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1 **Timing of the southward retreat of the ITCZ at the end of the Holocene Humid Period in**  
2 **Southern Arabia: data-model comparison**

3

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14

15 **Abstract**

16 New pollen data from Omani mangroves (Kwar-al-Jaramah [22.49° N - 59.76° E] and Filim  
17 [20.61° N - 58.17° E]), in addition to previously published paleohydrological records from  
18 Southern Arabia improve our understanding of the timing and amplitude of the southward  
19 retreat of the Indian monsoon influence in Southern Arabia along a north-south transect.  
20 Comparison with simulations performed with the IPSL climate model, considering both  
21 snapshot experiments and transient simulations from 6000 cal yr BP to the present, confirm  
22 the latitudinally time-transgressive nature of the humid-arid transition at the end of the  
23 Holocene Humid Period. This occurred in two steps, respectively dated at around 5000 and  
24 2700 cal yr BP. At around 5000 cal yr BP, the southward ITCZ shift was orbitally-driven and  
25 led to the abrupt aridification at Kwar-al-Jaramah and the progressive increase of dryness at

26 Filim as the mean position of the ITCZ was centered ca 22.30°N. At 2700 cal yr BP, aridity was  
27 fully in place over all of southern Arabia due to increased climate variability. More intense  
28 rainy events during the last millennium, however, may have contributed to the discrete  
29 hydrological improvement without any impact on the regional vegetation which has  
30 remained desert to the present day.

31

32 **Key words:** Pollen, climate simulations, IPSL model, Oman, ITCZ, end of the Holocene Humid  
33 Period

34

### 35 **1. Introduction**

36 The timing and amplitude of the end of the Holocene Humid Period and the transition  
37 toward the present day arid/semi-arid conditions in the northern tropics has been the  
38 subject of multiple debates involving numerous scientists from both the model (e.g.,  
39 Claussen and Gayler, 1997; Claussen et al., 2003; Liu et al., 2007) and data communities (e.g.,  
40 deMenocal et al., 2000; Kröpelin et al., 2008a and b, Bayon et al., 2012). Several scenarios  
41 have been developed to discuss the abrupt or gradual character of this period and to identify  
42 the forcings at work (e.g., Brovkin et al., 2002; Rensen et al., 2006). These debates have  
43 mostly focused on regions under the Atlantic monsoon influence, with a specific emphasis  
44 on the iconic “Green Sahara”. This region is well known to have hosted flourishing  
45 prehistoric cultures evidenced by widespread archaeological remains (e.g., Kuper and  
46 Kröpelin, 2006; Manning and Timpson, 2014), rock paintings and carvings (Le Quellec, 2013),  
47 and abundant tropical faunas (e.g., Jousse and Escarguel, 2006) during the Holocene. Based  
48 on paleohydrological (Lézine et al., 2011) and archaeological (Kuper and Kröpelin, 2006)  
49 evidence, it has been shown that the end of the “Green Sahara” period in northern tropical

50 Africa and the start of present day arid conditions has been latitudinally time-transgressive,  
51 with the lake phase ending from 6500 cal yr BP between 26° and 28°N to 3500 cal yr BP  
52 between 16° and 20° N. In this region, however, the response time of the systems (hydrology,  
53 vegetation), involving aquifer recharge or surficial runoff from distant origin and/or from the  
54 Saharan highlands make the evaluation of the precise timing of the climate signal alone  
55 difficult (Gasse, 2000; Lézine et al., 2011; Hély and Lézine, 2014).

56 The end of the Holocene Humid Period is also recorded in regions under the Asian summer  
57 monsoon influence by a dramatic weakening of rainfall ca 5000-4000 cal yr BP (e.g., Morrill  
58 et al., 2003), particularly in its western part (e.g., Ivory et al., 2009; Lézine et al., 2014). Here  
59 also dramatic impact of changing climate on past Harappan culture in the Indus Valley has  
60 been evoked (Farooki et al., 2013). In this paper, we focus our attention on southern Arabia,  
61 a region particularly suitable for investigating the late Holocene period owing to the quality  
62 of the available high-resolution records. Paleolakes are particularly scarce and poorly  
63 preserved due to the exceptionally arid conditions which prevail in the Rub-al-Khali desert  
64 today (e.g., Lézine et al., 2007; 2014). However, speleothems records in South-Eastern  
65 Arabia have led to observation of changing rainfall amounts at the study sites as well as  
66 changes in the origin of the rains (Neff et al. 2001, Fleitmann et al., 2003; 2007). In addition,  
67 specific geomorphological and ecological features in coastal areas favor the preservation of  
68 mangroves whose floristic composition is closely dependent on rainfall amount and  
69 distribution (Spalding et al., 1997). These sedimentary environments also have the  
70 advantage of rapid depositional rates and good preservation of the organic matter, and thus  
71 are powerful tools to trace fluctuations of the rain belt associated with past monsoon  
72 circulation and changes in the location of the Intertropical Convergence Zone (ITCZ) through  
73 time (Lézine et al., 2002; Berger et al., 2013).

74 We consider here new pollen data from Omani mangroves and compare the chronology of  
75 events with those deduced from the isotopic composition of speleothems and the extension  
76 of lakes and wetlands. Our aim is to discuss the timing and amplitude of the southward  
77 retreat of the Indian monsoon influence in Southern Arabia along a north-south transect  
78 from 23° to 17°N. The results of these new data are compared with results of simulations  
79 with the IPSL climate model (Dufresne et al., 2013), considering both snapshot experiments  
80 for key Holocene periods and a suite of transient simulations. This allows us to discuss the  
81 changes induced by long term alterations to Earth's orbit and provide an indication of the  
82 possible role of insolation in triggering some of the rapid changes observed in the pollen  
83 records. The remainder of the manuscript is organized as follows: section 2 presents the new  
84 records and the climate simulations, whereas section 3 discusses the timing of the  
85 environmental changes over the region of interest and their relationship to the southward  
86 shift of the ITCZ from the mid-Holocene to today. A conclusion is provided in section 4.

87

## 88 **2. Mid to late Holocene pollen records and climate simulations**

### 89 **2.1 Regional climate features**

90 Oman is situated at the present northern limit of the annual migration of the ITCZ and the  
91 associated rainfall belt. In summer, southwesterly surface winds carry moisture from the  
92 southern Indian Ocean along the Arabian coast but do not penetrate far north- and  
93 eastwards into Southern Arabia (Fig. 1). The mean annual rainfall rapidly decreases from the  
94 southernmost part of the peninsula (the mountains of Yemen) to the Dhofar region in South  
95 Oman to the east, where the coastal station of Salalah records about 83 mm of annual  
96 rainfall. SW monsoon fluxes barely penetrate the Gulf of Oman, and rains only rarely occur in  
97 the lowlands where dry conditions occur year round. In winter, the southward penetration

98 of Mediterranean cyclonic depressions follows the topographic corridor of the Arabo-Persian  
99 Gulf bounded by the Zagros Mountains, Iran, to the north-east and the Jebel-al-Akhdar  
100 range, Oman, to the southwest. Winter rainfall averages 90 mm along the coast and reaches  
101 up to 350 mm in the Jebel-al-Akhdar, where snow may also occur. Mean annual temperature  
102 varies from about 26°C at Salalah to 35°C at Muscat along the Gulf of Oman, with  
103 temperature falling with altitude from about 0.6°C per 100 m elevation in the Jebel-al-  
104 Akhdar (Gazanfar and Fischer, 1998).

## 105 **2.2 Sediment cores**

106 Two cores were collected at Kwar-al-Jaramah (KAJ) in the Gulf of Oman (22.49°N - 59.76°E)  
107 and at Filim at the Indian Ocean shore (20.61°N - 58.17°E) (Figs. 1 and 2). Both were  
108 recovered behind the forest remnants of *Avicennia marina*-dominated mangrove  
109 populations. Kwar-al-Jaramah (Lézine, 2009) is a sheltered creek fed by local wadis  
110 originating from the foothills of the Jebel al Akhdar (El-Baz, 2002). Filim is a bay located west  
111 of the Barr al Hikmân peninsula facing the Masirah island. It is fed by the wadi Halfayn/wadi  
112 Andam system originating from the Jebel al Akhdar, located several hundreds of kilometers  
113 to the north. The regional environment is of desert type at both sites, and the mangrove is  
114 only represented by a single species, *Avicennia marina*, which is particularly adapted to  
115 highly saline environments (Spalding et al., 1997).

116 The sedimentary columns are 440 cm long at both sites and consist of homogenous sandy  
117 mud with rare shell fragments. Chronologies are based on seven AMS <sup>14</sup>C ages on carbonates  
118 at Kwar-al-Jaramah and eight at Filim. Raw radiocarbon dates were reservoir-corrected  
119 (Saliège et al., 2005) and converted to calibrated ages using CALIB Radiocarbon Calibration  
120 software (Reimer et al., 2009). Then, a time scale was obtained by linear interpolation

121 between two ages taking into account the highly variable sedimentation rate in such a  
122 littoral environments undergoing sea level fluctuations (Lambeck, 1996) (Table 1a and b).

123

### 124 **2.3 Pollen analysis**

125 Ninety seven samples (each 1.5–3 cm<sup>3</sup>) were taken for pollen analyses. Samples were  
126 processed according to standard procedures (chemical treatment with HCL and HF; sieving  
127 at 5 µm) (Faegri and Iversen, 1975). They yielded an abundant microflora of 163 pollen taxa  
128 for pollen counts ranging between 299 to 463 at KAJ and 82 to 405 at Filim. Pollen grains  
129 were determined using pollen flora of Qatar (El-Ghazaly, 1991), Chad (Maley, 1970), and East  
130 Africa (Bonafille and Riollet, 1980). Littoral mangrove pollen percentages (*Rhizophora* and  
131 *Avicennia*) were calculated against the sum of all the pollen grains and fern spores counted.  
132 As usual in tropical marine and littoral palynology, these taxa were excluded from the pollen  
133 sum for the calculation of the percentages of the other pollen taxa originating from inland  
134 vegetation types in order to better represent the regional flora (Fig. 3).

135 Pollen analysis reveals that the southernmost site, Filim, is remarkably diverse, with 133 taxa  
136 including 46 trees and shrubs (AP), compared to Kwar-al-Jaramah, where only 103 taxa were  
137 identified, including 29 AP (Supplementary Table 1). This is mainly due to the proximity of  
138 the Dhofar region, an area of tropical phytogeographical affinity restricted to the  
139 escarpments of SW Oman/SE Yemen (Miller and Morris, 1988). The Dhofar escarpment is a  
140 crescent-shaped arc directly influenced by the Indian summer monsoon rains. In addition,  
141 cold sea surface temperatures from nearby upwelling maintains mists and clouds on its  
142 slopes allowing tropical plants to grow. The occurrence, even in small percentages, of  
143 numerous tropical taxa at Filim (e.g., *Rhus*, *Pistacia*, *Maerua*, *Boscia/Cadaba*, *Albizia*,

144 *Andrachne*) testifies to regional pollen transport by SW-NE (summer monsoon) wind fluxes  
145 and also, probably, the eastward expansion of this particular region during the Holocene.

146 Four main features emerge from the pollen assemblages allowing characterization of two  
147 main pollen zones at Filim and three at Kawr-al-Jaramah (KAJ – Lézine, 2009) (Fig. 3):

148 (1) the dominance of desert/halophytic herbaceous plant communities (mainly  
149 Amaranthaceae/Chenopodiaceae, Asteraceae, *Artemisia*, Poaceae, and Cyperaceae) from  
150 about 7000 cal yr BP to the present;

151 (2) a dramatic change in mangrove composition. Two mangrove taxa are present: *Avicennia*  
152 *marina* and *Rhizophora mucronata*. *Rhizophora mucronata* is typically a tropical species  
153 which requires freshwater from both rivers and summer rainfall (Spalding et al., 1997). It is  
154 absent today from the Omani mangroves. However, paleoenvironmental studies testify to its  
155 occurrence in the Northern Indian Ocean sector during the Holocene (Overpeck et al., 1996)  
156 and, particularly along the coasts of Southern Arabia at Suwayh (22°05N) (Lézine et al., 2002)  
157 or even northward (Tengberg, 2005). In Arabia, relict communities of *Rhizophora* persist  
158 today in only two restricted sectors: the Kamaran island in the Red Sea and near al-  
159 Hudaydah at 15.24°N. *Avicennia marina* is a mangrove species which has a high tolerance of  
160 salinity. It is widely distributed in the dry, desert coastal zones of Arabia, and it reaches up to  
161 27°N in the Arabo-Persian Gulf and 28°N in the Red Sea;

162 (3) the growing importance toward the end of the period studied of *Prosopis cineraria*.  
163 *Prosopis cineraria* is a native species of Saharo-Sindian vegetation zone, a region influenced  
164 by a bi-seasonal, Mediterranean-type climate with a rain maximum during winter and spring  
165 (Ghazanfar and Fisher, 1998). In Oman, its distribution encompasses the coastal plains along  
166 the Arabo-Persian Gulf, where rainfall is too low to maintain a typical tropical vegetation.



167 Modern pollen samples from this region do not record percentages of *Prosopis cineraria*  
168 higher than 9% (1.6% in average) (Lézine et al., 2000).

169 (4) pollen transport from distant origin, mainly afro-montane (e.g., Ericaceae, *Juniperus*,  
170 *Myrica*, *Olea europea*, *Podocarpus*) which is recorded at both sites. These taxa can originate  
171 either from Jebel-al-Akhdar to the north-east or from the Dhofar escarpment to the south-  
172 west in Oman, but also from more remote regions such as the highlands of Yemen or the  
173 Horn of Africa.

174 The pollen zones are as follows:

175 **Filim zone 1** (6800-2700 cal yr BP) is characterized by the presence of *Rhizophora*, the  
176 percentages of which reach up to 52%. Pollen grains from tropical plant communities are  
177 present, in scattered occurrence and low values. *Rhizophora* percentages decrease toward  
178 the end of this zone in two steps successively dated from 6800 to 5100 cal yr BP (52 to 20%)  
179 and from 5100 to 2700 cal yr BP (20% to 0). *Artemisia*, from desert/halophytic herbaceous  
180 plant communities, displays an opposite trend with values regularly increasing from 2% to  
181 23%.

182 **Filim zone 2** (2700 cal yr BP - present) is characterized by the disappearance of *Rhizophora*,  
183 which is replaced by *Avicennia*, the percentages of which increase from 0 to 4% toward the  
184 end of this zone. This zone is also characterized by the appearance, even in low percentages,  
185 of *Prosopis cineraria*. This taxon is associated with other semi-desert elements (*Salvadora*,  
186 *Maerua*, *Moltkiopsis*)

187 **KAJ zone 1** (6300- 4500 cal yr BP) is characterized by the presence of *Rhizophora*, which  
188 reaches a maximum of 13%. It is also associated with *Avicennia* abundances of 3 - 7%.

189 **KAJ zone 2** (4500-2700 cal yr BP). *Rhizophora* almost disappears from this zone whereas,  
190 *Avicennia* remain constant. *Artemisia* percentages slightly increase compared to the  
191 preceding zone (max = 11%).

192 **KAJ zone 3** (2700 cal yr BP – present) records the progressive increase of *Prosopis cineraria*,  
193 which reaches up to 11% in the uppermost levels, and the significant decrease of the  
194 mangrove pollen types: *Rhizophora* is rare with values less than 0.2%. *Avicennia* decreases  
195 to percentages of 0.9%

196

## 197 **2.4 Climate simulations with the IPSL-CM5 model**

198 Simulations of the mid to late Holocene were run with the same IPSL model version as the  
199 one used for the last CMIP5 ensemble of simulations (Dufresne et al., 2013). IPSL\_CM5A is a  
200 state-of-the-art coupled global general circulation model. It couples the LMDz atmosphere  
201 model (Hourdin et al., 2006), with a horizontal resolution of 96 × 96 grid points and a vertical  
202 resolution of 39 levels, to the ocean model NEMO/OPA with 182 grid points in longitude ×  
203 149 in latitude and 31 vertical levels (Madec et al., 1997), using the coupler OASIS (Valcke,  
204 2006). The land surface model ORCHIDEE is coupled to the atmosphere model and includes  
205 a river runoff scheme to close the water budget between land and ocean (Krinner et al.,  
206 2005). The sea-ice model LIM2 (Fichefet and Maqueda, 1997) is coupled to both atmosphere  
207 and ocean models. The carbon cycle is interactive in the ocean and in the land-surface. For  
208 the latter, the leaf area index is also fully interactive but vegetation is prescribed. Vegetation  
209 feedback is therefore partly represented in these simulations (Kageyama et al., 2013;  
210 Braconnot and Kageyama, 2015).

211 We consider both time slice experiments for the mid-Holocene (6 ka), the late Holocene (4  
212 ka), and the preindustrial period (PI, 0 ka), in addition to transient late Holocene

213 experiments starting from the 6 ka simulation. The model and mid-Holocene simulations are  
214 presented in Kageyama et al. (2013), and the 4 ka simulation is discussed in Saint-Lu et al.  
215 (2015). These time slice simulations consider only the changes in Earth's orbital parameters  
216 which are prescribed following Berger (1978) as shown in table 2. The mid-Holocene  
217 simulation considers in addition the small changes in greenhouse gases, following the PMIP3  
218 protocol (Braconnot et al., 2012). Each time slice simulation is 1000 years long, and the  
219 annual mean cycles and wind rose statistics were computed from the last 500 years of each  
220 simulation.

221 The model underestimates the northward extent of monsoon rain over the Sahel today  
222 (Kageyama et al., 2013). Despite the precipitation bias over land, the simulated changes at 6  
223 ka resemble the one produced by the ensemble PMIP3 simulation (Braconnot et al., 2012;  
224 Harrison et al., 2015). The major characteristics of the difference in African and Indian  
225 monsoon are consistent with the results obtained by Marzin and Braconnot (2009) with the  
226 previous version of the IPSL model. This is also the case for the 4 ka simulation over the  
227 southern hemisphere convergence zone (Saint-Lu et al., 2015). Interestingly, the monsoon  
228 flow is well represented over the Arabian Sea and along the coast as depicted by boreal  
229 summer surface winds in Figure 4. Monsoon precipitation is underestimated in Africa and  
230 India, but slightly overestimated in the northeastern part of the Arabian Sea. Figure 4 shows  
231 the reduction of the SW monsoon flow in July-August from the mid-Holocene to present day,  
232 together with the increase of the NE boreal winter monsoon flow. Monthly wind direction  
233 anomalies highlight the higher frequency of S-SW winds at 6 ka and strengthening of the  
234 wind from in the western quadrant from W-NW to S. During boreal winter the changes in  
235 frequency and intensity reflect a slight wind rotation from the N-NE to the NE.

236 The initial state of the PMIP3 transient simulations is from IPSL of the mid-Holocene climate  
237 (6 ka) described in Kageyama et al. (2013). We performed two simulations with an  
238 acceleration in the orbital parameters by a factor 10, following Lorenz and Lohmann (2004)  
239 (Fig. 5). With this acceleration, a 600 year-long simulation represents 6000 climate years.  
240 The orbital parameters (Table 2) vary with time and, because of the acceleration, the 4ka  
241 values are found for year 200 and those of PI for year 600. The long term trend can be  
242 attributed to the long term insolation forcing, but the short term variability represents only  
243 inter-annual to centennial variability, and not millennium scale variability. These two  
244 simulations start from different initial dates in the 6 ka simulation. The third simulation is a  
245 fully synchronous experiment in which the orbital parameters are updated every year. This  
246 experiment only covers the 2500 years from 6000 to 3500 cal yr BP. Due to storage  
247 problems, a period of time is missing in the model outputs between 4800 and 4750 cal yr BP.  
248 The representation of the monsoon has the same quality and biases as the ones highlighted  
249 above for the time slice experiments.

250 Figure 5 shows the evolution of precipitation as a function of time, comparing the  
251 accelerated and non-accelerated simulations for three latitudinal bands over the region  
252 20°N-24°N, 18°N-20°N and 14°N-18°N. As expected, precipitation is characterized in the  
253 three latitudinal bands by a long term decreasing trend over this period that can be related  
254 to the long term insolation forcing and the associated reduction and southward shift over  
255 the region of the boreal monsoon flow (Bassinot et al., 2011). Short term variability is also  
256 present. This variability is internal to the coupled system and is thus not synchronous  
257 between the simulations. However, the major events are synchronous between the  
258 latitudes, and major transitions seem also to be synchronous across the simulations,  
259 suggesting a response to a common forcing or to the same feedback from the ocean

260 circulation or vegetation. In particular, all simulations exhibit a rapid precipitation decrease  
261 around 5000 cal yr BP that occurs in several steps. The two accelerated simulation also  
262 exhibit periods with enhanced variability after 2000 cal yr BP. Even though both simulations  
263 do not change at the exact same time, we can conclude that this stochastic variability seems  
264 to be related to favorable conditions in the mean state. Further analyses to fully understand  
265 this is however outside the scope of the manuscript.

266

### 267 **3. Timing of environmental changes and linkage with the timing of the southward shift of** 268 **the summer monsoon rainbelt (Fig. 6)**

269 The analyses of the evolution of vegetation at the two sites and the ensemble of IPSL-CM5A  
270 simulations allow us to infer the long term changes and variability of the ITCZ rainbelt over  
271 the Arabian Sea and Arabian Peninsula. We have calculated two indices illustrating the local  
272 and regional evolution of the environment. The *Avicennia/Rhizophora* ratio compares a salt-  
273 adapted (*Avicennia*) to a fresh-water-adapted (*Rhizophora*) species (Spalding et al., 1997).  
274 This ratio aims at representing the fluctuations between freshwater and saline conditions  
275 locally, at each mangrove site. In addition, the *Artemisia/Rhizophora* ratio compares one of  
276 the most arid components of the regional environment typically *Artemisia* today mainly  
277 found north of the Arabian Peninsula in areas under Mediterranean climate conditions (El-  
278 Moslimany, 1990) to one of the most humid components of the environment characteristic  
279 of tropical climate conditions (*Rhizophora*). These ratios highlight the occurrence of two  
280 opposing phases during the mid to late Holocene. We discuss in the following the linkages  
281 between these phases and the location of boreal summer monsoon rainbelt (i.e., the limit  
282 between the zones of influence of winter and summer rains). For this, we compare our data  
283 to the oxygen isotope records of speleothems at Qunf and Hoti in southern Oman (Neff et

284 al., 2001; Fleitmann et al., 2003; 2007) and the dated records of past lakes and wetlands in  
285 the Arabian Peninsula (Lézine et al., 2014, Fersi et al., 2016) (Supplementary Table 2) (Fig. 5)  
286 and to the climate simulations.

287

288 **3.1 From 7500 to 2700 cal yr BP (Filim) and from 6358 to 4500 cal yr BP (Kwar-al-Jaramah):**  
289 **a summer monsoon-dominated climate regime**

290 At both sites, the pollen record is characterized by the presence of *Rhizophora* (Fig. 3).  
291 Percentages of this taxon reach 43 to 52% at Filim during a time interval from 6800 to 6700  
292 cal yr BP, that clearly indicate the presence of a developed freshwater mangrove forest at  
293 the core site. Then percentages decrease in two successive steps at ca. 6000 then 4500 cal yr  
294 BP. After 2700 cal yr BP, *Rhizophora* pollen grains become scarce and their percentages  
295 never exceed 2%. At Kwar-al-Jaramah, *Rhizophora* peaks at 13.5% only (4960-5100 cal BP),  
296 showing a less developed forest formation compared to the southernmost site. These  
297 percentages decrease rapidly, and *Rhizophora* almost completely disappears from the pollen  
298 diagram after 4500 cal yr BP. The presence of *Rhizophora* within the mangrove forests of  
299 Oman clearly points to the tropical influence and associated enhanced summer rainfall. We  
300 suggest that SW summer monsoon winds were responsible for the transport of tropical  
301 pollen grains from the Dhofar region, not only at Filim but also at Kwar-al-Jaramah.

302 During the mid-Holocene, the tropical influence covered a wide range of latitudes as shown  
303 by the isotope records (Neff et al., 2001; Fleitmann et al., 2003; 2007) and various lacustrine  
304 deposits over southern Arabia (Lézine et al., 2014 and references therein; Fersi et al., 2016)  
305 (Supplementary Table 2). This is also illustrated by the presence of *Rhizophora* populations  
306 reported at al-Balid at 17°N (Zarins, 2007), Suwayh at 22°N (Lézine et al., 2002), and tell  
307 Abraq at 25°N (Tengberg, 2005), as well as by multiple geomorphological observations and

308 archaeological findings along the Ja'alan coast in Oman (Giraud, 2009; Berger et al., 2013)  
309 suggesting widespread expansion of mangroves all along the Arabian coasts at that time.  
310 Wind roses computed over the large area that encompass all the sites show the June-July-  
311 August (JJA) and the evolution of simulated precipitation are in agreement with this  
312 assumption (Fig. 4 - 6). A rapid humid-arid transition around 5000 cal yr BP is depicted both  
313 in pollen records and in all simulations. It indicates that the insolation forcing is the major  
314 driver of this rapid decrease, suggesting that around that time, the meridional insolation  
315 gradient was not sufficient to maintain the associated pressure gradients driving the SW  
316 monsoon flow over the region. The rapid shifts indicate that the northern limit of the  
317 rainbelt did not reach the pollen sites and the abruptness of the shift is the signature of a  
318 threshold in amount of moisture necessary to maintain the vegetation there. This explains  
319 the connection between the disappearance of *Rhizophora* and the southward shift of the  
320 rainbelt.

321

### 322 **3.2 At 2700 cal yr BP, the reversal of main wind trajectories**

323 From 2700 cal yr BP onward, the disappearance of *Rhizophora* was mirrored by the  
324 development of *Prosopis cineraria*. This marks the reversal of the main regional climatic  
325 influences with the decreased importance of the SW Indian summer monsoon and the  
326 increased importance of Mediterranean wind fluxes of opposite direction. *Prosopis* occurred  
327 continuously at Ras al-Khaimah, Eastern Arabia (25° 42' 57''N) from 8500 cal yr BP to the  
328 present (Parker et al., 2004) and at Kwar-al-Jaramah from 6358 cal yr BP onwards (this  
329 study). It was absent at Suwayh (22°05'N) before 4000 cal yr BP (Lézine et al., 2002) and at  
330 Filim before 2700 cal yr BP (this study). As a consequence, we can suggest that the limit  
331 between the summer and the winter rains was situated between Kwar-al-Jaramah and

332 Suwayh ca 22°30 N during the mid-Holocene. At 2700 cal yr BP, it was displaced southward  
333 and situated at its present-day position between 18 and 19°N (Ghazanfar and Fischer, 1998).  
334 Climate simulations are consistent with this scenario. In addition, the two transient  
335 simulations suggest declining SW monsoon flux together with a period of enhanced  
336 variability after 2000 cal yr BP. Such enhanced variability and the associated increase of rainy  
337 events could have contributed to feed lakes and wetlands in the Arabian Peninsula (Fig. 6).  
338 The events are not synchronous between the simulations, suggesting that the large scale  
339 circulation is suitable for the development of periods with higher variability, but that this  
340 variability is not a direct response to an external forcing and appears thus at different times  
341 in the two simulations.

342

#### 343 **4. Concluding remarks**

344 Our study, based on transient climate simulations compared to high resolution and well  
345 distributed paleo-data provide for the first time a detailed chronology of the retreat of the  
346 rain belt associated to the southward shift of the ITCZ at the end of the Holocene in Eastern  
347 Arabia. This approach paves the way to a thorough understanding of rainfall variations and  
348 their impact on terrestrial ecosystems in arid areas.

349 Figure 6 shows that the timing and structure of the arid-humid transition strongly varied  
350 with latitude, such that north of 22°30 N, the humid-arid transition was abrupt at all  
351 latitudes. The southward shift of the rainbelt took place at 6026 cal yr BP at Hoti (Fig. 6F),  
352 then at 4500 cal yr BP at Kwar-al-Jaramah (Fig. 5D). In contrast, the increase in regional  
353 dryness was gradual south of 20°30 N as shown by the Qunf isotope record (Fig. 6B) and the  
354 *Artemisia/Rhizophora* ratio at Filim (Fig. 6C) and reached its maximum at 2700 cal yr BP.  
355 Both data and climate simulations agree that two major successive thresholds occurred at



356 ca. 4500-5000 cal yr BP and 2700 cal yr BP and punctuated the southward retreat of the ITCZ  
357 and associated rainbelt at the end of the Holocene Humid Period in Southern Arabia.

358 - All simulations (Fig. 6F) exhibit a sharp decrease in precipitation around 4500-5000  
359 cal yr BP. This first threshold coincides with the dramatic lowering of the water  
360 bodies in Southern Arabia (Fig. 5A) and the onset of arid conditions throughout the  
361 tropics in response to insolation forcing. A comparison of environmental conditions  
362 between Filim and Kwar-al-Jaramah help to more precisely locate the position of the  
363 ITCZ at ca. 22°30 N.

364 - At the time of the second threshold identified at 2700 cal yr BP, aridity was pervasive  
365 all over Southern Arabia. This second threshold corresponds not only to the  
366 disappearance of *Rhizophora* from the mangroves of Filim and the widespread  
367 expansion of *Prosopis cineraria* along the coasts of Oman, but also to the interruption  
368 of speleothem growth (Fleitmann et al., 2003; 2007) and river activity (Hoorn and  
369 Cremaschi, 2004) in Southern Oman. The beginning of very dry conditions and the  
370 prevalence of wind fluxes of NE origin at that time were already observed at Lake  
371 Yoa, Northern Chad (Lézine et al., 2010). Climate instability characterized by  
372 increased rainy events may have however contributed to the slight elevation of the  
373 lake levels observed towards the end of the period in Southern Arabia and  
374 particularly during the last millennium.

375

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389

## 390 **References**

391

392 Bayon, G., Dennielou, B., Etoubleau, J., Ponzevera, E., Toucanne, S., Bermell, S. 2012.  
393 Intensifying weathering and land use in Iron Age Central Africa. *Science* 335, 1219-1222.

394 Bassinot, F.C., Marzin, C., Braconnot, P., Marti, O., Mathien-Blard, E., Lombard, F., Bopp, L.  
395 2011. Holocene evolution of summer winds and marine productivity in the tropical  
396 Indian Ocean in response to insolation forcing: data-model comparison. *Clim. Past* 7,  
397 815-829.

398 Berger, A. 1978. Long-term variations of caloric solar radiation resulting from the Earth's  
399 orbital elements. *Quatern. Res.* 9, 139-167.

400 Berger, J.-F., Charpentier, V., Crassard, R., Martin, C., Davtian, G., Lopez-Saez, J.A. 2013. The  
401 dynamics of mangrove ecosystems, changes in sea level and the strategies of Neolithic  
402 settlements along the coast of Oman (6000-3000 cal. BC). *J. Archaeol. Sci.* 40, 3087-  
403 3104.

404 Bird, M.I., Austin, W.E.N., Wurster, C.M., Fifield, L.K., Mojtahid, M., Sargeant, C., 2010.  
405 Punctuated eustatic sea-level rise in the early mid-Holocene. *Geology* 38, 803–806.

406 Bonnefille, R., Riollet, G. 1980. *Pollens des savanes d’Afrique orientale*, CNRS, Paris, 140 p.

407 Braconnot, P., Harrison, S.P., Kageyama, M., Bartlein, P.J., Masson-Delmotte, V., Abe-Ouchi,  
408 A., Otto-Bliesner, B., Zhao, Y., 2012. Evaluation of climate models using palaeoclimatic  
409 data. *Nature Clim. Change*, 2,417-424.

410 Claussen, M., Brovkin, V., Ganopolski, A., Kubatzki, C., Petoukhov, V. 2003. Climate Change in  
411 Northern Africa: The Past is Not the Future. *Clim. Change* 57, 99.

412 Claussen, M., Gayler, V. 1997. The greening of the Sahara during the mid-Holocene: results  
413 of an interactive atmosphere-biome model. *Global Ecol. Biogeogr.* 6, 369–377.

414 deMenocal, P., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L., Yarusinsky, M.  
415 2000 Abrupt onset and termination of the African Humid Period: rapid climate  
416 responses to gradual insolation forcing. *Quatern. Sci. Rev.* 19, 347–361.

417 Dufresne, J. L., Foujols, M. A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y.,  
418 Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P.,  
419 Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., de Noblet, N., Duvel, J. P., Ethe,  
420 C., Fairhead, L., Fichefet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J. Y., Guez, L.,  
421 Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, J., Joussaume, S.,  
422 Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M. P., Lefevre, F., Levy,  
423 C., Li, Z. X., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S.,  
424 Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M.,  
425 Swingedouw, D., Szopa, S., Talandier, C., Terray, P., Viovy, N., and Vuichard, N. 2013.  
426 Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to  
427 CMIP5. *Clim. Dyn.* 40, 2123-2165.

428 El-Baz, F. 2002. Wadis of Oman, satellite images. Atlans. Sultanate of Oman, Office of the  
429 Advisor to His Majesty The Sultan for Cultural Affairs. 218 p.

430 El-Ghazali, G. 1991. Pollen flora of Qatar. Scientific and applied research Center, University of  
431 Qatar, 429 p.

432 Faegri, K., Iversen, J., 1975. Textbook of Pollen Analysis. Blackwell, Oxford.

433 Farooki, A., Gaur, A.S., Prasad, V. 2013. Climate, vegetation and ecology during Harappan  
434 period: excavations at Kanjetar and Kaj, mid-Saurashtra coast, Gujarat. J. Archaeol. Sci.  
435 40, 2631-2647.

436 Fichet, T., Maqueda, M.A.M. 1997. Sensitivity of a global sea ice model to the treatment of  
437 ice thermodynamics and dynamics. J. Geophys. Res., Oceans 102, C6, 12609 -12646.

438 Fleitmann, D., Burns, S.J., Mangini, A., Mudelsee, M., Kramers, J., Villa, I., Neff, U., Al-  
439 Subbary, A.A., Buettner, A., Hippler, D., Matter, A. 2007. Holocene ITCZ and Indian  
440 monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). Quatern.  
441 Sci. Rev. 26, 170-188.

442 Fleitmann, D., Burns, S.J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A., Matter, A. 2003.  
443 Holocene Forcing of the Indian Monsoon Recorded in a Stalagmite from Southern  
444 Oman. Science 300, 1737-1739.

445 Gasse, F. 2000. Hydrological changes in the African tropics since the Last Glacial maximum.  
446 Quatern. Sci. Rev. 19, 189-211.

447 Giraud, J. 2009. The evolution of settlement patterns in the eastern Oman from the Neolithic  
448 to the Early Bronze Age (6000-2000 BC). C. R. Geoscience 341, 739-749.

449 Ghazanfar, S.A., Fisher, M., 1998. Vegetation of the Arabian Peninsula. Geobot. 25, 1-362.

450 Harrison, S. P., Bartlein, P. J., Izumi, K., Li, G., Annan, J., Hargreaves, J., Braconnot, P.,  
451 Kageyama, M. 2015. Evaluation of CMIP5 palaeo-simulations to improve climate  
452 projections. *Nature Clim. Change* 5, 735-743.

453 Hély, C., Lézine, A.-M. and APD contributors. 2014. Holocene changes in African vegetation:  
454 tradeoff between climate and water availability. *Clim. Past* 10, 681-686.

455 Hoorn, C., Cremaschi, M. 2004. Late Holocene palaeoenvironmental history of Khawr Rawri  
456 and Kwar-al-Balid (Dhofar, Sultanate of Oman). *Palaeogeogr., Palaeoclim., Palaeoecol.*  
457 213, 1-36.

458 Hourdin, F., Musat, I., Bony, S., Braconnot, P., Codron, F., Dufresne, J.L., Fairhead L., Filiberti  
459 M.A., Friedlingstein P., Grandpeix J.Y., Krinner G., LeVan P., Li Z.X., Lott F. 2006. The  
460 LMDZ4 general circulation model: climate performance and sensitivity to parametrized  
461 physics with emphasis on tropical convection. *Clim. Dyn.* 27, 787–813.

462 Jousse, H., Escarguel, G. 2006. The use of Holocene bovid fossils to infer palaeoenvironment  
463 in Africa. *Quatern. Sci. Rev.* 25, 763-783.

464 Kageyama, M., Braconnot, P., Bopp, L., Caubel, A., Foujols, M.-A., Guilyardi, E., Khodri, M.,  
465 Lloyd, J., Lombard, F., Mariotti, V., Marti, O. 2013. Mid-Holocene and Last Glacial  
466 Maximum climate simulations with the IPSL model—part I: comparing IPSL\_CM5A to  
467 IPSL\_CM4. *Clim. Dyn.* 40, 2447-68.

468 Krinner, G., Viovy, N., de Noblet-Ducoudré, N., Ogée, J., Polcher, J., Friedlingstein, P., Ciais,  
469 P., Sitch, S., Prentice, I.C. 2005. A dynamic global vegetation model for studies of the  
470 coupled atmosphere–biosphere system. *Global Biogeochem. Cycles.*  
471 doi:[10.1029/2003GB002199](https://doi.org/10.1029/2003GB002199)

472 Kuper, R., Kröpelin, S. 2006. Climate-controlled Holocene occupation in the Sahara: motor of  
473 Africa's evolution. *Science* 313, 803–807.

474 Kutzbach, J.E., Street-Perrott, F.A. 1985. Milankovitch forcing of fluctuations in the level of  
475 tropical lakes from 18 to 0 k yr BP. *Nature* 317, 130–134.

476 Lambeck, K., 1996. Shoreline reconstructions for the Persian Gulf since the last glacial  
477 maximum. *Earth Planet. Sci. Let.* 142, 43-57.

478 Lézine, A.-M. 2009. Timing of vegetation changes at the end of the Holocene Humid Period  
479 in desert areas at the northern edge of the Atlantic and Indian monsoon systems. *C.R.  
480 Geoscience* 341, 750-759.

481 Lézine, A.-M., Bassinot, F., Peterschmitt, J.-Y. 2014. Orbitally-induced changes of the Atlantic  
482 and Indian monsoons over the past 20,000 years: new insights based on the comparison  
483 of continental and marine records. *Bull. Soc. Géol. France* 185, 3-12.

484 Lézine, A.-M., Hély, C., Grenier, C., Braconnot, P., Krinner, G. 2011. Sahara and Sahel  
485 vulnerability to climate changes, lessons from Holocene hydrological data. *Quatern. Sci.  
486 Rev.* 30, 3001-3012.

487 Lézine, A.-M., Robert, C., Cleuziou, S., Inizan M.-L., Braemer, F., Saliège, J.-F., Sylvestre, F.,  
488 Tiercelin, J.-J., Crassard R., Méry, S., Charpentier, V., Steimer-Herbet, T. 2010. Climate  
489 Evolution and Human Occupation in the Southern Arabian lowlands during the last  
490 deglaciation and the Holocene. *Glob. Planet. Change* 72, 4, 412-428

491 Lézine, A.-M., Saliège, J.-F., Mathieu, R., Tagliatela, T.L., Mery, S., Charpentier, V., Cleuziou,  
492 S. 2002. Mangroves of Oman during the late Holocene: climatic implications and impact  
493 on human settlements. *Veget. Hist. Archaeobot.* 11, 221-232.

494 Liu, Z., Wang, Y., Gallimore, R., Gasse, F., Johnson, T., deMenocal, P., Adkins, J., Notaro, M.,  
495 Prentice, I.C., Kutzbach, J., Jacob, R., Behling, P., Wang, L., Ong, E. 2007. Simulating the  
496 transient evolution and abrupt change of Northern Africa atmosphere–ocean–terrestrial  
497 ecosystem in the Holocene. *Quatern. Sci. Rev.* 26, 1818–1837.

498 Lorenz, S. J., Lohmann, G. 2004. Acceleration technique for Milankovitch type forcing in a  
499 coupled atmosphere-ocean circulation model: method and application for the Holocene.  
500 *Clim. Dyn.* 23, 727-743.

501 Maley, J. 1970. Contribution à l'étude du bassin tchadien : atlas des pollens du Tchad. *Bull.*  
502 *du J. Bot. Nat. Belgique* 40, 29-48.

503 Manning, K., Timpson, A. 2014. The demographic response to Holocene climate change in  
504 the Sahara. *Quatern. Sci. Rev.* 101, 28-35.

505 Marzin, C., Braconnot, P. 2009. Variations of Indian and African monsoons induced by  
506 insolation changes at 6 and 9.5 kyr BP. *Clim. Dyn.* 33, 215-231.

507 Miller, A.G., Morris, M. 1988. *Plants of Dhofar*. The Office of the Adviser for Conservation of  
508 the Environment, Diwan of Royal Court Sultanate of Oman, 361 p.

509 Morrill, C., Overpeck, J.T., Cole, J.E. 2003. A synthesis of abrupt changes in the Asian summer  
510 monsoon since the last deglaciation. *The Holocene* 13, 465-476.

511 Neff, U., S.J. Burns, A. Mangini, M. Mudelsee, D. Fleitmann, and A. Matter. 2001. Strong  
512 coherence between solar variability and the monsoon in Oman between 9 and 6 kyr  
513 ago. *Nature* 411, 290-293.

514 Overpeck, J., Anderson, D., Trumbore, S., Prell, W. 1996. The southwest Indian Monsoon  
515 over the last 18 000 years. *Clim. Dyn.* 12, 213–225.

516 Reimer, P.J., Baillie, M.G., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk, R.C., Buck,  
517 C.E., Burr, G.S., Edwards, R.L., Friedrich, M. 2009. IntCal09 and Marine09 radiocarbon  
518 age calibration curves, 0-50,000 years cal BP. *Radiocarbon* 51, 1111–1150.

519 Saint-Lu, M., Braconnot, P., Leloup, J., Lengaigne, M., Marti, O. 2015. Changes in the  
520 ENSO/SPCZ relationship from past to future climates. *Earth Planet. Sci. Let.* 412, 18-24.

- 521 Saliège, J.-F., Lézine, A.-M., Cleuziou, S. 2005. Estimation de l'effet réservoir  $^{14}\text{C}$  marine en  
522 mer d'Arabie. *Paléorient* 31,1, 64-69.
- 523 Spalding, M., Blasco, F., Field, C. 1997. The world mangrove atlas. Okinawa, Japan,  
524 International Society for Mangrove Ecosystems, 178 p.
- 525 Tengberg, M. 2005. Les forêts de la mer. Exploitation et évolution des mangroves en Arabie  
526 orientale du Néolithique à l'époque islamique. *Paléorient* 31, 39-45.
- 527 Valcke, S. 2006. OASIS3 user guide (prism\_2-5). PRISM Support Initiative Rep. 3,64p.
- 528 Zarins, J. 2007. Aspects of recent archaeological work at al-Balid (Zafar), Sultanate of Oman.  
529 *Proceed. Semin. Arab. Stud.* 37, 309-324.



530 **Figure Captions**

531 **Figure 1:** Modern surface winds at 925 hP for summer and winter months (NCEP-DOE AMIP-  
532 II Reanalysis) and location of the sites in the text: Kwar-al-Jaramah (KAJ) and Filim : pollen,  
533 this study; Qunf and Hoti: speleothems, Neff et al., 2001; Fleitmann et al., 2003; 2007. Aerial  
534 views from El-Baz (2002).

535 **Figure 2:** *Avicennia marina* mangroves at Filim (A, B) and Kwar-al-Jaramah (C, D)

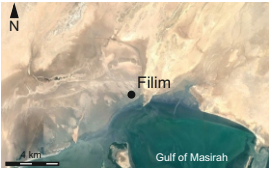
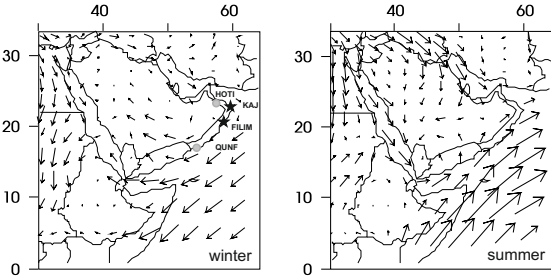
536 **Figure 3:** Simplified pollen diagrams at Filim and Kwar-al-Jaramah showing the percentages  
537 of the main pollen taxa over time. In grey x20 magnification.

538 **Figure 4:** Surface winds as simulated by the IPSL-CM5A climate model: Surface winds (m/s)  
539 for (A) summer (JA) and (B) winter (JF) months for three periods PI, 4ka, and 6ka (B) and  
540 wind roses (wind strength in m/s and frequency in %) for (C) summer and (D) winter for the  
541 same three periods: 6k (green), 4ka (blue), and PI (black).

542 **Figure 5:** Long-term evolution of June-July-August precipitation (mm/day) between 14-18,  
543 18-20 and 20-24°N; A : transient IPSL simulation from 6000 to 3900 cal yr BP and B : two IPSL  
544 transient simulations from 6000 cal yr BP to zero for which changes in earth orbital  
545 parameters have been accelerated by a factor 10 (see details in the text). These two  
546 simulations have different initial states. The curves have been smoothed by an equivalent  
547 hundred years in A (100 yrs) and B (10 yrs) (bold lines).

548 **Figure 6:** The end of the Holocene Humid Period in Southern Arabia: multiproxy records and  
549 climate simulations. A: dated records of lakes, wetlands, and rivers at 1000 year intervals  
550 (Lézine et al., 2014. See paleohydrological database and reference therein at NOAA), B:Qunf  
551 speleothem isotope record (Fleitmann et al., 2003; 2007), C and D: local  
552 (*Avicennia/Rhizophora*) and regional (*Artemisia/Rhizophora*) indexes of aridity at Filim (C)  
553 and Kwar-al-Jaramah (D), E: Hoti speleothem isotope record (Neff et al., 2001), F: hundred

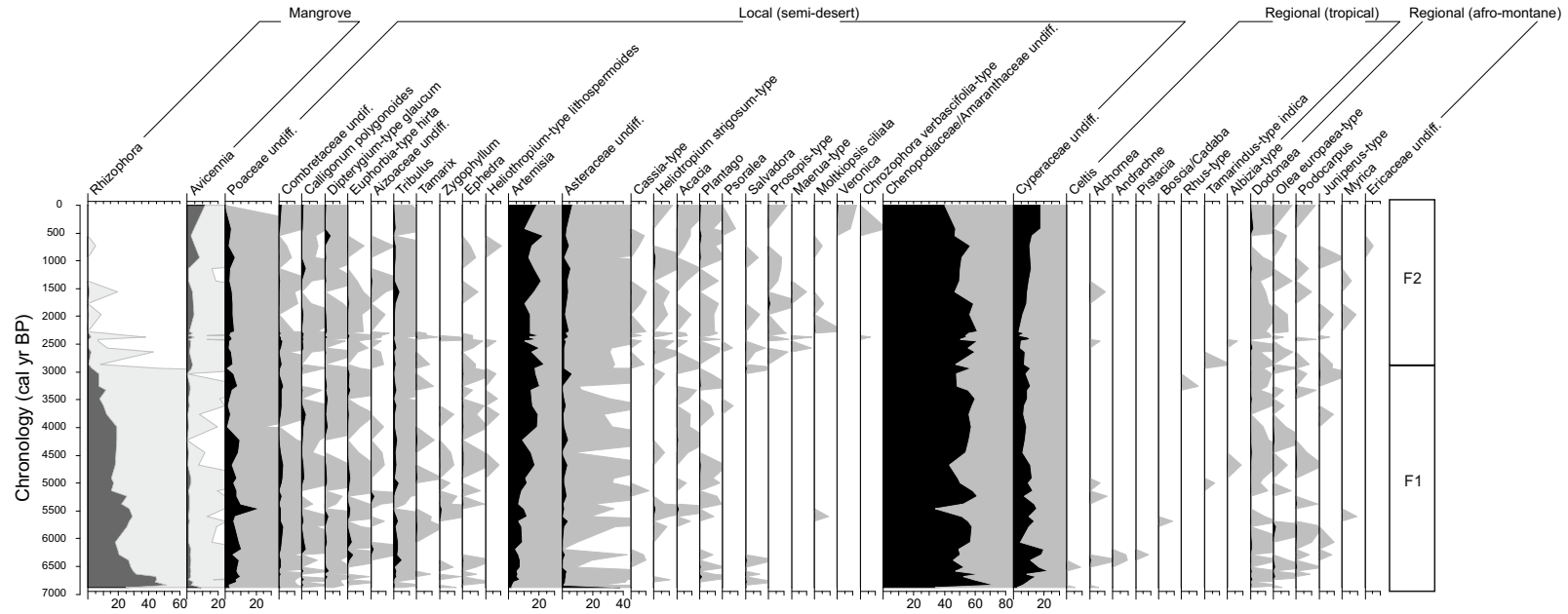
554 year smoothed transient IPSL simulations for the time interval between 6000 cal yr BP and  
555 present day (cf Fig. 4).



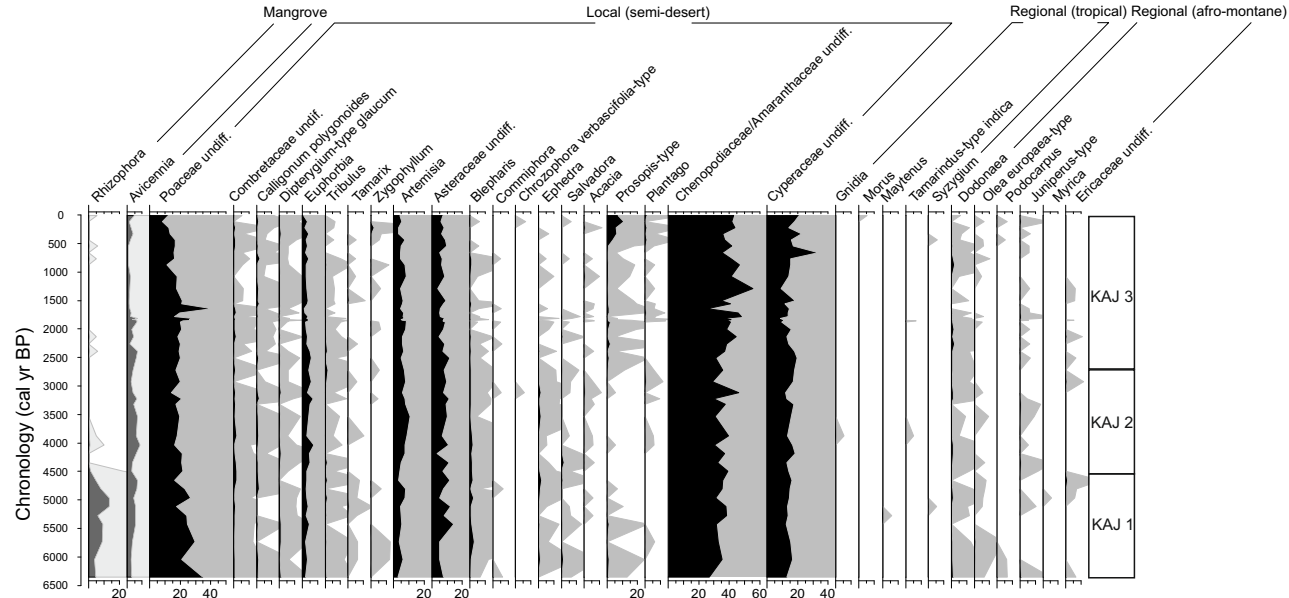


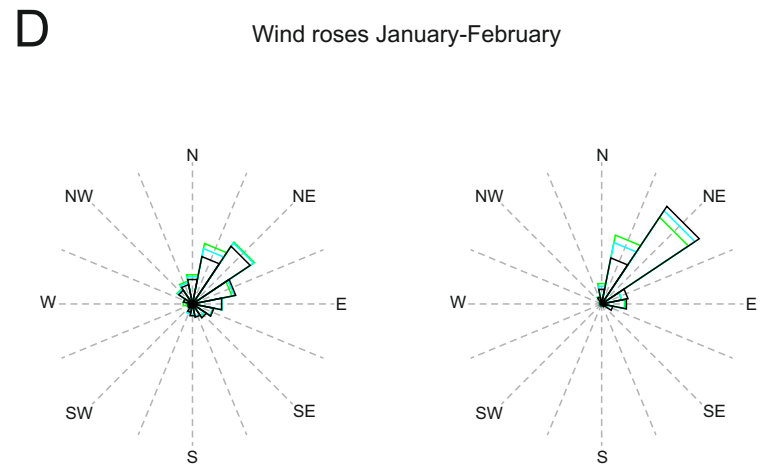
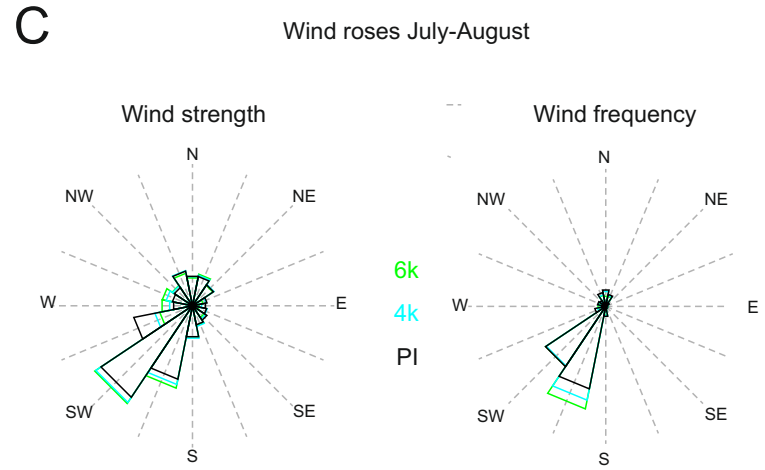
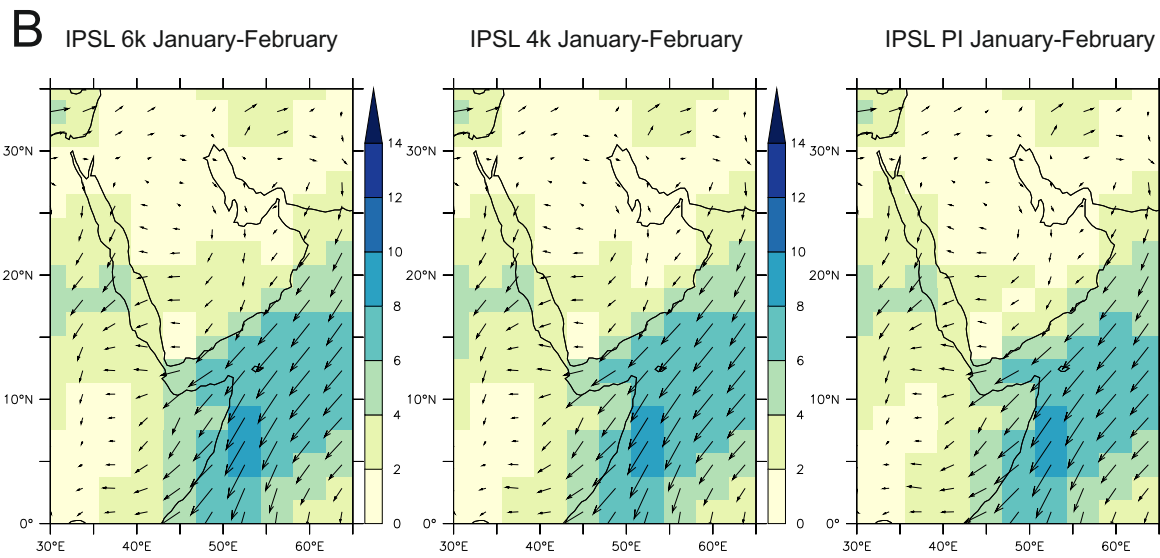
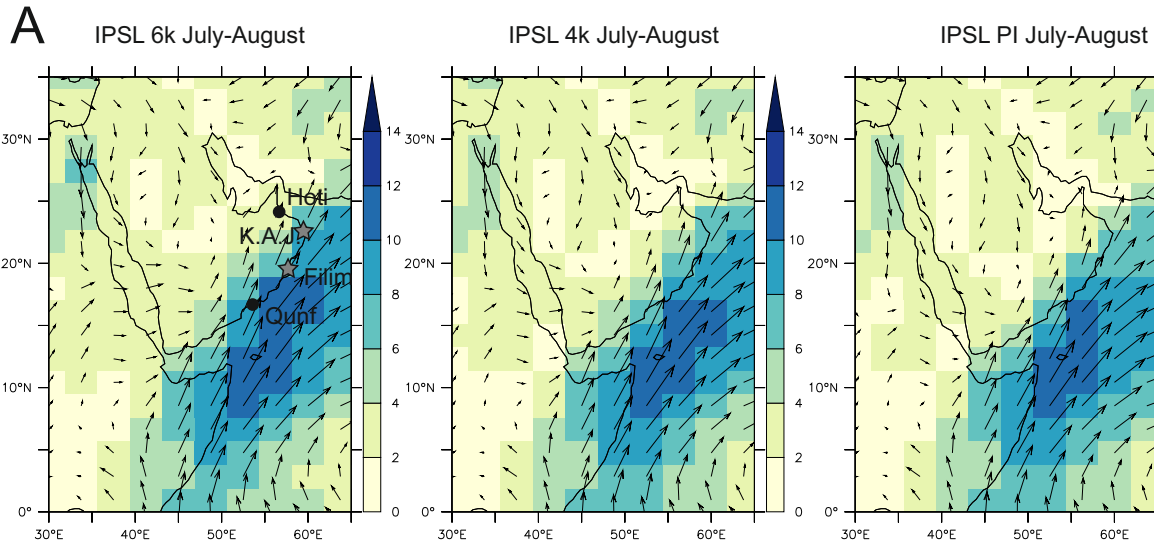


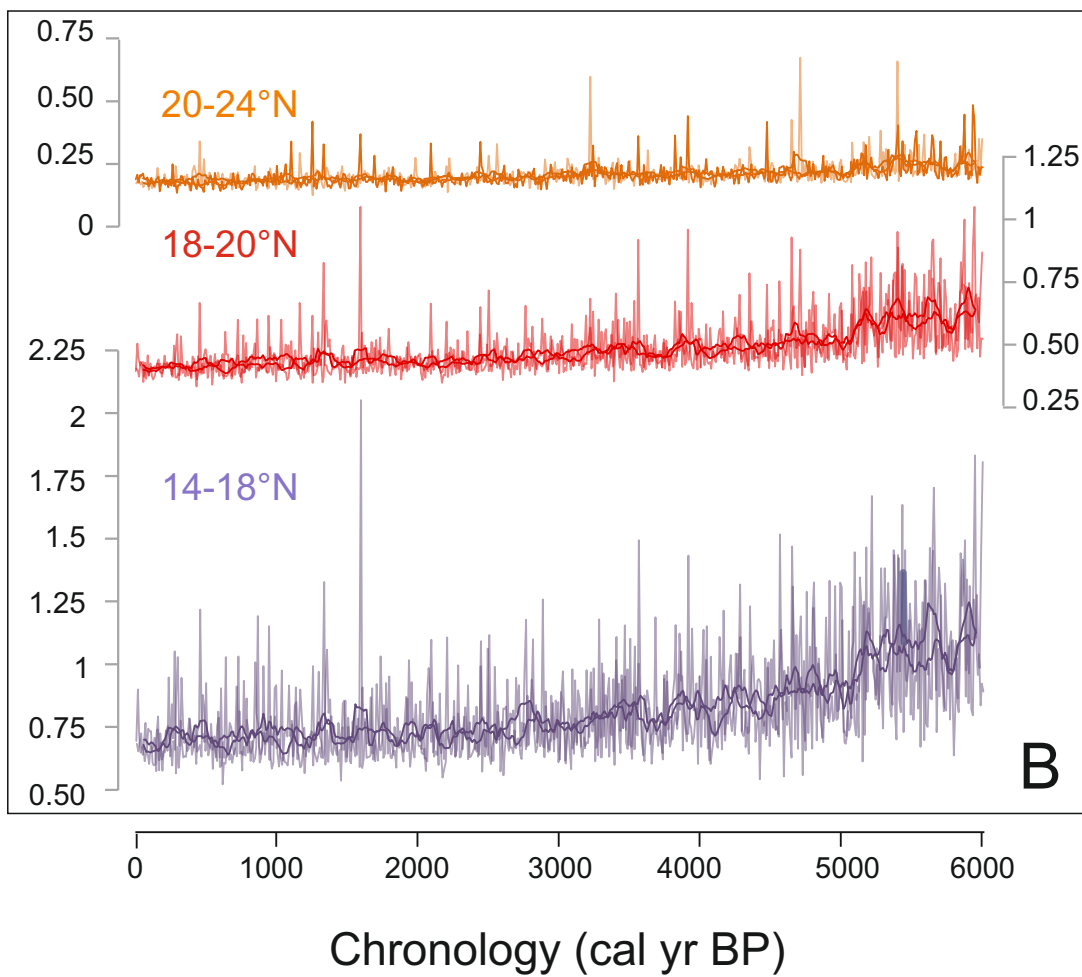
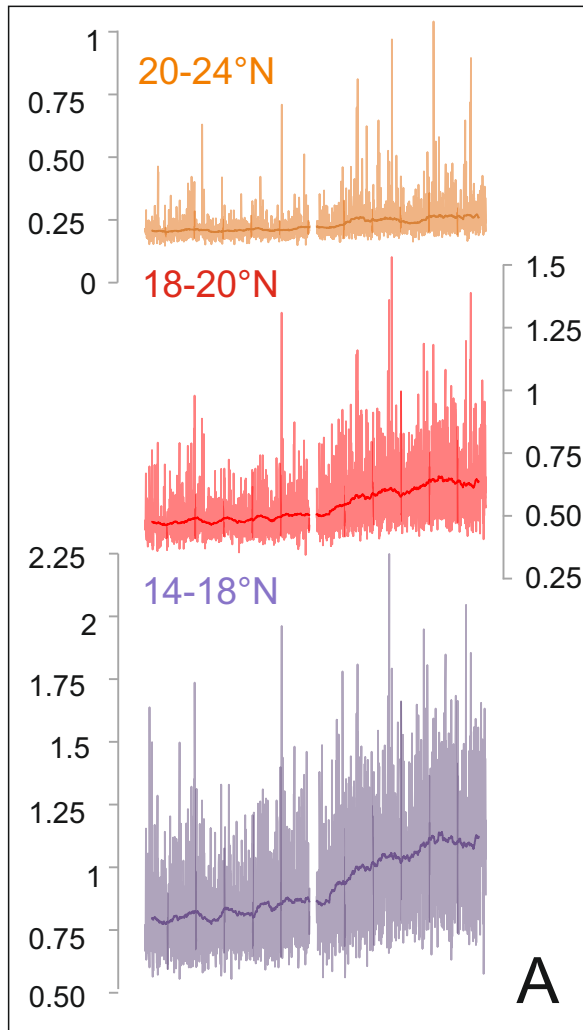
FILIM (OMAN) Main taxa



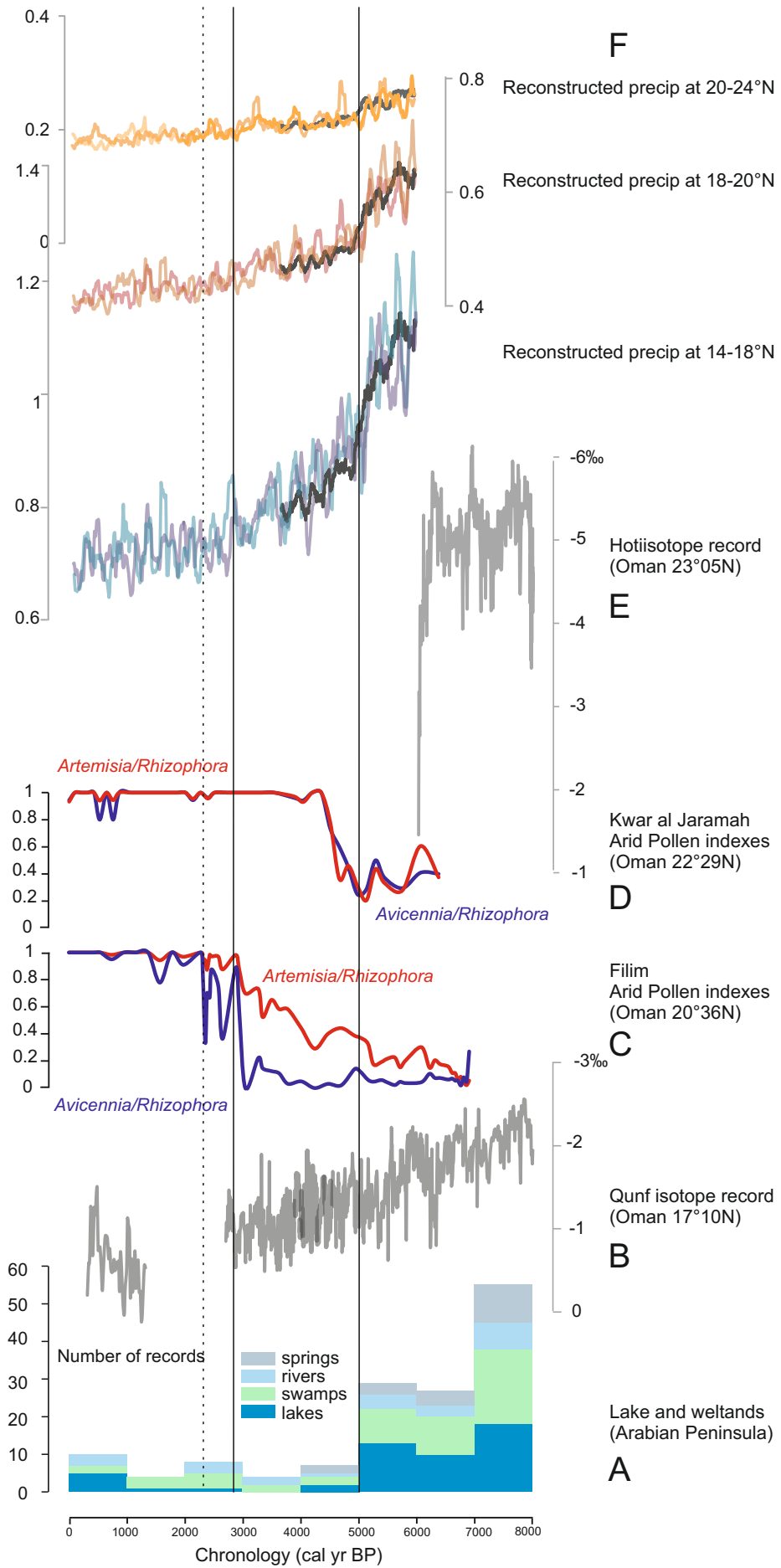
KWAR AL JARAMAH (OMAN) Main taxa











Depth (cm)	14C	material	Lab number	1 sigma calendar year ( $\Delta R= 210\pm 15$ )
55-56	1060 $\pm$ 30	shells	SacA 7200	456-505
105-106	1345 $\pm$ 30	shells	SacA 7201	654-712
149-150	1790 $\pm$ 50	shells	SacA 7202	1074-1207
205-206	2810 $\pm$ 45	shells	SacA 7203	2207-2334
215-216	3810 $\pm$ 30	shells	SacA 7205	3445-3544
305-306	4025 $\pm$ 30	shells	SacA 7208	3709-3818
365-366	6305 $\pm$ 30	shells	SacA 7209	6465-6574
404-406	6475 $\pm$ 30	shells	SacA 7210	6665-6759

Table 1a: Filim chronological control. AMS on marine shells (Saclay Artemis AMS Facilities). Calibrated ages from Reimer et al. (2009) applying the local  $\Delta R$  calculated by Saliège et al. (2005).

Depth (cm)	14C	material	Lab number	1 sigma calendar year ( $\Delta R= 210\pm 15$ )
70-71	1445 $\pm$ 30	shells	SacA 7217	722-820
149-150	2245 $\pm$ 30	shells	SacA 7219	1548-1653
205-206	2415 $\pm$ 30	shells	SacA 7220	1757-1858
249-250	2480 $\pm$ 30	shells	SacA 7221	1829-1922
299-300	3270 $\pm$ 30	shells	SacA 7222	2770-2262
345-346	3760 $\pm$ 40	shells	SacA 7223	3372-3484
399-400	5010 $\pm$ 35	shells	SacA 7224	5011-5194

Table 1b: Kwar-al-Jaramah chronological control on marine shells (Saclay Artemis AMS Facilities). Calibrated ages from Reimer et al. (2009) applying the local  $\Delta R$  calculated by Saliège et al. (2005).

Period	Excentricity	Obliquity	Perihelion – 180.
PI	0.0167	23.446	102.04
4ka	0.0181	23.929	34.26
6ka	0.0187	24.105	0.87

Table 2: Orbital parameters prescribed in the different time slice experiments.