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3 **Recent anthropogenic climate change exceeds the rate and**
4 **magnitude of natural Holocene variability on the Balearic Islands**

5
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37 **Highlights**

- 38 • An 8000-year climatic reconstruction from the Western Mediterranean
- 39 • Forty-three years of instrumental climatic data from Palma de Mallorca
- 40 • A sharp climate contrast between reconstructed and instrumental periods
- 41 • Present changes are rapid in contrast to the Holocene climate history of Mallorca

42

43 **Abstract**

44 Industrial-era warming and aridification have underlined the importance of past climate
45 reconstructions in contextualizing present-day anomalies from a long-term perspective. While
46 the issue of climate change is global, studies have long stressed the vulnerability of the
47 Mediterranean basin, especially with regard to its islands with likely acute environmental and
48 socioeconomic impacts. This study uses paleoecological data from Mallorca to quantify climate
49 changes during the last eight millennia. We compared and contrasted past ecosystem dynamics
50 with recent instrumental climate data to characterize the emergence of industrial-era warming.
51 We show that anthropogenic warming has transgressed both the rate and magnitude of natural
52 variability. At the scale of the last 8000 years, this study highlights the uniqueness of Mallorca's
53 present climate and emphasizes the rapidity of current changes compared to the climate history
54 of the island. The present-day mean annual temperature appears $3.3 \pm 1.2^{\circ}\text{C}$ warmer than the
55 reconstructed value for the last eight millennia, with a 33% drop in precipitation between the
56 last 8000 years and the industrial era. This long-term view underscores human impacts on
57 climate in Mallorca, the fourth most populated island of the Mediterranean. It suggests that the
58 ongoing warming and aridification trends will be a significant challenge to Mediterranean
59 islands, at both present and future timescales.

60

61

62 **Keywords**

63 Ecosystem dynamics, Pollen-based climate reconstruction, climate change, Industrial-era
64 warming, Aridification, island, Holocene, Mallorca, Mediterranean

65

66 **1. Introduction**

67 The emergence of the industrial economy has triggered climate anomalies since the mid-late
68 19th century (Abram et al., 2016; Gleckler et al., 2016). Although the resulting environmental
69 stresses have affected many regions of the world, the International Panel on Climate Change
70 (IPCC, 2001; IPCC, 2014; IPCC 2018) deem the Mediterranean to be "particularly sensitive"
71 to the effects of global warming (Fischer and Schär, 2010; Homar et al., 2010; López Mayol et
72 al., 2017; Cramer et al., 2018). For the period 2081-2100, the IPCC's climate models project a
73 2.6-4.8°C rise in average surface temperatures (relative to 1986-2005), accompanied by a
74 pronounced shift in rainfall regimes with anomalies of -4% to -27% in the Mediterranean (from
75 Representative Concentration Pathways 4.5 to 8.5; IPCC, 2014). Such changes will generate
76 exceptional stress on already limited water resources (Guiot and Cramer, 2016), particularly in
77 regions where anthropogenic demands already exceed supply. The projected warming of the
78 Mediterranean is clearly attested on the Balearic Islands, which have witnessed an
79 intensification of temperature anomalies during the last 40 years (~0.6°C per decade) and a
80 clear shortening of the cold season (Cuxart and Guijarro, 2010; Homar et al., 2010; López
81 Mayol et al., 2017). According to the IPCC (2001), a rise in temperature (1.5 to 3.6 °C) and a
82 drop in rainfall amounts (10% to 20%) are forecasted for 2080-2100 on the Balearics, with an
83 increased probability of drought (Kerr, 2005) and extreme weather events (Candela et al.,
84 2009). Even if the ocean's thermal inertia mitigates the temperature of the Mediterranean sea
85 surface, delaying the accumulation of heat in coastal zones, notable increases in sea surface

86 temperatures have already been recorded in the Balearic Sea (+1.1 °C during the last 40 years;
87 Marbà and Duarte, 2010; Jordà et al., 2012; Adloff et al., 2015).

88 Through the prism of Mallorca, this study aims to answer two main questions. First, to what
89 extent does the industrial-era warming and aridification of Mediterranean islands deviate
90 markedly from long-term Holocene trends? Second, how can an 8000-year palaeoecological
91 archive from the Albufera Natural Park serve as a basis to quantify the current climate
92 anomalies (1975-2018 CE)? As climate models project widespread anomalies across the
93 Mediterranean Basin by the end of the 21st century (Cook et al., 2015), and because warming
94 and aridification can significantly impact the environment, economy, society (Greve et al.,
95 2014) and human health (Gale et al., 2010), quantifying the present-day climate trend in relation
96 to the past is critical in improving climate-change projections. It is also important for
97 developing robust hazard assessments and adaptation strategies.

98

99 **2. Albufera Natural Park**

100 The swamp/wetland of Albufera (elevation 1 m a.s.l.; surface of ~25 km²; Fig. 1) is located in
101 the eastern part of a Plio-Quaternary depression, between the northern and southern ridges of
102 the island (dated from the Mesozoic to the Upper Miocene). The swamp is relict of a palaeo-
103 lagoon formed following the Holocene marine transgression (Fornós et al., 1996; Goy et al.,
104 1997; Giaime et al., 2017). This swamp area is fed by the Sant Miquel and Muro streams and
105 by groundwater inputs. We selected this protected natural reserve to limit any potential
106 anthropogenic influences on the environmental-climate reconstructions. Today, the swamp is
107 mostly populated by *Phragmites australis* (Cav. Trin. ex Steud.), *Cladium mariscus* (L. Pohl)
108 and *Typha latifolia* (L.). *Alisma plantago-aquatica* (L.) and *Sparganium erectum* (L.) are also
109 common around the edges, between the water and the marsh. In the water column, *Potamogeton*
110 *pectinatus* (L.), *Potamogeton crispus* (L.), *Riccia* (L.), *Myriophyllum spicatum* (L.),

111 *Ceratophyllum submersum* (L.) and *Zannichellia pedunculata* (Rchb. in Mössler) occur.
112 Around the park and closer to the dunes, the dominant plants are *Pinus halepensis* (Mill.),
113 *Pistacia lentiscus* (L.), *Rosmarinus officinalis* (L.), *Phillyrea angustifolia* (L.), *Cistus*
114 *salviifolius* (L.), *Smilax aspera* (L.), *Asparagus acutifolius* (L.), *Halimium halimifolium* (L.)
115 and *Brachypodium retusum* (L.). On the seaward flank of the swamp, *Juniperus oxycedrus*
116 subsp. *macrocarpa* (Sm. Ball) is the dominant tree species, with a cortege of *Cakile maritima*
117 (Scop.), *Eryngium maritimum* (L.), *Pancreatium maritimum* (L.), *Matthiola sinuata* (L.) and
118 *Helichrysum stoechas* (L. Moench). The nomenclature derives from the Flora Iberica
119 (<http://www.floraiberica.es/>).

120

121 **3. Materials and methods**

122 To answer the questions raised in the introduction, we used the instrumental climate dataset
123 from Mallorca's airport weather station and produced a pollen-based climate reconstruction
124 from a core drilled in the Albufera Natural Park (NE Mallorca). We used a ¹⁴C chronology to
125 calculate an age model for the core. We further tested the reliability of our climate
126 reconstruction by estimating the role of anthropogenic impacts in modulating ecosystem
127 dynamics. All data are available in tabulated form in the supplementary information.

128

129 *3.1. Present-day climate data*

130 The instrumental climate dataset was provided by Mallorca's airport weather station (Palma
131 Aeropuerto, 39°33'39"N, 02°44'12"E, 3 m. a.s.l.). The dataset constitutes the Balearic Islands'
132 longest temperature and precipitation records and covers the periods 1975-2018 (temperatures)
133 and 1972-2018 (precipitation). The records from Palma Puerto (39°33'12"N, 02°37'31"E; 1 m
134 a.s.l.; period 1978-2018) and Sa Pobla (39°44'57"N, 03°01'00"E; 27 m a.s.l.; period 2012-
135 2018) were used as independent controls (for extreme values). Previous datasets were already

136 available in the literature (e.g. Cuxart and Guijarro, 2010; Homar et al., 2010; Jansà et al., 2017;
137 López Mayol et al., 2017).

138

139 *3.2. Core chronology and stratigraphy*

140 We drilled an 8-m long core (39°47'44.43"N, 3°05'31.47"E, 1 m a.s.l.; termed POL12) at the
141 heart of the Albufera Natural Park using a hydraulic rotary corer (Fig. 2). The sedimentary
142 deposits mainly consist of clay with inclusions of silt and sand in the upper part. The chronology
143 of the core is based on ten ¹⁴C dates (Beta Analytic and Poznan Laboratory; see Table S1)
144 calibrated to 1 and 2 sigmas (σ) using Calib Rev 7.0.4 (Fig. 2). The oldest level (790 cm depth)
145 is dated to 7080 ± 40 ¹⁴C year BP, calibrated to 7905 year BP (7980-7830 calibrated 2σ BP,
146 7955-7865 calibrated 1σ BP). The age of each sample was calculated by interpolating between
147 two adjacent ¹⁴C dates. Our record thus covers ~8000 years of northeastern Mallorcan
148 environmental and climate history.

149

150 *3.3. Palaeoecological data*

151 We prepared a total of 120 samples for pollen analysis using standard procedures for clay
152 deposits (Faegri and Iversen, 1989). Pollen grains were counted under x400 and x1000
153 magnification using an Olympus Bh-2 BHS microscope. Pollen percentages are based on the
154 terrestrial pollen sum, excluding local helophytes (Cyperaceae and *Typha*), macrophytes and
155 spores of non-vascular cryptogams. Percentages of helophyte-macrophyte taxa were calculated
156 using a sum that includes local freshwater plants and terrestrial vegetation. The mean pollen
157 sum was 379 ± 53 pollen grains, with a minimum of 284 pollen grains. The median value was
158 374 pollen grains, with a 25th percentile of 336 pollen grains and a 75th percentile of 409 pollen
159 grains. The mean number of taxa was 28 ± 3 taxa, with a minimum of 21 taxa. The median
160 value was 27 taxa, with a 25th percentile of 26 taxa, and a 75th percentile of 29 taxa. The

161 calculation of pollen concentrations follows the formula developed by Cour (1974), using 1
162 cm³ of sediment. The mean concentration was 2728 ± 382 pollen grains per cm³ with a median
163 value of 2692 pollen grains per cm³, a 25th percentile of 2419 pollen grains per cm³, and a 75th
164 percentile of 2948 pollen grains per cm³. Atlases (Reille, 1992, 1995, 1998), books (e.g. Faegri
165 and Iversen, 1989; Moore et al., 1991; Punt and Blackmore, 1991), articles (e.g. Renault-
166 Miskovsky et al., 1976; Colombo et al., 1983; Gortemaker, 1986), as well as local reference
167 slides were used for pollen identification. A plate with pollen photos is provided in the
168 supplementary information (see Fig. S1). The fire history of the coastal plain was reconstructed
169 by counting charcoal particles (50-200 µm) on the pollen slides. The 50 µm size criterion was
170 chosen to avoid confusion between microscopic charcoal fragments and opaque minerals,
171 which are typically < 50 µm (Parshall and Foster, 2002; Pederson et al., 2005). We followed
172 the 200-300 items (sum of charcoal particles) defined by Finsinger and Tinner (2005). A
173 charcoal concentration curve (fragments per cm⁻³) was drawn on a linear age-scale (Marriner et
174 al., 2019). The mean concentration was 77 ± 19 fragments including the standard error, with a
175 maximum value of 1550 fragments and minimum of 0. The pollen data are detailed and
176 presented as a pollen diagram (Fig. 3), with a focus on cereals, olive trees and fire activity (Fig.
177 4). All of these elements can be consulted in the supplementary information. We curated all the
178 pollen slides at the Université Toulouse 3.

179

180 3.4. Statistical analyses

181 We applied a homogeneity test to fire activity, cereals and olive trees to detect potential shifts
182 in their long-term dynamics (Fig. 4). The homogeneity test is based on a null hypothesis that a
183 time series is homogenous. Possible alternative hypotheses such as change in distribution,
184 changes in average or presence of trend can be detected and subdivided. Each change is
185 highlighted and its average is indicated by *mu*. Before any modelling, a CABFAC analysis (Fig.

186 5) was used to test the potential weight of anthropogenic factors in mediating the ecological
187 signal (e.g. Hammer and Harper, 2006; Kaniewski et al., 2018). The CABFAC factor analysis
188 (Q-mode factor analysis) implements the classic method of factor analysis and environmental
189 regression (CABFAC and REGRESS). We regressed selected environmental data on the
190 CABFAC factors using the second-order (parabolic) method, with cross terms. The
191 environmental regression model (RMA) reports the observed values against the values
192 reconstructed from the factors (Kaniewski et al., 2018). The selected environmental data for
193 this study (wet/dry conditions, warm/cool conditions, anthropogenic activities, and fire) cover
194 a wide range of natural and anthropogenic pressures. The consistency of each reconstructed
195 model is indicated by the coefficient of determination R^2 . The R^2 values were ordered from
196 highest to lowest, and used as a hierarchy of pressures on ecosystems.

197

198 3.5. Reconstructions of past climate variables

199 We did not consider local helophytes, macrophytes and spores of non-vascular cryptogams in
200 the pollen-based climate reconstruction. The cultivated species (primary anthropogenic
201 indicators: Poaceae cerealia) were also excluded from the pollen-based climate reconstruction
202 in addition to the secondary anthropogenic indicators (e.g. *Plantago*, *Rumex*).

203 Pollen assemblages were used to reconstruct the palaeoclimate history of Mallorca. Our
204 statistical approach presents two key caveats: (1) a fossil pollen assemblage may not have a
205 modern analog *sensu stricto*; and (2) the climate range of a species/genus can shift in time
206 (Cheddadi et al., 2016). Our new method is based on the assumption that the co-occurrence of
207 plant taxa in an assemblage may only occur under a common climate range or an overlap of the
208 climatic range of plant taxa comprising a given assemblage. Based on this assumption, one
209 should not expect two plant species to occur in the same assemblage if their climate ranges do
210 not intersect. We assigned the fossil pollen taxa to modern species, and subsequently calculated

211 a weighted median value and its standard deviations of the climate range encompassed by all
212 assigned modern species. Such an approach has been used to infer past climate variables using
213 insects (Elias, 1997), plant fossil remains (Pross et al., 2000), mollusks (Moine et al., 2002),
214 and ostracods (Horne, 2007) or to derive climate probability density functions (Kühl et al.,
215 2002) from fossil pollen data.

216 Our method (Cheddadi et al., 2017) also performs a “leave-one-out calculation” to
217 accommodate the temporal variability of pollen taxa in the fossil record. For each fossil sample,
218 a taxon is removed and a weighted median (using the pollen percentages as a weight) is
219 calculated using all of the remaining taxa. For each sample, we calculated the weighted median
220 as many times as there were taxa in each fossil level. The final figure is the median value of all
221 iterations. In addition, the standard deviations correspond to the median value of all the standard
222 deviations.

223 This additional leave-one-out approach reduces the effects of either large variations in the fossil
224 record or over- or under-representation of some pollen species. The code was written using the
225 software R and exploits the available libraries (Akima and Gebhardt, 2016), RMySQL (Ooms
226 et al., 2016), and the statistical functions which are part of R. The modern plant database is
227 based on georeferenced species from Flora Europaea (Jalas and Suominen, 1973, 1979, 1980)
228 and from GBIF (Heughebaert, 2019). We obtained present climate variables from the
229 WORLDCLIM database (Hijmans et al., 2005).

230

231 *3.6. Data availability*

232 All data needed to evaluate the conclusions reported in the paper are present in the article and/or
233 the supplementary information (excel files).

234

235

236 **4. Results**

237 *4.1. The core*

238 The bottom of the core comprises clay deposits (from 800 cm to 320 cm depth) consistent with
239 a low-energy environment (Fig. 2). We identified a sand lens between 320 and 300 cm depth,
240 which probably results from aeolian transport into the lagoon (Giaime et al., 2017). The upper
241 part (from 300 cm to 170 cm depth) consists of silt associated with freshwater inputs into the
242 area. Some sand particles from the shallowing lagoon were mixed with the silt deposits during
243 this period. The human-modified deposits correspond to the last 170 cm.

244

245 *4.2. Pollen analysis*

246 The ¹⁴C dates (Fig. 2) frame the chronology of core POL12. The pollen data allowed us to
247 reconstruct ecosystem dynamics during the past 8000 years at Albufera Natural Park (Fig. 3).
248 We compared and contrasted our data with earlier studies by Burjachs et al. (1994, 2017) in the
249 same area, and with cores drilled on Minorca and Ibiza (Yll et al., 1997; Pérez-Obiol and Sadori,
250 2007; Pérez-Obiol et al., 2011; Carrión et al., 2012; Burjachs et al., 2017).

251 The date proposed for the introduction of agricultural practices and human-induced fires in the
252 Albufera Natural Park is ~3600 BP (Fig. 4). According to the 2-sigma calibration, the full range
253 is framed between 3650 and 3550 BP (3600 ± 50 BP). As stated by Burjachs et al. (2017),
254 cereals are relatively scarce in the area. Data from the core POL12 depict a similar trend, with
255 a maximum value < 10%. In the core POL12, the earliest record of human impacts on the
256 environment thus occurred after the shift from a mesophilous community to a maquis scrub
257 (~5900 BP; Fig. 3).

258 The abrupt decline of *Juniperus* at ~5900 BP clearly illustrates this phenomenon (Fig. 3). The
259 drop seems to result from environmental pressures because no strong anthropogenic footprints
260 (fire activity or agriculture) were detected (Fig. 4). This decline is associated with greater aridity

261 in the Mediterranean at ~5900 BP (Jalut et al., 2000; Fletcher et al., 2010). As mentioned by
262 Burjachs et al. (2017), this climate event (along with others at 8.2 and 4.3 ka BP) directly
263 influenced the composition and evolution of vegetation on the Balearic Islands. According to
264 Pérez-Obiol and Sadori (2007), the important ecosystems changes ~5000-4000 BP seem to have
265 been amplified, but not caused, by human action. Most south-western European pollen records
266 show a general change from wetter to drier climatic conditions (Jalut et al. 2000; Magny et al.
267 2002). The core POL12 meshes perfectly with previously published data.

268 A homogeneity test was applied to three curves (fire activities, cereals and olive trees) to detect
269 potential shifts in their long-term dynamics (averages are indicated by *mu*; Fig. 4). Results
270 showed that cereals and fire activity are well correlated, whereas olive trees are mediated by a
271 different dynamic. To further establish whether olive trees were an integral part of early
272 diversified agriculture, we calculated a cross-correlation ($P_{\text{value}} = 0.05$). We considered positive
273 correlation coefficients, focusing on the Lag_0 value (with +0.50 as the significant threshold).
274 The test, applied to *Poaceae cerealia* versus *Olea europaea*, showed no correlation between the
275 two ($\text{Lag}_0 = 0.008$, $P_{\text{value}} < 0.001$). A second test, based on fire activity versus *Olea europaea*,
276 also demonstrated no correlation ($\text{Lag}_0 = -0.07$, $P_{\text{value}} < 0.001$). According to Pérez-Obiol and
277 Sadori (2007), from ~5000 to ~4000 BP, some taxa (*Buxus* and *Corylus*) were replaced by
278 others such as *Olea europaea*, a process that reflects an ecological response to global climatic
279 trends. A similar phenomenon was clearly recorded at Albufera (Fig. 3). At Cala'n Porter
280 (Minorca), high occurrences of olive trees have been recorded since ~6500 BP. At Algendar
281 (Minorca) and Prat de Vila (Ibiza), high values are recorded since ~5500 BP (Burjachs et al.,
282 2017). It appears that olive-tree dynamics are independent of human influence in the Balearics.
283 Nonetheless, some chronological discrepancies exist between the two studies in the Albufera
284 Natural Park. These differences may result from the absence of dates between the ^{14}C ages 6270
285 ± 70 and 2440 ± 60 (respectively 7330-6985 and 2625-2350 calibrated 2σ BP) in the sequence

286 published by Burjachs et al. (1994, 2017). Because the quality of an age model is dependent on
287 the number of dated levels, more ^{14}C dates for the core POL12 have probably reduced the
288 uncertainties for the older part of the sequence (Fig. 2).

289

290 *4.3. Anthropogenic influence on the signal*

291 Our pollen diagram from the Albufera Natural Park shows that, while human activities may
292 have partially shaped the area since ~ 3600 BP (attested through an increase in cereal cultivation
293 and fire activity), the CABFAC analyses indicate that the two main factors controlling the
294 ecological signal are humidity ($R^2 = 0.73$, $P_{\text{value}} < 0.001$) and temperatures ($R^2 = 0.65$, $P_{\text{value}} <$
295 0.001). Human impacts ($R^2 = 0.33$, $P_{\text{value}} < 0.001$) and fire activities ($R^2 = 0.31$, $P_{\text{value}} <$
296 0.001) do not meet the significance threshold of 0.5 (Fig. 5). A further control is provided by
297 the evolution of olive trees *versus* cereals (Fig. 4). The highest scores of *Olea europaea* are
298 recorded long before the emergence of human impacts on the environment and also long before
299 the oldest known date of human presence on the island (Burjachs et al., 2017). Olive trees,
300 therefore, are seemingly not a corollary of anthropogenic activities but rather of warmer
301 conditions. The rank of pressures deriving from the CABFAC analyses clearly suggests the
302 dominant role of environmental/climatic agents in mediating the island's palaeoecological
303 dynamics (wet/dry and cool/warm).

304

305 *4.4. Mallorca's mean seasonal temperatures*

306 We first converted past and present-day datasets into mean seasonal temperatures to probe when
307 climate change was most prominent (Fig. 6). According to the instrumental and reconstructed
308 datasets, the sharpest "warming" contrasts between the last eight millennia and the period 1975-
309 2018 occur in winter and autumn, with a respective difference in mean temperature of $4.8 \pm$

310 1.8°C and $3.9 \pm 1.5^\circ\text{C}$. Spring and summer seasons display less pronounced shifts of $2.1 \pm$
311 1.3°C and $2.3 \pm 1.4^\circ\text{C}$.

312

313 *4.5. Mallorca's mean annual temperatures*

314 We then calculated mean annual temperatures (MAT) for the instrumental and reconstructed
315 datasets (Fig. 7A). The present-day MAT is $16.6 \pm 0.8^\circ\text{C}$ (Fig. 7A), with a mean high (T_{max}) of
316 $22.5 \pm 0.7^\circ\text{C}$ and a mean low (T_{min}) of $10.6 \pm 0.9^\circ\text{C}$. The warming trend is 0.55°C per decade
317 for the period 1975-2018. A previous study based on the whole Balearic archipelago, for the
318 period 1977-2006, showed that T_{min} and T_{max} are respectively 12.78°C and 21.76°C , with an
319 estimated warming trend of 0.5°C per decade (Homar et al., 2010). The two warming estimates
320 are similar, with a minor difference of 0.05°C . In comparison, warming on the island of Tenerife
321 (Canary archipelago, North Atlantic Ocean) is much lower, with an average of $0.09 \pm 0.04^\circ\text{C}$
322 per decade since 1944 (Martín et al., 2012). Focusing on the last eight millennia, the MAT is
323 $13.3 \pm 1.5^\circ\text{C}$, close to the present-day T_{min} of the Balearic Islands (difference of $\sim 0.5^\circ\text{C}$; Homar
324 et al., 2010), but with significant temporal variations. The warmest period ($15.6 \pm 0.4^\circ\text{C}$, $\sim 4000-$
325 3000 BP) is counterbalanced by the coolest phase ($12.5 \pm 1.1^\circ\text{C}$, $\sim 8000-7000$ BP), which yields
326 a thermal adjustment that has not been observed since the 20th century. A comparison between
327 present-day and past scores shows that only the $\sim 4000-3000$ BP values are similar to those
328 recorded during the 1970s (MAT of 15.6 ± 0.2 ; Fig. 7A). Since the 1980s (MAT of $16.3 \pm$
329 0.5°C), according to our pollen-based model, the measured temperatures seem to have no
330 analogue in the Holocene climate history of Mallorca.

331 This finding is supported by the MAT for the last 400 years that clearly shows a major
332 ecological break between the pre-industrial and industrial eras (Fig. 7B). The shift dates back
333 to $\sim 1900 \pm 30$ (according to our age-model) but changes have been particularly acute since the
334 1980s (instrumental data). It has been suggested that while the onset of the industrial-era

335 warming can be dated to the 19th century (~1830; Abram et al., 2016), the effects were more
336 acute during the second half of the 20th and 21st centuries (Brohan et al., 2006; IPCC, 2007;
337 Abram et al., 2016). In the Balearic Islands, scholars have demonstrated that climate-change
338 anomalies have mainly increased since the 1980s (Homar et al., 2010; López Mayol et al.,
339 2017). Our dataset (reconstructed and instrumental data) suggest a transition between the pre-
340 and post-1980s.

341

342 *4.6. Temperature anomalies*

343 We subsequently calculated our reconstructed past climate data as anomalies compared to
344 present-day conditions (Fig. 7C), using the period 1900-1980 (mean: $15 \pm 0.6^\circ\text{C}$) as a baseline.
345 Two phases, centered on ~5800-5600 BP and ~4200-3000 BP, were warmer than the first period
346 of industrial-era warming. By contrast, when the second period of instrumental data (1981-
347 2018; mean: $16.7 \pm 0.6^\circ\text{C}$) is used as a baseline, all reconstructed temperatures from the pre-
348 industrial era were lower (i.e. cooler). Only two peaks at $\sim 5665 \pm 40$ BP (with a range from -
349 0.66 to 0.26°C) and $\sim 4065 \pm 30$ BP (with a range from -0.39 to 0.31°C) are close to the 1981-
350 2018 baseline (Fig. 8A). If the mean of the whole instrumental dataset is used as a baseline (Fig.
351 8B), the results illustrate the rapidity of the current changes compared to the climate history of
352 Mallorca.

353 The warming pattern that emerges from our study suggests that the instrumental MAT is $3.3 \pm$
354 1.2°C warmer than the reconstructed MAT (for the last eight millennia). Furthermore, the
355 reconstructed MAT is closer to the present-day T_{\min} (difference of $2.7 \pm 1.2^\circ\text{C}$). With a mean
356 warming rate of 0.55°C per decade, the present-day T_{\min} may become equivalent to the pre-
357 /early industrial-era MAT in about five decades.

358

359

360 *4.7. Mallorca's precipitation*

361 We subsequently reconstructed the dynamics of the rainfall regime during the last 8000 years
362 because variations in humidity were identified as the main forcing agent by the CABFAC
363 analysis (Fig. 5). The MedCLIVAR consortium, and other scholars, have long insisted on the
364 aridification of the Mediterranean area, with a likely increase in heat waves and droughts in the
365 coming decades (Homar et al., 2010; Lionello et al., 2012; Luterbacher et al., 2012; López
366 Mayol et al., 2017). In effect, from 1900 to 2019, droughts and heat waves killed more than
367 62,000 people in the Mediterranean and affected a further > 9 million with total damages
368 exceeding US\$ 29 billion (EM-DAT, 2020).

369 We compared the trends highlighted in the reconstructed and instrumental data to assess
370 whether major changes are detectable (Fig. 9). The two average values showed a significant
371 shift, with a 33% drop in precipitation between the last 8000 years and the industrial era.
372 Focusing on the instrumental period, the driest years were recorded in 1983 (258.8 mm), 1995
373 (265.3 mm), 1999 (227.3 mm) and 2000 (255.9 mm). During the past 8,000 years, the driest
374 millennium was ~4000-3000 BP (Fig. 9), with the lowest score recorded at $\sim 3820 \pm 30$ BP
375 (579.7 ± 11.8 mm). Although important variations were recorded during the Holocene, the
376 highly variable annual precipitation patterns of the industrial era appear to be lower than
377 reconstructed values for the last 8000 years.

378

379 *4.8. Holocene climate dynamics*

380 We finally compared our long-term Holocene reconstruction with other proxy records (Fig. 10).
381 The temperatures and precipitation data mimic variations in solar activity (Solanski et al., 2005;
382 Vonmoos et al., 2006; Steinhilber et al., 2012), particularly the warm and dry long interval that
383 started ~5700 years ago and ended ~2400 years ago (Fig. 10).

384

385 **5. Discussion**

386 This paper reports a new climate reconstruction for the Balearics and underlines the fragility
387 and vulnerability of these islands in the face of ongoing industrial-era warming. The long-term
388 temperature and precipitation trend for Mallorca, based on both reconstructed and instrumental
389 data, clearly depicts a marked offset between the present-day situation and the last 8000 years
390 (Figs 6-9).

391

392 *5.1. Caveats*

393 Nonetheless, some caveats follow. A first limitation to the study results from missing data for
394 a 35-yr interval spanning 1940-1975 (Fig. 6) or 1940-1972 (Fig. 9) due to a gap in the
395 instrumental records. A composite record, based on several Balearic weather stations, was not
396 a viable option as no station has a complete time series for this interval. A second limitation
397 relates to the ^{14}C chronology, which is based on calibrations with varying chronological ranges.
398 Although our reconstructions rely on these chronological data to provide a climate framework,
399 the furnished climate signal remains unchanged. A third limitation relates to the influence of
400 human activities on ecosystem dynamics. As suggested by the CABFAC analyses, human
401 impacts are not the main pressures on ecosystem dynamics (for the pre-industrial era) but their
402 influence is evidently recorded and must be accommodated in our reconstruction, because it is
403 impossible to clearly separate natural forcing agents from anthropogenic activities. A final
404 limitation concerns the number of endemic species in Mallorca and the potential non-analogue
405 ecology when the present-day components are compared to the pre-anthropogenic era. Despite
406 these limitations, our reconstructions are relevant because we focus on long-term trends,
407 limiting over-interpretations resulting from a focus on particular events in the past. In effect,
408 several similar climate reconstructions based on pollen (with the same limitations) have already
409 been published and are relevant to ongoing global warming debates (e.g. Feurdean et al., 2008;

410 Guiot and Kaniewski, 2015; Mauri et al., 2015; Guiot and Cramer, 2016; Kaniewski et al.,
411 2019).

412

413 *5.2. Local environmental significance*

414 Our data provide a long-term perspective on current climate change on the Balearic Islands, as
415 evoked by several authors (Cuxart and Guijarro, 2010; Homar et al., 2010; Jansà et al., 2017;
416 López Mayol et al., 2017). The rate and the magnitude of observed changes during the industrial
417 era are significant when compared to the Holocene climate history of Mallorca (Figs 6-9).
418 Moreover, the CABFAC analysis (Fig. 5) underscores that human activity was not the main
419 pressure behind observed changes in the northeastern part of the island during the pre-industrial
420 period. This argument was previously raised by Burjachs et al. (1994; 2017) for the same area.
421 Our study also stresses that, during the pre-industrial period, warmer and drier conditions
422 developed from 5700 to 2400 BP (Figs 7 and 10). The same chronological boundary of 5700
423 BP was indicated by Bar-Matthews and Ayalon (2011), with a major shift in aridity in the
424 Levant, considered by the authors as the driest event of the mid-Holocene. Anderson et al.
425 (2011) also stressed this boundary for the Sierra Nevada (Laguna de Río Seco, southern Spain),
426 where drier conditions commenced regionally after 5700 BP, marked by the onset of
427 aridification of the flora of southern Spain. Our precipitation reconstruction tightly meshes with
428 this observation (Fig. 9). According to Pérez-Sanz et al. (2013), milder climate conditions
429 characterized northern Spain from 8100 to 5700 BP. Mediterranean climate (warmer and drier)
430 has spread since 5700 BP. Guiot & Kaniewski (2015) previously demonstrated that
431 temperatures increased during the interval 5600-5700 BP. Although the period 5700-2400 BP
432 was warm and dry, it never exceeded the values recorded since the end of the 20th century and
433 those of the 21st century CE.

434 A major consequence of the ongoing warming is falling water availability in island contexts,
435 whose environmental pressure absorption capacities are much lower than for mainland areas
436 (Marriner et al., 2019). As stated by Kent et al. (2002), water shortages are a key environmental
437 problem in Spanish islands, attracting both popular and political attention. Our pollen-based
438 climate reconstruction supports these challenges, suggesting that current precipitation levels are
439 substantially lower than reconstructed values for the Holocene (Fig. 9). For much of the
440 Mediterranean, recent studies have indicated that, for each 1°C of global warming, mean rainfall
441 will probably decrease by about 4% (Cramer et al., 2018; Lionello and Scarascia, 2018).

442

443 *5.3. Global significance*

444 This study suggests two different climate pacemakers for the Balearic Islands. The climate
445 oscillations playing out during the Holocene seem to result from an ocean-atmosphere coupling
446 with a clear imprint of solar activity as the main driver. A connection between solar irradiance
447 and water balance has previously been suggested for Spain (Morellón et al., 2011). On
448 Mallorca, the warmest and driest interval (2400-5700 BP) during the pre-industrial period
449 correlates with increases in solar activity (Fig. 10) as reconstructed from total solar irradiance
450 (Δ TSI; Steinhilber et al., 2012), sunspot numbers (Solanski et al., 2005) and from the solar
451 modulation function Φ [MeV] based on cosmogenic radionuclides (^{10}Be production rates;
452 Vonmoos et al., 2006). The industrial era shows a different trend with a rate and magnitude of
453 changes that exceed the long-term natural variability (Fig. 7; IPCC, 2014, 2018). Changes in
454 solar activity appear to have been a primary pacemaker of long-term climate variations in
455 Mallorca. By contrast, anthropogenic change has been the primary pacemaker since the
456 industrial era, with a clear acceleration of warming and aridification trends.

457

458

459 *5.4. Social and political implications*

460 In the coming decades, warming will have a significant impact on the local economy of the
461 Balearics, which is heavily dependent on tourism (e.g. Kent et al., 2002; Amelung and Viner,
462 2006). Since the 1960s, tourism has reached an apex on Mallorca and Ibiza, with approximately
463 11 million visitors in 2000-2001 and more than 12 million in 2011 (Hof and Blázquez-Salom,
464 2013). As shown by a recent tourism model, climate is an important variable in estimating the
465 economic sustainability of these islands (Álvarez-Díaz and Rosselló-Nadal, 2010). Different
466 climate change scenarios coupled with the Tourism Climatic Index suggest that, during the 21st
467 century, the Balearic Islands, in addition to the wider Mediterranean region, will probably
468 become unsustainably hot during the summer months, while, by contrast, northern Europe will
469 be climatically more attractive for tourism (Amelung and Viner, 2006). Socially and
470 economically, the elucidated changes could become detrimental to tourist-based economies
471 throughout the Mediterranean (Amelung and Viner, 2006).

472 Water management on Mallorca is already under pressure from increasing variability in
473 seasonal and inter-annual rainfall patterns (Candela et al., 2009; Homar et al., 2010; López
474 Mayol et al., 2017), creating an unbalanced distribution of water/groundwater resources
475 (domestic supply and irrigation-based agriculture versus natural ecosystem replenishment).
476 This situation is likely to present serious challenges to the future sustainability of the island and
477 its economic model based on mass tourism (Candela et al., 2009; Hof and Schmitt, 2011).

478

479 *5.4. Reducing the impact*

480 Climate change concerns have led to major political changes on the Balearic Islands. Its
481 parliament, for instance, has recently passed a law on energy transition and climate change that
482 commits local tourism to draw all of its energy needs from renewable sources by 2050. This

483 study reinforces the idea that the Balearics must rapidly adopt such measures to ensure the
484 medium- to long-term viability of its economic model based on mass tourism.

485

486 **6. Conclusions**

487 In conclusion, the analyses presented above provide answers to the two research questions
488 posed in this paper. First, through the prism of Mallorca, results have shown that the industrial-
489 era warming and aridification of Mediterranean islands deviates markedly from the long-term
490 Holocene trends. The instrumental MAT appears $3.3 \pm 1.2^\circ\text{C}$ warmer than the reconstructed
491 MAT for the last eight millennia, with a 33% drop in precipitation between the last 8000 years
492 and the industrial era. Second, this study has also demonstrated the importance of
493 palaeoecological archives in contextualizing current climate anomalies. It has revealed the slow
494 pace of climate dynamics on Mallorca over the past 8000 years, both in rate and magnitude,
495 compared to the speed of changes during the industrial era. This contrast also suggests that,
496 despite human colonization of the Balearic Islands around 4400 years ago, the “Anthropocene”
497 of accelerating human interactions with Earth systems closely intertwines with the industrial
498 era. A human imprint on climate is clearly recorded in the data since 1900 CE, with a sharp
499 acceleration in temperatures and aridity since the 1980s. When temperatures and precipitation
500 during the last 40 years are used as benchmarks (period 1980-2018), the pre-industrial climate
501 of Mallorca appears cooler and wetter than anything that has been recorded since.

502

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522

523 **Declaration of Competing Interest**

524 The authors declare that they have no known competing financial interests or personal
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526

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774

775 **Figures**

776 **Figure 1.** Geographical location the Albufera Natural Park in Mallorca. The study area is
777 denoted by a red star. The geomorphological map of the Bay of Alcúdia and the swamp area
778 (Albufera Natural Park) is adapted from Giaime et al. (2017).

779

780 **Figure 2.** Age-model for the core POL12. The lithology of the core is described in relation to
781 depth. The radiocarbon dates are depicted as intercepts and 2-sigma calibrations (95%
782 probability).

783
784 **Figure 3.** Detailed pollen diagram (arboreal pollen – AP; non-arboreal pollen - NAP) of the
785 core POL12. The arboreal and herbaceous taxa are plotted on a linear age-scale. The vertical
786 lines indicate the main transitions.

787
788 **Figure 4.** Fire activity, agriculture (Poaceae cerealia) and olive trees (*Olea europaea*) plotted
789 on a linear age-scale. The vertical lines denote the results of the homogeneity test (each average
790 is indicated by the letters mu).

791
792 **Figure 5.** Environmental regression models from the Albufera Natural Park. The selected
793 environmental data are indicated in each graph. The consistency of each reconstructed model
794 is indicated by the R2. The lower graph corresponds to a ranking of the environmental data
795 based on the R2 values.

796
797 **Figure 6.** Long-term trends in Mallorca's mean seasonal temperatures. The chronological
798 scales are expressed in years BP and Before Common Era - Common Era (BCE - CE). The
799 modelled temperatures for each season are displayed, with the standard deviation for each data
800 point. The univariate analyses (mean, 25th percentile-Q1, median-Q2, 75th percentile-Q3,
801 minimum value, maximum value) are summarized using a boxplot. The period with no data
802 (1940 to 1975 CE) is denoted by a vertical grey bar.

803
804 **Figure 7.** Long-term evolution of mean annual temperatures on Mallorca. (A) The modelled
805 and measured values are presented as curves and smoothing splines with the standard deviation
806 for each reconstructed data point. The mean value for each dataset is represented in purple. (B)
807 Focus on the period 1600-2018, showing the mean annual temperatures and associated standard
808 errors. The curves are continuous despite the absence of data between 1940 and 1975. (C)
809 Temperature anomalies for the pre-industrial era with the mean 1900-1980 used as the baseline.

810
811 **Figure 8.** Long-term temperature anomalies on Mallorca. (A) Temperature anomalies for the
812 pre-industrial era, with the mean 1981-2018 (16.71°C) used as the baseline. A smoothing spline
813 and a polynomial curve were fitted to the sequence. (B) Temperature anomalies for the pre-
814 industrial and industrial eras with a mean calculated on the whole dataset (14.12°C). This value
815 was used as the baseline. A smoothing spline and a polynomial curve were added to the
816 sequence. The age is expressed as b2k.

817
818 **Figure 9.** Long-term trends in Mallorca's precipitation. The chronological scales are expressed
819 in years BP and the Common Era (CE). The reconstructed annual precipitation values are
820 displayed with the standard deviation. The univariate analyses (mean, 25th percentile-Q1,
821 median-Q2, 75th percentile-Q3, minimum value, maximum value) are summarized using
822 boxplots. The period with no data (1940 to 1972 CE) is denoted by a vertical grey bar. Two
823 different vertical scales are used (right: reconstructed values; left: instrumental data).

824

825 **Figure 10.** Temperature and precipitation trends on Mallorca during the pre-industrial period
826 compared with the long-term solar activity (Solanski et al., 2005; Steinhilber et al., 2012). The
827 yellow shaded part underscores the warmer and driest phase during the last 8,000 years.



















