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

Lisa M. Baldini[1*], Frank McDermott[2,3], James U. L. Baldini[1], Pablo Arias[4], Marián Cueto[4], Ian J. Fairchild[5], Dirk L. Hoffmann[6,7], David P. Mattey[8], Wolfgang Müller[8], Dan Constantin Nita[6], Roberto Ontañón[4], Cristina Garciá-Moncó[4], David A. Richards[6]

[1]Department of Earth Sciences, Durham University, Science Labs, South Road, Durham DH1 3LE, UK
[2]School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland
[3]UCD Earth Institute, University College Dublin, Belfield, Dublin 4, Ireland.
[4]International Institute for Prehistoric Research of Cantabria, University of Cantabria, Spain
[5]School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[6]School of Geographical Sciences, University of Bristol, University Road, Clifton, Bristol BS8 1SS, UK
[7]CENIEH, Paseo Sierra de Atapuerca s/n, 09002-Burgos, Spain
[8]Department of Earth Sciences, Royal Holloway, University of London,, Egham, Surrey, TW20 0EX, UK
*email: l.m.baldini@durham.ac.uk

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

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

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

1. Introduction

The Younger Dryas Event (YD; 12.846 to 11.653 kyr BP based on NGRIP chronology (GICC05)) is the most extensively studied abrupt climate event of the last deglaciation, but its cause and internal structure are still debated. A catastrophic outburst of proglacial lake meltwater associated with the retreating Laurentide Ice Sheet that consequently slowed Atlantic meridional overturning circulation (AMOC) is most often invoked to explain the YD (Broecker, 2006; Broecker et al., 1989; Carlson et al., 2007), although other causes have been proposed, including a bolide impact (Firestone et al., 2007; Kennett et al., 2009). The YD was historically considered to be an event characterised by a return to near glacial conditions, but recent research indicates that colder conditions were restricted to the Northern Hemisphere, and that the Southern Hemisphere actually warmed (Shakun and Carlson, 2010). Recently, attention has focussed on constraining possible large-scale atmospheric shifts within the YD. Lake sediment records from Norway (Lake Kråkenes: LK) and Germany (Meerfelder Maar: MFM) indicate atmospheric circulation changes, with a dramatic climatic amelioration approximately mid-way through the YD at 12.15 kyr (‘the 12.15 kyr event’). These studies suggest that sea ice variability during the YD could have caused switching of the meridional position of the North Atlantic westerlies (Bakke et al., 2009; Brauer et al., 2008). Thus, it has been argued that during the early YD (prior to 12.15 kyr), southward expansion of North Atlantic sea ice may have steered westerlies in a more zonal path over central Europe and MFM, whereas during the late YD (after 12.15 kyr), sea ice breakup redirected the westerlies northwards towards LK. The high resolution records from the same two sites were used in a subsequent study to suggest that warming associated with the 12.15 kyr event was locally abrupt, but occurred at different times in different locations, and may relate to the gradual northward migration of the Polar Front (Lane et al., 2013). However, these records are located away from the North Atlantic, and no similarly high resolution record exists proximal to the North Atlantic seaboard to provide an independent test of these interpretations.

Here we present geochemical records from a speleothem from La Garma Cave in northern Spain that constrain regional temperature and local wind strength shifts during the YD at a very high temporal resolution (monthly). The cave is set in a maritime climate that is strongly sensitive to the NAO (Gouveia et al., 2008) (i.e. the modern control on the position of the North Atlantic westerlies), AMOC strength (Pohlmann et al., 2006), and, through teleconnections, to the position of the Intertropical Convergence Zone (ITCZ) (Souza and Cavalcanti, 2009). During the YD, this region also marked the southern boundary of the Polar Front (Ruddiman and Mcintyre, 1981). The site is therefore ideally situated for clarifying the complex interplay between possible AMOC weakening, sea ice growth, and the basin-wide atmospheric response.

2. Site description

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

Developed in lower Cretaceous limestone on seven main levels within a 187 m high hill, La Garma cave contains ten principal archaeological sites (Arias and Ontañón, 2012), the most important of which are located in the levels at 59 and 80 m.a.s.l. (the Lower Gallery and La Garma A, respectively) (Fig. 1). The former is a 300m long passage, whose original entrance was blocked by rockfall in the Pleistocene. This rockfall abruptly isolated a Palaeolithic (16.5 kyr BP) site within this passage (Supplementary Fig. S1), thus preserving the remains of the activity of its last occupants, including dwelling structures and ritual areas directly observable without excavation (Arias, 2009; Arias and Ontañón, 2012). The site's Upper Palaeolithic archaeology is important, with a very high density of well-preserved material scattered across approximately 800 m^2 of cave floor. Stalagmite GAR-01 was deposited on top of these Upper Palaeolithic floors in the Lower Gallery. The gallery also has an important ensemble of Palaeolithic cave art representing several different cultural periods, and was used as a burial cave during the Middle Ages (~1.3 kyr). In 2008, La Garma Cave was included in the UNESCO World Heritage List.

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

3. Methods

3.1. Sample GAR-01 description and preparation

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

3.2. Stable isotope and trace elemental analysis

Stable isotopes of carbon and oxygen were analysed using a laser ablation–gas chromatography–isotope ratio mass spectrometry (LA-GC-IRMS) system at Royal Holloway University of London, providing a mean resolution of 8.5 years. The system uses a continuous helium flow sample chamber and a 25W CO_2 laser heat source linked to a gas chromatograph (GC) and mass spectrometer (MS). 400-ms laser bursts (beam diameter, approximately 150 µm) produce CO_2 through thermal reaction; this CO_2 is then swept through an 80-cm packed GC column into the mass spectrometer for isotope analysis. Measurements are relative to reference gas injected at the start of each run. Replicate analyses of standards indicate that the isotope data are reproducible to better than 0.1‰ for $\delta^{13}C$ and 0.2‰ for $\delta^{18}O$. The data reproduce the features apparent from the low-resolution conventional drilling and conventional gas-source mass spectrometer (GV Instruments Multiflow-Isoprime systems at RHUL) analysis.

The high spatial resolution trace element datasets were ~~was~~ obtained using a custom-designed excimer (193 nm; laser fluence ~4 J/cm^2) LA-ICPMS system at RHUL (RESOlution M-50 prototype coupled to an Agilent 7500ce quadrupole ICP-MS) that features a two-volume Laurin LA cell. Concentrations were determined for Na, Mg, Al, P, Ca, Cu, Zn, Rb, Sr, Y, Ba, Pb, and U, but only the concentrations of Mg, P, Ca, and Sr are discussed here. Stalagmite sections were analysed as continuous profiles using a rectangular spot (285 x 12 µm) which improves spatial resolution for layered samples more than fivefold relative to equivalent circular spots while maintaining high ICP-MS sensitivity. Profiles were analysed at 10 µm/s speed and a laser repetition rate of 15 Hz. The resultant spatial resolution is ~15 µm, (equivalent to approximately a bi-monthly mean temporal resolution). Concentration quantification is based on ^{43}Ca as internal standard and NIST612 as external standard (Müller et al., 2009). A second trace element profile parallel but offset by 5 MFM obtained across the YD interval during a separate LA-ICP-MS session replicates the original track.

3.3. GAR-01 chronology

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

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

4. Results and discussion

4.1. Stable isotope ratios

A 3.1‰ shift in $\delta^{18}O$ in GAR-01 to more negative values (the largest in the last 13.66 kyrs) occurs between 12.902 and 12.653 kyr, consistent with the NGRIP ice core YD onset at 12.846 ± 0.138 kyr (Blockley et al., 2012; Rasmussen et al., 2006b), suggesting that the GAR-01 $\delta^{18}O$ record is responding predominantly to regional North Atlantic air temperatures, and that YD-related temperature reductions in Greenland and northern Iberia were synchronous (Figs 4 and 5). Based on the GAR-01 $\delta^{18}O$ record, the coldest YD temperature in northern Iberia occurred at 12.653 kyr, again synchronous with the lowest Greenland YD temperatures (12.65 kyr, NGRIP). Additionally, Iberian margin SST reconstructions (Bard, 2002) very closely track Greenland temperature throughout the Late Glacial and Holocene (Fig. 5), indicating that air temperatures in at least the Iberian coastal regions directly reflected North Atlantic conditions and supporting our interpretation of GAR-01 $\delta^{18}O$ as a proxy for regional temperature. Reduced air temperatures increased the water vapour-meteoric precipitation fractionation factor leading to lower meteoric precipitation $\delta^{18}O$ (Rozanski et al., 1993) and consequently lowering stalagmite calcite $\delta^{18}O$. A negative 3.1‰ shift implies a reduction in temperature of perhaps 6-9^{o}C from Allerød temperatures (depending on assumptions regarding the slope of the rainfall $\delta^{18}O$ versus air temperature relationship), broadly consistent with terrestrial western European cooling estimates of 5-10°C (Denton et al., 2005). The timing and amplitude of shifts evident in the GAR-01 $\delta^{18}O$ record and other stalagmite records from El Pindal Cave (the Candela stalagmite) (Moreno et al., 2010) (northern Spain, 70 km to the west) and Chauvet Cave (Genty et al., 2006b) (southwestern France, 650 km to the east) further suggest that $\delta^{18}O$ in all these records reflects regional climatic (temperature-induced isotope fractionation) rather than local or cave-specific hydrological routing effects (Fig. 5).

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

4.2. High resolution LA-ICP-MS Mg data

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

YD whereas $\delta^{13}C$ increases, and the process of PCP or increased bedrock interactions would have resulted in a positive, not negative (-r = -0.28 for the entire Mg-$\delta^{13}C$ relationship), correlation. Furthermore, Mg and Sr do not plot along a PCP vector (Fig. 6), although this relationship is often not diagnostic because Sr incorporation is prone to competition effects (Borsato et al., 2007; Sinclair et al., 2012). Increased groundwater residence times (and consequently increased bedrock contributions to the dripwater) would have produced a trend similar to PCP (Sinclair et al., 2012), and are similarly inconsistent with the observed Mg-Sr relationship (Fig. 6). Temperature, however, changed dramatically during the interval reconstructed, and would have affected D_{mg}. Based the Iberian margin SST record (Bard, 2002) and the experimentally derived D_{mg}-temperature relationship (Huang and Fairchild, 2001), the maximum possible shift in the GAR-01 Mg record attributable to temperature is a decrease of ~200 ppm, considerably less than the observed decrease of ~675 ppm from the Allerød to the coldest part of the YD. Consequently, although temperature change was undoubtedly a factor, it could not have been the dominant control on GAR-01 Mg concentrations over the YD. Importantly however, Mg and Sr concentrations in GAR-01 calcites do plot along a mixing curve constructed by calculating the Mg and Sr concentrations of hypothetical calcites in equilibrium with drip water combined with variable marine aerosol contributions (Fig. 6), which is unsurprising given the cave site's proximity to the coast. The high resolution GAR-01 Mg record is therefore interpreted as reflecting predominantly meteoric precipitation Mg concentrations (controlled largely by marine aerosol contributions) and to a lesser extent temperature through variations in (the temperature-dependent) D_{mg}. Currently, the strongest winds over northern Iberia are the westerlies, present predominantly during negative NAO phases. Research demonstrates that marine aerosol emission rates are critically dependent on wind speed (Tsyro et al., 2011), and a logical consequence of this link is that the greatest amount of marine aerosol contributions to rainfall approximate westerly position. Importantly, research has already linked marine aerosol contribution amounts to NAO phase (Hindar et al., 2004). In Norway for example, NAO+ phases are associated with a northward shift in westerly wind position, higher wind speeds, and greater marine aerosol (and specifically Mg) contributions to rainfall (Hindar et al., 2004). It is likely that westerly winds probably controlled past marine aerosol fluxes in rainfall as well; high aerosol contributions to the GAR-01 dripwater implying that the westerlies were positioned over the site, whereas reduced Mg fluxes suggest that the westerlies were positioned elsewhere. Based on elemental compositions in rainwater collected 70 km from La Garma, but approximately the same distance from the coast (Banasiek, 2008), modern marine aerosol contributions range up to 1%, well below the values of ~3.5% calculated here for the YD (Fig. 6). This difference likely reflects increased storminess during the late Glacial compared to current conditions (Fig. 6).

At 12.679 kyr, synchronous with the MFM-defined YD onset (Brauer et al., 2008), the Mg record exhibits high frequency variability in marine aerosol contributions, suggesting rapid meridional oscillation of the westerly storm tracks (Fig. 7). High amplitude, high frequency Mg variability between 12.679 and 12.150 kyr is interpreted to reflect alternating strong and weak westerlies over northern Iberia resulting from rapid north-south repositioning of the dominant westerlies, very similar to the wind reconstructions from MFM (at a similar latitude) across the same time interval (Fig. 7). Decadal-scale oscillations within the GAR-01 Mg record during this early stage of the YD those characteristic of the modern NAO, suggesting that a modern NAO-like dipole mechanism controlled westerly track position during the first half of the YD. Because sea ice extent is thought to largely control the position of the westerlies during this part of the Late Glacial (Brauer et al., 2008), we infer that sea ice extent is oscillating on similar timescales. Existing sea ice reconstructions for the North Atlantic based on the IP25 sea-ice proxy are too coarse to resolve sea ice extent directly at that resolution (Müller and Stein, 2014; Pearce et al., 2013), so it is important to use other means, such as terrestrial wind records, to infer sea ice extent indirectly. Mg concentration oscillations decreased from approximately ~10 years in the earliest YD to ~40 years at 12.150 kyr, possibly reflecting reduced meridional repositioning of westerly winds as a result of northward retreat and stabilisation of North Atlantic sea ice extent. Mg concentration values are at their sustained YD maximum at 12.15 kyr, coincident with positive $\delta^{18}O$ excursions in the GAR-01, Greenland (Rasmussen et al., 2006a), Chauvet cave (Genty et al., 2006b), and Lake Ammersee (von Grafenstein et al., 1999b) records that all imply rapid warming (Figs 4 and 5). The GAR-01 Mg data therefore suggest strong westerlies over La Garma during this interval coincident with warmer North Atlantic temperatures, implying that a lag existed between mid-YD warming and sea ice collapse (i.e., warmer conditions should melt sea ice and redirect westerlies to the north, but this did not occur immediately). This scenario is further supported by the subsequent long-term northward displacement of westerly storm tracks after 12.15 kyr from mid-latitude Europe to high-latitude Europe implied by the Mg data and by previous reconstructions (Fig. 7), suggesting a progressive northerly retreat of sea ice extent during this time (Bakke et al., 2009; Brauer et al., 2008), postdating the temperature increases. However, this major shift in westerly wind latitude beginning at 12.15 kyr precedes a major decrease in sea ice extent inferred off of Newfoundland at 11.70 kyr (Pearce et al., 2013), suggesting that sea ice off of NW Europe retreated earlier than that off of North America. This pattern is consistent with previous coarsely resolved planktonic foraminifera based reconstructions that indicated a rapid northward sweeping retreat of the Polar Front along the eastern Atlantic Ocean margin compared with a more sluggish retreat along its western margin (Lowe et al., 1994; Ruddiman and Mcintyre, 1977).

The GAR-01 interannual Mg variability suggests that NAO-like atmospheric circulation existed over Europe prior to 12.15 kyr. However, after 12.15 kyr, reduced Mg variability is consistent with a substantially reduced influence of the westerlies in northern Iberia and suggests that subtropical high pressure centres (such as the Azores High) migrated to the north, resembling a persistent positive NAO. This is interpretation is consistent with evidence for the initiation of high frequency wind strength variability (‘flickering’) at the more northerly LK site after 12.15 kyr (Figs 4 and 7). The GAR-01 data and our interpretations are thus consistent with the inferred northerly migration of the westerlies and Polar Front implied by central and northern European records at MFM and LK (Lane et al., 2013) and provides the first evidence from Iberia or lower latitude Europe to corroborate this previously inferred atmospheric repositioning.

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

4.3. Implications

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

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

The new GAR-01 records provide information regarding both regional temperature ($\delta^{18}O$) and Iberian wind strength (Mg) on a common timescale, and so can clarify the temporal relationships between the two parameters (Fig. 8), as well as any links to the ITCZ. Northern Iberian temperature and wind strength do indeed covary at the outset of the YD, implying that North Atlantic temperature change controlled sea ice extent which in turn was the principal forcing on westerly wind latitude at this time (Fig. 8). However, at ~12.4 kyr, north Iberian temperature and wind strength become decoupled, and at 12.15 kyr an abrupt warming occurs that is not immediately reflected by northward migration of the westerlies. The GAR-01 record therefore suggests that regional warming preceded shifts in atmospheric circulation. Although northward migration of the westerlies over northern Iberia lagged the initial warming, it did track northward migration of the ITCZ (Fig. 7). Pearce et al. (2013) suggest that AMOC strengthening at around 12.3 kyr brought warmth to the North Atlantic, but that rapid sea ice loss off the coast of Newfoundland and associated atmospheric circulation shifts only occurred around 11.700 kyr. They suggest that the 12.3 kyr AMOC strengthening resulted in ITCZ shifts through a yet poorly-defined teleconnection, and then these ITCZ shifts were then propagated northward to higher latitudes via shifts in Hadley circulation cells and associated wind fields. Evidence from the high-resolution La Garma, MFM, and LK records broadly supports this interpretation, but the meridional shift in the westerlies and Polar Front implied by the records predates the break-up of sea ice off of Newfoundland suggested by Pearce et al. (12.150 versus 11.700 kyr, respectively). This suggests that sea ice loss occurred earlier off of NW Europe than off of North America.

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

5. Conclusions

The GAR-01 record reveals considerable interannual variability within the YD that is undetectable in lower resolution proxies. The GAR-01 Mg data are consistent with interpretations based on other high resolution proxies from central and northern Europe constraining the latitude of the westerly winds, supporting the concept that a northerly migration of westerly wind position began at around 12.15, approximately halfway through the YD (Lane et al., 2013). However, the shifts observed at La Garma occurred over a longer timescale (about 50 years) that those inferred for LK and MFM, suggesting that Polar Front migration northward was spatially heterogeneous across Europe, and that the persistence of North Atlantic sea ice along western Europe compared to further east reduced the rate of westerly wind migration over northern Iberia compared to over central Europe. Additionally, the GAR-01 Mg (wind strength) and $\delta^{18}O$ (temperature) data suggest decoupling between sea ice extent and regional temperature at about 12.4 kyr (Fig. 8), synchronous with the initiation of AMOC strengthening and associated warming inferred by marine sediment records from off the coast of Newfoundland (Pearce et al., 2013). A correlation between inferred westerly wind position and the low latitude ITCZ corroborates previous research (Pearce et al., 2013) suggesting that strengthened AMOC resulted in northward migration of the ITCZ and associated atmospheric circulation, including westerlies over Europe. This eventually resulted in the break-up of sea ice first proximal to Scandinavia, then along NW Europe, and finally along northeastern North America.

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

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Figure captions

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

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

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

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

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

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

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

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

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

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

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