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1 **Regional temperature, atmospheric circulation, and sea ice variability within the Younger**
2 **Dryas Event constrained using a speleothem from northern Iberia**

3
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18

19 **Precisely-dated, high-resolution stable isotope and trace element data from a stalagmite from**
20 **La Garma Cave, northern Spain, reveal several stages of distinct climatic variability along the**
21 **northern Iberian Atlantic margin, and provide new constraints on the latitude of North**
22 **Atlantic westerlies during the Younger Dryas (YD). Westerly wind position (reconstructed**
23 **using our very high resolution Mg data, a proxy for sea spray contributions and therefore**
24 **wind strength at our coastal cave site) during the early YD (12.85-12.15 kyr) oscillated**
25 **meridionally, resembling the decadal-scale component of the modern North Atlantic**
26 **Oscillation (NAO). Northward repositioning of westerly storm tracks began at 12.150 kyr and**
27 **continued until 12.100 kyr, consistent with other high-resolution wind reconstructions from**
28 **central and northern Europe but occurring somewhat less rapidly. From approximately**

29 **12.100 kyr to the YD termination, the westerlies maintained this more northerly position, with**
30 **atmospheric circulation resembling that of a persistently positive NAO. The early YD was**
31 **also characterised by in-phase shifts in air temperature (reconstructed using our $\delta^{18}\text{O}$ data)**
32 **and north Iberian wind strength, suggesting that temperature modulated sea ice extent, which**
33 **subsequently controlled westerly wind latitude. However, temperature and Iberian wind**
34 **strength were decoupled from 12.4 kyr until the YD termination, but a clear correlation with**
35 **the Intertropical Convergence Zone (ITCZ) position exists throughout. Temperature**
36 **increases at 12.4 kyr, possibly resulting from Atlantic Meridional Overturning Circulation**
37 **(AMOC) strengthening, occurred before northward westerly wind repositioning (at 12.150**
38 **kyr). This delay between North Atlantic warming and subsequent atmospheric reorganisation**
39 **over Europe may have resulted from a teleconnection between the North Atlantic and the**
40 **ITCZ as suggested by marine sediment-based research (Pearce et al., 2013). We suggest that**
41 **northward shifts in the ITCZ were subsequently propagated northward to higher latitudes**
42 **via migrations in Hadley cells and associated wind fields, and are manifested by the**
43 **meridional repositioning apparent in the GAR-01 and other European wind strength**
44 **reconstructions.**

45 **Key Words:** Younger Dryas; isotopes; NAO; westerlies; ITCZ; AMOC; stalagmite; trace elements;
46 atmospheric circulation

47

48

49 **1. Introduction**

50 The Younger Dryas Event (YD; 12.846 to 11.653 kyr BP based on NGRIP chronology (GICC05))
51 is the most extensively studied abrupt climate event of the last deglaciation, but its cause and
52 internal structure are still debated. A catastrophic outburst of proglacial lake meltwater associated

53 with the retreating Laurentide Ice Sheet that consequently slowed Atlantic meridional overturning
54 circulation (AMOC) is most often invoked to explain the YD (Broecker, 2006; Broecker et al.,
55 1989; Carlson et al., 2007), although other causes have been proposed, including a bolide impact
56 (Firestone et al., 2007; Kennett et al., 2009). The YD was historically considered to be an event
57 characterised by a return to near glacial conditions, but recent research indicates that colder
58 conditions were restricted to the Northern Hemisphere, and that the Southern Hemisphere actually
59 warmed (Shakun and Carlson, 2010). Recently, attention has focussed on constraining possible
60 large-scale atmospheric shifts within the YD. Lake sediment records from Norway (Lake Kråkenes:
61 LK) and Germany (Meerfelder Maar: MFM) indicate atmospheric circulation changes, with a
62 dramatic climatic amelioration approximately mid-way through the YD at 12.15 kyr ('the 12.15 kyr
63 event'). These studies suggest that sea ice variability during the YD could have caused switching of
64 the meridional position of the North Atlantic westerlies (Bakke et al., 2009; Brauer et al., 2008).
65 Thus, it has been argued that during the early YD (prior to 12.15 kyr), southward expansion of
66 North Atlantic sea ice may have steered westerlies in a more zonal path over central Europe and
67 MFM, whereas during the late YD (after 12.15 kyr), sea ice breakup redirected the westerlies
68 northwards towards LK. The high resolution records from the same two sites were used in a
69 subsequent study to suggest that warming associated with the 12.15 kyr event was locally abrupt,
70 but occurred at different times in different locations, and may relate to the gradual northward
71 migration of the Polar Front (Lane et al., 2013). However, these records are located away from the
72 North Atlantic, and no similarly high resolution record exists proximal to the North Atlantic
73 seaboard to provide an independent test of these interpretations.

74 Here we present geochemical records from a speleothem from La Garma Cave in northern Spain
75 that constrain regional temperature and local wind strength shifts during the YD at a very high
76 temporal resolution (monthly). The cave is set in a maritime climate that is strongly sensitive to the
77 NAO (Gouveia et al., 2008) (i.e. the modern control on the position of the North Atlantic
78 westerlies), AMOC strength (Pohmann et al., 2006), and, through teleconnections, to the position

79 of the Intertropical Convergence Zone (ITCZ) (Souza and Cavalcanti, 2009). During the YD, this
80 region also marked the southern boundary of the Polar Front (Ruddiman and McIntyre, 1981). The
81 site is therefore ideally situated for clarifying the complex interplay between possible AMOC
82 weakening, sea ice growth, and the basin-wide atmospheric response.

83

84 **2. Site description**

85

86 La Garma Cave (43°25'N, 3°40'W) is located 12 km ESE of Santander and 5 km inland from the
87 Bay of Biscay in the northern Spanish province of Cantabria at an elevation of 85 m.a.s.l.. The cave
88 was discovered in 1995 at which time a detailed survey was conducted and gates erected to restrict
89 access via the two modern cave entrances, Garma A and Garma B (Fig. 1). Detailed archaeological
90 investigations of the cave, conducted by P. Arias and co-researchers at the University of Cantabria,
91 are ongoing.

92

93 Developed in lower Cretaceous limestone on seven main levels within a 187 m high hill, La Garma
94 cave contains ten principal archaeological sites (Arias and Ontañón, 2012), the most important of
95 which are located in the levels at 59 and 80 m.a.s.l. (the Lower Gallery and La Garma A,
96 respectively) (Fig. 1). The former is a 300m long passage, whose original entrance was blocked by
97 rockfall in the Pleistocene. This rockfall abruptly isolated a Palaeolithic (16.5 kyr BP) site within
98 this passage (Supplementary Fig. S1), thus preserving the remains of the activity of its last
99 occupants, including dwelling structures and ritual areas directly observable without excavation
100 (Arias, 2009; Arias and Ontañón, 2012). The site's Upper Palaeolithic archaeology is important,
101 with a very high density of well-preserved material scattered across approximately 800 m² of cave
102 floor. Stalagmite GAR-01 was deposited on top of these Upper Palaeolithic floors in the Lower
103 Gallery. The gallery also has an important ensemble of Palaeolithic cave art representing several

104 different cultural periods, and was used as a burial cave during the Middle Ages (~1.3 kyr). In 2008,
105 La Garma Cave was included in the UNESCO World Heritage List.

106

107 Vegetation above the cave consists of dense C3 vegetation, including hazel, bay and eucalyptus
108 (Rudzka-Phillips et al., 2013). Soil depth varies, but is typically about one meter. The mean annual
109 temperature at the site is 13.7°C, the mean annual total rainfall is 1278 mm yr⁻¹, with a mean annual
110 water excess (total rainfall – actual evapotranspiration) of 1090 mm yr⁻¹ (Rudzka-Phillips et al.,
111 2013).

112

113 **3. Methods**

114

115 **3.1. Sample GAR-01 description and preparation**

116

117 Stalagmite GAR-01 was collected in 2004 from the Lower Gallery in La Garma Cave and is
118 composed entirely of coarsely crystalline calcite. An unusual discontinuity exists in the stratigraphy
119 of the sample GAR-01 B (Fig. 2), and it was determined that the growing stalagmite was broken by
120 visitors to the cave during the Middle Ages at around 1.3 kyr. The section of the sample
121 representing the top of the stalagmite when it was broken at 1.3 kyr (termed GAR-01 A) was found
122 adjacent to GAR-01 B, and matches GAR-01 B section petrographically, geometrically, and
123 chronologically. Stalagmite GAR-01 therefore grew continuously from ~14.0 kyr to the date of
124 collection, and represents 80 cm of total growth with a mean growth rate of 57 micron yr⁻¹. Both
125 GAR-01 A and B were sectioned, polished, and cleaned, and a conventional drill was used to
126 extract powders at a mean resolution of 37 years for stable isotope analysis. The stalagmite slabs
127 were then cut into 3cm long ‘pencils’ for high resolution microbeam stable isotope and trace
128 element analyses.

129

130 3.2. Stable isotope and trace elemental analysis

131

132 Stable isotopes of carbon and oxygen were analysed using a laser ablation–gas chromatography–
133 isotope ratio mass spectrometry (LA-GC-IRMS) system at Royal Holloway University of London,
134 providing a mean resolution of 8.5 years. The system uses a continuous helium flow sample
135 chamber and a 25W CO₂ laser heat source linked to a gas chromatograph (GC) and mass
136 spectrometer (MS). 400-ms laser bursts (beam diameter, approximately 150 μm) produce CO₂
137 through thermal reaction; this CO₂ is then swept through an 80-cm packed GC column into the mass
138 spectrometer for isotope analysis. Measurements are relative to reference gas injected at the start of
139 each run. Replicate analyses of standards indicate that the isotope data are reproducible to better
140 than 0.1‰ for δ¹³C and 0.2‰ for δ¹⁸O. The data reproduce the features apparent from the low-
141 resolution conventional drilling and conventional gas-source mass spectrometer (GV Instruments
142 Multiflow-Isoprime systems at RHUL) analysis.

143

144 The high spatial resolution trace element datasets ~~were~~ ~~was~~ obtained using a custom-designed
145 excimer (193 nm; laser fluence ~4 J/cm²) LA-ICPMS system at RHUL (RESolution M-50
146 prototype coupled to an Agilent 7500ce quadrupole ICP-MS) that features a two-volume Laurin LA
147 cell. Concentrations were determined for Na, Mg, Al, P, Ca, Cu, Zn, Rb, Sr, Y, Ba, Pb, and U, but
148 only the concentrations of Mg, P, Ca, and Sr are discussed here. Stalagmite sections were analysed
149 as continuous profiles using a rectangular spot (285 x 12 μm) which improves spatial resolution for
150 layered samples more than fivefold relative to equivalent circular spots while maintaining high ICP-
151 MS sensitivity. Profiles were analysed at 10 μm/s speed and a laser repetition rate of 15 Hz. The
152 resultant spatial resolution is ~15 μm, (equivalent to approximately a bi-monthly mean temporal
153 resolution). Concentration quantification is based on ⁴³Ca as internal standard and NIST612 as
154 external standard (Müller et al., 2009). A second trace element profile parallel but offset by 5 MFM
155 obtained across the YD interval during a separate LA-ICP-MS session replicates the original track.

156

157 **3.3. GAR-01 chronology**

158

159 Twenty four powder samples were drilled from distinct growth layers along the central axis of the
160 800mm long stalagmite using a handheld drill and a tungsten carbide drill bit. Chemical separation
161 and purification of U-Th isotopes and analytical methods followed procedures outlined in
162 Hoffmann et al. (2007) with samples analysed on a ThermoFinnigan Neptune multicollector
163 inductively coupled mass spectrometer (MC-ICP-MS) at the University of Bristol. U concentrations
164 range between 80 and 150 ng/g, ^{232}Th concentrations are between 0.02 and 0.6 ng/g indicating
165 negligible to low detrital components in the samples. The $^{230}\text{Th}/^{232}\text{Th}$ activity ratio, which indicates
166 the degree of detrital correction, varies between 22 and 2400. All ages were calculated using the
167 half-lives reported in Cheng et al. (2000) and corrected for detrital contamination assuming a
168 $^{238}\text{U}/^{232}\text{Th}$ activity ratio of 0.8 ± 0.4 and a detrital component in U-series secular equilibrium
169 (Wedepohl, 1995). Corrected and uncorrected results are given in Table 1. All quoted uncertainties
170 are at the 95% confidence level. The U-Th ages show that speleothem growth occurred between 0.5
171 and 14 kyr, and all twenty four dates from GAR-01 are in stratigraphic order along the growth axis.
172 Initial $^{234}\text{U}/^{238}\text{U}$ activity ratios range between 1.125 and 1.155. U-Th dating was performed in
173 several steps: first low spatial resolution dating results indicated that calcite precipitated during the
174 YD phase is found between 680 and 730 MFM and subsequently high spatial resolution dating was
175 done for the bottom 350 MFM of the stalagmite to constrain timing and duration of the YD. A
176 distance-age model was generated using the algorithm StalAge (Scholz and Hoffmann, 2011). The
177 distance-age model is very well constrained between 440 and 800 MFM from top (9 to 14 kyr)
178 which is the focus of this study.

179

180 Based on the 24 $^{230}\text{Th}/\text{U}$ dates, stalagmite GAR-01 from La Garma grew continuously from 13.660
181 kyr to 2004 C.E., when it was collected (Fig. 3 and Table 1). Here we only discuss the record during
182 and around the YD (from 14-11 kyrs), which is constrained by 11 $^{230}\text{Th}/\text{U}$ dates.

183

184 **4. Results and discussion**

185

186 **4.1. Stable isotope ratios**

187

188 A 3.1‰ shift in $\delta^{18}\text{O}$ in GAR-01 to more negative values (the largest in the last 13.66 kyrs) occurs
189 between 12.902 and 12.653 kyr, consistent with the NGRIP ice core YD onset at 12.846 ± 0.138
190 kyr (Blockley et al., 2012; Rasmussen et al., 2006b), suggesting that the GAR-01 $\delta^{18}\text{O}$ record is
191 responding predominantly to regional North Atlantic air temperatures, and that YD-related
192 temperature reductions in Greenland and northern Iberia were synchronous (Figs 4 and 5). Based on
193 the GAR-01 $\delta^{18}\text{O}$ record, the coldest YD temperature in northern Iberia occurred at 12.653 kyr,
194 again synchronous with the lowest Greenland YD temperatures (12.65 kyr, NGRIP). Additionally,
195 Iberian margin SST reconstructions (Bard, 2002) very closely track Greenland temperature
196 throughout the Late Glacial and Holocene (Fig. 5), indicating that air temperatures in at least the
197 Iberian coastal regions directly reflected North Atlantic conditions and supporting our interpretation
198 of GAR-01 $\delta^{18}\text{O}$ as a proxy for regional temperature. Reduced air temperatures increased the water
199 vapour-meteoric precipitation fractionation factor leading to lower meteoric precipitation $\delta^{18}\text{O}$
200 (Rozanski et al., 1993) and consequently lowering stalagmite calcite $\delta^{18}\text{O}$. A negative 3.1‰ shift
201 implies a reduction in temperature of perhaps 6-9°C from Allerød temperatures (depending on
202 assumptions regarding the slope of the rainfall $\delta^{18}\text{O}$ versus air temperature relationship), broadly
203 consistent with terrestrial western European cooling estimates of 5-10°C (Denton et al., 2005). The
204 timing and amplitude of shifts evident in the GAR-01 $\delta^{18}\text{O}$ record and other stalagmite records from
205 El Pindal Cave (the Candela stalagmite) (Moreno et al., 2010) (northern Spain, 70 km to the west)

206 and Chauvet Cave (Genty et al., 2006b) (southwestern France, 650 km to the east) further suggest
207 that $\delta^{18}\text{O}$ in all these records reflects regional climatic (temperature-induced isotope fractionation)
208 rather than local or cave-specific hydrological routing effects (Fig. 5).

209

210 Approximately 50 years after the initial $\delta^{18}\text{O}$ shift in GAR-01, $\delta^{13}\text{C}$ exhibits a well-defined +4.5‰
211 anomaly (Fig. 4b) implying a lagged soil/ecosystem response to the initial climate forcing, a
212 decrease in land surface bioproductivity, and a vegetation shift to a more cold/drought tolerant type,
213 consistent with local pollen data that indicate a transition from temperate forest to herbaceous
214 species in northern Iberia in response to drier and cooler conditions at this time (Moreno et al.,
215 2010). Based on the GAR-01 $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data, maximum YD cooling and ecosystem decline in
216 northern Iberia occurred early within the YD, at approximately 12.7-12.5 kyr. This was followed by
217 gradual warming and ecosystem recovery to pre-YD values at 11.65 kyr, again consistent with both
218 regional and Greenland temperature reconstructions. This gradual temperature increase is
219 punctuated with centennial-scale warming events, particularly at 11.68, 12.07, and 12.51 kyr, when
220 northern Iberian temperature returned nearly back to Allerød values, before dropping back to lower
221 YD values (Figs 4 and 5).

222

223 **4.2. High resolution LA-ICP-MS Mg data**

224

225 Whereas the GAR-01 isotope data are interpreted to reflect the regional temperature ($\delta^{18}\text{O}$) and
226 local ecosystem ($\delta^{13}\text{C}$) response to the YD (Figs 4 and 5), the Mg dataset could in principle reflect
227 several processes: a) various degrees of prior calcite precipitation (PCP) from the waters that fed
228 stalagmite GAR-01, b) varying degrees of water-rock interaction, c) temperature via the
229 temperature-sensitive Mg distribution coefficient in calcite (D_{Mg}), or d) varying marine aerosol
230 contributions to the cave dripwater. Mg and Sr concentrations considered with $\delta^{13}\text{C}$ indicate that
231 PCP did not significantly affect GAR-01 drip geochemistry. Mg concentrations decrease into the

232 YD whereas $\delta^{13}\text{C}$ increases, and the process of PCP or increased bedrock interactions would have
233 resulted in a positive, not negative ($-r = -0.28$ for the entire Mg- $\delta^{13}\text{C}$ relationship), correlation.
234 Furthermore, Mg and Sr do not plot along a PCP vector (Fig. 6), although this relationship is often
235 not diagnostic because Sr incorporation is prone to competition effects (Borsato et al., 2007;
236 Sinclair et al., 2012). Increased groundwater residence times (and consequently increased bedrock
237 contributions to the dripwater) would have produced a trend similar to PCP (Sinclair et al., 2012),
238 and are similarly inconsistent with the observed Mg-Sr relationship (Fig. 6). Temperature, however,
239 changed dramatically during the interval reconstructed, and would have affected D_{mg} . Based the
240 Iberian margin SST record (Bard, 2002) and the experimentally derived D_{mg} -temperature
241 relationship (Huang and Fairchild, 2001), the maximum possible shift in the GAR-01 Mg record
242 attributable to temperature is a decrease of ~ 200 ppm, considerably less than the observed decrease
243 of ~ 675 ppm from the Allerød to the coldest part of the YD. Consequently, although temperature
244 change was undoubtedly a factor, it could not have been the dominant control on GAR-01 Mg
245 concentrations over the YD. Importantly however, Mg and Sr concentrations in GAR-01 calcites do
246 plot along a mixing curve constructed by calculating the Mg and Sr concentrations of hypothetical
247 calcites in equilibrium with drip water combined with variable marine aerosol contributions (Fig.
248 6), which is unsurprising given the cave site's proximity to the coast. The high resolution GAR-01
249 Mg record is therefore interpreted as reflecting predominantly meteoric precipitation Mg
250 concentrations (controlled largely by marine aerosol contributions) and to a lesser extent
251 temperature through variations in (the temperature-dependent) D_{mg} . Currently, the strongest winds
252 over northern Iberia are the westerlies, present predominantly during negative NAO phases.
253 Research demonstrates that marine aerosol emission rates are critically dependent on wind speed
254 (Tsyro et al., 2011), and a logical consequence of this link is that the greatest amount of marine
255 aerosol contributions to rainfall approximate westerly position. Importantly, research has already
256 linked marine aerosol contribution amounts to NAO phase (Hindar et al., 2004). In Norway for
257 example, NAO+ phases are associated with a northward shift in westerly wind position, higher

258 wind speeds, and greater marine aerosol (and specifically Mg) contributions to rainfall (Hindar et
259 al., 2004). It is likely that westerly winds probably controlled past marine aerosol fluxes in rainfall
260 as well; high aerosol contributions to the GAR-01 dripwater implying that the westerlies were
261 positioned over the site, whereas reduced Mg fluxes suggest that the westerlies were positioned
262 elsewhere. Based on elemental compositions in rainwater collected 70 km from La Garma, but
263 approximately the same distance from the coast (Banasiak, 2008), modern marine aerosol
264 contributions range up to 1%, well below the values of ~3.5% calculated here for the YD (Fig. 6).
265 This difference likely reflects increased storminess during the late Glacial compared to current
266 conditions (Fig. 6).

267

268 At 12.679 kyr, synchronous with the MFM-defined YD onset (Brauer et al., 2008), the Mg record
269 exhibits high frequency variability in marine aerosol contributions, suggesting rapid meridional
270 oscillation of the westerly storm tracks (Fig. 7). High amplitude, high frequency Mg variability
271 between 12.679 and 12.150 kyr is interpreted to reflect alternating strong and weak westerlies over
272 northern Iberia resulting from rapid north-south repositioning of the dominant westerlies, very
273 similar to the wind reconstructions from MFM (at a similar latitude) across the same time interval
274 (Fig. 7). Decadal-scale oscillations within the GAR-01 Mg record during this early stage of the YD
275 those characteristic of the modern NAO, suggesting that a modern NAO-like dipole mechanism
276 controlled westerly track position during the first half of the YD. Because sea ice extent is thought
277 to largely control the position of the westerlies during this part of the Late Glacial (Brauer et al.,
278 2008), we infer that sea ice extent is oscillating on similar timescales. Existing sea ice
279 reconstructions for the North Atlantic based on the IP25 sea-ice proxy are too coarse to resolve sea
280 ice extent directly at that resolution (Müller and Stein, 2014; Pearce et al., 2013), so it is important
281 to use other means, such as terrestrial wind records, to infer sea ice extent indirectly. Mg
282 concentration oscillations decreased from approximately ~10 years in the earliest YD to ~40 years
283 at 12.150 kyr, possibly reflecting reduced meridional repositioning of westerly winds as a result of

284 northward retreat and stabilisation of North Atlantic sea ice extent. Mg concentration values are at
285 their sustained YD maximum at 12.15 kyr, coincident with positive $\delta^{18}\text{O}$ excursions in the GAR-01,
286 Greenland (Rasmussen et al., 2006a), Chauvet cave (Genty et al., 2006b), and Lake Ammersee (von
287 Grafenstein et al., 1999b) records that all imply rapid warming (Figs 4 and 5). The GAR-01 Mg
288 data therefore suggest strong westerlies over La Garma during this interval coincident with warmer
289 North Atlantic temperatures, implying that a lag existed between mid-YD warming and sea ice
290 collapse (i.e., warmer conditions should melt sea ice and redirect westerlies to the north, but this did
291 not occur immediately). This scenario is further supported by the subsequent long-term northward
292 displacement of westerly storm tracks after 12.15 kyr from mid-latitude Europe to high-latitude
293 Europe implied by the Mg data and by previous reconstructions (Fig. 7), suggesting a progressive
294 northerly retreat of sea ice extent during this time (Bakke et al., 2009; Brauer et al., 2008),
295 postdating the temperature increases. However, this major shift in westerly wind latitude beginning
296 at 12.15 kyr precedes a major decrease in sea ice extent inferred off of Newfoundland at 11.70 kyr
297 (Pearce et al., 2013), suggesting that sea ice off of NW Europe retreated earlier than that off of
298 North America. This pattern is consistent with previous coarsely resolved planktonic foraminifera
299 based reconstructions that indicated a rapid northward sweeping retreat of the Polar Front along the
300 eastern Atlantic Ocean margin compared with a more sluggish retreat along its western margin
301 (Lowe et al., 1994; Ruddiman and McIntyre, 1977).

302

303 The GAR-01 interannual Mg variability suggests that NAO-like atmospheric circulation existed
304 over Europe prior to 12.15 kyr. However, after 12.15 kyr, reduced Mg variability is consistent with
305 a substantially reduced influence of the westerlies in northern Iberia and suggests that subtropical
306 high pressure centres (such as the Azores High) migrated to the north, resembling a persistent
307 positive NAO. This interpretation is consistent with evidence for the initiation of high frequency
308 wind strength variability ('flickering') at the more northerly LK site after 12.15 kyr (Figs 4 and 7).
309 The GAR-01 data and our interpretations are thus consistent with the inferred northerly migration of

310 the westerlies and Polar Front implied by central and northern European records at MFM and LK
311 (Lane et al., 2013) and provides the first evidence from Iberia or lower latitude Europe to
312 corroborate this previously inferred atmospheric repositioning.

313

314 The northward migration of subtropical high pressure centres is supported by similarities between
315 GAR-01 Mg and the low-latitude Cariaco Basin Ti record (Fig. 7) ($r = 0.45$, $p < 0.0001$), a well-
316 established proxy for ITCZ position (Haug et al., 2001). The ITCZ is intrinsically linked to
317 subtropical high pressure centres through the Hadley Cell; the ITCZ representing the rising limb
318 and subtropical high pressure centres the descending limb. Although northern Iberian temperature
319 proxy data (GAR-01 $\delta^{18}\text{O}$) closely parallels Greenland temperature (Fig. 5), our atmospheric
320 circulation proxy (GAR-01 Mg) exhibits a sharp initial drop, a more gradual decrease until a
321 minimum at 11.7 kyr, followed by a gradual recovery to pre-YD conditions some 200 years later
322 than in the NGRIP and GISP2 records (Fig. 4). This pattern is more consistent with low latitude
323 ITCZ migration than with Greenland temperature, and reinforces the concept of a direct link
324 between low- and high-latitude atmospheric circulation. Recent research suggests a strong
325 relationship between high- and low-latitude climate on longer timescales (Deplazes et al., 2013).
326 The good correlation between the Cariaco Basin and GAR-01 Mg records provides a high-
327 resolution glimpse of this relationship in the more recent past, further suggesting that North Atlantic
328 atmospheric circulation and ITCZ position are in fact intrinsically linked.

329

330 **4.3. Implications**

331

332 The GAR-01 record supports the interpretations of the MFM and LK records from central and
333 northern Europe (Bakke et al., 2009; Brauer et al., 2008; Lane et al., 2013), but provides a new
334 perspective from an Atlantic margin site, proximal to the regions most affected by YD cooling
335 (Shakun and Carlson, 2010). The timing of the initiation of Polar Front northward migration at the

336 La Garma (43°N) site at ~12.15 kyr is also indistinguishable (i.e., within dating uncertainties) from
337 that at the MFM (50°N) or LK (62°N) sites, supporting previous interpretations that the Polar Front
338 retreated northward from its maximum southward extent at this time (Lane et al., 2013). However,
339 the northward shift is much more abrupt in the latter two records (<20 years; Fig. 7) than at La
340 Garma, where the westerly wind migration from the site took ~100 years to complete (Fig. 7b). This
341 implies that meridional repositioning nearer the Atlantic occurred at a slower rate than further to the
342 east in continental Europe, possibly linked to the effects of lingering North Atlantic sea ice
343 compared to sea ice off Scandinavia, potentially due to the influence of a freshwater cap distributed
344 over the North Atlantic (Müller and Stein, 2014). This suggests that the Polar Front did not retreat
345 uniformly northwards at a constant rate across Europe, but that its migration rate and timing varied
346 longitudinally, and was linked to differential decay rates of sea ice.

347

348 The new GAR-01 records provide information regarding both regional temperature ($\delta^{18}\text{O}$) and
349 Iberian wind strength (Mg) on a common timescale, and so can clarify the temporal relationships
350 between the two parameters (Fig. 8), as well as any links to the ITCZ. Northern Iberian temperature
351 and wind strength do indeed covary at the outset of the YD, implying that North Atlantic
352 temperature change controlled sea ice extent which in turn was the principal forcing on westerly
353 wind latitude at this time (Fig. 8). However, at ~12.4 kyr, north Iberian temperature and wind
354 strength become decoupled, and at 12.15 kyr an abrupt warming occurs that is not immediately
355 reflected by northward migration of the westerlies. The GAR-01 record therefore suggests that
356 regional warming preceded shifts in atmospheric circulation. Although northward migration of the
357 westerlies over northern Iberia lagged the initial warming, it did track northward migration of the
358 ITCZ (Fig. 7). Pearce et al. (2013) suggest that AMOC strengthening at around 12.3 kyr brought
359 warmth to the North Atlantic, but that rapid sea ice loss off the coast of Newfoundland and
360 associated atmospheric circulation shifts only occurred around 11.700 kyr. They suggest that the
361 12.3 kyr AMOC strengthening resulted in ITCZ shifts through a yet poorly-defined teleconnection,

362 and then these ITCZ shifts were then propagated northward to higher latitudes via shifts in Hadley
363 circulation cells and associated wind fields. Evidence from the high-resolution La Garma, MFM,
364 and LK records broadly supports this interpretation, but the meridional shift in the westerlies and
365 Polar Front implied by the records predates the break-up of sea ice off of Newfoundland suggested
366 by Pearce et al. (12.150 versus 11.700 kyr, respectively). This suggests that sea ice loss occurred
367 earlier off of NW Europe than off of North America.

368

369 The sequence suggested by the GAR-01 data, considered with the other terrestrial wind records and
370 marine sea ice proxy records is: i) 12.400 kyr: gradual warming of the North Atlantic, possibly due
371 to AMOC strengthening, ii) 12.150 kyr: rapid loss of sea ice off of Scandinavia, redirecting
372 westerly winds to the north in Central Europe but only slightly in northern Iberia, iii) 12.150-12.100
373 kyr, gradual loss of sea ice along NW Europe, northward migration of westerlies across all of
374 Europe including northern Iberia, and iv) 11.700 kyr: wholesale collapse of sea ice along the NW
375 Atlantic Ocean, adjacent to Newfoundland. This sequence suggests that sea ice loss through the YD
376 occurred gradually from east to west across the Atlantic over approximately 500 years.

377

378 **5. Conclusions**

379

380 The GAR-01 record reveals considerable interannual variability within the YD that is undetectable
381 in lower resolution proxies. The GAR-01 Mg data are consistent with interpretations based on other
382 high resolution proxies from central and northern Europe constraining the latitude of the westerly
383 winds, supporting the concept that a northerly migration of westerly wind position began at around
384 12.15, approximately halfway through the YD (Lane et al., 2013). However, the shifts observed at
385 La Garma occurred over a longer timescale (about 50 years) than those inferred for LK and MFM,
386 suggesting that Polar Front migration northward was spatially heterogeneous across Europe, and
387 that the persistence of North Atlantic sea ice along western Europe compared to further east reduced

388 the rate of westerly wind migration over northern Iberia compared to over central Europe.
389 Additionally, the GAR-01 Mg (wind strength) and $\delta^{18}\text{O}$ (temperature) data suggest decoupling
390 between sea ice extent and regional temperature at about 12.4 kyr (Fig. 8), synchronous with the
391 initiation of AMOC strengthening and associated warming inferred by marine sediment records
392 from off the coast of Newfoundland (Pearce et al., 2013). A correlation between inferred westerly
393 wind position and the low latitude ITCZ corroborates previous research (Pearce et al., 2013)
394 suggesting that strengthened AMOC resulted in northward migration of the ITCZ and associated
395 atmospheric circulation, including westerlies over Europe. This eventually resulted in the break-up
396 of sea ice first proximal to Scandinavia, then along NW Europe, and finally along northeastern
397 North America.

398

399 Our data further detail the nature of North Atlantic sea ice loss during the Younger Dryas and of the
400 subsequent atmospheric reorganisation. Further research should focus on determining the exact
401 nature of the AMOC/ITCZ teleconnection, and better constraining the reason behind our inferred
402 300-year lag between the initiation of AMOC strengthening (at 12.4 kyr) and sea ice loss in the
403 eastern North Atlantic (at 12.1 kyr). This lag suggests that a threshold was passed, that resulted in a
404 rapid transition from cold-unstable to warmer-stable climate over a few decades in northern Iberia.
405 This mid-Younger Dryas shift provides an example of substantial atmospheric circulation
406 reorganization that occurred over just a few decades, that led to a stormier northern Europe and a
407 drier but warmer Mediterranean. This result reinforces the concept that rapid climate change due to
408 repositioned atmospheric circulation is often of greater local importance than climate change
409 averaged over large geographic areas.

410

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416

417

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555 **Figure captions**

556 **Fig. 1.** (a) Locations of YD palaeoclimate archive sites along the North Atlantic margin discussed
557 in the text. Large continental glaciers are represented by the semi-transparent white areas. Glacier
558 extent is based on several recent publications (O'Cofaigh et al., 2013; Young et al., 2012) but
559 probably represents a minimum extent because limited evidence is preserved for YD ice extent on

560 shelves, particularly around Greenland (O'Cofaigh et al., 2013). LG, La Garma Cave; MFM,
561 Meerfelder Maar; LA, Lake Ammersee; PC, El Pindal Cave; LK, Lake Krakenes; CC, Chauvet
562 Cave; SU8118 & MD952042, Iberian margin sediment cores; NGRIP, North GRIP ice core; GISP2,
563 GISP2 ice core. (b) Location of La Garma Cave in northern Spain and section and (c) plan of the
564 main levels of the karst system (Arias and Ontañón, 2012). Stalagmite GAR-01 was obtained from
565 the Lower Gallery. The position of the sample is represented by a red filled circle.

566

567 **Fig. 2.** Photograph of stalagmite GAR-01 A and B with U-Series sample locations (black boxes)
568 and corresponding ages (in years before 1950). U-Series powders were drilled at regular intervals
569 along the length of GAR-01. GAR-01 A was the first portion of GAR-01 to be collected. This
570 portion of GAR-01 was broken off in the Middle Ages and discovered on the ground adjacent to the
571 *in situ* portion of GAR-01 (GAR-01 B) in 2003. GAR-01 A (Holocene portion) and GAR-01 B
572 (pre-Holocene with Middle Ages break and post-Middle Ages growth to present-day). The red bar
573 marks the location of the Younger Dryas (YD) isotope anomaly in GAR-01.

574

575 **Fig. 3.** U-series age model for the GAR-01 stalagmite. GAR-01 U-series dates are plotted with 2σ
576 error bars and the age model (black line) was calculated using the StalAge algorithm (Scholz and
577 Hoffmann, 2011). The location of the YD based on the NGRIP dates is illustrated by the shading,
578 and growth rate based on the slope of the plotted age model is shown as an inset.

579

580 **Fig. 4.** Northern Hemisphere proxies of Younger Dryas conditions from the northern North
581 Atlantic, mid-latitude Europe, and low latitude regions. (a) GAR-01 $\delta^{18}\text{O}$ laser ablation data (solid
582 blue line) and conventional drill data (blue circles). The gap in the laser dataset between 12.33 and
583 12.48 ka is due to material lost in preparing the slabs for LA-ICP-MS analysis. (b) GAR-01 $\delta^{13}\text{C}$
584 laser ablation data (solid green line) and conventional drill data (large green circles). (c) GAR-01
585 Mg data original track (dark orange) and replicate track (light orange). (d) NGRIP and GISP2 $\delta^{18}\text{O}$

586 data (Steig et al., 1994). (e) MFM varve thickness data (Brauer et al., 2008). (f) LK Ti Count Rate
587 (Bakke et al., 2009). The grey line is a three-point moving average. (g) Chauvet cave stalagmite
588 $\delta^{18}\text{O}$ data (Genty et al., 2006a). (h) Lake Ammersee ostracod $\delta^{18}\text{O}$ data (von Grafenstein et al.,
589 1999a). (i) Cariaco Basin Ti% index data (Haug et al., 2001). GAR-01 U-Series dates obtained
590 across the event are shown at the bottom of the diagram plotted with 2σ error bars. The vertical
591 black dashed line highlights the '12.15 kyr event'. The turquoise and grey bars mark the timing of
592 the YD according to NGRIP divided into the first and second stages of the event, respectively.

593

594 **Fig. 5.** Records proximal to La Garma Cave and those interpreted as reflecting regional
595 temperature. The GAR-01 laser $\delta^{18}\text{O}$ record (blue), the Iberian margin SST record (black) (Bard,
596 2002), and the Candela stalagmite record from El Pindal Cave (orange squares) (Moreno et al.,
597 2010) (lower panel) as well as Greenland ice core $\delta^{18}\text{O}$ records (Steig et al., 1994) (upper panel).

598

599 **Fig. 6.** Mean LA-ICP-MS Sr and Mg values for GAR-01 for the Allerød, early YD, late YD, early
600 Holocene, and mid-Holocene. The bars illustrate one standard deviation from the mean for each
601 dataset. The solid line is a modelled calcite vector representing different amounts of marine aerosol
602 contributions to the drip water. The 0% marine aerosol contribution is defined as the Mg and Sr
603 concentrations in calcite precipitated from a dripwater with Mg and Sr concentrations derived
604 exclusively from the dissolution of the bedrock surrounding La Garma Cave. The Mg and Sr
605 concentrations of seawater are derived from global averages (Chester, 1990). The percentages
606 represent increasing percentage contribution of seawater to the dripwater (i.e., 0% = no seawater
607 contribution, 5% = 5% of the dripwater is composed of seawater). These dripwater Mg and Sr
608 values are then used to model the Mg and Sr values in calcite precipitated from this dripwater of
609 varying marine aerosol contributions (the solid line), using the distribution coefficients given in
610 Huang and Fairchild (2001). The range of marine aerosols found in modern rainfall was calculated
611 using rainfall elemental concentrations compiled in Banasiek (2008) near Pindal Cave (70 km west

612 of La Garma Cave) for a short interval from January 14, 2006, to February 26, 2007, and therefore
613 may represent an underestimation of the total modern marine aerosol range possible. The samples
614 were collected at a similar distance from the coast as La Garma.

615

616 **Fig. 7.** The GAR-01 Mg compared to other low- and mid-latitude records. **(a)** The GAR-01 Mg
617 (orange) and the Cariaco Basin (Haug et al., 2001) (black) records. The interval from 11.7 to 12.6
618 kyr for the GAR-01 Mg record is expanded in **(b)** and compared to the MFM (Brauer et al., 2008)
619 and LK (Bakke et al., 2009) records. The dark double arrow to the left shows the modern % aerosol
620 contribution near Pindal Cave (70 km west of La Garma Cave).

621

622 **Fig. 8.** The GAR-01 Mg and $\delta^{18}\text{O}$ records, with intervals where they are coherent and decoupled
623 indicated by the black lines over the records. The interval of the YD is indicated by the black line
624 underneath the records.

625