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1 **Stalagmite-inferred European westerly drift in the early Weichselian with**  
2 **centennial-scale variability in marine isotope stage 5a**

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29           **Abstract:** The Weichselian glaciation is characterized by significant ocean circulation  
30 variations starting from ~115 thousand years ago (ka) and terminating at ~11.5 ka. The early  
31 Weichselian (115–74 ka), especially marine isotope stage (MIS) 5a at 85–74 ka, provides a  
32 window for understanding the linkage between the European westerlies and Mediterranean  
33 climate. However, lack of highly-resolved paleoclimate records with absolute chronologies  
34 hampers our knowledge of decadal- to centennial-scale climate changes and forcings in the  
35 circum-Mediterranean realm. Here, we present  $^{230}\text{Th}$ -dated stalagmite-inferred hydroclimate  
36 records from Observatoire cave (43°44' N, 7°25' E), Monaco, for the period between  $88.7 \pm 0.4$   
37 and  $80.3 \pm 0.1$  ka, covering portions of MIS 5b and 5a. Agreement between Observatoire and  
38 circum-Mediterranean stalagmite records confirm large-scale warming over the Atlantic-Europe  
39 territory during the transition from MIS 5b to 5a. Subdecadally-resolved Observatoire  $\delta^{18}\text{O}$  and  
40  $\delta^{13}\text{C}$  records express four multi-centennial arid intervals in southern Europe at 84-80 ka in the  
41 first-half of MIS 5a, suggesting centennial westerly drifts, a finding supported by a model  
42 simulation. Westerly changes and associated arid events can be attributed to slowdowns of the  
43 Atlantic meridional overturning circulation, North Atlantic Oscillation states, and solar activity.

44           **Keywords: Southern Europe, Stalagmite, Model simulation, Precipitation, Weichselian,**  
45           **MIS 5a, Multi-centennial arid intervals, AMOC**

#### 46 47           **Highlights**

- 48           1. Stalagmite  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  records from Monaco show precipitation changes in southern Europe  
49           from 89-80 ka at MIS 5b-5a.
- 50           2. Multi-centennial arid intervals at 84-80 ka in southern Europe during MIS 5a could be linked to  
51           AMOC slowdowns, NAO states, and solar activity.
- 52           3. A transient simulation of MIS 5a suggests that centennial-scale AMOC slowdowns could induce  
53           reduced precipitation over western Europe.

## 54 1. Introduction

55 The last glacial cycle, starting from marine isotope stage (MIS) 5e at ~130 thousand years  
56 ago (ka, relative to AD 1950, hereafter), features rapid and recurrent millennial climate  
57 variations, as documented in Greenland ice cores with relatively warm interstadials (GI) and cold  
58 stadials (GS) (Johnsen et al., 1992; Dansgaard et al., 1993; NorthGRIP-Members, 2004) (Fig.  
59 1a). Northern hemisphere summer insolation (NHSI) peaks (Fig. 1b) brought warm temperatures  
60 and ice volume reductions, interrupting the Earth's transition from the last interglacial to last  
61 glacial maximum (Lambeck and Chappell, 2001). In the early Weichselian (~115–74 ka), two  
62 warm intervals, MIS 5c and 5a (Fig. 1) started following the NHSI maximum at 105 and 85 ka  
63 (Fig. 1b), with the global sea-level maximum reaching -10 to -20 m at 100 and 83 ka,  
64 respectively (Fig. 1e). These two warm intervals featured unstable ice-sheet configurations in  
65 Fennoscandia, Greenland, and North America (Chapman and Shackleton, 1999; Mokeddem and  
66 McManus, 2016; Batchler et al., 2019). Ice-sheet instability and the associated meltwater input in  
67 the North Atlantic may have resulted in multi-centennial to millennial oscillations in Asian  
68 stalagmite  $\delta^{18}\text{O}$  values associated with Asian monsoon intensity variations (Cheng et al., 2016)  
69 (Fig. 1b). Fluctuations in Atlantic planktic foraminiferal  $\delta^{18}\text{O}$  ( $\delta^{18}\text{O}_{\text{pf}}$ ) values (Fig. 1c; de Abreu  
70 et al., 2003) and sea surface temperatures (SST) off the Iberian margin (Fig. 1c; Martrat et al.,  
71 2004) during MIS 5c and 5a also suggest variations in the Atlantic meridional overturning  
72 circulation (AMOC), which can modulate the hydroclimate of the North Atlantic and Europe  
73 (Stouffer et al., 2006; Margari et al., 2010; Kageyama et al., 2013; Jackson et al., 2015;  
74 Stockhecke et al., 2016; Tzedakis et al., 2018). For example, abrupt  $\delta^{18}\text{O}$  shifts in Alpine  
75 stalagmite records (NALPS; Fig. 1d) which correspond to the  $\delta^{18}\text{O}$  shifts in Greenland ice cores  
76 (Fig. 1a; NorthGRIP-Members, 2004) could have been affected by ocean circulation changes

77 (Boch et al., 2011). At the end of MIS 5b (~85 ka), the abrupt positive shift in NALPS  $\delta^{18}\text{O}$  has  
78 been linked to the end of GS22, accompanying warming in the North Atlantic (Boch et al.,  
79 2011).

80 The circum-Mediterranean region has a classical Mediterranean climate featuring hot/dry  
81 summers and mild/wet winters (Beck et al., 2018). Over the past two decades, droughts in  
82 southern Europe have threatened water supply, ecosystem, and agricultural instabilities over the  
83 past two decades (Hoerling et al., 2012; Naumann et al., 2021). Complex forcings from rising  
84 greenhouse gases, ice-sheet meltwater input, and changes in the strength of AMOC hinder our  
85 ability to reliably predict Mediterranean hydroclimate over the next century. As NHSI values  
86 during MIS 5a are as high as those in the Holocene (Berger, 1978; Laskar et al., 2011), highly-  
87 resolved proxy records during MIS 5a offer important clues to better understand the future  
88 climate. Previous studies have highlighted centennial-to-millennial scale climatic variability in  
89 the North Atlantic during MIS 5 (e.g., Oppo et al., 1997; Mokeddem and McManus, 2016),  
90 especially in southern Europe (Budsky et al., 2019; Denniston et al., 2018, Tzedakis et al., 2018).  
91 Most cases, however, have focused on the Eemian warm period (MIS 5e; e.g., Allen and  
92 Huntley, 2009; Drysdale et al., 2005; Milner et al., 2013; Tzedakis et al., 2003, 2018). Less  
93 attention has been given to subcentennial- to centennial-scale variability during MIS 5a due to  
94 the limitation of archive resolution and dating precision.

95 Here, we present a subdecadal- to multidecadal-resolved stalagmite-inferred precipitation  
96 record with robust chronology, from Monaco (northern Mediterranean) to understand  
97 hydroclimate variability associated with the westerly changes during 88.7–80.3 ka in the early  
98 Weichselian, especially focusing on MIS 5a. This is complemented by results from a transient

99 experiment for the period 86–80 ka performed with the Earth system model (LOVECLIM), to  
100 assess the potential hydroclimatic variability drivers in southern Europe.

## 101 **2. Material and Methods.**

### 102 2.1. Cave and regional settings

103 Observatoire Cave ([43°43' N, 7°24' E], 103 m above sea level) (Figs. 2 and 3) preserves  
104 evidence of the oldest human occupations in Monaco, southern Europe (Rossoni-Notter et al.,  
105 2016). The cave is located along the northwestern Mediterranean coastline, in upper Jurassic  
106 bedrock - a limestone block from the “Arc de Nice” subalpine mountain chain (Gilli, 1999). This  
107 600 m-long cave opens to the south and its entrance hall is 17 m in length, 6 m in width, and 7 m  
108 in height (Fig. 3a). After the entrance, the cave splits into two long and narrow 500 m passages,  
109 1-2 m in width and height, with an innermost chamber, 5 m in width and 6 m in height at the  
110 terminus (Fig. 3a). A thin 0-5-cm clay soil lies above the 90 m cap rock of Jurassic limestone.

111 The average annual rainfall and temperature during AD 2003–2012 was  $631 \pm 400$  mm ( $2\sigma$ )  
112 and  $21.1 \pm 2.6$  °C ( $2\sigma$ ; Monaco weather station, [43°43' N, 7°24' E], 131 m above sea level, 1  
113 km from the cave), with monthly temperatures ranging from 9–37 °C. Modern climate in  
114 Monaco is a typical Mediterranean climate with hot/dry summers and mild/wet winters. Over  
115 80% of the annual precipitation, brought by prevailing westerly winds, falls between September  
116 and February. The cave is situated in the transition zone between the subtropical high-pressure  
117 belt and the westerlies. During summer, a subtropical high-pressure system promotes dry sinking  
118 air and causes regional arid conditions. In the winter, precipitation is supplied from the westerlies  
119 and winter storms (García-Ruiz et al., 2011).

### 120 2.2. Samples and U-Th dating

121 Two candle-shaped stalagmites, OV12-1 and OV12-5, were collected from Observatoire  
122 cave ([43°43' N, 7°24' E], 103 m above sea level) (Fig. 3) in November, 2012. OV12-1 is a 350-  
123 mm-long calcitic stalagmite (Fig. 3b) and OV12-5 a 180 mm-long aragonitic stalagmite (Fig.  
124 3c). The collection chamber features high humidity (98-100%) and an annual temperature of  
125 18.5 °C, within the modern range of  $21.1 \pm 2.6$  °C ( $1\sigma$ , AD 2003–2012). Both stalagmites feature  
126 clear growth bands with milky white and light tan layers, without visible porosity or detritus.

127 Five powdered subsamples, 50 mg each, were drilled from OV12-1 and forty-seven chipped  
128 subsamples, 75-230 mg each, were cut from OV12-5 for U-Th chemistry and instrumental  
129 analyses (Fig. 3b and c). Chemistry procedure was performed on class-100 benches in the class-  
130 10000 subsampling room at the High-Precision Mass Spectrometry and Environment Change  
131 Laboratory (HISPEC), Department of Geosciences, National Taiwan University (NTU) (Shen et  
132 al., 2003; 2008). U and Th isotopic compositions were measured on a multiple collector  
133 inductively coupled plasma mass spectrometer, Thermo-Fisher Neptune at the NTU. A dry  
134 sample introduction system, Cetec Aridus, was used (Shen et al., 2012). Half-lives of U-Th  
135 nuclides used are listed in Cheng et al. (2013).  $^{230}\text{Th}$  age was calculated using an assumed initial  
136 atomic  $^{230}\text{Th}/^{232}\text{Th}$  ratio of  $4 (\pm 2) \times 10^{-6}$ . Uncertainties in the isotopic data and  $^{230}\text{Th}$  dates are  
137 given at two-sigma ( $2\sigma$ ) uncertainty level or two standard deviations of the mean ( $2\sigma_m$ ). StalAge  
138 algorithm techniques (Scholz and Hoffmann, 2011) were used to build age model.

### 139 2.3. C/O Stable Isotope Analysis

140 One layer on OV12-1 at 130 mm from the top and seven layers on OV12-5 at 14, 60, 70,  
141 114, 120, 156, and 178 mm from the top were selected for the Hendy test (Hendy, 1970) (Fig. 3b  
142 and c), with five to seven coeval powdered subsamples on each layer. A total of 238 powdered  
143 subsamples on OV12-1 at 1-mm intervals and 710 powdered subsamples on OV12-5 at 0.1 to 1.0

144 mm intervals, 50-100  $\mu\text{g}$  each, drilled along the central growth axis on the polished surface (Fig.  
145 3b and c) using a 0.2-mm dental drill, were analyzed. Instrumental measurements were  
146 conducted on a Micromass IsoPrime isotope ratio mass spectrometer at the Stable Isotope  
147 Laboratory of the Department of Earth Sciences, National Taiwan Normal University, and on a  
148 Finnigan MAT 253 IRMS connected to an on-line, automated carbonate preparation system,  
149 Gasbench II, at the College of Geography Science, Fujian Normal University. Stable oxygen and  
150 carbon isotope values are reported as  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ , respectively, relative to the reference  
151 standard, Vienna Pee Dee Belemnite (VPDB), calibrated with the NBS-19 standard ( $\delta^{18}\text{O} = -$   
152 2.20‰). One-sigma external errors of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  measurements were  $\pm 0.12\text{‰}$  and  $\pm 0.06\text{‰}$ ,  
153 respectively.

#### 154 2.4. Model simulation

155 A transient simulation of MIS 5 was performed with the Earth system model of intermediate  
156 complexity LOVECLIM (Goosse et al., 2010). This simulation includes an ocean general  
157 circulation model ( $3 \times 3$  degree and 20 vertical levels), a dynamic thermodynamic sea-ice model,  
158 a quasi-geostrophic T21 atmospheric model, as well as a land surface scheme and a vegetation  
159 model (VECODE). This model is forced by transient changes in orbital parameters (Berger,  
160 1978), greenhouse gases (Köhler et al., 2017), northern hemispheric ice-sheet, and associated  
161 albedo (Abe-Ouchi et al., 2007). The experiment starts at MIS 5e (Tzedakis et al., 2018) and was  
162 integrated forward in time until 80 ka, to investigate the impact of changes in boundary  
163 conditions on climate across MIS 5a.

### 164 **3. Results**

#### 165 3.1. U-Th data and age model

166 Detailed U-Th isotopic and concentration data and dating results of Observatoire stalagmite  
167 OV12-1 and 12-5 are given in Table S1. Stalagmite OV12-1 has  $^{238}\text{U}$  content of  $0.4\text{--}0.7 \times 10^{-6}$   
168 g/g and  $^{232}\text{Th}$  content of  $10\text{--}2200 \times 10^{-9}$  g/g. Stalagmite OV12-5 features high  $^{238}\text{U}$  contents of  
169  $1.5\text{--}8.5 \times 10^{-6}$  g/g and low  $^{232}\text{Th}$  contents of  $0.01\text{--}2.1 \times 10^{-9}$  g/g. The uncertainties of corrected  
170  $^{230}\text{Th}$  dates are from  $\pm 368$  to  $\pm 597$  years on OV12-1 and from  $\pm 19$  to  $\pm 180$  years on OV12-5.  
171 The dates are in stratigraphic order except for one outlier on OV12-5 at 136 mm ( $\sim 82.7$  ka) from  
172 the top. The uncertainties of StalAge model range from  $\pm 277$  to  $\pm 1723$  years (average  $\pm 486$   
173 years) on OV12-1 (Fig. S1a) and  $\pm 10$  to  $\pm 176$  years (average  $\pm 48$  years) on OV12-5 (Fig. S1b).  
174 Stalagmite OV12-1 and OV12-5 deposited from  $88.75 \pm 0.4$  to  $81.96 \pm 1.7$  ka and  $83.6 \pm 0.2$  to  
175  $80.3 \pm 0.1$  ka, respectively. The average growth rate is  $56 \mu\text{m/yr}$  for OV12-1 and  $54 \mu\text{m/yr}$  for  
176 OV12-5. No noticeable hiatus can be distinguished with the current age models (Fig. S1).

### 177 3.2. Stalagmite $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ time series

178 Results of stalagmite OV12-1 and 12-5  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values are given in Table S2. The  
179 StalAge model reveals an average temporal resolution of 28 years for each stable isotope data  
180 point on OV12-1 and 5 years on OV12-5. The isotope series of OV12-1 and OV12-5 cover MIS  
181 5b-5a and overlap from 83.7–81.7 ka. The  $\delta^{18}\text{O}$  values range from  $-6.5$  to  $-3.6\text{‰}$  on OV12-1 and  
182 from  $-4.6$  to  $-2.8\text{‰}$  on OV12-5 (Fig. 4a). OV12-1  $\delta^{18}\text{O}$  display millennial fluctuations with  
183 relatively high values of  $-3.8\text{‰}$  centered at  $87 \pm 0.4$  ka. OV12-5  $\delta^{18}\text{O}$  record shows a  $1.2\text{‰}$   
184 increase from  $-4.6$  to  $-3.4\text{‰}$  between  $83.5 \pm 0.1$  and  $82.9 \pm 0.1$  ka, a  $0.7\text{‰}$  decrease from  $82.9 \pm$   
185  $0.1$  to  $82.8 \pm 0.1$  ka, and then a  $0.9\text{‰}$  increase from  $82.8 \pm 0.1$  to  $82.5 \pm 0.1$  ka. Between  $82.5 \pm$   
186  $0.1$  ka and  $80.5 \pm 0.1$  ka,  $\delta^{18}\text{O}$  data hovers between  $-4.1$  and  $-2.8\text{‰}$ , with  $0.8\text{--}1.2\text{‰}$  fluctuations  
187 on a multi-centennial timescale.

188 OV12-1  $\delta^{13}\text{C}$  data range from -10.1 to -8.1‰ and OV12-5  $\delta^{13}\text{C}$  from -7.6 to -6.4‰ (Fig.  
189 4b). OV12-1  $\delta^{13}\text{C}$  record reveals relative positive values of average -8.8‰ from  $88.8 \pm 0.4$  to  
190  $85.6 \pm 0.3$  ka and relative negative values of average of -9.7‰ from  $84.0 \pm 0.5$  to  $82.0 \pm 1.7$  ka.  
191 Both  $\delta^{13}\text{C}$  records are characterized by clear multi-centennial timescale variability.

192 We adopted the method described by Fohlmeister et al. (2012) to combine the OV12-1 and  
193 OV12-5 stalagmite records. OV12-1 was tuned to the OV12-5  $\delta^{18}\text{O}$  record, at a 95% confidence  
194 level (Fig. 4a). The OV12-1  $\delta^{13}\text{C}$  record using the  $\delta^{18}\text{O}$ -tuned age is shown in Fig. 4b. The  
195 tuning method utilizes a Monte Carlo approach to optimize the correlation between the two  
196 series.

### 197 3.3. Climate simulations

198 Simulated AMOC strengths are presented in a six thousand year-long window at 86–80 ka  
199 in Figure 5b. The modelled regional precipitation series on the [42–46 °N, 5–10 °E] sector is  
200 plotted in Figure 5c and simulated Greenland temperature record in Figure 5a. The two records  
201 (Fig. 5b and c) show that multi-centennial regional hydrological changes in Monaco are  
202 synchronous with those of AMOC strength in the North Atlantic. Atmosphere pressure field and  
203 wind field anomalies from two 200 year-long intervals with weak AMOC and with strong  
204 AMOC are illustrated in Figures 5d and e.

## 205 **4. Discussion**

### 206 4.1. Tests for stalagmite isotopic equilibrium conditions

207 Factors affecting isotopic compositions in stalagmites depend on a variety of isotopic  
208 fractionation processes during rainfall condensation and water infiltration in karst systems  
209 (McDermott, 2004). Unexpected kinetic effects that are usually associated with degassing during  
210 carbonate precipitation could bias the isotope signals from the climatic imprint. The Hendy test

211 (Hendy, 1971) and duplication test (Dorale and Liu, 2009) have been widely used for evaluating  
212 isotopic equilibrium. The results of the Hendy tests in this study all show a 1-sigma variations of  
213 less than  $\pm 0.13\text{‰}$  for  $\delta^{18}\text{O}$  (Fig. S2a) and  $\pm 0.16\text{‰}$  for  $\delta^{13}\text{C}$  (Fig. S2b). On these layers, the  
214 absolute differences between the isotopic values,  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ , at  $\pm 2$  mm and center range  
215 from 0.01 to 0.16‰, except for one layer at 178 mm (OV12-5), which has a difference of 0.30‰  
216 for  $\delta^{18}\text{O}$  and 0.39‰ for  $\delta^{13}\text{C}$ . The standard deviations of all differences to center for all layers  
217 are  $\pm 0.09\text{‰}$  for  $\delta^{18}\text{O}$  and  $\pm 0.10\text{‰}$  for  $\delta^{13}\text{C}$ . Considering that the measurement external errors of  
218  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  are  $\pm 0.12\text{‰}$  and  $\pm 0.06\text{‰}$ , respectively, the results suggest that kinetic  
219 fractionation is insignificant at an interval of  $\pm 2$  mm from the layer center.

220 Good agreement of concurrent variations between contemporaneous stalagmite OV12-1 and  
221 OV12-5  $\delta^{18}\text{O}$  records during 83.7–81.7 ka satisfy a sound duplication test (Dorale and Liu,  
222 2009). The agreement indicates little kinetic effect on  $\delta^{18}\text{O}$  data. An observed  $\delta^{18}\text{O}$  offset of -1‰  
223 of calcitic OV12-1 is observed from aragonitic OV12-5. This offset can be attributed to different  
224 fractionation of 0.6–1.4‰ (Lachniet, 2009) between the calcite-water and aragonite-water  
225 system. The OV12-1  $\delta^{13}\text{C}$  values are 2.5‰ lower than those of OV12-5. This difference is  
226 compatible with reported calcite-aragonite offsets of between 1.1 and 2.3‰ (Romanek et al.,  
227 1992; Fohlmeister et al., 2018). The similarity of both  $\delta^{13}\text{C}$  records suggests that the  $\delta^{13}\text{C}$  time  
228 series captures environmental signals. In summary, the duplication between isotope records in  
229 OV12-1 and OV12-5 suggests an insignificant kinetic effect and implies that isotopic variations  
230 are mainly of environmental origin.

#### 231 4.2 Climatic significance of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$

232 Mediterranean stalagmite  $\delta^{18}\text{O}$  could be controlled by various factors, such as dripwater  
233  $\delta^{18}\text{O}$ , temperature, precipitation amount, and moisture source (e.g. Bar-Matthews et al., 1996;

234 Mangini et al., 2005; Fairchild et al., 2006; Lachniet, 2009). Precipitation  $\delta^{18}\text{O}$  ( $\delta^{18}\text{O}_p$ ) mainly  
235 governs dripwater  $\delta^{18}\text{O}$  values that are eventually registered in the stalagmite. Based on modern  
236 observed precipitation data from Monaco (AD 1999-2016, GNIP-IAEA), the temperature effect  
237 on modern monthly  $\delta^{18}\text{O}_p$  data is  $0.30 \pm 0.10\text{‰}/^\circ\text{C}$  ( $2\sigma$ ,  $r = 0.42$ ,  $n = 177$ ,  $p < 0.01$ ) (Fig. S3a).  
238 This gradient is largely counterbalanced by the temperature-dependence fractionation of  $\sim -$   
239  $0.23\text{‰}/^\circ\text{C}$  (O'Neil et al., 1969). Considering estimated marine temperature changes of  $\sim 3^\circ\text{C}$   
240 between 87.5 and 77.5 ka (Drysdale et al., 2020), the net temperature effect on speleothem  $\delta^{18}\text{O}$   
241 is only  $\sim 0.1\text{‰}$  and negligible. Studies in the Mediterranean (Bar-Matthews and Ayalon, 2011;  
242 Domínguez-Villar et al., 2017; Baldini et al., 2019) also consider the regional temperature effect  
243 on Mediterranean stalagmite  $\delta^{18}\text{O}$  to be negligible.

244 The amount effect, which is a negative correlation between  $\delta^{18}\text{O}_p$  and rainfall amount due to  
245 vapor-water  $\delta^{18}\text{O}$  fractionation in air masses, is one of the key factors that control Mediterranean  
246 stalagmite  $\delta^{18}\text{O}$  (Ruan et al., 2016; Columbu et al., 2019, 2020; Regattieri et al., 2019; Thatcher  
247 et al., 2020). Monthly modern precipitation data (1999-2016 AD, GNIP-IAEA) indicate average  
248 values of  $-2.4 \pm 0.8\text{‰}$  per 100 mm/month precipitation ( $2\sigma$ ,  $r = 0.40$ ,  $n = 186$ ,  $p < 0.01$ ) (Fig.  
249 S3b), consistent with a simulated amount effect of  $-2.0 \pm 0.6\text{‰}$  per 100 mm/month (Bard et al.,  
250 2002) and regional mean values of  $-1.6 \pm 0.2\text{‰}$  per 100 mm/month in the western  
251 Mediterranean (Bard et al., 2002).

252 Precipitation originating from the Mediterranean region displays more positive  $\delta^{18}\text{O}$  values  
253 of  $-4.62\text{‰}$  (weighted mean) than from the Atlantic ( $-8.48\text{‰}$ ) (Celle-Jeanton et al., 2001).  
254 Proportional changes of the moisture sourced from the two regions could alter  $\delta^{18}\text{O}_p$ . As  
255 Observatoire cave is located  $< 100$  m from the coast, it receives Mediterranean-sourced moisture,  
256 and the “source effect” could be important on Observatoire stalagmite isotope records. While it

257 is difficult to track moisture sources during MIS 5b–5a, modern Monaco precipitation is sourced  
258 primarily from the Atlantic, with minor Mediterranean or mixed sources (Columbu et al., 2019,  
259 2020). Significant Mediterranean-sourced moisture can, however, be observed along with large  
260 ice-sheets (Merz et al., 2015; Drysdale et al., 2009). For example, the presence of the Laurentide  
261 ice-sheet could disturb Rossby wave configuration and push the region where the eddies form  
262 equatorially (Merz et al., 2015; Ludwig et al., 2016), shifting westerly tracks towards the south  
263 and increasing Mediterranean-sourced moisture at Monaco (Luetscher et al., 2015). Strong  
264 AMOC, usually observed in warm periods, can lead to high moisture transport from the Atlantic  
265 into the Mediterranean (Sanchez Goni et al., 1999), seen as relatively negative Mediterranean  
266 stalagmite  $\delta^{18}\text{O}$  (Drysdale et al., 2009; Dumitru et al., 2018). Intense vapor advection and high  
267 efficiency of Atlantic moisture transport can accompany strong westerly winds and high rainfall  
268 in Monaco, modulating  $\delta^{18}\text{O}_p$  in a negative way. Observatoire stalagmite  $\delta^{18}\text{O}$  can, therefore, be  
269 considered as a qualitative indicator of the strength of the westerlies at this region, with strong  
270 westerlies associated with intense precipitation and a high proportion of Atlantic-sourced  
271 moisture corresponding to low  $\delta^{18}\text{O}$ , and *vice versa*.

272 The source of carbon for stalagmites is soil  $\text{CO}_2$ , mainly governed by plant roots’  
273 respiration and organic matter decomposition. The roots form carbonic acid in contact with  
274 water, which dissolves cave host-rock (e.g., Columbu et al., 2018). Pedogenic carbonate  $\delta^{13}\text{C}$   
275 values are related to surrounding vegetation (McDermott, 2004), such as C3 and C4 plants. The  
276 respective aragonitic OV12-1 and calcitic OV12-5  $\delta^{13}\text{C}$  values of -8 to -10.4‰ and -7.6 to -6.5‰  
277 are within the predicted stalagmite  $\delta^{13}\text{C}$  range of -14 to -6‰ dominated by C3 type vegetation  
278 (McDermott, 2004), similar to the plants in Monaco today (Mediterranean bush). C3 plants  
279 dominated the land surface in the Mediterranean region during both glacial and interglacial

280 periods (Columbu et al., 2020), and stalagmite  $\delta^{13}\text{C}$  during MIS 5b-5a was not dominated by  
281 vegetation shifts between C4 and C3 plants. OV12-5  $\delta^{13}\text{C}$  variations are mainly governed by soil  
282 microbial activity and/or vegetation density (Columbu et al., 2019, 2020), both affected by  
283 regional alternation of wet/warm or dry/cold conditions in the Mediterranean. High soil  
284 microbial activity and dense vegetation can lead to negative stalagmite  $\delta^{13}\text{C}$  values.

285 Prior carbonate precipitation (PCP), a process of progressive  $\text{CO}_2$  degassing and carbonate  
286 formation in the percolation pathway, can also influence stalagmite  $\delta^{13}\text{C}$  (Fairchild et al., 2000).  
287 In wet (dry) conditions with high (low) precipitation, diminished (enhanced)  $\text{CO}_2$  degassing and  
288 short (long) water residence time during the pathway disfavor (favor) the formation of PCP, and  
289 then lower (elevate)  $\delta^{13}\text{C}$  in dripwater. Accordingly, multi-centennial  $\delta^{13}\text{C}$  variability in  
290 Observatoire stalagmite could mainly reflect precipitation changes and related bioproductivity.  
291 Low (high) stalagmite  $\delta^{13}\text{C}$  values reflect high (low) precipitation or bioproductivity.

292 Increasing rainfall can lower  $\delta^{18}\text{O}$  by the amount effect and  $\delta^{13}\text{C}$  by increasing soil moisture  
293 content and soil respiration rates or by reducing PCP, resulting in a positive correlation of  $\delta^{13}\text{C}$   
294 and  $\delta^{18}\text{O}$ . OV12-5  $\delta^{13}\text{C}$  data express a degree of correlation with  $\delta^{18}\text{O}$  values ( $r = 0.48$ ,  $n = 710$ ,  
295  $p < 0.05$ ), supporting our argument that stalagmite  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  reflect precipitation changes.  
296 General similarity of multi-centennial variations between records of carbon and oxygen isotopes  
297 on OV12-5 (Fig. S4a and b) and uranium concentration (Fig. S4c) could further support this  
298 argument. Uranium is easily leached out of bedrock and the high content in the stalagmite  
299 suggests enhanced water leaching associated with increased precipitation. Initial  $\delta^{234}\text{U}$   
300 ( $\delta^{234}\text{U}_{\text{initial}}$ ) (Fig. S4d) and growth rate (Fig. S4e) can sometimes be used to infer hydroclimate  
301 changes (e.g., Columbu et al., 2020). In Observatoire cave, however,  $\delta^{234}\text{U}_{\text{initial}}$  and growth rate  
302 are distinctively different from C/O isotopic time series (Fig. S4a, b, d and e), indicating

303 additional complicated effects from changing redox conditions, percolation pathway on both, and  
304 possibly growth rate on  $\delta^{234}\text{U}$  (Zhou et al., 2005, Day and Henderson, 2011).

#### 305 4.3. Circum-Mediterranean climate patterns during MIS 5b–5a

306 Over the entire MIS 5 period, MIS 5b was notable as a cold period with minimum  
307 temperatures anchored around  $87.8 \pm 0.4$  ka (NorthGRIP-Members, 2004; Lisiecki and Raymo,  
308 2005). MIS 5b ended at  $84.7 \pm 0.4$  ka, when NH summer insolation reached a maximum (Fig.  
309 1b; Laskar, 2011; NorthGRIP-Members, 2004). At  $84.7 \pm 0.4$  ka, Greenland ice core  $\delta^{18}\text{O}$   
310 feature a positive excursion (Fig. 1a), suggesting warming in the North Atlantic, concurrent with  
311 Iberian warming (Fig. 1c). In line with positive  $\delta^{18}\text{O}$  shifts in the NALPS stalagmite series at  
312  $85.0 \pm 0.4$  ka (Fig. 1d), these geological proxy records confirm large-scale warming over the  
313 Atlantic-European sector during the transition from MIS 5b to 5a. During this transition, 87–85  
314 ka, Observatoire stalagmite  $\delta^{18}\text{O}$  decreased (Fig. 4a), along with  $\delta^{13}\text{C}$  (Fig. 4b), suggesting  
315 increased precipitation at Monaco, similar to Portugal (Fig. 4c; Denniston et al., 2018), Spain  
316 (Fig. 4d; Budsky et al., 2019), Sardinia (Fig. 4e; Columbu et al., 2019) and southern Italy (Fig.  
317 4f; Columbu et al., 2020), all with negative shifts in stalagmite  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ . The consistency  
318 suggests that westerly winds were enhanced in the Mediterranean at the onset of MIS 5a  
319 (Denniston et al., 2018; Budsky et al., 2019; Columbu et al., 2019, 2020). The increasing water  
320 budget in the Mediterranean realm and the concurrent strengthening of the African monsoon, and  
321 sea-level rise, may have been responsible for Sapropel event 3 (S3, 86–81 ka; Rohling et al.,  
322 2015). Increased  $^{18}\text{O}$ -depleted freshwater input into the Mediterranean region is manifest as a  
323 negative  $\delta^{18}\text{O}$  shift in Israel speleothems (Fig. 4g) and marine planktonic foraminifera from core  
324 LC21 (Fig. 4g; Grant et al., 2012; Rohling et al., 2015).

325 From the onset of MIS 5a, Portugal (Fig. 4c; Denniston et al., 2018) and Spanish (Fig. 4d;  
326 Budsky et al., 2019) stalagmite records both show relatively stable  $\delta^{13}\text{C}$  values until the end of  
327 S3 at 81 ka. Sardinia stalagmite  $\delta^{18}\text{O}$  (Fig. 4e; Columbu et al., 2019) display a persistent value of  
328  $\sim -4.7\text{‰}$ , while southern Italy stalagmite  $\delta^{18}\text{O}$  (Fig. 4f; Columbu et al., 2020) show a depletion of  
329  $\sim 1\text{‰}$ . Taken together, these records suggest that strong westerly winds may have prevailed  
330 during the whole of S3. These climate patterns are consistent with the relatively low  $\delta^{13}\text{C}$  values  
331 in OV12-5, as compared with those during MIS 5b (Fig. 4b).

332 The millennial increasing trend of  $\sim 1\text{‰}$  in the OV12-5  $\delta^{18}\text{O}$  record from 83.5–80.5 ka could  
333 be attributable to increasing Mediterranean seawater-sourced  $\delta^{18}\text{O}$ . This agreement is supported  
334 by a  $\sim 0.8\text{‰}$  enrichment in  $\delta^{18}\text{O}_{\text{pf}}$  of a Mediterranean sediment core, LC21, in Figure 6g (Bar-  
335 Matthews et al., 2003; Grant et al., 2012), as the concurrent decrease of NHSI led to a weakened  
336 African monsoon that reduced the proportion of freshwater with depleted- $^{18}\text{O}$  in the  
337 Mediterranean Sea at the end of S3 (Rohling et al., 2015). Another possibility is an increase in  
338 Mediterranean-sourced moisture at the Monaco cave when the NHSI shifted the intertropical  
339 convergent zone southward, promoting more southerly water advections in southern Europe  
340 (Vanghi et al., 2018; Columbu et al., 2019)

#### 341 4.4. Multi-centennial dry events of early MIS 5a

342 Both OV12-5  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  series are characterized by four concurrent multi-centennial  
343 high-value intervals, centered at  $83.1 \pm 0.1$ ,  $82.4 \pm 0.1$ ,  $81.6 \pm 0.1$ , and  $80.7 \pm 0.1$  ka (Fig. 6b,  
344 events **i** to **iv**). These events show multi-centennial dry conditions at MIS 5a in Monaco,  
345 probably caused by shifting of the westerlies. Similar drought 8.2-k and 4.2-k events in the  
346 Holocene (e.g., Ait-Brahim et al., 2019; Thatcher et al., 2020) were proposed to be caused by  
347 migrations of the westerlies under the changing phase of centennial North Atlantic Oscillation

348 (NAO)-like states (Hurrell, 1995). A positive NAO state can enhance both the Icelandic Low and  
349 Azores High, and divert the westerlies towards northern Europe, resulting in dry climate in the  
350 Mediterranean (e.g., Ait-Brahim et al., 2019). Modern instrumental rainfall data around Monaco  
351 reveal a strong dipole correlation with zonal winds centered at  $\sim 42$  and  $\sim 62$  °N (Fig. S5),  
352 suggesting that a latitudinal westerly migration could be an important factor in determining  
353 precipitation patterns in Monaco. Hence, we argue that the multi-centennial dry conditions  
354 recorded in OV12-5 isotopic records could be attributed to the drift of the westerlies.

355 Over centennial scales, studies have indicated that the westerlies could shift latitudinally  
356 under different Atlantic Multidecadal Oscillation states (e.g., Morley et al., 2014) or NAO (e.g.,  
357 Deininger et al., 2017; Ait-Brahim et al., 2019). Meltwater input in the North Atlantic and  
358 Atlantic oceanic circulation changes could also alter westerly trajectories that penetrate into  
359 Europe (e.g., Wassenburg et al., 2016). During MIS 5a, some ice-sheet remnants still covered  
360 North America, Greenland, and northern Europe (Batchelor et al., 2019). The meltwater input  
361 from ice-sheets in the North Atlantic and associated AMOC variations (e.g., Ait-Brahim et al.,  
362 2019) could contribute to the Monaco stalagmite-inferred dry events during the early MIS 5a  
363 (Fig. 5a).

#### 364 4.5. Connecting the multi-centennial dry events to Atlantic Ocean circulation

365 The LOVECLIM simulation in Figure 5a–c features multi-centennial scale AMOC  
366 reductions centered at 85.2, 84.5, 83.5, and 82.6 ka (Fig. 5b) associated with relatively cold  
367 conditions in Greenland (Fig. 5a) and dry conditions in southern Europe ( $[42-46^{\circ}\text{N}, 5-10^{\circ}\text{E}]$ , Fig.  
368 5c). The duration and frequency of multicontinental dry conditions observed in our simulation  
369 (Fig. 5c) are similar to those inferred from Observatoire stalagmite  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  records (Fig.  
370 6b). One simulated cold period in the North Atlantic and dry phase in southern Europe centered

371 at 83.5 ka generally matches the one recorded in marine sediment cores and stalagmite records  
372 (Fig. 6b-d).

373 Our model reveals an AMOC slowdown can trigger a deepened Icelandic Low and  
374 enhanced the Azores High in winter (December-February; Fig. 5d), as seen in Tzedakis et al  
375 (2018). Simulated winter (December-February) zonal winds at 800 mb over the Atlantic basin  
376 [60°W-0] (Fig. 5d) reveal that the westerlies migrated slightly poleward when AMOC was weak.  
377 An enhanced Azores High connecting high pressures at Barents Sea is also observed (Fig. 5d).  
378 This atmospheric configuration could weaken the westerlies with moisture blowing into the  
379 northern Mediterranean region and most of mainland Europe (Ionita et al., 2016), as evidenced  
380 by negative (westward) wind anomalies at 45–55 °N over Europe shown in our simulation (Fig.  
381 5d).

382 Two cold periods inferred from low *Globigerinoides ruber* abundances of the marine  
383 sedimentary core ODP 963 in the central Mediterranean at 83.5–82.5 ka and 81.6–81.1 ka,  
384 defined by Sprovieri et al. (2006) (orange intervals in Fig. 6c), match dry events **ii** and **iv**  
385 observed in Observatoire records (Fig. 6b). These two events are also synchronous with cold  
386 periods identified in the western Atlantic (Heusser and Oppo, 2003) and recorded in Greenland  
387 ice cores (Fig. 6a) (Kindler et al., 2014). The cooling events in the high-latitude North Atlantic  
388 and arid events in southern Europe could be attributable to periods with weakened AMOC. A  
389 weakened AMOC could also explain concurrent relatively high Ca/Sr ratios in marine cores of  
390 U1302 and U1303, which are associated with enhanced meltwater input and detrital carbonate in  
391 the Atlantic (Fig. 6d; Channell et al., 2012). Similar to the Holocene and the last glacial cycle,  
392 these AMOC slowdowns are not necessarily associated with ice-rafted detrital (IRD) events (Air-  
393 Brahim et al., 2019; Channell et al., 2012). Indeed, only one IRD event was registered in marine

394 core MD99-2304 from the Nordic Sea (Fig. 6e; Risebrobakken et al., 2005) with high values at  
395 83.6–82.8 ka and no other IRD events were discovered so far in the rest of MIS 5a.

396 Stalagmite-inferred droughts **i** and **iii** (Fig. 6b) was not captured by marine records,  
397 probably attributable to relatively low temporal resolution and chronology uncertainty. They  
398 could be still induced by centennial-scale intrinsic AMOC variability. Previous studies suggest  
399 that the triggering of internally generated AMOC could be initiated by stochastic atmospheric  
400 forcing (Drijfhout et al., 2013; Kleppin et al., 2015), with enhanced atmospheric blocking over  
401 the eastern subpolar gyre inducing a southward progression of the sea-ice margin. Another  
402 possible process is linked to stochastic changes in sea ice (Friedrich et al., 2010). Sea ice shifts  
403 that cover a large portion of the sinking region could cause a reduction in the strength of  
404 overturning. For example, Yin et al. (2021) highlighted a major centennial-scale AMOC  
405 periodicity induced by the interaction between sea ice and ocean circulation. AMOC can be  
406 weakened when sea ice in Nordic Sea increases and impedes overturning, as the Nordic Sea is  
407 one of the major sinking areas for AMOC. Once AMOC slows, ocean heat accumulates in the  
408 subsurface seawater and the heat further elevates sea temperature. As surface waters warm, sea  
409 ice in the Nordic Sea could melt again, increasing overturning.

#### 410 4.6. Other possible forcings for centennial Monaco hydroclimate changes

411 Model simulations show that AMOC slowdowns lead to distinct air temperature drops over  
412 Greenland (Fig. 5a and b). However, low Greenland temperature is observed at events **ii** and **iv**,  
413 but only slightly observed at drought event **i** and obscure during event **iii** (Fig. 6a and b). We  
414 argue that centennial NAO-state variations could also induce low precipitation in southern  
415 Europe in addition to the occurrence of AMOC slowdown. Ait Brahim et al. (2019) proposed  
416 that a positive-NAO-like condition lead to a northward shift of the westerlies and centennial-

417 scale dry conditions in western and northern Mediterranean regions in the Holocene. The NAO-  
418 correlated 100s-yr dry events are also observed since the middle Holocene in stalagmite  $\delta^{18}\text{O}$   
419 records from Bàsura cave in northern Italy (Hu et al., 2022), where is located in the same climate  
420 territory of Observatoire cave in Monaco. The evidence supports that change in NAO phase  
421 could be one of forcings to cause multi-centennial arid intervals at MIS 5a expressed in Figure  
422 6b.

423 Spectral analyses of Observatoire  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  records (Fig. 7) show several significant  
424 multi-decadal to multi-centennial periodicities. A 210-year periodicity is revealed in both  $\delta^{18}\text{O}$   
425 (Fig. 7a) and  $\delta^{13}\text{C}$  (Fig. 7b) above the 90% and 80% confidence levels, respectively. This  
426 bicentennial cycle is close to the De Vries-Suess 210-year solar cycle (Suess, 1980) and was not  
427 observed in existing MIS 5a proxy records. Previous studies have revealed the similar impact of  
428 solar activity on the regional Holocene hydroclimate in the western Mediterranean (e.g., Frisia et  
429 al., 2003; Scholz et al., 2012; Smith et al., 2016; Ait-Brahim et al., 2018, 2019). For example, the  
430 210-year periodicity is observed in the Holocene stalagmite  $\delta^{18}\text{O}$  record from northern Morocco  
431 (Ait-Brahim et al., 2019). During solar minima, an enhanced blocking frequency at Greenland  
432 could shift the westerly trajectory towards the Mediterranean region, resulting in more  
433 precipitation in the western Mediterranean (Ait-Brahim et al., 2019). The downward-propagation  
434 of the solar signal from the stratosphere to the surface induces a southward shift of the northern  
435 subtropical jet and a decrease in temperature in northern high latitudes (Bond et al., 2001;  
436 Koder, 2002; Thiéblemont et al., 2015; Yukimoto et al., 2017). Our stalagmite records suggest  
437 that centennial-scale hydroclimate oscillations at MIS 5a in Monaco could also be influenced by  
438 solar activity (Ait-Brahim et al., 2019), as the case in the Holocene.

## 439 5. Conclusions

440 We present stalagmite  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ -inferred precipitation records from  $88.7 \pm 0.4$  to  $80.3$   
441  $\pm 0.1$  ka covering parts of MIS 5b to 5a from Observatoire cave, Monaco, southern Europe. The  
442 inferred precipitation record features four multi-centennial arid events during MIS 5a, suggesting  
443 that the westerlies moved away from Monaco. New transient simulation suggests that AMOC  
444 slowdowns can divert the westerlies from the Mediterranean region, which would result in  
445 stalagmite-inferred dry conditions in Monaco. A positive NAO-like scenario is also one possible  
446 forcing. A bicentennial periodicity revealed in Observatoire isotope records highlight the  
447 potential of additional solar forcing on Mediterranean hydroclimate during MIS 5a. Our findings  
448 provide a clue for future climate prediction as the AMOC was observed to slow down over the  
449 past decade (Smeed et al., 2018).

450  
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460 conceived the project. C.-C.S., V.M., P.V., P.S., E.R.-N. and A.M. conducted field surveys and  
461 collected stalagmites. Y.-C.C. and H.-M.H. conducted subsample preparation. Y.-C.C. and H.-  
462 M.H performed U-Th dating. H.-S.M. and X.J. conducted carbon and oxygen stable isotope  
463 analyses. L.M. conducted model simulations. A.M. conducted statistical analyses. Y.-C.C., C.-  
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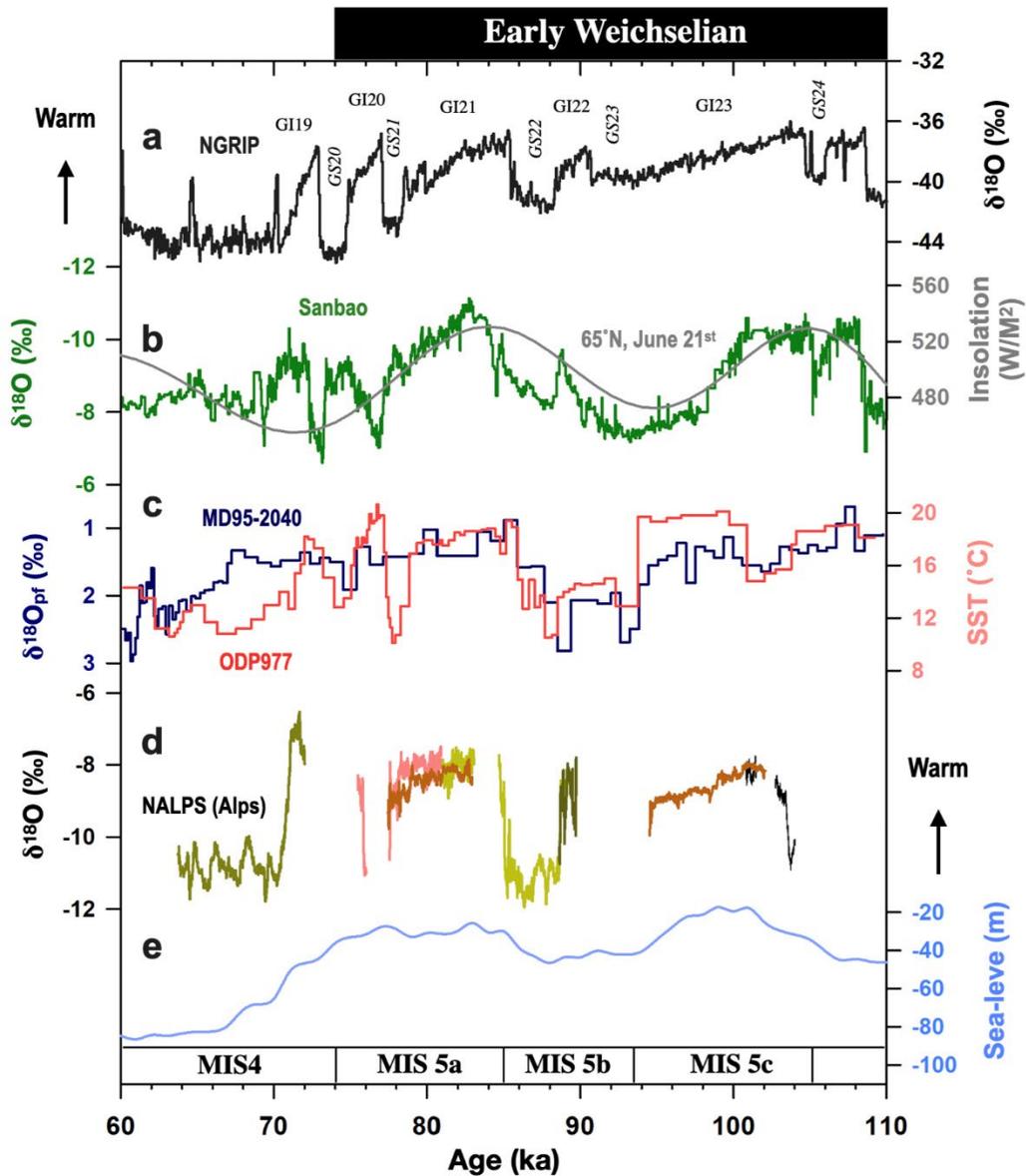
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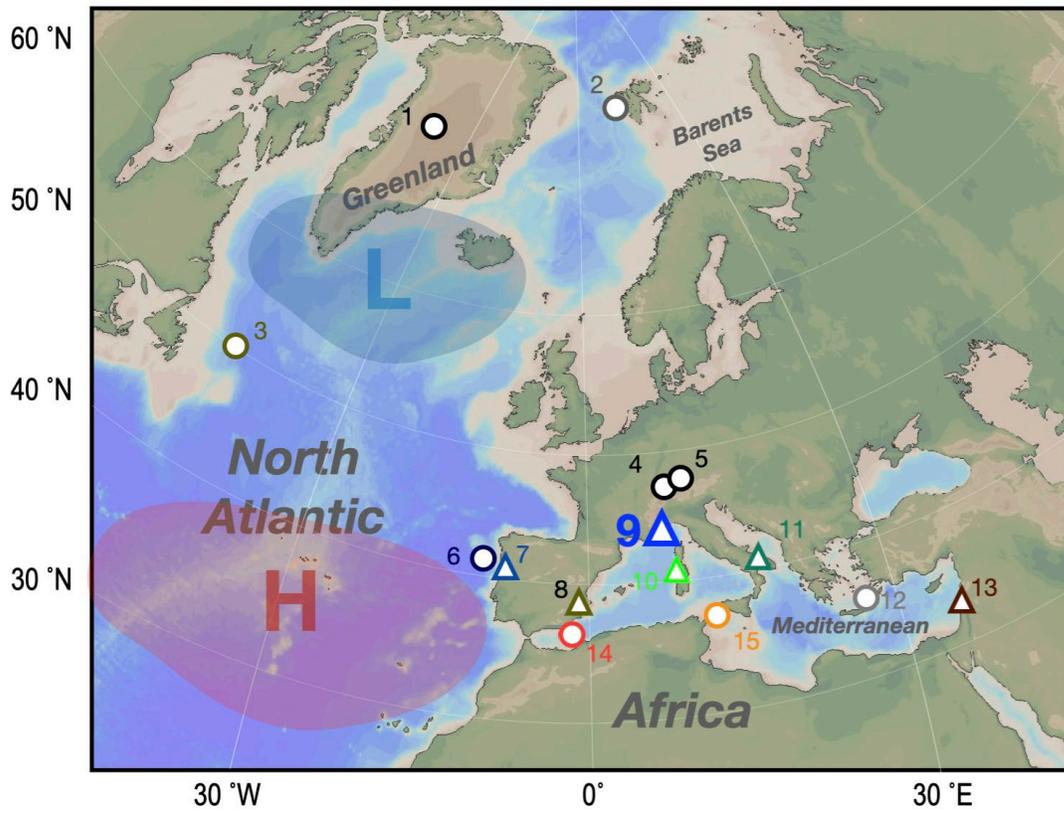
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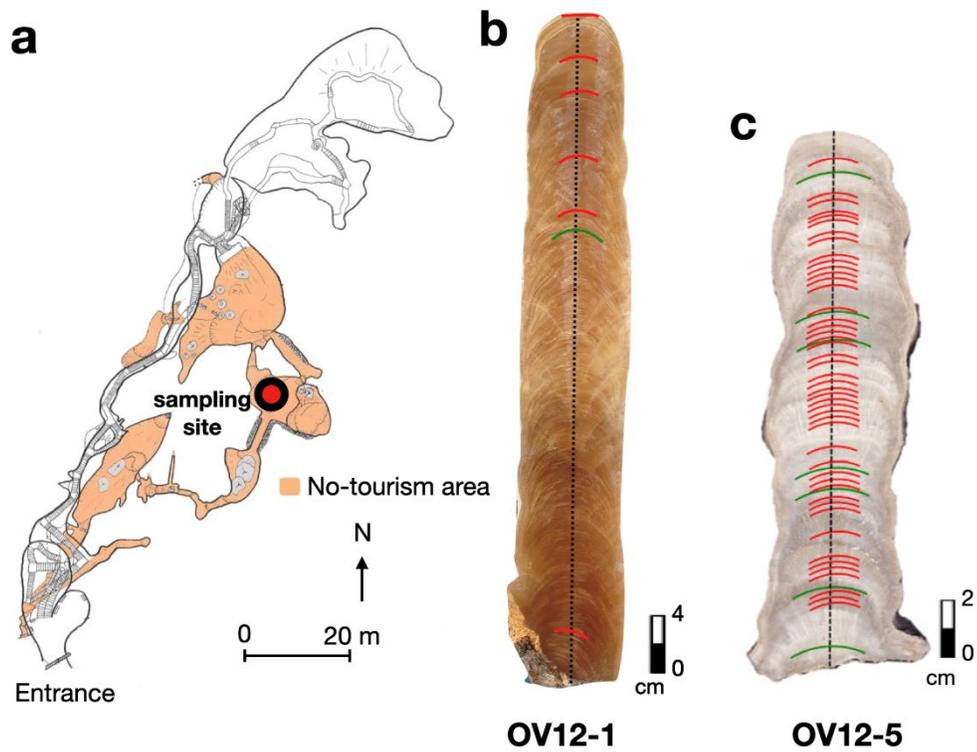


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 775 **Figure 1. Paleoclimate records during the early Weichselian.** (a)  $\delta^{18}\text{O}$  values in NGRIP  
 776 Greenland ice core (NorthGRIP-Members, 2004). High  $\delta^{18}\text{O}$  values imply warm climate in the N  
 777 Atlantic. GI: Greenland interstadial. GS: Greenland stadial. (b) Grey: North hemisphere insolation  
 778 at  $65^\circ\text{N}$ , June 21<sup>st</sup> (Laskar, 2011). Green: Stalagmite  $\delta^{18}\text{O}$  from Sanbao cave, China, as a proxy for  
 779 Asian summer monsoon intensity (Cheng et al., 2016). Negative  $\delta^{18}\text{O}$  values represent a strong  
 780 Asian summer monsoon. (c) Orange: sea surface temperature (SST) from marine core ODP977 at  
 781 Iberia (Martrat et al., 2004). Dark blue: Planktonic foraminiferal  $\delta^{18}\text{O}$  ( $\delta^{18}\text{O}_{\text{pf}}$ ) from marine core  
 782 MD95-2040 (de Abreu et al., 2003). (d) Stalagmite  $\delta^{18}\text{O}$  from the Alps (NALPS) (Boch et al.,  
 783 2011). High  $\delta^{18}\text{O}$  values indicate warm conditions. (e) Global stacked sea level record (Spratt et  
 784 al., 2016).  
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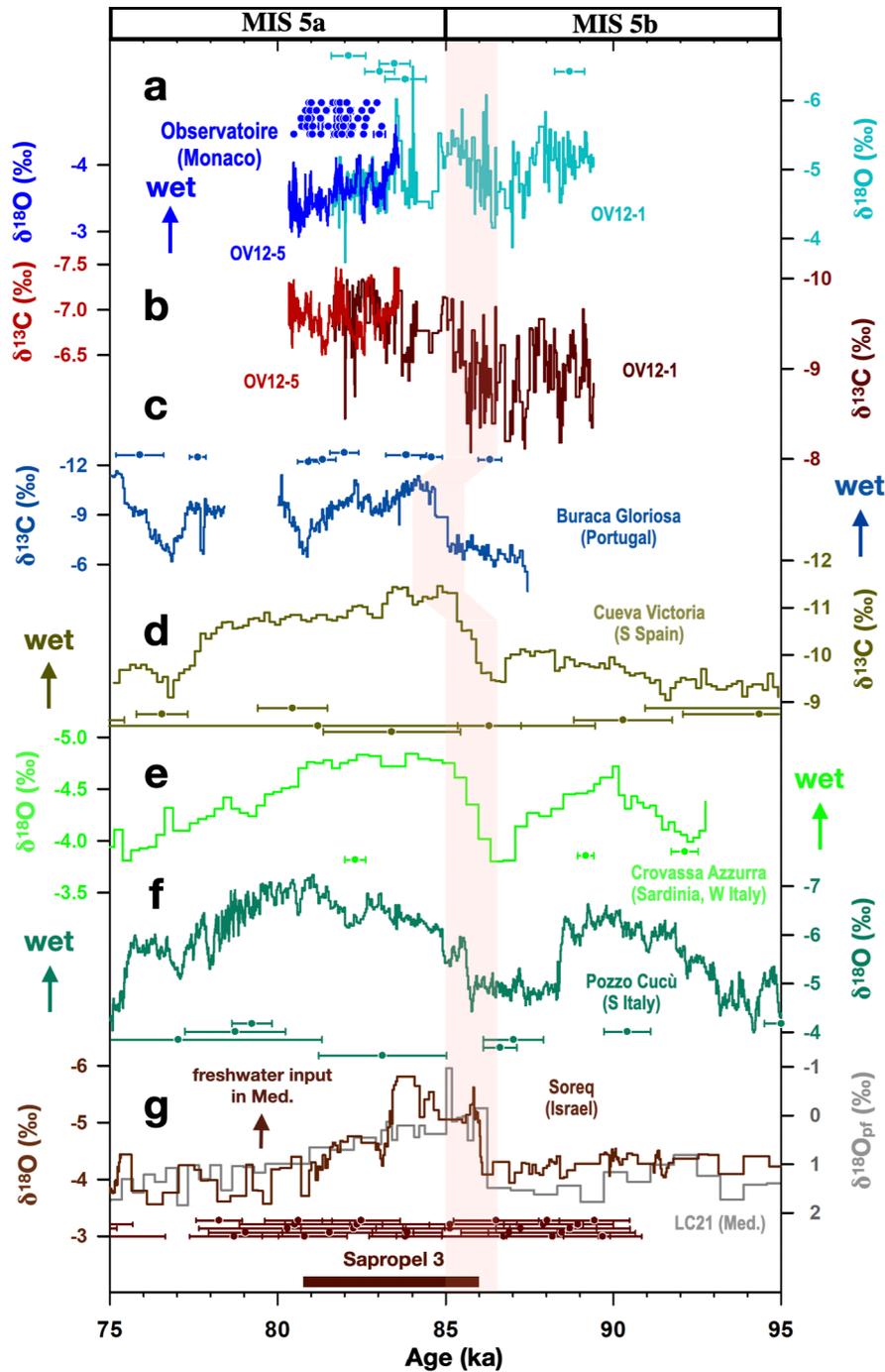
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**Figure 2. Locations of Observatoire cave and other terrestrial and marine sites mentioned in this text.** Triangles and circles denote cave records and other sites, respectively. 1. Greenland ice core NGRIP (NorthGRIP-Members, 2014; Wolff et al., 2010). 2. Marine sediment core MD99-2304 (Risebrobakken et al., 2005). 3. Marine cores U1302 and U1303 (Channell et al., 2012). 4 and 5. Beatus cave (Switzerland), Baschg cave (Austria), Klaus-Cramer- and Schneckenloch caves. All contribute to NALPS records (Boch et al., 2011). 6. Marine core MD95-2040 (de Abreu et al., 2003). 7. Buraca Gloriosa cave, Portugal (Denniston et al., 2018). 8. Cueva Victoria cave, Spain (Budsky et al., 2019). 9. Observatoire cave, Monaco (this study). 10. Crovassa Azzurra cave, Sardinia (Columbu et al., 2019). 11. Pozzo Cucù cave, southern Italy (Columbu et al., 2020). 12. Marine sediment core LC21 (Grant et al., 2012). 13. Soreq cave, Israel (Bar-Matthews et al., 2003). 14. Marine core ODP977 (Martrat et al., 2004). 15. Marine sediment core ODP963 (Sprovieri et al., 2006). Blue and red shades indicate the schematic positions of the Icelandic Low and the Azores High, respectively. Map was generated using Ocean Data View.

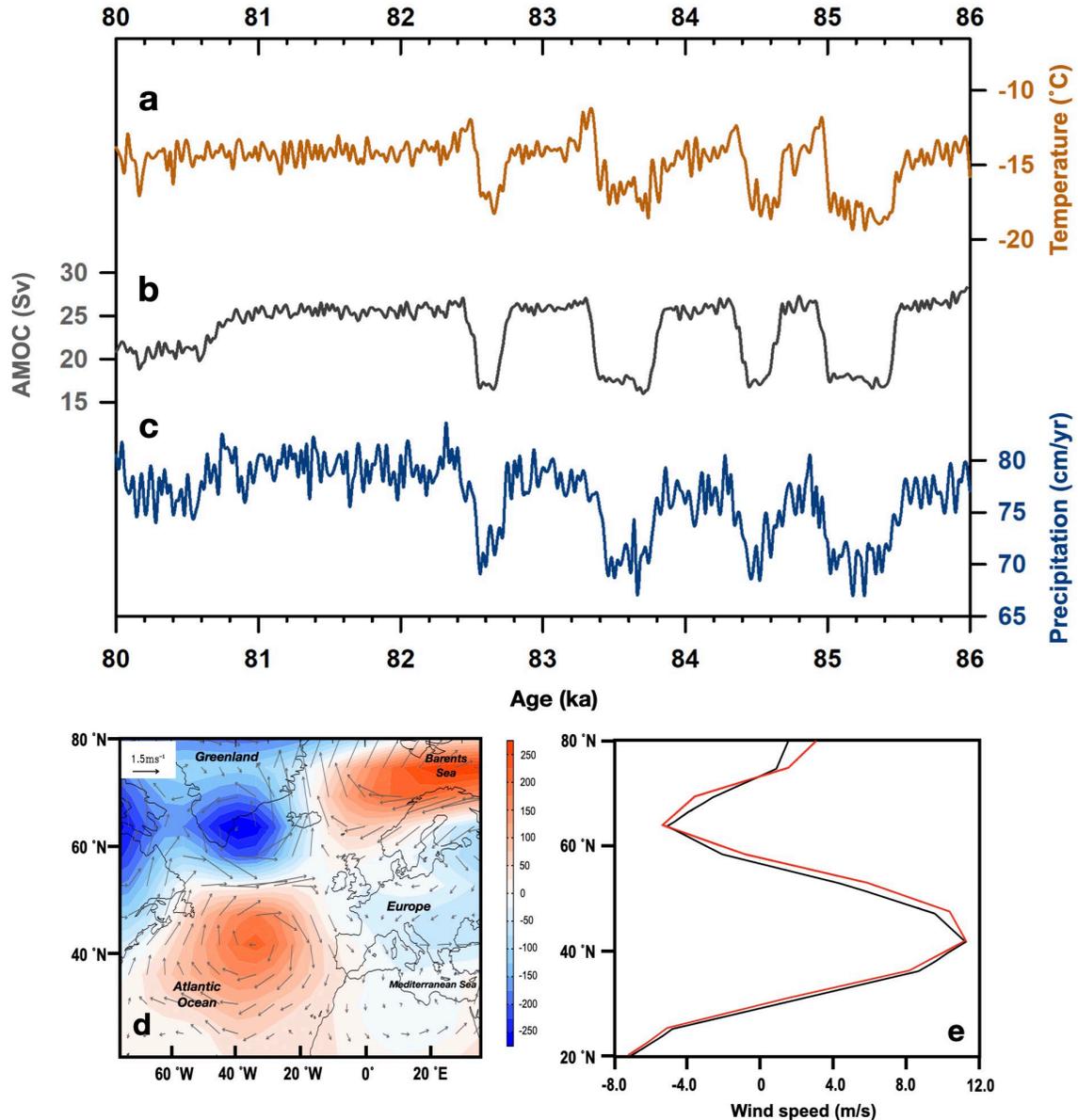


**Figure 3. Cave map and stalagmites.** (a) Sketch map of Observatoire cave. Red circle indicates the location of stalagmites OV12-1 and OV12-5. Photographs of (b) OV12-1 and (c) OV12-5. In (b) and (c), Green lines represent layers for the Hendy test (Hendy, 1971). Subsamples for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  analyses were drilled from the black dashed line along the central growth axis. Red layers are depths for U-Th dating.

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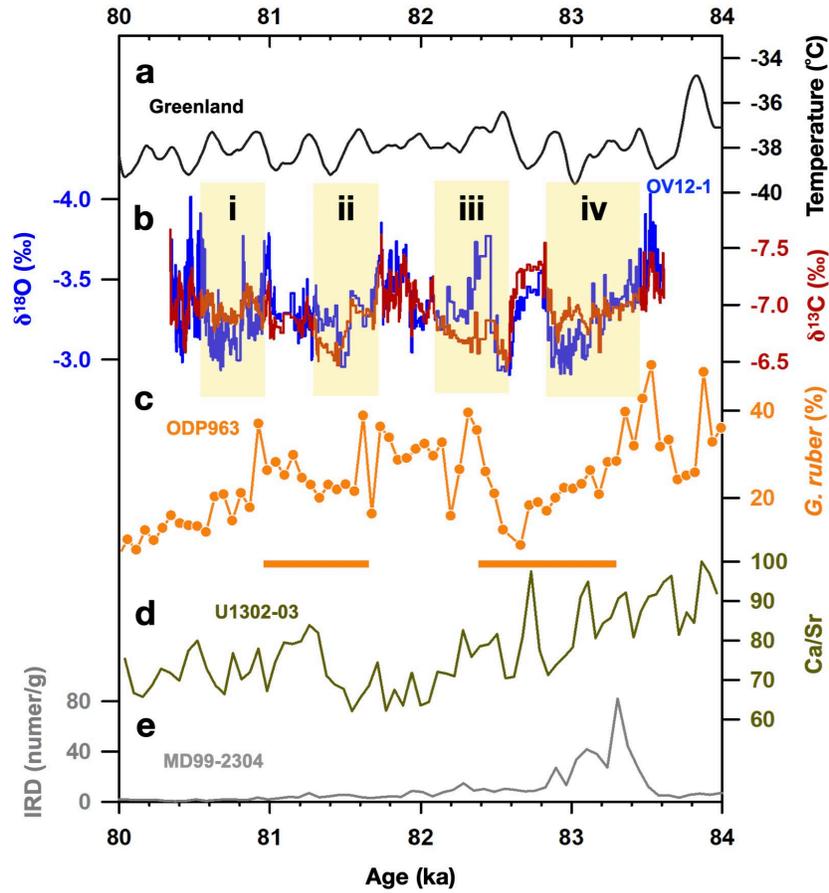
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 809 **Figure 4. Circum-Mediterranean paleoclimate records at 95-75 ka.** (a) Tuned OV12-1  
 810 (tiffany) and OV12-5 (blue)  $\delta^{18}\text{O}$ . (b) Tuned OV12-1 (brown) and OV12-5 (red)  $\delta^{13}\text{C}$ . (c)  
 811 Stalagmite  $\delta^{13}\text{C}$  from Buraca Gloriosa, Portugal (Denniston et al., 2018). (d) Stalagmite  $\delta^{13}\text{C}$  from  
 812 Cueva Victoria, southern Spain (Budsky et al., 2019). (e) Stalagmite  $\delta^{18}\text{O}$  from Crovassa Azzurra,  
 813 Sardinia (Columbu et al., 2019). (f) Stalagmite  $\delta^{18}\text{O}$  from Pozzo Cucù (Columbu et al., 2020). (g)  
 814 Stalagmite  $\delta^{18}\text{O}$  from Soreq cave (brown; Bar-Matthews et al., 2003) and planktonic foraminiferal  
 815  $\delta^{18}\text{O}$  ( $\delta^{18}\text{O}_{\text{pf}}$ ) from marine LC21, Mediterranean Sea (Grant et al., 2012).  $^{230}\text{Th}$  ages and errors are  
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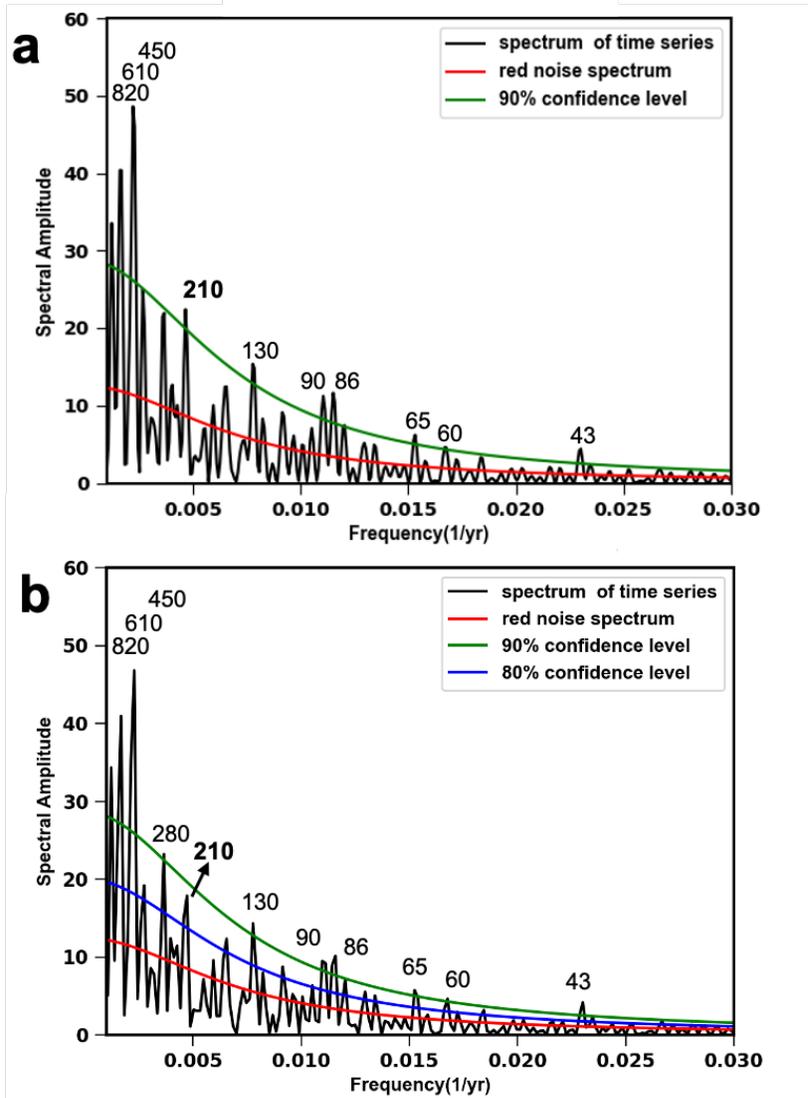
**Figure 5. Results of a transient experiment with LOVECLIM. (a)** Simulated Greenland temperature variations. **(b)** Simulated AMOC (unit: Sv). **(c)** Simulated annual precipitation at [42–46 °N, 5–10 °E]. **(d)** 800 mb geopotential height (hPa, shades) and 800 mb wind (m/s, vectors) anomalies between winters (December–February) with weak AMOC and strong AMOC. **(e)** Zonal winter (December–February) wind speed at 800 mb averaged over the Atlantic basin [60°W–0] for periods with strong AMOC (black) and weak AMOC (red).

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**Figure 6. North Atlantic proxy records during 84-80 ka. (a)** Greenland NGRIP temperature reconstruction on the ss09sea06bm timescale (Kindler et al., 2014). **(b)** Stalagmite OV12-5  $\delta^{18}\text{O}$  (blue; detrended, this study) and  $\delta^{13}\text{C}$  (red). Light yellow bars denote dry events, **i-iv**, identified by stalagmite OV12-5 records. **(c)** Abundance percentage of *G. ruber* (orange) in marine core ODP963, Mediterranean Sea (Sprovieri et al., 2006). Orange bars indicate the periods with cooling in the North Atlantic, defined by Sprovieri et al. (2006). **(d)** Ca/Sr ratio in two marine cores of U1302 and U1303, North Atlantic, as proxy of ice-sheet melting histories (Channell et al., 2012). **(e)** Ice rafted debris (IRD) in marine core MD99-2304, Nordic sea (Risebrobakken et al., 2005).



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**Figure 7. Results of spectral analyses for Observatoire OV12-5 isotope time series. (a)  $\delta^{18}\text{O}$  and (b)  $\delta^{13}\text{C}$  spectral amplitude against red noise (Schulz and Mudelsee, 2002). Numbers indicate periodicities in years for the peak.**