134

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

135 3.4 Geochronology

136

137 The chronology of core MM2 was carried out using ^{137}Cs and ^{210}Pb method on a centennial time-
138 scale by gamma spectrometry at the Géosciences Montpellier Laboratory (Montpellier, France).
139 ^{14}C analyses were realized on mollusk shells at the Laboratoire de Mesure on ARTEMIS in CEA
140 institute at Saclay. These measurements were obtained from monospecific samples of
141 *Cerastoderma glaucum* at each level. ^{14}C ages were corrected for reservoir age (see Sabatier et
142 al., 2010 for method) and converted to calendar years using the computer program OxCal v4.2
143 (Bronk Ramsey, 2001, 2008) at two standard deviations (see chapter 4.3).

144

145 3.5 Spectral analyses

146 Cyclic patterns in the Mar Menor lagoonal sequence were studied from spectral analyses by using
147 several methods in order to reduce possible biases of a single method (Desprat et al., 2003). We
148 used the maximum entropy method (MEM) and the multi-taper method (MTM). The MEM
149 selects the spectrum with the highest entropy, which represents the least biased estimate for the
150 given information, or put in other terms, the maximally noncommittal with regard to missing
151 information (Harremoës and Topsoe, 2001). The spectrum obtained by this method shows an
152 excellent frequency resolution with sharp spectral features (Berger et al., 1991; Dubar, 2006;
153 Pardo-Iguzquiza and Rodriguez-Tovar, 2006). The MTM is a non-parametric method that (1)
154 reduces the variance of spectral estimates by combining multiple orthogonal windows in the time
155 domain before Fourier transforming, and (2) provides a narrowband F-test useful to assess the
156 significance of periodic components (Thomson, 1982, 1990; Percival and Walden, 1993).

157

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

158

159 4. Results

160

161 4.1 Core description

162

163 Photo, X-ray images, X-ray fluorescence and high-resolution grain-size analysis for MM2
164 indicate several thin, coarse-grained layers preserved within mud sediments. These coarse layers
165 are constituted by a mixture of shell debris and siliciclastic sand and have basal boundaries easily
166 identified from a change to coarser grain size and darker color on X-ray images (Figure 2).
167 Theses coarser grain size layers indicate "energetic" events, relative to the background
168 sedimentation (i.e mud facies) and are probably link to washover events (storm or tsunami).

169

170 4.2 Sediment source

171 The terrigenous fraction in Mar Menor lagoon is mainly controlled by terrestrial and marine
172 inputs. The core (MM2) was collected at 800 m from the sandy barrier and more than 8,500 m
173 from the different river mouths. On our study site, watercourses are the source of fine fraction
174 dispersed in the lagoon and marine inputs are characterized by coarse sands. The lagoon barrier
175 beach sand samples show unimodal distribution with a mean grain population ranging between
176 160 and 653 μm. The percentages of this grain population decrease from the sea to the lagoon in
177 surface samples. The evolution with depth of this population displays eight main changes in
178 MM2 core revealed by the grey bands on Figure 3. The main peaks of coarse sands occur around
179 5, 40, 60, 150, 170, 210, 255 and 290 cm (Figure 3).

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

Major chemical elements using the ITRAX core scanner provide high-resolution palaeoenvironmental information in a variety of sedimentary environments. In the present study we chose the ratio Si/Al and Zr/Al that better discriminate between the two source areas, marine vs drainage basin (Dezileau et al., 2011, Sabatier et al., 2012; Raji et al., 2015). The high Zr/Al ratio value is probably explained by the presence of heavy minerals (like zircon) from marine sand and the high Si/Al ratio is due to Quartz minerals in marine sand. Si/Al and Zr/Al ratios have the same evolution with depth, especially in the first three meters of the sediment core (Figure 4, shaded bands).

A fundamental step in the core analysis is to establish criteria to correctly identify overwash layers. We systematically used grain size variation and geochemical signatures (i.e. Si/Al and Zr/Al ratios). As the background sedimentation shows a fine silt facies, we consider values higher than 20% of the 63μm fraction as outlining "high energy" events (figure 3). Positive anomalies of the Si/Al and Zr/Al ratios above 12 and 2,5 respectively (Figure 4), indicate a higher relative contribution of marine sand. The marine origin of these "high energy" events was also highlighting through molluscs identification (*Bittium recticulatum* and *Rissoa ventricosa*) (see chapter 4.3, Figure 6).

4.3. Faunal variations

Macro-fauna analyses are a good indicator of a lagoon paleo-isolation state because species develop in different ranges of salinity, temperature and oxygenation and colonization of marine species into the lagoon environments depends of the isolation degree and connectivity between

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

both systems. Taxon richness range between 0, at depths higher than 365 cm, and 18 reached at a 260 cm depth

The impoverished depths, after the earlier azoic one, corresponds to 302-362 cm with a mean of 4.76 taxons, 72-78 cm with a mean of 5 taxons and 30-36 cm with a mean of 5.7 taxons. The depths with highest species richness are from 192 to 266 cm and from 81 to 186 cm. These depths would correspond to a higher marine influence. Above 150 cm take place a progressive impoverishment in the number of species reflecting a progressive isolation of the Mar Menor from the Mediterranean, with punctual picks in species richness, probably related to episodes of rupture of the sandbar (figure 5).

The most frequent species, present in more than 50% of the samples, excluding the azoic depths, are *Corbula gibba* (Olivi, 1792) (92.4%), *Bittium reticulatum* (da Costa, 1778) (84.9%), *Tellina* sp (78.9%), Pusillina (=Rissoa) lineolata (Michaud, 1830) (78.2%), *Acanthocardia paucicostata* (G. B. Sowerby II, 1834) (77.3%), *Cerastoderma glaucum* (Bruguière, 1789) (71.4%), *Anthalis* sp (63.9%), Abra sp (74.8%), *Loripes lacteus* (Linnaeus, 1758) (61.3%) and *Philine aperta* (Linnaeus, 1767) (59.7%). Hydrobiidae sp appear in the 47.9 % of the samples, but is restricted to the upper 150 cm, constituting the 61.5% of the assemblage at 15 cm depth section. This specie is a typical lagoon inhabitant. By its part, *Conus ventricosus* (Gmelin, 1791) appear only in the 13.5% of the samples, comprised between 162 and 293 cm depth, reaching dominance up to 7% of the assemblage, but characterize typical marine conditions, reinforced with the presence of abundant seaurchin spines.

Data of Figure 6 show a main change in mollusc population at around 150-130 cm characterized by an increase of the most typical lagoonal specie *Hydrobia acuta*, whereas the abundance of species with marine affinity like Pusillina (=Rissoa) lineolata and Conus ventricosus decrease

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

(Figure 6). This main change in mollusc population also reveals a major palaeoenvironmental change around 150 cm, this faunal variation is probably due to a change in environmental context from a lagoonal environment, with a marine influence to a more isolated environment.

4.3 Age model

The chronology of core MM2 has been established for the last 6,500 years BP using ^{137}Cs, ^{210}Pb and (AMS) ^{14}C dates on monospecific shell sample, geochemical analysis of mining-contaminated lagoonal sediments and paleomagnetism (Dezileau et al., in prep). Radiocarbon age of lagoonal and marine organisms is usually older than the atmospheric ^{14}C age and has to be corrected by substraction of the "reservoir age" (Siani et al., 2001; Reimer and McCormac 2002; Zoppi et al., 2001; Sabatier et al., 2010; Dezileau et al., 2015). We evaluated the modern reservoir ^{14}C age by comparing an age derived from ^{137}Cs, ^{210}Pb data and geochemical analysis of mining-contaminated lagoonal sediments with an AMS ^{14}C age of a pre-bomb mollusc shell (see Sabatier et al., 2010 for method). The reservoir age (R(t)) with a value of 1003 ± 62 ^{14}C yr is 600 yr higher than the mean marine reservoir age (around 400 yr) and may be explained by an isolation of the lagoon from the Mediterranean Sea. This high reservoir age value is similar to other estimates in different Mediterranean lagoons (Zoppi et al., 2001; Sabatier et al., 2010).

^{14}C ages were also obtained on a series of Holocene mollusc shells sampled at different depths of the ~2-m-long core MM2 (Figure 7, Dezileau et al., in prep). Comparing paleomagnetic ages and ^{14}C ages versus depth, we show that the reservoir age has changed in the past and was lower (505 yr) than the modern value (1003 yr, Dezileau et al., in prep). This change was also observed in another Mediterranean lagoons (Sabatier et al., 2010). In the Mar Menor lagoon, Linear

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

248 Sedimentation Rate (LSR) obtained for the core MM2 suggest a low mean accumulation rate of
249 0.6 mm.yr^{-1}, from the base to the top of the core.
250

251 5. Discussion

252

253 5. 1 Site sensitivity to overwash deposits

254

255 Site sensitivity to overwash deposits may result from different factors such as barrier-elevation,
256 sediment supply, inlet, and change in sea level (Donnelly and Webb, 2004; Scileppi and
257 Donnelly, 2007, Dezileau et al., 2011). An increase of sea level induces a shift of the barrier
258 landward. Therefore, an increase of sand layers in a sediment core may be due to a sea level
259 change. In the Mediterranean Sea, the sea level has remained more or less constant during the last
260 5000 yrs (< 2m, Pirazzoli, 1991; Lanbeck and Bard, 2000). Before this period, a significant
261 change in sea level occurred. During the first phase of lagoonal sediment deposit (between 6500
262 and 5000 years Cal B.P), the number of sand layers is low. The sandy barrier was probably at
263 more than 1 km from the present position and may probably explain why sand layers are not
264 observed. The strong increase in coarse grain layer frequency after ca. 5400 years Cal B.P can be
265 explained by a migration of the barrier up to a position, which is not far away from the present
266 position.
267 Fauna content reveals a major palaeoenvironmental change around 150 cm (i.e. 2400 yr cal B.P.,
268 Figure 6). Such change is probably due to a shift from a leaky lagoon to a restricted and choked
269 lagoon environment, sensu Kjerfve (1996). Thus, after this date (i.e 2400 yr cal B.P.) the barrier

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

was continuous with sometimes inlet formation in relation to intense overwash events. To conclude, between 2400 yr cal B.P. and today, the lagoon is isolated from the sea. During this period the general morphology of the lagoon and the barrier have not changed drastically. Between 5400 yr cal B.P. and 2400 yr cal B.P. the lagoon was less isolated from the Mediterranean Sea, typical from a leaky lagoon environment. During this period, fine sediments were accumulated. The lagoon experienced quiescent sedimentation probably protected behind a sandy barrier more or less continuous. The presence of sand layers may be interpreted by intense overwash events. Between 6500-5400 yrs BP, the morphology of the lagoon and the barrer is different. The position of the sandy barrier was far away from the present position. In that case, the number and the intensity of surge events recorded are not comparable to the upper part of the core (Figures 3 and 8). During this period, the lack of sand layers does not mean any surge events but simply they are not recorded.

5. 2 Storms or tsunamis?

The Zr/Al and Si/Al ratios of sandy layers are above 12 and 2,5 respectively (Figure 8), indicating a higher relative contribution of marine sand. The marine origin of these “high energy” events was also highlighting through molluscs identification (*Bittium recticulatum* and *Rissoa ventricosa*, Figure 8). This multiproxy approach suggests the occurrence of eight period of increase of overwash events reflecting perturbations of coastal hydrodynamic due to paleostorm or paleotsunami events (grey band on Figure 8).

Both tsunamis and storms induce coastal flooding. It is difficult to discriminate storm and tsunami deposits (Kortekaas and Dawson, 2007; Morton et al., 2007; Engel and Brückner, 2011). The coarse-grained layers observed in the core MM2 could be a signature of tsunamis or storms.

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

Records of historic and contempory coastal hazards (storms and tsunamis) may help us to determine which historical events left a sedimentological signature in the Mar Menor lagoon.

In textual archives, extreme storm events were described due to the strong economic and societal impact of these events (Seisdedos et al., 2013). For the last 200 years, 27 storms affected the coast of Murcia. Among all of these storms, some seems to be more catastrophic. The storm of November first, 1869 produced the wreckage of a numerous ships in the Torrevieja harbour. Between Isla Grosa and San Pedro del Pinatar more than thirty-five ships were collapsed and crashed. In the Mar Menor lagoon, fifty fishing boats were destroyed and thrown to the ground. Wave heights associated with this storm were estimated higher than 8 m. This severe storm also affected La Union and Cartagena cities destroying houses and paralyzing its for many days. From the hydrological and ecological point of view, the 1869 storm led to drastic and persistent changes in the salinity of the lagoon and to the colonization of new species of marine origin (Navarro, 1927), affecting also the fisheries in the lagoon (Pérez-Ruzafa et al., 1991). There are historical references to some other storms that led to the breaking of the sandbar in the Mar Menor (in 1526, 1676, 1687, 1690, 1692, 1694, 1706, 1762, 1765, 1787, 1795) (Jiménez de Gregorio, 1957; Pérez-Ruzafa et al., 1987), although there is no information about their magnitude, the extent and exact location of the breaks and their impact on the lagoon environment. Some ups and downs in the number of species observed in Figure 5 could be related to these events, but an extensive and detailed study would be required for understanding the relationship between the frequency, duration and intensity of the storms and the spatial and temporal scales of their effects and their impact on the fossil record.

Different tsunamis occurred on the Spanish coasts, they are more catastrophic and intense on the Atlantic than on the Mediterranean side (Alvarez-Gomez et al., 2011). In the occidental part of

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

316 the Mediterranean area, there are historical disastrous tsunami events recorded. In Northern
317 Algeria, in addition to the 2003 tsunami, the first well documented event remains the tsunami in
318 the Djijelli Area associated with the seismic event of August 1856, which was also recorded in
319 the Balearic Islands (Maouche et al., 2009). In the Alboran Sea area some reports mention
320 tsunamis that affected the African and Spanish coasts in 1790, 1804 and 1522 (IGN, 2009). For
321 an earthquake magnitude 6.8 (2003 Boumerdes earthquake) with its epicenter calculated at 15 km
322 offshore of Zemmouri, Wang and Liu (2005) show a regional character of the tsunami
323 phenomenon from a numerical simulation. The tsunami propagating from the Algerian coast to
324 the Murcia Province has a lesser amplitude and the tsunami wave height is very low (< 25 cm).
325 The Boumerdes-Zemmouri tsunami did not induce any damage along the province of Murcia and
326 the La Manga sandbar. Alvarez-Gomez et al. (2011) identified the hazardous sources and the
327 areas where the impact of tsunamis is greater from numerical simulations. From a set of 22
328 seismic tsunamigenic sources, the Maximum Wave Elevation was estimated between 0,5 and 1 m
329 along the South-Eastern Spanish coast. All these historical events have been classified as a
330 magnitude between 1 and 3 in the Tsunami Intensity Scale (on a scale of 6 for a maximum
331 intensity, Maramai et al., 2014). Since these different historical events have a magnitude equal or
332 lower than the Boumerdes-Zemmouri tsunami (3 in the Tsunami Intensity Scale), and that this
333 event did not have affected significantly the La Manga sandbar and the Province of Murcia,
334 considering the available data, historical tsunami events do not seems to be associated to the
335 different sand layers in the Mar Menor lagoon for the last 500 years. From the "Catálogo de
336 Tsunamis en las Costas Españolas", none tsunamis are recorded along the South Eastern coast of
337 Spain from -218 BC to 1756 AD. No information on the existence of tsunamis is recorded over
338 longer periods of time. However, more than 100 boulders were identified along the coastal zone

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

339 of Algiers and Maouche et al. (2009) suggested that the deposition of the biggest boulders could
340 be attributed to tsunami events. The radiocarbon results highlight two groups of boulders dated to
341 around 419 AD and 1700 AD. Although no historical accounts report these events, tsunami
342 events are extremely rare and of low magnitude and cannot be at the origin of the different sand
343 layers in the Mar Menor lagoon.
344 To determine which historical events may let sandy layers, we compared our high-resolution
345 record of past extreme sea events from the core MM2 to the catalogue of historical storm and
346 tsunami events in the area. The first coarse-grained event layer has been dated at 80 cal. BP (i.e.
347 1880 A.D+/-30 years). This sandy deposit could be associated to the storm of November first,
348 1869, recorded in many city archives between Cartagena and Torrevieja and in the Mar Menor,
349 and considered as the most catastrophic storm event in the Province of Murcia for the last 200
350 years. In the core MM2, no sand layers are consistent with the Algerian tsunamis dated to around
351 419 AD and 1700 AD (Figure 8). There is clear evidence that this sand layer is compatible with
352 large storm waves.
353
354 5.3 Storm activity in the context of past climatic changes
355
356 Based on our ^{14}C age model, marine coarse grained event layers occurred around 5250, 4000,
357 3600, 3010, 2300, 1350, 650 and 80 years cal B.P. Except one period dated at 3600 years cal
358 B.P., the seven other periods of most frequent surge events in the Mar Menor lagoon seem to
359 coincide with the coldest periods in Europe during the late Holocene, taking into account
360 chronological uncertainty (Figure 8, Bond et al., 2001). A spectral analysis was performed on the
361 ca. 6.5-kyr time series of the sand percentage from the MM2 sequence. The results show four

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

major frequencies with high spectral power densities and significant F-test values at ca. $8x10^{-4}$, $1.4x10^{-3}$, $1.8x10^{-3}$, and $3.1x10^{-3}$ yr^{-1} (Figure 9A). Considering the full width at half maximum (FWHM) of these peaks on the MTM spectrum, this yields respective periodicities of 1228 ±327, 732 ±80, 562 ±58, and 319 ±16 yr for the MM2 sand % proxy. Multi-centennial to millennial timescale climate variabilities similar to these periodicities have been reported in the literature for the Holocene (Bond et al., 1997, 2001; Langdon et al., 2003; Debret et al., 2007, 2009; Wanner et al., 2011; Kravchinsky et al., 2013; Soon et al., 2014). Amongst the well-known proxies that have revealed a millennial-scale climate variability during the Holocene, the ice-rafted debris (IRD) indices in North Atlantic developed by Bond et al. (1997, 2001) present a cyclicity of 1470 ±500 yr, which matches the 1228 ±327 yr periodicity evidenced in the Mar Menor lagoon, considering the respective uncertainties on the periodicities. When filtering the raw data of the Mar Menor sand % record by a Gaussian filter with a frequency of $8x10^{-4}$ yr^{-1} (1228 years), it appears 6 cycles with a noteworthy enhancement of the cyclic amplitude after 5500 cal yr BP (Figure 9B). The five ascending phases occurring on the 1228-yr filtered curve at ca. 5715/5115, 4525/3945, 3365/2775, 2145/1215, and 575/-35 cal yr BP approximate the high storm activity periods evidenced in the French Mediterranean lagoon of Pierre-Blanche for the last 7000 years (Sabatier et al., 2012).

The origin of the storminess periods evidenced by the spectral analysis in the Mar Menor lagoon can be discussed in the light of previous works mentioning analogous climate variabilities during the Holocene. Bond et al. (1997, 2001) associated the 1470 ±500 yr IRD cycle to a solar forcing, amplified by a change of North Atlantic Deep Water production. Langdon et al. (2003) found a sub-millennial climate oscillation in Scotland possibly related to the North Atlantic thermohaline circulation (THC). Moreover, Debret et al. (2007, 2009) showed a cyclicity of 1500 yr since the Mid-Holocene probably link to an internal forcing due to the THC.

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

386 Concerning the multi-centennial periodicities, Soon et al. (2014) used global proxies to evidence
387 a 500-yr fundamental solar mode and to identify intermediary derived cycles at 700 and 300-yr
388 which could be rectified responses of the Atlantic THC to external solar modulation and pacing.
389 Kravchinsky et al. (2013) found also a 500-yr climate cycle in the southern Siberia presumed
390 driven by increased solar insolation and possibly amplified by other mechanisms. Some authors
391 found a relationship between the ca. 700-yr period and the monsoonal/ITCZ regimes in equatorial
392 Africa (Russell et al., 2003; Russell and Johnson, 2005), southern Asian (Staubwasser et al.,
393 2003), and eastern Arabian Sea (Sarkar et al., 2000), while other authors suggested that the ca.
394 700-800 yr period could be a subharmonic mode derived from the fundamental 1500-year cycle
395 of the THC (Von Rad et al., 1999; Wang et al., 1999). Besides, Rimbu et al. (2004) mentioned a
396 700 yr variability from sea-surface temperature (SST) records in the tropical and North Atlantic.
397 Hence, our results seem to indicate that the Late Holocene multi-centennial variability of the
398 cyclogenesis in Western Mediterranean was steered by both, external (solar) and internal
399 (THC/ITCZ) forcings. Further investigations of additional sequences and high-resolution coastal
400 imagery will be required to assert reliably the origin of these multi-centennial periods in the
401 Mediterranean area.
402

403 7. Conclusion

404 This study provides a 6500-yr high-resolution record of past overwash events using a multi-proxy
405 approach of a sediment core from the Mar Menor lagoon in Spain in the Western Mediterranean
406 Sea. Eight sandy layers are preserved in the core and seems to be associated to periods of
407 increased extreme sea events. The results indicate little likehood of a tsunami origin for these
408 coarse grained layers, although historical tsunami events are recorded in this area. These surge

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

409 events seem to coincide with climatic cold periods in Europe during the late Holocene,
410 suggesting a control by a climatic mechanism for periods of increased storm activity. From the
411 available data, we have identified seven periods of high storm activity at around 5250, 4000,
412 3600, 3010, 2300, 1350, 650 and 80 years cal B.P. Except one period dated at 3600 years cal
413 B.P., the seven other periods of most frequent surge events in the Mar Menor lagoon seem to
414 coincide with the coldest periods in Europe during the late Holocene, taking into account
415 chronological uncertainty. Spectral analyses performed on the sand % revealed four major
416 periodicities of 1228 ±327, 732 ±80, 562 ±58, and 319±16 yr. The origin of the storminess
417 periods evidenced by the spectral analysis in the Mar Menor lagoon can be discussed in the light
418 of previous works mentioning analogous climate variabilities during the Holocene. Our results
419 seem to indicate that the Late Holocene multi-centennial variability of the cyclogenesis in
420 Western Mediterranean was steered by both, external (solar) and internal (THC/ITCZ) forcings.
421 However, further investigations, such as additional coring, high-resolution coastal imagery, are
422 needed to better constrain the main cause of these multiple-events.
423
424

425 Acknowledgments

426

427 The authors would like to thank all participants in the coring expedition, particularly E. Regnier
428 (Technician, LSCE - IPSL, Paris) for his collaboration in the various stages of this study. This
429 study is funded by the MISTRALS PALEOMEX project. We thank the Laboratoire de Mesure
430 ^{14}C (LMC14) ARTEMIS in the CEA Institute at Saclay (French Atomic Energy Commission) for
431 the ^{14}C analyses.

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

References

Álvarez-Gómez, J. A., González, M., and Otero, L.: Tsunami hazard at the Western Mediterranean Spanish coast from seismic sources, Natural Hazards and Earth System Science, 11, 227-240, 2011.

Berger, A., Melice, J.-L., Hinnov, L.: A strategy for frequency spectra of Quaternary climate records. Climate Dynamics 5, 227-240, 1991.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G.: Persistent solar influence on North Atlantic climate during the Holocene, Science, 294, 2130-2136, 2001.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., DeMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G.: A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climates. Science 278, 1257-1266, 1997.

Bronk Ramsey, C., Development of the Radiocarbon calibration program OxCal, Radiocarbon, 43, 355-363, Proceedings of 17th International 14C Conference, 2001.

Bronk Ramsey, C., Deposition models for chronological records, Quaternary Science reviews, 27, 42-60, 2008.

Debret, M., Bout-Roumazeilles, V., Grousset, F., Desmet, M., McManus, J.F., Massei, N., Sebag, D., Petit, J.-R., Copard, Y., Trentesaux, A.: The origin of the 1500-year climate cycles in Holocene North-Atlantic records. Climate of the Past 3, 569-575, 2007.

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

454 Debret, M., Sebag, D., Crosta, X., Massei, N., Petit, J.-R., Chapron, E., Bout-Roumazeilles, V.:
455 Evidence from wavelet analysis for a mid-Holocene transition in global climate forcing.
456 Quaternary Science Reviews 28, 2675-2688, 2009.

457 Desprat, S., Sanchez-Goni, M.F., Loutre, M.-F.: Revealing climatic variability of the last three
458 millennia in northwestern Iberia using pollen influx data. Earth and Planetary Science
459 Letters 213, 63-78, 2003.

460 Dezileau, L., Pérez-Ruzafa, A., Camps P., Blanchemanche P., Grafenstein U., Holocene
461 variations of radiocarbon reservoir ages in the Mar Menor lagoon system, Radiocarbon, in
462 prep.

463 Dezileau, L., Sabatier, P., Blanchemanche, P., Joly, B., Swingedouw, D., Cassou, C., Castaings,
464 J., Martinez, P., and Von Grafenstein, U.: Intense storm activity during the Little Ice Age
465 on the French Mediterranean coast, Palaeogeography, Palaeoclimatology, Palaeoecology,
466 299, 289-297, 2011.

467 Dezileau L**.,** Lehu R., Lallemand S., Hsu S-K., Babonneau N., Ratzov G., Lin A.T., Dominguez
468 S., Historical reconstruction of submarine eartquakes using 210Pb, 137Cs and 241Am
469 turbidite chronology and radiocarbon reservoir age estimation off East Taiwan.
470 Radiocarbon. doi:10.1017/RDC.2015.3, 2016.

471 Donnelly, J. P., Webb III, T., Murnane, R., and Liu, K.: Backbarrier sedimentary records of
472 intense hurricane landfalls in the northeastern United States, Hurricanes and Typhoons:
473 Past, Present, and Future, 58-95, 2004.

474 Dubar, M.: Approche climatique de la période romaine dans l'est du Var : recherche et analyse
475 des composantes périodiques sur un concrétionnement centennal (Ier-IIe siècle apr. J.-C.)
476 de l'aqueduc de Fréjus. ArchéoSciences 30, 163-171, 2006.

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

477 Engel, M., and Brückner, H.: The identification of palaeo-tsunami deposits–a major challenge in
478 coastal sedimentary research, Dynamische Küsten–Grundlagen, Zusammenhänge und
479 Auswirkungen im Spiegel angewandter Küstenforschung. Proceedings of the 28th Annual
480 Meeting of the German Working Group on Geography of Oceans and Coasts, 2011, 22-25,
481 Gaertner, M.A., Jacob, D., Gil, V., Domínguez, M., Padorno, E., Sánchez, E., Castro, M.:
482 Tropical cyclones over the Mediterranean Sea in climate change simulations. Geophysical
483 Research Letters 34. doi:10.1029/2007GL029977, 1-5, 2007.
484 Harremoës, P., Topsoe, F.: Maximum entropy fundamentals. Entropy 3, 191-226, 2001.
485 IGN: Catalogo de Tsunamis en las Costas Espanolas. Instituto Geografico Nacional, www.ign.es,
486 2009.
487 Jimenez de Gregorio, F.: *El Municipio de San Javier en la historia del Mar Menor y su ribera*.
488 Ayuntamiento de San Javier, Murcia, 1957.
489 Kelletat, D., and Schellmann, G.: Tsunamis on Cyprus: field evidences and 14C dating results,
490 Zeitschrift für Geomorphologie, NF, 19-34, 2002.
491 Kjerfve, B.: Coastal lagoons. In Kjerfve B (ed). *Coastal lagoon processes*. Elsevier
492 Oceanography Series 60: 1-8, 1994.
493 Kortekaas, S., and Dawson, A.: Distinguishing tsunami and storm deposits: an example from
494 Martinhal, SW Portugal, Sedimentary Geology, 200, 208-221, 2007.
495 Kravchinsky, V.A., Langereis, C.G., Walker, S.D., Dlusskiy, K.G., White, D.: Discovery of
496 Holocene millennial climate cycles in the Asian continental interior: Has the sun been
497 governing the continental climate? Global and Planetary Change 110, 386-396, 2013.
498 Lambeck, K., and Bard, E.: Sea-level change along the French Mediterranean coast for the past
499 30 000 years, Earth and Planetary Science Letters, 175, 203-222, 2000.

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

500 Langdon, P.G., Barber, K.E., Hugues, P.D.M.: A 7500-year peat-based palaeoclimatic
501 reconstruction and evidence for an 1100-year cyclicity in bog surface wetness from Temple
502 Hill Moss, Pentland Hills, southeast Scotland. Quaternary Science Reviews 22, 259-274,
503 2003.

504 Lionello, P., Bhend, J., Buzzi, A., Della-Marta, P.M., Krichak, S., Jansá, A., Maheras, P., Sanna,
505 A., Trigo, I.F., Trigo, R. : Cyclones in the Mediterranean region: climatology and effects on
506 the environment, in Mediterranean Climate Variability. In: Lionello, P., Malanotte-Rizzoli,
507 P., Boscolo, R. (Eds.), Mediterranean Climate Variability. : Developments in Earth and
508 Environmental Sciences, 4. Elseviered., 324–372, 2006.

509 Maouche, S., Morhange, C., and Meghraoui, M.: Large boulder accumulation on the Algerian
510 coast evidence tsunami events in the western Mediterranean, Marine Geology, 262, 96-104,
511 2009.

512 Maramai, A., Brizuela, B., and Graziani, L.: The Euro-Mediterranean Tsunami Catalogue,
513 Annals of Geophysics, 57, S0435, 2014.

514 Morhange, C., Marriner, N., and Pirazzoli, P. A.: Evidence of Late-Holocene Tsunami Events in
515 Lebanon Z. Geomorphol NFSuppl.-Bd., 146, 81-95, 2006.

516 Morton, R. A., Gelfenbaum, G., and Jaffe, B. E.: Physical criteria for distinguishing sandy
517 tsunami and storm deposits using modern examples, Sedimentary Geology, 200, 184-207,
518 2007.

519 Navarro, F.: Observaciones sobre el Mar Menor (Murcia). Notas y resúmenes del Instituto
520 Español de Oceanografía, Ser. II, 16:1-63, 1927.

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

521 Paillard, D., Labeyrie, L., Yiou, P.: Macintosh program performs time-series analysis. EOS
522 Transactions AGU 77(39), 379-379, 1996.
523 Pardo-Iguzquiza, E., Rodriguez-Tovar, F.J.: Maximum entropy spectral analysis of climatic time
524 series revisited: Assessing the statistical significance of estimated spectral peaks. Journal of
525 Geophysical Research 111, D10102, 2006.
526 Percival, D.B., Walden, A.T.: Spectral analysis for physical applications: multitaper and
527 conventional univariate techniques. Cambridge University Press, New York, 583 p, 1993.
528 Pérez-Ruzafa, A., Marcos, C., Pérez-Ruzafa, I., and Ros, J.: Evolución de las características
529 ambientales y de los poblamientos del Mar Menor (Murcia, SE de España), Anales de
530 Biología, 1987, 53-65,
531 Pérez-Ruzafa, A., Marcos-Diego, C., and Ros, J.: Environmental and biological changes related
532 to recent human activities in the Mar Menor (SE of Spain), Marine Pollution Bulletin, 23,
533 747-751, 1991.
534 Pérez-Ruzafa, A., Marcos, C., and Gilabert, J.: The ecology of the Mar Menor coastal lagoon: a
535 fast-changing ecosystem under human pressure, Coastal Lagoons. CRC Press, Boca Racon,
536 392-421, 2005.
537 Pirazzoli, P. A.: World atlas of Holocene sea-level changes, Elsevier Oceanography Series, 58, 1-
538 280, 1991.
539 Raji, O., Dezileau L., Snoussi M., and Niazi, S.: Extreme sea events during the last millennium in
540 North-East of Morocco. Natural Hazards and Earth System Sciences, 15,203-211, 2015.
541 Reimer P.J., McCormac F.G.: Marine radiocarbon reservoir corrections for the Mediterranean
542 and Aegean seas. Radiocarbon 44(1):159–66, 2002.

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

543 Rimbu, N., Lohmann, G., Lorenz, S.J., Kim, J.H., Schneider, R.R.: Holocene climate variability
544 as derived from alkenone sea surface temperature and coupled ocean-atmosphere model
545 experiments. Climate Dynamics 23, 215-227, 2004.
546 Russell, J.M., Johnson, T.C.: Late Holocene climate change in the North Atlantic and equatorial
547 Africa: Millennial-scale ITCZ migration. Geophysical Research Letters 32, L17705, 2005.
548 Russell, J.M., Johnson, T.C., Talbot, M.R.: A 725 yr cycle in the climate of central Africa during
549 the late Holocene. Geology 31(8), 677-680, 2003.
550 Sabatier, P., Dezileau, L**.,** Blanchemanche, P., Siani, J., Condomines, M., Bentaleb, I., Piques, G.:
551 Holocene variations of radiocarbon reservoir ages in a Mediterranean lagoonal system.
552 Radiocarbon, 52, (1), 91-102, 2010.
553 Sabatier, P., Dezileau, L., Colin, C., Briqueu, L., Bouchette, F., Martinez, P., Siani, G., Raynal,
554 O., Von Grafenstein, U.: 7000 years of paleostorm activity in the NW Mediterranean Sea in
555 response to Holocene climate events. Quaternary Research 2012, 1-11, 2012.
556 Sarkar, A., Ramesh, R., Somayajulu, B.L.K., Agnihotri, R., Jull, A.J.T., Burr, G.S.: High
557 resolution Holocene monsoon record from the eastern Arabian Sea. Earth and Planetary
558 Science Letters 177, 209-218, 2000.
559 Scileppi, E., Donnelly, J.P. : Sedimentary evidence of hurricane strikes inwestern Long Island,
560 NY. Geochemistry, Geophysics and Geosystems 8, Q06011. doi:10.1029/ 2006GC001463,
561 2007.
562 Seisdedos, J., Mulas, J., González de Vallejo, L. I., Rodríguez Franco, J. A., Gracia, F. J., Del
563 Río, L., y Garrote, J. :Estudio y cartografía de los peligros naturales costeros de la región
564 de Murcia. Boletín Geológico y Minero, 124 (3): 505-520, 2013.

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

565 Siani G., Paterne M., Michel E., Sulpizio R., Sbrana A., Arnold M., Haddad G. : Mediterranean
566 sea surface radiocarbon age changes since the last glacial maximum. Science
567 294(5548):1917–20, 2001.
568 Soon, W., Velasco Herrera, V.M., Selvaraj, K., Traversi, R., Usoskin, I., Arthur Chen, C.-T.,
569 Lou, J.-Y., Kao, S.-J., Carter, R.M., Pipin, V., Severi, M., Becagli, S.: A review of
570 Holocene solar-linked climatic variation on centennial to millennial timescales: Physical
571 processes, interpretative frameworks and a new multiple cross-wavelet transform
572 algorithm. Earth-Science Reviews 134, 1-15, 2014.
573 Staubwasser, M., Sirocko, F., Grootes, P.M., Segl, M.: Climate change at the 4.2 ka BP
574 termination of the Indus valley civilization and Holocene south Asian monsoon variability.
575 Geophysical Research Letters 30(8), 1425, 2003.
576 Thomson, D.J.: Spectrum estimation and harmonic analysis. Proceedings of the IEEE 70(9),
577 1055-1096, 1982.
578 Thomson, D.J.: Time series analysis of Holocene climate data. Philosophical Transactions of the
579 Royal Society of London, Series A, Mathematical and Physical Sciences 330, 601-616,
580 1990.
581 Trigo, I.F., Davies, T.D., Bigg, G.R., : Decline in Mediterranean rainfall caused by weakening of
582 Mediterranean cyclones. Geophysical Research Letters 27, 2913–2916, 2000.
583 Von Rad, U., Schaaf, M., Michels, K.H., Schulz, H., Berger, W.H., Sirocko, F. A 5000-yr Record
584 of Climate Change in Varved Sediments from the Oxygen Minimum Zone off Pakistan,
585 Northeastern Arabian Sea. Quaternary Research 51, 39-53, 1999.
586 Wang, L., Sarnthein, M., Erlenkeuser, H., Grimalt, J., Grootes, P., Heilig, S., Ivanova, E.,
587 Kienast, M., Pelejero, C., Pflaumann, U.: East Asian monsoon climate during the Late

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

588 Pleistocene: high-resolution sediment records from the South China Sea. Marine Geology
589 156, 245-284, 1999.
590 Wang, X., Liu, P.L.-F.,: A numerical investigation of Boumerdes-Zemmouri (Algeria)
591 earthquake and tsunami. Computer Modeling in Engineering Science 10 (2), 171–184,
592 2005.
593 Wanner, H., Solominac, O., Grosjean, M., Ritz, S.P., Jetel, M.: Structure and origin of Holocene
594 cold events. Quaternary Science Reviews 30, 3109-3123, 2011.
595 Zoppi U., Albani A., Ammerman A.J., Hua Q., Lawson E.M., Serandrei Barbero R. :Preliminary
596 estimate of the reservoir age in the Lagoon of Venice. Radiocarbon 43(2A):489–94, 2001.
597
598
599

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

Figures captions

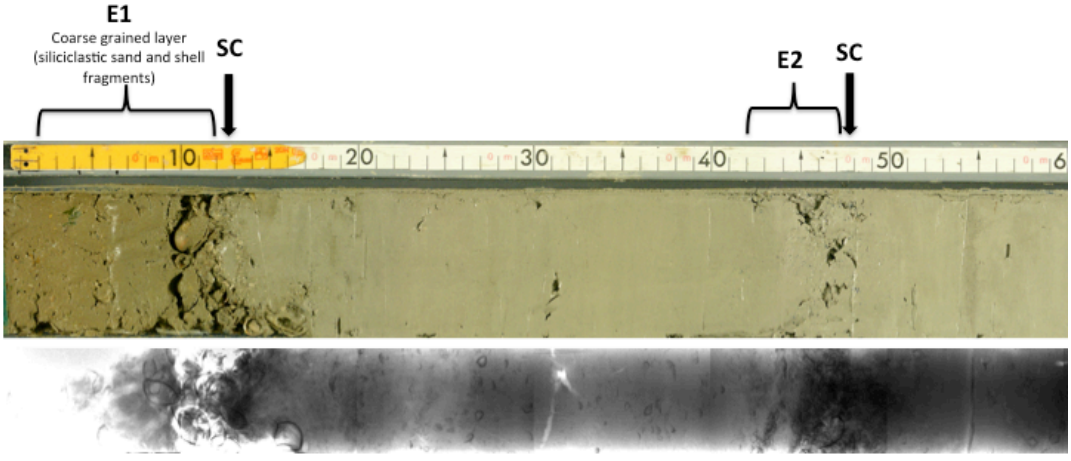
Figure 1. Map of the Mar Menor lagoon with localisation of the core MM2.

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

Climate of the Past
Discussions
Open Access
EGU

634

635



636

637

638

639 **Figure 2.** Photography and X-ray of the core MM2 (0 and 60 cm). Coarse grained layers are a
640 mixture of siliciclastic sand and shell fragments. These layers have often sharp contacts (SC)
641 with the clay and silt sediments below.

642

643

644

645

646

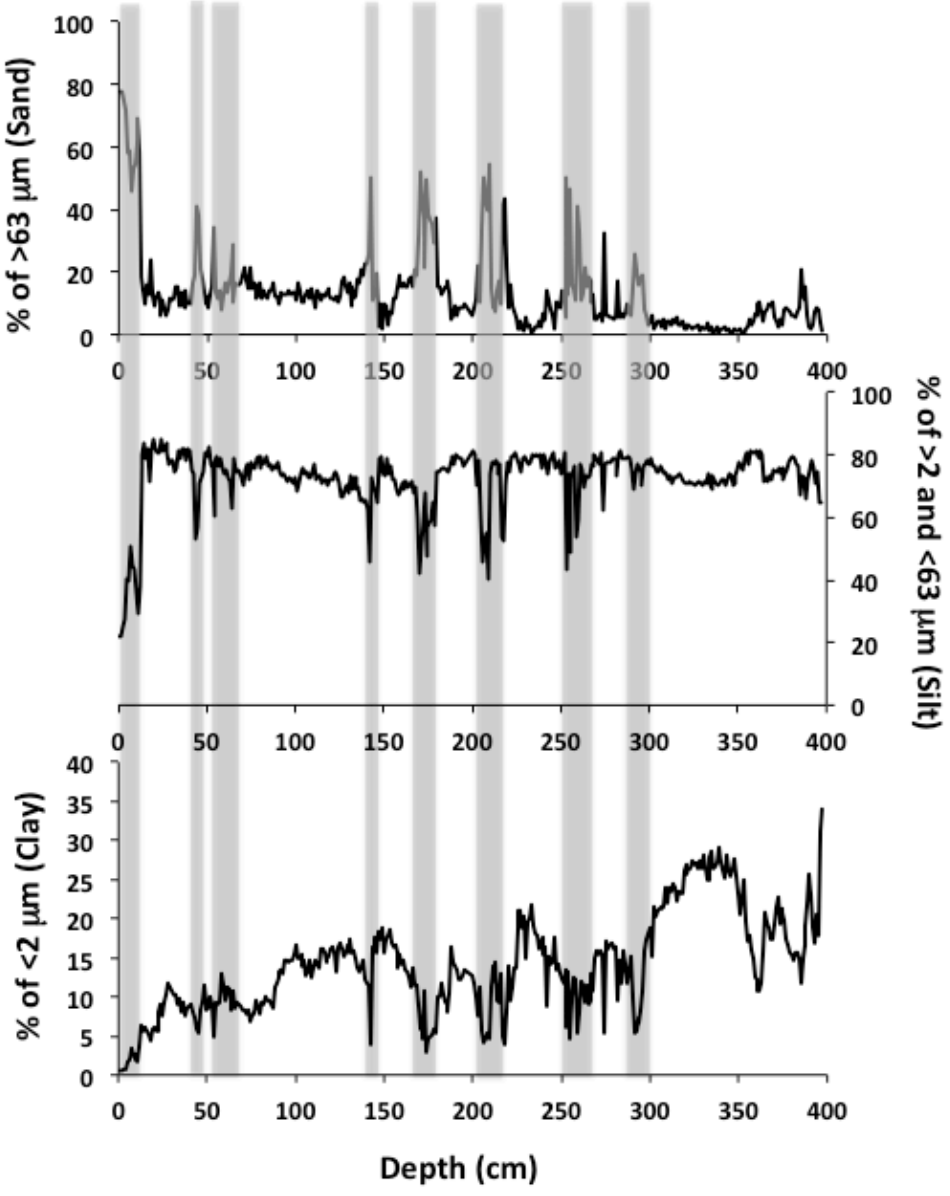
647

648

649

650

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016



651

652 **Figure 3.** Grain size population from the Mar Menor MM2 record with clay (<2 µm), silt (>2 and

653 <63 µm) and sand fraction (>63µm). Shaded areas mark the main variations of the sand fraction.

654

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

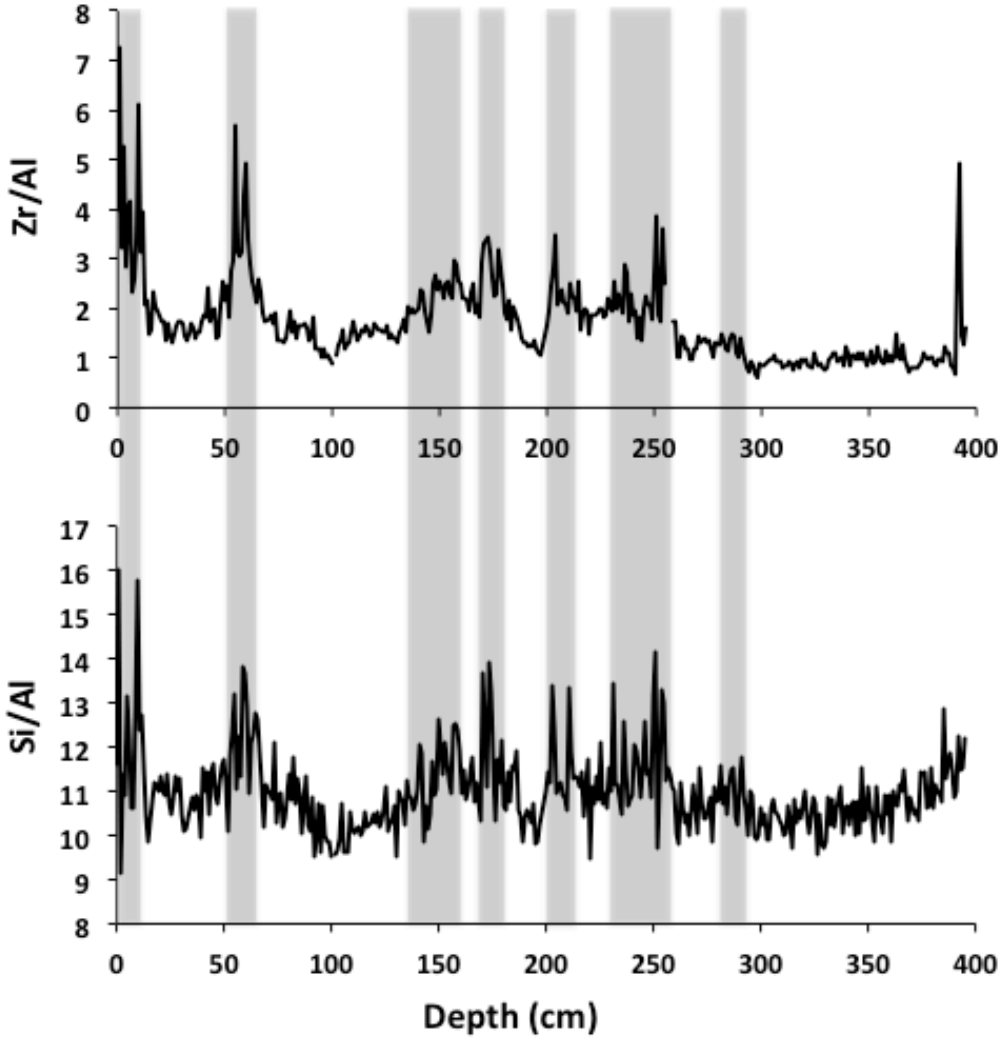


Figure 4. XRF records from the core MM2 with down-core variations of ratio Zr/Al and Si/Al. Shaded areas mark the main variations of Zr/Al and Si/Al.

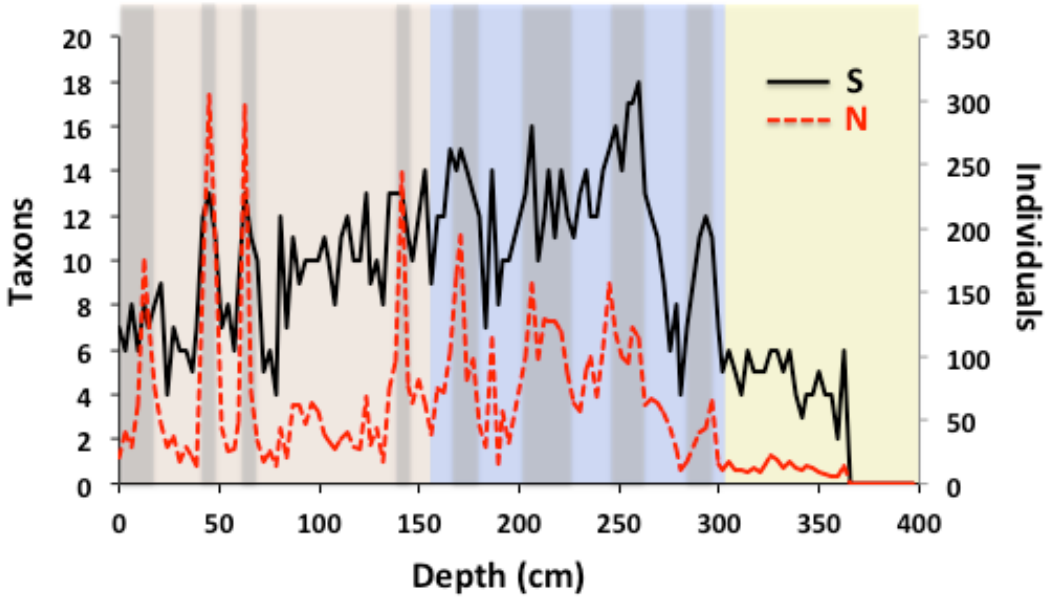
Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

Climate of the Past Discussions
Open Access
EGU

662

663

664



665

666 **Figure 5.** Taxon and specie richness with depth from the core MM2.

667

668

669

670

671

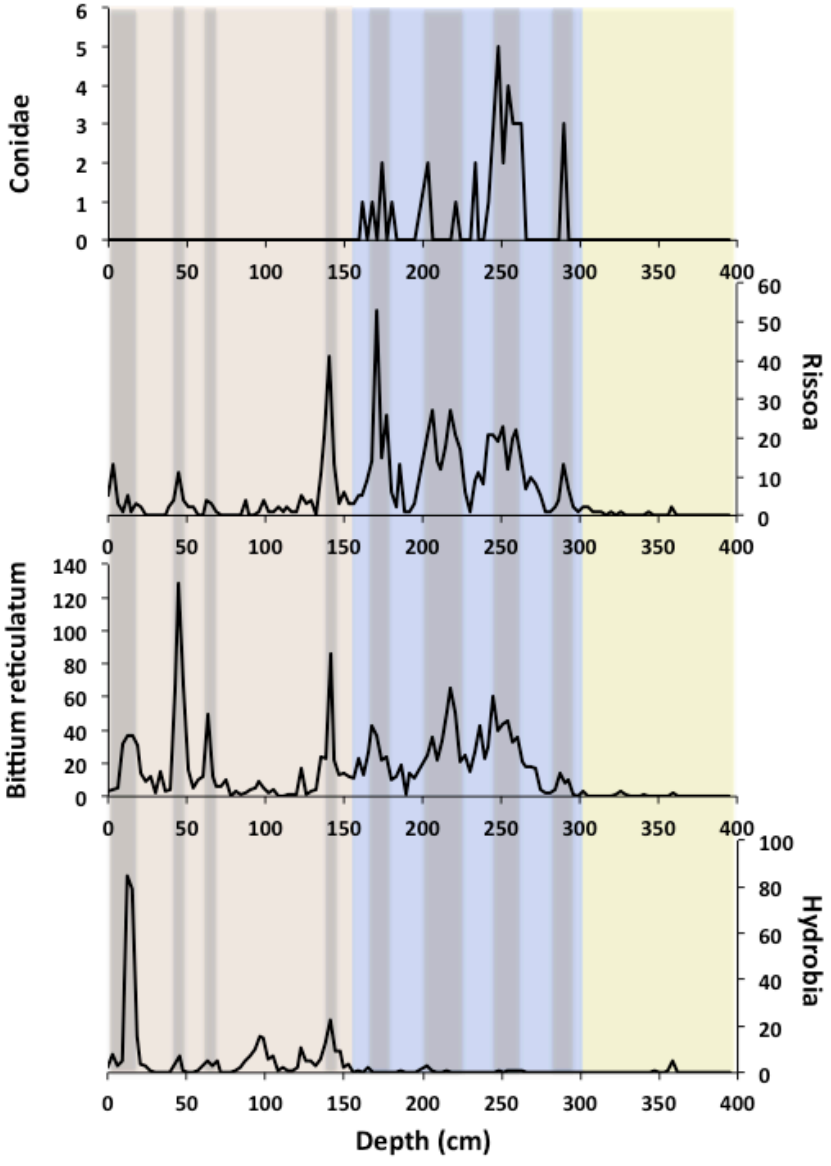
672

673

674

675

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016



676

677 **Figure 6.** Evolution in mollusc population with depth: lagoonal specie (*Hydrobia acuta*); typical

678 marine specie (*Conus ventricosus*: Conidae), marine influence (*Bittium Reticulatum* and *Pusillina*

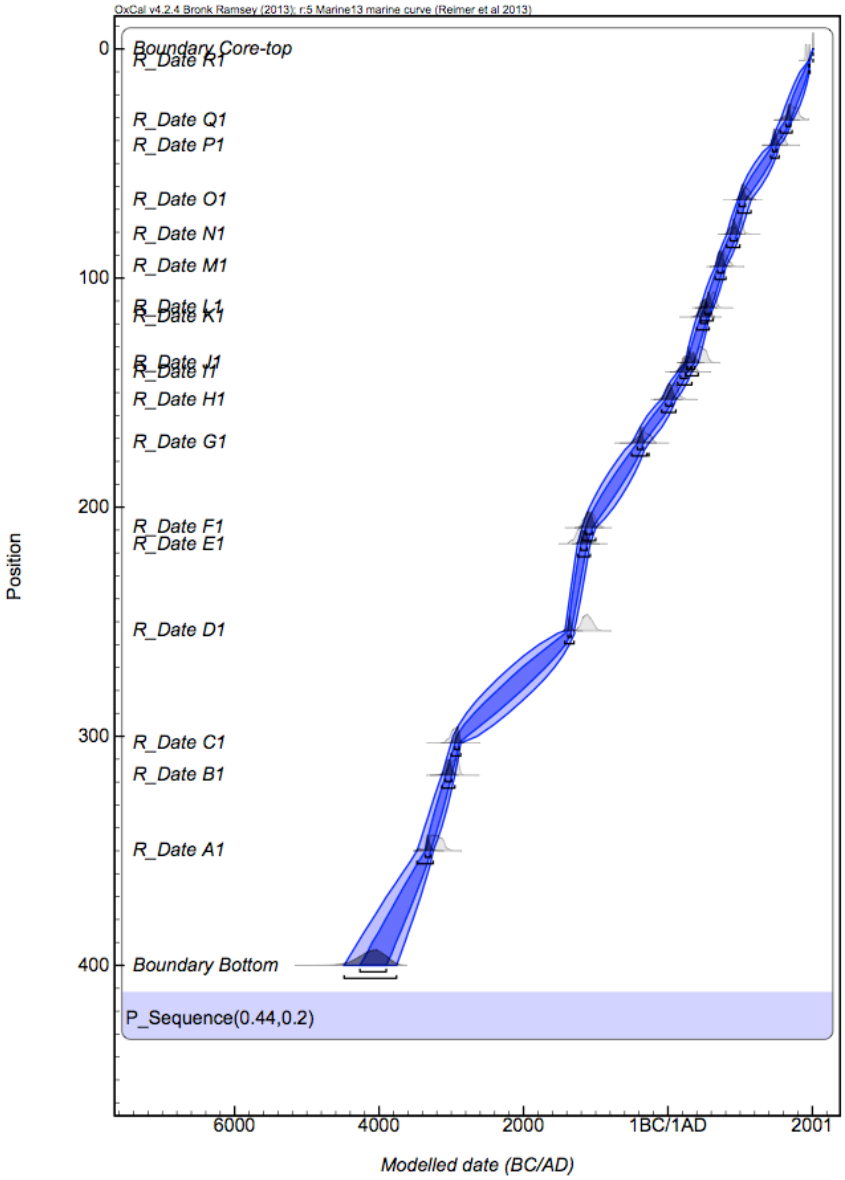
679 *lineolata:* Rissoa).

680

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

Climate of the Past Discussions
Open Access
EGU

681



682

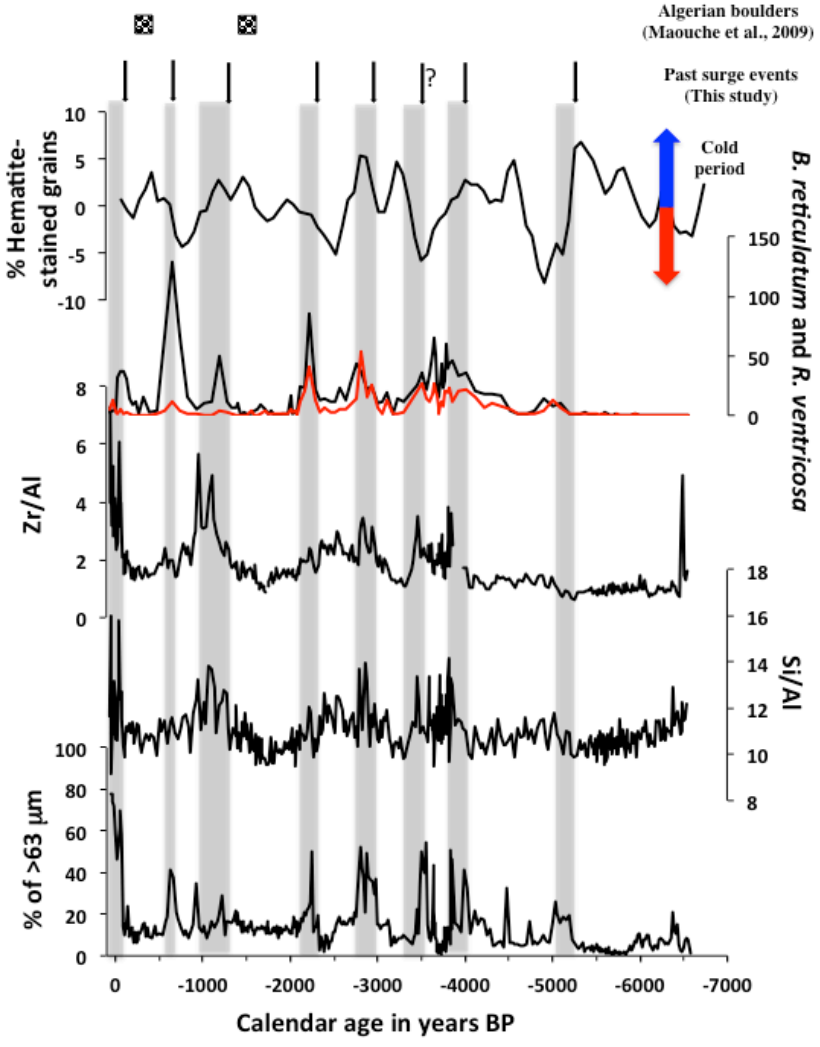
683 **Figure 7.** Age vs Depth for the core MM2. The Age model was calculated using OxCal 4 with 17

684 ^{14}C dates.

685

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016

Climate of the Past Discussions
Open Access
EGU



686

687

688 **Figure 8.** Core MM2 with from bottom to top: Grain size (sand fraction); Si/Al and Zr/Al XRF

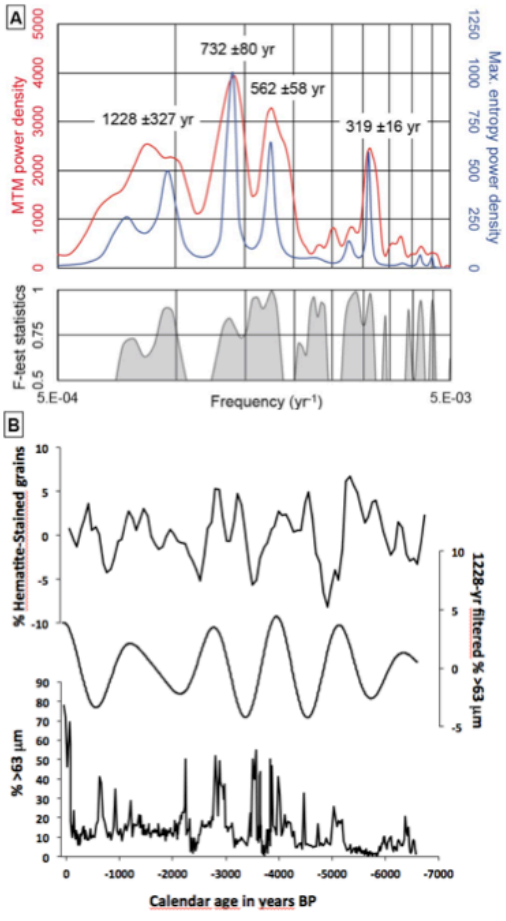
689 ratio; number of B. reticulatum and R. Ventricosa, % Hematite-stained grains (Bond et al., 1997,

690 2001), ages of Algerian boulders (Maouche et al., 2009). Grey bands are the past surge events.

691

692

Clim. Past Discuss., doi:10.5194/cp-2016-20, 2016
Manuscript under review for journal Clim. Past
Published: 18 February 2016



693

694 **Figure 9.** Time series analysis from the Mar Menor MM2 record. (A) Spectral analyses of the %
695 of sand with AnalySeries v.2.0.8 (Paillard et al., 1996) by using the Multi-Taper method (linear
696 trend removed, width.ndata product: 1.3; number of windows: 2) and the Maximum entropy
697 method (linear trend removed, % of series: 40, number of lags: 133). (B) Comparison between
698 the % Hematite-stained grains (Bond et al., 1997, 2001), the Gaussian filter on the % of sand for
699 the 1228-yr period (frequency: 0.0008, bandwidth: 0.0002) and the sand fraction of the core
700 MM2.

701