A speleothem record from Portugal reveals phases of increased winter precipitation in western Iberia during the Holocene

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Abstract
The European climate during the Holocene period is characterised by frequent changes of temperature and precipitation. The North Atlantic plays a major role as a driver for European climate and is a dominant precipitation source, particularly for the western European and north African realm. Atmospheric pressure gradients over the Atlantic (North Atlantic Oscillation, NAO), Atlantic circulation patterns (Atlantic Multidecadal Oscillation, AMO) or positioning of the Atlantic jet stream have been suggested to be responsible for precipitation patterns across western Europe. However, proxy data provide an inconsistent picture on how precipitation responds to changes in the Atlantic realm such as changes of Atlantic temperature (IRD), atmospheric pressure (NAO), water circulation (AMO) or the jet stream. Here we present a record of speleothem-based winter precipitation amount from Portugal. The record covers most of the Holocene and demonstrates that wetter conditions were synchronous in western and southern Iberia during early and mid Holocene. The record also shows a correlation between increased winter precipitation amount in western Iberia and Atlantic cooling, evidenced by Bond events, between 10 and 4ka.

Keywords
bond events, Holocene, Iberian Peninsula, palaeoclimate, precipitation, speleothem, terrestrial record

Introduction
Despite relative climate stability during the Holocene, frequent climatic changes are nevertheless observed in the northern Hemisphere (Mayewski et al., 2004), for example in the form of episodic Atlantic cooling (Bond et al., 2001), North Atlantic storminess (Goslin et al., 2018) or changes of precipitation and temperature over continental Europe (Mauri et al., 2015). The Atlantic plays an important role for precipitation patterns across Europe via atmospheric pressure cells and the North Atlantic Oscillation (NAO), Atlantic circulation patterns (Atlantic Multidecadal Oscillation, AMO) or positioning of the Atlantic jet stream. The NAO index characterises relative changes of the average pressure differences between the Azores (sub-tropical) high-pressure cell and the Icelandic (sub-polar) low-pressure cell (Wanner et al., 2001). A positive NAO is indicated when both sub-tropical high and sub-polar low are stronger than average and during a positive NAO phase westerlies are positioned more northward (Visbeck et al., 2001; Wanner et al., 2001). As a result, climatic conditions are typically colder and drier across the Iberian Peninsula and Mediterranean regions and warmer and wetter in northern Europe. When the NAO is negative, both the sub-tropical high and sub-polar low are weaker than average, positioning the westerlies more southerly and bringing moisture to the Mediterranean realm with colder and drier conditions in northern Europe. Also, a connection between NAO, Atlantic sea surface temperature (SST) and Atlantic Multidecadal Oscillation (AMO) has been suggested, with a positive (negative) NAO leading to Atlantic warming (cooling) resembling the AMO (Delworth et al., 2017). Furthermore, western Europe late winter precipitation and the Atlantic jet stream

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variability are found to correlate with Atlantic sea surface temperature (Simpson et al., 2019).

While it has generally been documented by proxy data that the Holocene climate in Europe was variable in precipitation and temperature, detailed palaeoclimate data about spatial or seasonal differences and connections between the Atlantic (e.g. SST) and continental climate (e.g. precipitation) are lacking. In particular, a possible connection between Atlantic cold phases and western European precipitation remains ambiguous. A Holocene speleothem record from northern Spain indicates dry conditions during North Atlantic cold events (Smith et al., 2016). In contrast, a speleothem record from Morocco suggests that, during the early and late Holocene, Atlantic cold phases evidenced as Bond events are associated with a negative NAO resulting in wetter conditions in the western Mediterranean realm (Ait Brahim et al., 2019). A recent study using instrumental data over the last hundred years suggests that in late winter a positive AMO is accompanied by enhanced precipitation over Iberia (Simpson et al., 2019). Further Holocene winter precipitation records from Iberia would be ideal to test the relationship between Atlantic cooling phases and precipitation in the peninsula.

Stable isotopes, in particular variations of δ18O, are commonly used as climate proxies, linking various archives such as ice cores, deep sea sediments or speleothems. However, interpretation of δ18O variation in various proxy archives is not always straightforward. Here we present past precipitation changes based on an alternative proxy – stalagmite growth rate – which can only be applied under specific circumstances and is not generally applicable as a palaeo rainfall proxy. We present two stalagmite records from Portugal, which formed during the Holocene in close proximity in the same cave. Growth rates, isotope data and monitoring results for the two specimens reveal that one of the two stalagmites formed largely as a result of increased late winter rain and provides a Holocene winter precipitation record for western Iberia.

Setting and methods

Cave site

The Almonda karst system (Torres Novas, Portugal; 39.5057°N 8.6157°W) is located on the ~40 km long fault escarpment separating Portuguese Estremadura’s Central Limestone Massif from the Tagus Cenozoic basin. The karst system is situated approximately 40 km inland between 75 and 150 m a.s.l., oriented in a NE-SW direction and is home to a network of cave passages and archaeological sites, namely Galeria da Cisterna, Gruta da Oliveira, Gruta da Arroeira and Galeria das Lâminas (GdL) (Figure 1). (Daura et al., 2017; Deschamps and Zilhão, 2018; Marks et al., 2001; Trinkaus et al., 2007, 2011; Zilhão, 2009; Zilhão et al., 1991, 2010). The site is situated on the boundary between present-day climate zones Csa and Csb, according to the Iberian Climate Atlas (AEMET, 2011). Vegetation cover today consists of subhumid thermomediterranean and woody flora dominates the area. The most abundant species are: Olea europaea var. sylvestris, Rhamnus alaternus, Pistacia terebinthus, Pistacia lentiscus, Myrtus communis, etc. In the areas with deeper soils, Pinus pinaster and Quercus sp. evergreen grow (Badal et al., 2012).

The site was selected due to its proximity to the Portuguese coast and potential sensitivity to large-scale climatic changes, such as the NAO and sea surface temperature fluctuation. Two stalagmites (GdL2014-1 and GdL2016-1) were collected in Galeria das Lâminas, a passage through which flows the Ribeira do Norte, one of the two underground rivers that come together at the Almonda spring. GdL is currently accessed via a subvertical shaft connected to the surface via an artificial entrance opened in the Vale da Serra syncline, ca. 1 km upstream from the spring and approximately 70 m above the level of the underground river (Supplemental, Figure S1). During the wet period in late winter/early spring, large amounts of water flow through the passage. In spring some sections are still inundated but, in summer, the phreatic level is much lower and the floor of the passage, mostly rocky but sandy in patches, becomes exposed.

Speleothem collection

Both speleothems – GdL2014-1 and GdL2016-1 – were active upon collection and were removed in situ in 2014 and 2016. The passage is rather large and has a patchy decoration of speleothems. The collection locality is well above the level reached during winter flooding. The two specimens were situated approximately 20 m apart and grew from spots approximately 1.8 to 2 m (or more) above the locality’s current floor. Both specimens are candle type stalagmites with average diameters of 68 mm (GdL2014-1) and 60 to 98 mm (GdL2016-1). GdL2014-1 measures 104 mm in length, while GdL2016-1 measures 780 mm (Figure 2). The specimens were selected based on their unique features: both had a distinct colour change from clear-translucent white to a reddish tint: The top 10 cm of GdL2016-1 consist of clear, transparent calcite while the longer bottom part has a distinct reddish discolouration. The top 8 cm of GdL2014-1 are also clear and transparent. A reddish band is visible at approximately 2 cm from its base. The colour change was interpreted as a possible growth hiatus or a change in cave system dynamics.

Cave monitoring

Basic cave monitoring was undertaken to better understand the current cave system and the response to changes outside the cave.
Cave monitoring for GdL includes temperature and relative humidity, drip rates for the positions of the specimens analysed for this study and CO₂ logging.

Two Hobo temperature loggers were installed at the collection locality and one was positioned in the access shaft, half way down from the entrance. A Hobo relative humidity logger was also positioned in the collection locality. Temperature and relative humidity were recorded at 4 hour intervals. As the two stalagmites were active upon collection, Stalagmite drip counters (Collister and Mattey, 2008) were installed at the position of sample removal for both specimens to record current drip rates.

Upon visits to the cave, CO₂ levels were measured throughout the descent, using a handheld Vaisala CO₂ meter. Additionally, a CORA CO₂ monitor (Luetscher and Ziegler, 2012) was installed in close proximity to the position of the two stalagmites in the cave. CO₂ levels were then recorded at 4h intervals throughout one seasonal cycle. We also obtained rainfall amount and air temperature data for Torres Novas from Meteoblue History+ (www.meteoblue.com, 30.01.2020), to compare the cave logging data to outside cave weather conditions. Meteoblue History+ provides simulation data compiled from nearby weather stations and various national weather services that are incorporated into model simulations to provide high precision data at high spatial resolution. More information regarding meteoblue data sources can be found here: https://docs.meteoblue.com/en/meteo/data-sources/data-sources. Stable isotope data of rainfall for selected Portuguese locations were retrieved from the GNIP data base.

**Speleothem sub sampling**

The stalagmites were cut into two halves along the growth axis using a diamond coated circular saw. The surfaces were then polished to reveal the calcite structure and possible laminations. The dense and pristine calcite shows no visible indications of recrystallisation and its structure varies from translucent white to light cream in colour. Possible growth hiatuses were observed along

![Image](GdL 2014-1)

![Image](GdL 2016-1)

**Figure 2.** (a) GdL2014-1 speleothem profile with sub-sample positions. The sample positions for U-Th dates are shown in blue, with respect to the central growth axis and indicated with a sample number. The sampling tracks for stable isotopes are indicated by white lines with a yellow dot at both ends of each section of the track. (b) Age model for GdL2014-1 created using the algorithm StalAge (Scholz and Hoffmann, 2011). The dates are shown in black with 2σ error bars. The central purple line represents the mean age, with outlying lines indicating the 2σ uncertainty bands. The growth rate of the stalagmite is superimposed on the image (black line). (c) GdL2016-1 speleothem profile with sub-sample positions. The sample positions for U-Th dates are shown in blue, with respect to the central growth axis and indicated with a sample number. The sampling tracks for stable isotopes are indicated by white lines with a yellow dot at both ends of each section of the track. (d) Age model for GdL2016-1 created using the algorithm (Scholz and Hoffmann, 2011). The dates are shown in black with 2σ error bars. The central purple line represents the mean age, with outlying lines indicating the 2σ uncertainty bands. The growth rate of the stalagmite is superimposed on the image (grey line).
the growth axes of both stalagmites in the form of a thin, red layer approximately 90 mm from the tip of each specimen. Subsamples for U-Th dating and stable isotope analyses were collected using a handheld micro drill with tungsten carbide drill bits. Uranium-Thorium (U-Th) samples with masses ranging between 19 and 40 mg were collected from isolated layers along the growth axis of each stalagmite. Stable isotope sampling was done at 1 mm intervals from base to tip of both specimens.

**U-Th analyses**

For U-Th dating, a total of 13 samples for GdL2014-1 and 34 samples for GdL2016-1 were processed and analysed at the Max Planck Institute for Evolutionary Anthropology (MPI-EVA) in Leipzig, Germany. A modified, double resin procedure was used for chemical separation and purification of U and Th for MC-ICPMS, as described by Hoffmann et al. (2016). Uranium series measurements were undertaken on a ThermoFinnigan Neptune MC-ICPMS with a Cetac Aridus II and a Savillex PFA 50 μl/min micro concentric nebulizer. Refer to Hoffmann (2008), Hoffmann et al. (2007) and Hoffmann et al. (2018) for further details regarding measurement methods, including standards and protocols used to assess and correct instrumental biases. An age model for each stalagmite was created using StalAge (Scholz and Hoffmann, 2011).

**Stable isotopes**

Stable isotope records for δ18O and δ13C were also measured at the MPI-EVA isotope laboratory. In total, 104 sub-samples for GdL2014-1 and 772 sub-samples for GdL2016-1 were drilled along the central growth axis of each specimen using a drill bit diameter of 0.7 mm. Samples were measured on a Thermo Scientific MAT-253plus Isotope ratio mass spectrometer (IRMS) connected to a KIEL IV Carbonate Device.

**Results**

**Monitoring**

Monitoring in Galeria das Lâminas was started in 2016. Seasonal cave flooding of passages occasionally prevented continuous maintenance and data collection, resulting in non-continuous fragmented data sets. However, the period of November 1, 2016 to April 1, 2018 is nearly complete and provides detailed information about the cave environment over an annual cycle. Cave monitoring data support that GdL is generally well suited for speleothems to record palaeoenvironmental proxy data. For example, the passage is non-ventilated and temperature stays constant, even though part of the underground Ribeira do Norte water flows through GdL after extensive rain events in spring.

**Cave temperature, humidity and CO2 levels**

Temperature and relative humidity in Galeria das Lâminas are stable. The temperature inside the cave at the collection locality remains stable at 16.5°C. Figure 3 shows the cave temperature over the course of one and a half years together with the outside mean daily temperature. Outside temperatures fluctuate between 9°C and 30°C (Meteoblue History+, www.meteoblue.com), and do not appear to affect the cave temperature (Figure 3). The relative humidity in the cave is constant at 100%.

A CORA CO2 logger was installed in November 2016 and over the course of one year recorded CO2 levels for one seasonal cycle. CO2 in the cave atmosphere is generally high in GdL with values between 12,000 and 22,000 ppm. The lowest CO2 levels were found in winter between January and March, coinciding with a period of increased drip rates for GdL 2016-1 (see below), while highest levels are reached in June (Figure 3).

**Drip rates and rain events**

Average annual rainfall across the Iberian Peninsula is rather variable, with the highest levels of precipitation occurring in north and northwest Iberia (AEMET, 2011). The Iberian climate Atlas (AEMET, 2011) provides mean monthly precipitation values (1971–2000) for Coimbra (about 100 km north of Torres Novas), Santarém (about 40 km south of Torres Novas) and Lisbon (about 100 km south of Torres Novas). Highest monthly rainfall occurs between October and February, while the driest months are around July, supporting that north–western Portugal is generally affected by increased winter precipitation and dry summers.

The drips feeding the two stalagmites have very different patterns. GdL2014-1 is fed by a constant very slow drip rate with a drip interval d of ~2000 s. In contrast, the drip rate feeding GdL2016-1 is highly seasonal (Figure 3). During summer/autumn (July–Dec) it has a similar long drip interval as GdL2014-1 with d ~ 1300 s. However, in winter/spring (January–June) the average drip interval is shorter with about 530 s and we find peaks where d is as short as 18 s. Meteoblue data show that variable rainfall amounts are evident throughout November to May in Torres Novas, with particular phases of high precipitation occurring between January and April (Figure 4). Periods with increased drip rates/short drip intervals are found in late winter/early spring and correlate with heavy rain events. However, strong rain events also occur in early winter (Figure 4), but a drip rate response cannot be detected before late winter. Thus, there is a delay in response of the drip rate to the outside precipitation volume. It appears that the overlying soil and epikarst need to reach field capacity before changes of the drip rate feeding GdL2016-1 can be observed (Figure 4). Once the epikarst is saturated, the peaks in drip rate closely follow strong rain events (Figure 4) as found in February and March.

After the period including two peaks in drip rate in February and April 2017, we found a ‘lake’ in the bottom parts of GdL (visit Figure 3 for details).
on 06/04/17). The water was more than two meters deep and covered a roughly 20 m long section of the cave. This indicates that a significant rise of the karst’s phreatic level occurred after the rain events in February and March. During the period with a very strong rain/drip peak in 2018, we found extremely high water levels and the subsequent groundwater response responsible for feeding GdL2016-1, during: (1) the wet phase 01/01/2017 to 01/04/17 and (2) wet phase 01/01/18 to 01/04/18. The sections highlighted with green boxes with numbers 1 and 2 are shown in detail below. (1) and (2): Detailed sections to illustrate the slight delay between increased outside precipitation and the subsequent groundwater response responsible for feeding GdL2016-1, during: (1) the wet phase 01/01/2017 to 01/04/17 and (2) wet phase 01/01/18 to 01/04/18.

U-Th dating and chronology

U-Th ages reveal that GdL2014-1 started to form at 11.4 ± 0.5 ka. The youngest sample two mm below the active surface has an age of 2 ± 1.1 ka. U-Th ages for GdL2016-1 fall between 9.14 ± 0.31 and 0.62 ± 0.27 ka, again with an active surface. Figure 2 shows the distance-age models based on all of the dates for GdL2014-1 and GdL2016-1 respectively, with interpolated values and associated confidence levels generated using the StalAge algorithm (Scholz and Hoffmann, 2011). Figure 2 also illustrates the growth rates of the two specimens, derived from StalAge interpolated ages along the growth axis. Growth rates for both specimens are highly variable. GdL2014-1 has a mean growth rate around 14 mm/ka and GdL2016-1 has a mean growth rate around 96 mm/ka. In more detail, for GdL2014-1, we find two main growth phases, with initial growth averaging 81.9 mm/ka until 9.3 ka, at which point the rate decreases to 6.6 mm/ka (Figure 2). The formation of GdL2016-1 appears to be more variable, averaging 120 mm/ka between 9.4 and 7.5 ka, with a reduction to 24 mm/ka occurring between 6.7 and 7.2 ka. Growth increases again to 121 mm/ka between 6.7 and 4.5 ka, followed finally by a steady decrease in growth of 51 mm/ka from 4.5 ka towards the present (Figure 2). Supplemental Table S2 provides reference data for U-series calculations for both specimens.

Uranium concentrations are relatively consistent within each of the two stalagmites but we find a difference of mean U concentration between the two specimens. GdL2014-1 has quite low concentrations between 10 and 46 ng/g and an average of 30 ng/g. 238U concentrations of GdL2016-1 are about twice as high as GdL2014-1 with values between 49 and 112 ng/g and an average of 69 ng/g (Figure 5). Overall, a shared trend of steadily decreasing values can be observed in both stalagmites from initial growth towards the present. Additionally, the initial 234U/238U activity ratios calculated for the two stalagmites are also significantly different, with GdL2014-1 displaying higher values (~1.27) than GdL2016-1 (~1.14) (Figure 5), which suggests different water sourcing for the two specimens. 232Th concentrations are quite variable in both specimens. GdL2014-1 has generally very low 232Th concentrations (below 1 ng/g) but has a peak of 4 and 44 ng/g at the base (Supplemental, Table S2). This peak is associated with a red layer indicating increased detritus incorporated in this sample. The sample with 44 ng/g 232Th is not datable by U-Th due to a dominating detrital component. There is also a slightly elevated concentration at the top (Figure 5). The 232Th concentration in GdL2016-1 is generally higher than in GdL2014-1, as also found for U, and the 232Th concentration is typically more variable with values between 0.2 and 2 ng/g (Figure 5). We also find concentration peaks up to 25 ng/g, again typically associated with red layers pointing to increased detrital contamination. The observed higher 238U and 232Th concentrations in GdL2016-1 and the 232Th concentration peaks can probably be explained by colloidal or particle bound transport of U and Th during periods of increased rainfall and subsequent ‘overflow’ which today feeds GdL2016-1. GdL2014-1 was possibly fed by a similar mechanism for the first 2 ka where we find the increased 232Th concentrations as well as a higher growth rate. This changed at 9.7 ka, the time when growth of GdL2016-1 started (Figure 5).

For most GdL2014-1 samples, the 230Th/232Th activity ratios are above 20 which, for a Holocene specimen, indicates a small or negligible detrital fraction. Only the section affected by the red layer has very low 230Th/232Th activities with values of 4.8 and 1.1. Here, a detrital correction is significant, sample UEV A 1059 is dominated by detritus making the U-Th result inconclusive (Supplemental Table S2). Due to the young age and low U concentration, the U-Th age of the top sample (UEVA 1779) is also significantly affected by a detrital correction resulting in a large uncertainty for the top age. Corrected U-Th ages of GdL2014-1 are all in stratigraphic order (Figure 2). 230Th/232Th activity ratios of GdL2016-1 are overall lower and quite variable with values between 0.8 and 29. Thus, U-Th dating of this specimen is generally more affected by detrital correction. Samples UEVA 1084, 1087 and 1073 are dominated by detritus and the dating results are not diagnostic (Supplemental Table S2). The so-called ‘bulk earth’ detrital factor based on the average U and Th composition of the upper crust (Hans Wedepohl, 1995) is used for detrital correction. The corrected U-Th ages, especially for sample UEVA 1073, fall in stratigraphic order, except for sample UEVA 1085 (Figure 2), which is suggested as a criterion for accurate detrital correction (Hellstrom, 2006). However, a conservative uncertainty of the correction factor of 50% increases U-Th dating uncertainties leading to age model uncertainties of several
hundred years. For more details regarding analytical U-series results for both specimens, please refer to Supplemental Table S2.

Stable isotopes

In order to facilitate adequate interpretation of our data with other records, the δ¹⁸O data were corrected for the global ice volume effect following Bintanja et al. (2005) (Supplemental Figure S2). For GdL2014-1 the δ¹³C values range from −10.46‰ to −8‰, with a mean value of −9.47‰ (Figure 6). Positive excursions are observed at 5.26, 10.25, 10.77 and 11.29 ka respectively. δ¹⁸O values range from −4.2‰ to −3.22‰, with a mean value of −3.76‰. Amplitudes of both, δ¹³C and δ¹⁸O were generally higher between 11.7 and 9.5 ka. ‘Stepped’ increases, followed by large negative excursions are observed during the initial growth phase until ~9.5 ka, which is somewhat mirrored in the δ¹³C values.

For GdL2016-1 the δ¹³C values range from −11.93‰ to −9.6‰, with a mean value of −10.96‰ (Figure 6). δ¹⁸O values range from −5.98‰ to −3.66‰, with a mean value of −4.66‰. Notably, there is a large, negative double excursion between 8.06 and 8.16 ka, where δ¹⁸O values drop from −4.48‰ to −5.98‰. In order to replicate the values and structure of this excursion, this section was reanalysed to ensure robustness of the record. The duplicate measurements verified initial findings. Considering the timing between 8.06 and 8.16 ka, this drop in values corresponds with the 8.2 ka cold event (Alley et al., 1997; Bond et al., 2001; Born and Levermann, 2010; Daley et al., 2011; Domínguez-Villar et al., 2009; Thomas et al., 2007).

Discussion

Speleothem δ¹⁸O records

δ¹⁸O is an important palaeoclimate proxy, linking speleothem CaCO₃ oxygen isotopes to rain water oxygen isotopes and thus potentially climate information. Of course, δ¹³O in the CaCO₃ (precipitated from drip water in the cave), is not only dependent on the rain water signature, but is also affected by a range of
effects including temperature, rain amount or disequilibrium fractionation (McDermott, 2004). Therefore, interpretation of speleothem δ18O requires knowledge about a series of controlling conditions inside and outside the cave. We derived two independent δ18O records from the two coeval Gdl specimens. The two records overlap for a substantial period during the Holocene, but have different temporal resolution. Gdl.2016-1 has a growth rate around 100 µm/a, thus the sampling size here mixes several years. Gdl.2014-1 has an about ten times lower growth rate and the sampling size mixes decades. Based on the drip rate monitoring results we expect δ18O of Gdl.2014-1 to represent annual mean rain values while δ18O of Gdl.2016-1 is dominated by winter rain. We use modern precipitation data from Portuguese GNIP stations (Porto, Lisbon, Portalegre, and Penhas Douradas) to identify typical δ18O values of winter months rainwater (December to March) and annual mean values for comparison with our proxy data for each record (Supplemental, Fig. S3). Overall, winter/early spring months exhibited higher precipitation rates and lower δ18O values compared to annual mean values (Supplemental, Table S1). The offset typically ranges between 0.22‰ and 0.84‰ and indeed, we also find an offset of 0.87‰ between the two records.

The low temporal resolution of the Gdl.2014-1 δ18O record does not provide a detailed structure. In contrast, Gdl.2016-1 provides relatively high temporal resolution, albeit also sampled only at 1 mm spacing. The Gdl.2016-1 record exhibits several negative excursions, the most prominent at 8.15 ka which we assign to the 8.2 ka event, an abrupt cooling episode which brought very cold and dry conditions to the northern-hemisphere, especially in the winter time (Alley and Ágústsdóttir, 2005; Daley et al., 2011; Thomas et al., 2007). The 8.2 ka event was caused by a freshwater influx pulse into the North Atlantic which weakened the meridian overturning circulation (AMOC). In turn, this reduced northward heat transport, subsequently cooling the North Atlantic region (Born and Levermann, 2010; LeGrande and Schmidt, 2008; Renssen et al., 2002). We can identify a response of δ18O in Gdl.2016-1 to the 8.2 ka event including the typical double trough. During the 8.2 ka event the Gdl.2016-1 δ18O values drop by 1‰, exhibiting the lowest values observed in the entire record (Figure 6). We cannot identify the 8.2 ka event in the Gdl.2014 δ18O record, which is best explained by the low temporal resolution of this record.

Recently, the 4.2 ka event (Arz et al., 2006; Geirsdóttir et al., 2019; Isola et al., 2019) has been assigned as a global marker for the subdivision of the Holocene by the International Subcommission on Quaternary Stratigraphy (Walker et al., 2018). The 4.2 ka aridification event marks the beginning of the Meghalayan stage. We thus tried to identify a response of δ18O in our record to this event. There is a slight trough centred around 4.2 ka, but it does not stand out as a significant peak. So despite being a global marker, there is only a weak potential 4.2 ka signal in the Gdl.2016-1 δ18O record. There is also no detectable significant hiatus at 4.2 ka visible in the growth rate and thus no indication of a severe aridification event in western Iberia. However, following 4.2 ka (from about 4 ka) the growth rate of Gdl.2016-1 becomes relatively low and is steadily decreasing, which could indicate overall dryer winter conditions for the Meghalayan period.

In Figure 7 we compare our record with other Iberian δ18O speleothem records from the Atlantic influenced realm from La Garma (Baldini et al., 2019), Kaite Cave (Dominguez-Villar et al., 2017) and Cueva de Asial (Smith et al., 2016). We also briefly compare to a record from north Africa in the western Mediterranean realm (Ait Brahimi et al., 2019). Due to age model uncertainties of the Gdl.2016-1 record we do not provide a detailed comparison or interpretation of centennial scale variations. Overall, the Gdl.2016-1 δ18O record is broadly similar to GAR-01 (Baldini et al., 2019) for early and mid Holocene. The mean δ18O values are around −4.5‰ for both stalagmites and they display a similar structure between 9.5 and 4 ka. This represents over 80% of the Gdl.2016-1 record. We note an opposite trend for the remaining record, covering the late Holocene between 4 ka and present. The structure of the δ18O record from Kaite cave (Dominguez-Villar et al., 2017) is also quite similar to Gdl.2016-1, albeit about 2‰ lighter. The most striking similarity of the records shown in Figure 7 is that the 8.2 ka excursion is present in all records except for Cueva de Asial, which has a hiatus around this time. We note that the timing of 8.15 ka found for the 8.2 ka event in our record demonstrates accuracy of the U-Th dates and derived age model despite detrital correction.

Baldini et al. (2019) suggest temperature and rain amount to be main drivers for δ18O variability in the GAR-01 record, while Dominguez-Villar et al. (2009) suggest based on the δ18O record...
of stalagmite LV5 from Kaite cave that $\delta^{18}O$ in Iberian speleothems traces changes of ocean surface water isotope composition. Additionally, using $\delta^{18}O$ records of four stalagmites from Kaite cave, Domínguez-Villar et al. (2017) hypothesised that the Holocene $\delta^{18}O$ record from Kaite Cave (Figure 7) is controlled on a millennial scale by a variable proportion of recycled precipitation in the total rain amount and suggest that the millennial $\delta^{18}O$ anomalies can be explained by a zonal displacement of atmospheric pressure fields over the North Atlantic. The $\delta^{18}O$ records from Cueva de Asiiol (Smith et al., 2016) and north Africa (Ait Brahimi et al., 2019) are detrended and normalised (Figure 7). The two records are both interpreted to be proxies for Atlantic driven precipitation changes, albeit with opposing conclusions. Smith et al. (2016) propose reduced moisture availability to coincide with North Atlantic cold periods as also suggested by Zielhofer et al. (2019) based on a north African lake record. In contrast, Ait Brahimi et al. (2019) suggest humid conditions to be synchronous with Atlantic cold events during early and late Holocene. We now further investigate the timing of palaeoprecipitation in Iberia compared to Atlantic cold events using an alternative proxy.

**Gdl2016-1 growth rate as winter precipitation proxy**

Gdl2014-1 and Gdl2016-1 formed more or less coevally only 20 m apart in the same section of the cave and shared almost identical conditions like cave temperature, cave $P_{\text{CO}_2}$, humidity and outside climatic conditions. However, a distinct difference between the two sampling positions is the response of the feeding drip rate to outside rain. Gdl2014-1 was continuously fed by a slow and steady drip rate throughout a year. In contrast, Gdl2016-1 was fed by a similarly slow drip rate in summer/autumn, but during winter/spring the drip rate is episodically significantly higher and has large peaks when outside rainfall amount is large (Figure 4). Thus, our cave monitoring shows a strong correlation between increased outside precipitation and high drip rates during late winter/early spring months for Gdl2016-1, suggesting that growth of this specimen is due primarily to increased late winter precipitation.

This correlation is not observed for Gdl2014-1, which is constantly fed by a steady drip throughout the year. Gdl2016-1 is approximately eight times longer than Gdl2014-1, and has an average growth rate of 96 mm/ka compared to an average of 14 mm/ka for Gdl2014-1 for the period when both specimens formed. The difference in growth rate and size between the two specimens is best explained by the difference of the drip rate with seasonally high drip rate phases in late winter/spring for Gdl2016-1, suggesting that the phases with high drip rate are the reason for the significantly higher growth rate for Gdl2016-1. This means that Gdl2016-1 growth was fed by a higher proportion of winter rain. This is supported by stable isotope values for the two specimens (Figure 6). An average of 0.87‰ offset is observed in the $\delta^{18}O$ stable isotope values between the two records, with Gdl2016-1 exhibiting the lighter values (Figure 6). GNIP data confirm a $\delta^{18}O$ value offset in rainwater between annual mean and the winter/early spring months throughout Portugal. The average annual versus winter (December–April) offset from Portuguese GNIP stations ranges from 0.1% to 0.68‰, averaging 0.37‰. For Lisbon, the closest station near the coast, we find an offset of 0.46‰. The average $\delta^{18}O$ difference of 0.87‰ between Gdl2014-1 and Gdl2016-1 is slightly larger than today’s difference of $\delta^{18}O$ between annual and winter rain so there are additional local effects at play. For example, it has been shown that drip rates also influence stable isotopes in speleothem calcite (Mühlhinghaus et al., 2009). The effect is strongest for $\delta^{13}C$ and we find that the average offset in $\delta^{13}C$ values between Gdl2014-1 and Gdl2016-1 is also quite large (1.17‰). The enrichment of $\delta^{13}C$ in speleothem calcite values is dependant of the water residence time on the stalagmite surface and drip interval. Long drip intervals (i.e. $d=\sim2000$ s) result in higher overall carbon isotope ratios, while shorter intervals ($d=\sim50$ s) will result in lower ratios (Mühlhinghaus et al., 2009). Indeed, we observe a considerable offset in the $\delta^{13}C$ values in our records, with the higher values attributed to Gdl2014-1 with long drip intervals. Other factors that could contribute to the $\delta^{13}C$ difference between the two specimens include residence time of water in the host rock and potential prior calcite precipitation. Drip intervals potentially affect oxygen isotope ratios as well. However, for long and short drip intervals, $\delta^{18}O$ of drip water and the bicarbonate should be almost identical (Mühlhinghaus et al., 2009). Thus, the influence of drip rate on the $\delta^{18}O$ in Gdl2014-1 (long drip interval) and Gdl2016-1 (short drip interval for main growth) is probably small. Additionally, we observe no obvious correlation between $d^{18}O$ and $d^{13}C$, indicating that disequilibrium is not playing a dominant role here.

We argue that the high growth rate for Gdl2016-1 is a result of high drip rate events during winter and the water source feeding the formation of Gdl2016-1 was dominated by the winter/early spring precipitation, while Gdl2014-1 formed constantly during summer and winter with no seasonal bias. Therefore, we suggest to largely assign the observed offset of $\delta^{18}O$ to different feeding water compositions, dominated by winter rain signature for Gdl2016-1 and mean annual rain signature for Gdl2014-1. The variation of the growth rate of Gdl2016-1 is suggested to be a proxy for winter rain amounts for this particular specimen.

The interpretation that Gdl2016-1 largely formed and was dominated by fast water transfer through the epikarst as evidence for high winter rain drip rate events is supported by significant differences in U and (common) Th concentrations between the two specimens (Figure 5). Th is not soluble in natural waters which is a precondition for U-Th dating of speleothems. However, Th can be present in particles or colloids which can be transported by groundwater through larger fissures. This is the main reason for potential transport of Th in groundwaters and subsequent inclusion in speleothem CaCO$_3$. Typically water flow through epikarst bedrock filters particles or colloids from water entering caves. However, flow through larger fissures, as typical for the 'overflow' scenario inferred for Gdl2016-1, might allow a larger fraction of particles and/or colloids to be transported resulting in detectable amounts of common Th in speleothems. The colloids would also be an additional effective transport for U. Indeed, U and Th concentrations are higher in Gdl2016-1 (Figure 5). Particularly the high $^{232}$Th contents point towards colloids and/or particles transported by drip waters, indicating that the high drip rates of late winter/early spring are fed via a different water pathway. The difference in water feeding mechanism between Gdl2016-1 and Gdl2014-1 is further supported by significantly lower initial $^{234}$U/$^{238}$U activity ratio in Gdl2016-1. The colloidal/particle transported fraction of U has a different isotopic signature than the water soluble fraction as shown by the different $^{234}$U/$^{238}$U activity ratios in Gdl2016-1 compared to Gdl2014-1.

**Atlantic cold phases and winter precipitation**

Here we have presented evidence that the growth rate of one of our two stalagmites, Gdl2016-1, is dominated by the amount of winter precipitation. The growth rate of Gdl2016-1 is about eight times higher than for Gdl2014-1 and indicates that the amount of winter rain and hence winter drip rate has a direct influence on the growth of Gdl2016-1. The variable growth rate of Gdl2016-1 throughout the Holocene is therefore suggested to be a proxy for winter rain amount. It is important to point out that we do not suggest stalagmite growth rate to be a general rain amount proxy, as evident by our two different records from the same cave.

Based on Gdl2016-1 growth rates we find a humid phase starting around 9.5 ka, when Gdl2016-1 formation initiated...
Figure 8. From top to bottom: Insolation at 30°N for winter (light blue dashed line) and summer (yellow line) as presented by Berger and Loutre (1991). Growth rates for GdL2016-1 (grey line), plotted against time of growth. The data has been calculated using model age estimates every mm along the stalagmite axes. The growth rate record is plotted with the Bond stack (% Icelandic Glass, or HSG) (Bond et al., 2001) (red line), where wet/cold phases are represented by large peaks and corresponding event number (in red) and warmer phases by troughs (Bond et al., 2001). Between 9.7 and 4 ka HSG peaks coincide with increased growth rates of GdL2016-1.

Between 9.7 and 4 ka, the REF-07 record shows a steadily increasing winter rain intensity towards the peak around 6.5 ka. This could indicate that summer rain intensity also contributes to the REF-07 precipitation record. Between 6.2 and 3 ka the REF-07 CT numbers are more variable and alternating between wet and dry conditions (Walczak et al., 2015). During this mid Holocene phase the peak structure of the REF-07 CT numbers record closely matches the winter rain intensity variation record of GdL2016-1, albeit with a difference in absolute timing of peaks between the two records, with the REF-07 record being younger by about 400 years. This can be explained by younger material mixed into the U-Th dating samples due to the sampling strategy, but there is no d^{18}O record for REF-07 that could be used to further compare timing of excursions like the 8.2 ka to check the chronology as is the case for GdL2016-1 where the timing of the 8.2 ka event confirms accuracy of the detrital corrected chronology. However, we note that the 400 years offset between 6.2 and 3 ka is mostly within uncertainty of the GdL2016-1 age model, which is in the range of 300 a between 6.2 and 4.5 ka and corresponding peaks for drift ice cycles 0 and 1 and 2 (Bond et al., 2001).
Other speleothem δ18O records from Spain and Morocco have also been employed previously to investigate past precipitation amounts. For example, Ait Brahim et al. (2019) analysed a stalagmite from Morocco and suggest that the δ18O record is dominated by the amount effect. They suggest that during the early and late Holocene Bond events are associated with a negative NAO resulting in wetter conditions in the western Mediterranean realm as found by our precipitation record for western Iberia. In contrast, Smith et al. (2016) suggest that dry conditions prevailed in northern Spain during North Atlantic cold events based on the δ18O record of a stalagmite from northern Spain and suggest that a positive NAO is associated dry conditions in southern Europe during Holocene cold phases in the North Atlantic, which is not supported by our record. A Holocene sediment record from southern Iberia (Ramos-Román et al., 2018) indicates a wet phase between 9.5 and 7.6 ka, in agreement with our record, but also suggests another wet phase between 7 and 5 ka which includes a dry phase in our record. This shows that past precipitation patterns are potentially depending on a variety of boundary conditions like the type of proxy archive and which season is recorded or the location of the archive. Galeria das Lâminas is located just within climate zone Csb (AEMET, 2011), more or less at the boundary between two different climate zones Csa and Csb. La Garma is located in zone Ctb, whereas Refugio is located in zone Csa. A southward/more inland displacement of zone Csb would bring more precipitation to GdL, in turn a northward displacement of the boundary would lead to dryer Csa conditions at the location of GdL. The impact of zonal displacement is strongest at the boundary between zones as is the case for GdL.

Conclusions

We present a Holocene growth rate-based precipitation reconstruction for western Iberia. Palaeoprecipitation patterns for the Iberian Peninsula are important for understanding the climate system of the western Iberian – North Atlantic realm. The Holocene precipitation proxy archives analysed so far provide a diverse and in parts contrasting picture pointing to potential differences between archives, proxies and/or regions. For example, it is important to constrain whether a proxy records precipitation of a specific season or annual mean values and whether local factors might play a role.

The growth rate of a stalagmite as a proxy for precipitation amount, used in this study for GdL2016-1, can only be applied under very specific circumstances. Here, two coeval stalagmites from the same cave chamber together with cave monitoring results could be used to show that the formation of one of the speleothem is fed by a larger proportion of late winter precipitation amounts and hence the growth rate could be used to assess past precipitation intensity for the (late) winter season. Our data support increased winter precipitation during cold Bond phases which would indicate a more negative NAO prevailed in early and mid-Holocene winter if a connection between NAO and precipitation intensity in the western Iberian realm was accepted for the early and mid Holocene. Lake sediment data from Iberian sites (Morellón et al., 2018; Pelach et al., 2011) support our findings. Our results are complemented by another speleothem-based precipitation record for southern Iberia (Walczak et al., 2015). Here, the CT scan density of a stalagmite was used to infer precipitation amounts. The stalagmite (REF-07) formed exactly during periods when our record shows overall increased precipitation and a hiatus started synchronous to a dry phase recorded in GdL2016-1. Between 6.2 and 4 ka the two independent records show an almost identical structure, albeit the timing of the precipitation peaks does not perfectly align which can be explained by a potential sampling bias for the REF-07 chronology. The coherence of the records for the mid Holocene indicates that
southern Iberia experienced wetter conditions when winter rain intensity in western Iberia was higher.

Baldini et al. (2019) used the d\text{18}O record of a northern Iberian stalagmite (GAR-01) to model the distribution between summer and winter rain intensity. The reconstructed winter rain intensity shows similar intensity peaks as found in GdL2016-1, albeit the relative peak heights do not match which could be related to the locations of GdL and GAR in different climate zones (AEMET, 2011). The differences in peak heights could also be a result of a model constraint that keeps the total annual precipitation constant during the Holocene. The model ‘only’ determines how the total annual rain was distributed between summer and winter, limiting the geographic implications.

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Author contributions
Sample collection was done by all authors; cave monitoring was done by all authors; U-series was carried out by A.B. and D.L.H.; stable isotope analysis was done by A.B. Site mapping and on-site maintenance was done by F.R., P.S. and J.Z. A.B and D.L.H. wrote the paper with contributions from all authors.

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References
AEMET (2011) Atlas climático ibérico/Iberian climate atlas. Agencia Estatal de Meteorología, Ministerio de Medio Ambiente y Rural y Marino, Madrid. Instituto de Meteorología de Lisbon, Portugal.
Ait Brahim Y, Wassenburg JA, Sha L et al. (2019) North Atlantic ice-rafting, ocean and atmospheric circulation during the Holocene: Insights from Western Mediterranean speleothems. Geophysical Research Letters 46(13): 7614–7623.
Alley R and Ágústsdóttir A (2005) The 8k event: cause and consequences of a major Holocene abrupt climate change. Quaternary Science Reviews 24: 1123–1149.
Alley RB, Mayewski PA, Sowers T et al. (1997) Holocene climatic instability: A prominent, widespread event 8200 yr ago. Geology 25: 483–486.
Arz HW, Lamy F and Pätzold J (2006) A pronounced dry event recorded around 4.2 ka in brine sediments from the northern Red Sea. Quaternary Research 66: 432–441.
Badal E, Villaverde V and Zilhão J (2012) Middle Palaeolithic wood charcoal from three sites in south and west Iberia: biogeographic implications. Saguntum Extra 13: 13–24.
Baldini LM, Baldini JU., McDermott F et al. (2019) North Iberian temperature and rainfall seasonality over the Younger Dryas and Holocene. Quaternary Science Reviews 226: 105998.
Baldini LM, McDermott F, Baldini JU. et al. (2015) Regional temperature, atmospheric circulation, and sea-ice variability within the Younger Dryas Event constrained using a speleothem from northern Iberia. Earth and Planetary Science Letters 419: 101–110.
Berger A and Loutre M-FJ (1991) Insolation values for the climate of the last 10 million years. Quaternary Science Reviews 10: 297–317.
Bintanja R, van de Wal RSW and Oerlemans J (2005) Modelled atmospheric temperatures and global sea levels over the past million years. Nature 437: 125–128.
Bond G, Heinrich H, Broecker W et al. (1992) Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial period. Nature 360: 245–249.
Bond G, Kromer B, Beer J et al. (2001) Persistent solar influence on North Atlantic climate during the Holocene. Science 294: 2130–2136.
Born A and Levermann A (2010) The 8.2 ka event: Abrupt transition of the subpolar gyre toward a modern North Atlantic circulation. Geochemistry Geophysics Geosystems 11: 6.
Collister C and Mattey D (2008) Controls on water drop volume at speleothem drip sites: An experimental study. Journal of Hydrology 358: 259–267.
Daley TJ, Thomas ER, Holmes JA et al. (2011) The 8200yr BP cold event in stable isotope records from the North Atlantic region. Global and Planetary Change 79: 288–302.
Daura J, Sanz M, Arsuaga JL et al. (2017) New Middle Pleistocene hominin cranium from Gruta da Areóia (Portugal). Proceedings of the National Academy of Sciences 114: 3397–3402.
Deininger M, McDermott F, Mudelsee M et al. (2017) Coherency of late Holocene European speleothem 618O records linked to North Atlantic Ocean circulation. Climate Dynamics 49(1-2): 595–661.
Delworth TL, Zeng F, Zhang L et al. (2017) The central role of ocean dynamics in connecting the North Atlantic Oscillation to the extratropical component of the Atlantic Multidecadal Oscillation. Journal of Climate 30: 3789–3805.
Deschamps M and Zilhão J (2018) Assessing site formation and assemblage integrity through stone tool refitting at Gruta da Oliveira (Almonda karst system, Torres Novas, Portugal): A Middle Paleolithic case study. PLoS One 13: e0192423.
Dominguez-Villar D, Fairchild IJ, Baker A et al. (2009) Oxygen isotope precipitation anomaly in the North Atlantic region during the 8.2 ka event. Geology 37: 1095–1098.
Dominguez-Villar D, Wang X, Krklec K et al. (2017) The control of the tropical North Atlantic on Holocene millennial climate oscillations. Geology 45: 303–306.
Geirsdóttir A, Miller GH, Andrews JT et al. (2019) The onset of Neoglacialization in Iceland and the 4.2 ka event. Climate of the Past 15: 25–40.
Goslin J, Fruefgaard M, Sander L et al. (2018) Holocene centennial to millennial shifts in North-Atlantic storminess and ocean dynamics. Scientific Reports 8: 1–12.
Hans Wedepohl K (1995) The composition of the continental crust. Geochimica et Cosmochimica Acta 59: 1217–1232.
Hellstrom J (2006) U–Th dating of speleothems with high initial 230Th using stratigraphical constraint. Quaternary Geochronology 1: 289–295.

Hoffmann DL (2008) 230Th isotope measurements of femtogram quantities for U-series dating using multi ion counting (MIC) MC-ICPMS. International Journal of Mass Spectrometry 275: 75–79.

Hoffmann DL, Pike AWG, García-Diez M et al. (2016) Methods for U-series dating of CaCO 3 crystals associated with Palaeolithic cave art and application to Iberian sites. Quaternary Geochronology 36: 104–119.

Hoffmann DL, Pyrtulak J, Richards DA et al. (2007) Procedures for accurate U and Th isotope measurements by high precision MC-ICPMS. International Journal of Mass Spectrometry 264: 97–109.

Hoffmann DL, Standish CD, García-Diez M et al. (2018) U-Th dating of carbonate crystals reveals Neandertal origin of Iberian cave art. Science 359: 912–915.

Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science 269: 676–679.

Isola I, Zanchetta G, Drysdale RN et al. (2019) The 4.2 ka event in the central Mediterranean: new data from a Corchia speleothem (Apuan Alps, central Italy). Climate of the Past 15(1): 135–151.

Kuper R and Kropelin S (2006) Climate-controlled Holocene occupation in the Sahara: Motor of Africa’s evolution. Science 313: 803–807.

LeGrande AN and Schmidt GA (2008) Ensemble, water isotope-enabled, coupled general circulation modeling insights into the 8.2 ka event. Paleogeography 23: PA3207.

Luettscher M and Ziegler F (2012) CORA: a dedicated device for carbon dioxide monitoring in cave environments. International Journal of Speleology 41: 273–281.

Marks A, Monigal K and Zilhão J (2001) The lithic assemblages of the Late Mousterian at Gruta da Oliveira, Almonda, Portugal. In: Zilhão J, Aubry T and de Carvalho AF (eds) Le Abbondanza di Palma (Apuan Alps, central Italy). Climate of the Past 15(1): 135–151.

McDermott F (2004) Palaeo-climate reconstruction from stable isotope variations in speleothems: a review. Quaternary Science Reviews 23: 901–918.

Mauri A, Davis BA, Collins PM et al. (2015) The climate of Europe during the Holocene: a gridded pollen-based reconstruction and its multi-proxy evaluation. Quaternary Science Reviews 112: 109–127.

Mayewski PA, Rohling EE, Curt Stager J et al. (2004) Holocene climate variability. Quaternary Research 62: 243–255.

McDermott F (2004) Palaeo-climate reconstruction from stable isotope variations in speleothems: a review. Quaternary Science Reviews 23: 901–918.

Morellón M, Aranbarri J, Moreno A et al. (2018) Early Holocene humidity patterns in the Iberian Peninsula reconstructed from lake, pollen and speleothem records. Quaternary Science Reviews 181: 1–18.

Mühlhans H, Scholz D and Mangini A (2009) Modelling fractionation of stable isotopes in stalagmites. Geochimica et Cosmochimica Acta 73: 7275–7289.

Pélashs A, Júlía R, Pérez-Obil R et al. (2011) Potential influence of Bond events on mid-Holocene climate and vegetation in southern Pyrenees as assessed from Burg lake LOI and pollen records. The Holocene 21: 95–104.

Ramos-Román MJ, Jiménez-Moreno G, Camuera J et al. (2018) Millennial-scale cyclical environment and climate variability during the Holocene in the western Mediterranean region deduced from a new multi-proxy analysis from the Padul record (Sierra Nevada, Spain). Global and Planetary Change 168: 35–53.

Renssen H, Goosse H and Fichefet T (2002) Modeling the effect of freshwater pulses on the early Holocene climate: The influence of high-frequency climate variability. Paleoceanography 17: PA000649.

Scholz D and Hoffmann DL (2011) StalAge: An algorithm designed for construction of speleothem age models. Quaternary Geochronology 6: 369–382.

Simpson IR, Yeager SG, McKinnon KA et al. (2019) Decadal predictability of late winter precipitation in western Europe through an ocean–jet stream connection. Nature Geoscience 12: 613–619.

Smith AC, Wynn PM, Barker PA et al. (2016) North Atlantic forcing of moisture delivery to Europe throughout the Holocene. Scientific Reports 6: 24745.

Thomas ER, Wolff EW, Mulvaney R et al. (2007) The 8.2ka event from Greenland ice cores. Quaternary Science Reviews 26: 70–81.

Trinkaus E, Bailey SE, Davis SJ et al. (2011) The Magdalenian human remains from the Galeria da Cisterna (Almonda karstic system, Torres Novas, Portugal) and their archaeological context. O Arqueólogo Português sér. 1: 395–413.

Trinkaus E, Maki J and Zilhão J (2007) Middle paleolithic human remains from the Gruta da Oliveira (Torres Novas, Portugal). American Journal of Physical Anthropology 134: 263–273.

Visbeck MH, Hurrell JW, Polvani L et al. (2001) The North Atlantic Oscillation: past, present, and future. Proceedings of the National Academy of Sciences 98: 12876–12877.

Walczak IJ, Baldini JUL, Baldini LM et al. (2015) Reconstructing high-resolution climate using CT scanning of unsectioned stalagmites: A case study identifying the mid-Holocene onset of the Mediterranean climate in southern Iberia. Quaternary Science Reviews 127: 117–128.

Walker M, Head MJ, Berkelhammer M et al. (2018) Formal ratification of the subdivision of the Holocene Series/Epoch (Quaternary System/Period): two new Global Boundary Stratotype Sections and Points (GSSPs) and three new stages/subseries. Episodes 41: 213–223.

Wanner H, Brönnimann S, Cisty C et al. (2001) North Atlantic oscillation: concepts and studies. Surveys in Geophysics 22: 321–381.

Zielhofer C, Köhler A, Mischke S et al. (2019) Western Mediterranean hyro-climatic consequences of Holocene ice-raftered debris (Bond) events. Climate of the Past 15: 463–475.

Zilhão J (2009) The Early Neolithic artifact assemblage from the Gruta da Oliveira (Torres Novas, Portugal). In: Zilhão J, Angelucci DE, Argant J et al. (eds) O Arqueólogo Português, pp.161–166.