The timing, duration and magnitude of the 8.2 ka event in global speleothem records

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Abrupt events are a feature of many palaeoclimate records during the Holocene. The best example is the 8.2 ka event, which was triggered by a release of meltwater into the Labrador Sea and resulted in a weakening of poleward heat transport in the North Atlantic. We use an objective method to identify rapid climate events in globally distributed speleothem oxygen isotope records during the Holocene. We show that the 8.2 ka event can be identified in >70% of the speleothem records and is the most coherent signal of abrupt climate change during the last 12,000 years. The isotopic changes during the event are regionally homogenous: positive oxygen isotope anomalies are observed across Asia and negative anomalies are seen across Europe, the Mediterranean, South America and southern Africa.

The magnitude of the isotopic excursions in Europe and Asia are statistically indistinguishable. There is no significant difference in the duration and timing of the 8.2 ka event between regions, or between the speleothem records and Greenland ice core records. Our study supports a rapid and global climate response to the 8.2 ka freshwater pulse into the North Atlantic, likely transmitted globally via atmospheric teleconnections.

The Holocene epoch (11,700 years BP to present) has been punctuated by several large-scale and rapid changes in the climate system1–3, termed abrupt events. Numerous abrupt events have been identified, although many have not been studied extensively or have only been identified in a limited number of regions, and the causes of the events are not always clear. Two events that have been studied and examined more extensively are the 4.2 and 8.2 ka (ka; thousand years ago) events. The 4.2 ka event is a 300-year megadrought identified predominantly in Eurasian and Middle Eastern palaeoclimate records4–6, although the exact mechanism is still debated7,8.

The largest and most-significant abrupt event of the last 12,000 years in Greenland ice core records is the 8.2 ka event9. During this event, an influx of freshwater into the Labrador Sea from the retreating Laurentide ice sheet slowed down the Atlantic Meridional Overturning Circulation (AMOC), reducing northwards meridional heat transport10,11. This triggered a large drop in temperature across the North Atlantic region; Greenland ice cores show > 2 °C cooling over an interval of 165 years12. The 8.2 ka event has been identified in a large number of palaeoclimate records. A global compilation of reconstructions using marine, lake, ice and peat cores and speleothem records by Morrill et al.13 showed widespread cooling over Europe of ~ 1 to 1.5 °C. Drier conditions were shown in the northern hemisphere tropics, with wetter conditions in the southern hemisphere tropics. While this compilation has been used to evaluate climate model simulations of the 8.2 ka event14–16, only 13% of the records provide quantitative estimates of temperature and precipitation and most of the information consists of qualitative indications of the direction of the change in climate. Furthermore, most of the records included in this compilation were of insufficient temporal resolution to estimate the duration of the event, and the exact timing of the event was also not examined. Questions therefore remain about the global signature and nature of this event.

Speleothem oxygen isotope (δ18O) records are ideal for reconstructing global-scale patterns of abrupt climate events, such as the 8.2 ka event, because they often have sub-annual to decadal temporal resolution and well-constrained chronologies. Speleothem δ18O can be influenced by multiple climate factors, including regional precipitation, atmospheric circulation and temperature17–19, which can make their climate interpretation challenging. Nevertheless, the 8.2 ka event has been identified in numerous individual speleothem records around the world20–23 and there are now sufficient numbers of published speleothem records, especially compared to the status at the time of the Morrill et al.13 8.2 ka synthesis, to facilitate a global-scale analysis24.

Here, we used the Speleothem Isotope Synthesis and Analysis (SISAL) database25,26 to identify potential abrupt climate events in the Holocene, by using breakpoint analysis to detect shifts in δ18O values objectively and determining whether these excursions were above the inherent variability of climate and spatially coherent.

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We then focus on the nature of the 8.2 ka event, and specifically the timing, duration and magnitude of the anomalies registered in each speleothem record at this time. We compare our speleothem synthesis to other lines of evidence, including Greenland ice core data, speleothem trace element records and the global synthesis by Morrill et al.13. Our new global synthesis allows us to address the following questions: (1) Is the 8.2 ka event a significant and prominent feature of the Holocene epoch? (2) How rapidly was the event transmitted to regions distant from the North Atlantic? (3) What is the speleothem δ18O spatial fingerprint of this event, and what does it tell us about the climate response?

Results

We examined the presence and timing of significant abrupt climate events through the Holocene using 275 globally distributed speleothem records (Fig. 1). There are several intervals where the proportion of records showing an abrupt isotope excursion exceeds the randomly generated noise (Fig. 2), including at 0.6–0.9, 1.5–1.8, 3.6–3.9, 6.6–6.9, 8.1–8.4, 10.2–10.5 and 11.1–11.4 ka. The early Holocene peaks coincide with Bond event 7 (10.3 ka) and 8 (11.1 ka, or the pre-Boreal oscillation)27,28. However, the isotope excursions associated with each of these two peaks show little coherency in their spatial pattern, timing and duration (Fig. S1). The excursions identified
between 8 ka and present do not coincide with any previously identified abrupt climate events. Although the interval around 4.2 ka is often identified as a period of rapid climate change4–6, it is not detected by the speleothem records. The most prominent period of abrupt climate change in the Holocene is at ~ 8.2 ka, where 72% of the records show an abrupt isotope excursion. We examined the isotope excursion at 8.2 ka using 73 speleothem δ18O records (Fig. 1) of sufficiently high temporal resolution and length (see “Methods” section). Most records show a remarkably consistent timing (Fig. 3) of the event, allowing for age uncertainties. The global speleothem records show the event starting at 8.22 ± 0.012 ka and ending at 8.06 ± 0.014 ka (Table 1). Furthermore, the timing of the global δ18O excursion coincides with the 8.2 ka event excursion identified in Greenland ice core records, within age uncertainties12. The median duration registered globally in speleothem δ18O records (Table 1) is ~ 159 years, which is the same (within error) as the duration of the event calculated by layer counting in Greenland ice cores (of 160.5 years12). Both the timing and the duration of the event are statistically indistinguishable between Europe and Asia, the two regions with sufficient records to perform a t-test, and between these two regions and Greenland. The median magnitude of the 8.2 ka δ18O excursion is also indistinguishable between Europe and Asia (Table 1).

Figure 3. Start and end of the 8.2 ka event for each record and each age-depth modelling approach, constrained by breakpoint analysis. The original chronologies are shown together with the SISALv2 chronologies. Upper and lower age uncertainties associated with each age-depth model are given (dashed lines). The 8.2 ka event timing in the Greenland ice core record is shown12.

Table 1. Median start, end and duration of the 8.2 ka event registered in speleothem records, globally and for the Europe/Mediterranean and Asia regions. Standard error associated with each value is given in brackets. For all variables, regional values are insignificant from one another, according to a t test (at $P < 0.01$). Timing and duration of the 8.2 ka event in Greenland ice core are also shown, with their uncertainty9,12.

|          | Magnitude (permil) | Start (years BP) | End (years BP) | Duration (years) |
|----------|-------------------|-----------------|----------------|-----------------|
| Global   | 0.5 (0.04)        | 8223 (12)       | 8062 (14)      | 159 (11)        |
| Europe   | 0.4 (0.05)        | 8192 (27)       | 7968 (33)      | 166 (22)        |
| Asia     | 0.49 (0.07)       | 8257 (14)       | 8081 (16)      | 163 (15)        |
| Greenland| 8247 (47)         | 8086 (47)       | 160.5 (5.5)    |                 |
Speleothem δ¹⁸O anomalies of the 8.2 ka event show homogeneous signals over broad regions (Fig. 4a). Over Europe and the Mediterranean region, 15 out of 20 sites exhibit an 8.2 ka excursion. These excursions show negative 8.2 ka δ¹⁸O anomalies, i.e. δ¹⁸O values across the event are lower (more negative) than before or after. Over Asia, anomalies are registered in 13 out of 16 sites, with consistently higher (positive) δ¹⁸O anomalies, where δ¹⁸O across the event are less negative than before and after the event. Speleothem δ¹⁸O anomalies are negative across the South American continent and southern Africa, registered in 4 out of 6 sites. All the central American sites show an 8.2 ka isotope excursion, although more southerly sites show positive excursions and more northern sites show negative δ¹⁸O anomalies. However, these sites show larger age uncertainties (Fig. 3) than other regions and there is therefore some uncertainty associated with the identification of the 8.2 ka isotope excursion. There is no significant 8.2 ka isotope excursion recorded in any of the four sites located in the Oceania region or in the two sites from North America.

The patterns in the speleothem δ¹⁸O anomalies (Fig. 4a) can be compared with evidence from speleothem growth rate, trace element and calcium isotope data (Fig. 4b, Table S3) and the Morrill et al.13 8.2 ka reconstructions. The homogenous negative speleothem isotope signals across Europe are mirrored by widespread cooling signals (Fig. 4d). However, the precipitation anomalies (Fig. 4c) inferred by Morrill et al.13 and indicated by other speleothem evidence (Fig. 4b) are heterogeneous over the region, and indeed differ from one another. This heterogeneity could reflect the fact that different climate archives record different aspects of the hydrological cycle. For example, wet anomalies in west Europe from the Morrill et al. synthesis were explained as reflecting increased runoff from spring snowmelt, whilst dry signals in the east were inferred from pollen-based reconstructions of annual precipitation. Site-specific influences may also be obscuring regional climate signals in some records. Nevertheless, precipitation patterns in Fig. 4b, c do not show the homogeneity characteristic of the δ¹⁸O anomalies. The widespread positive speleothem isotope anomalies over Asia are mirrored by dry anomalies over the region (Fig. 4c), inferred from speleothem trace elements, growth rate and calcium isotopes, and peat δ¹⁳C and a South China Sea salinity record13. There are very few high-resolution 8.2 ka records in South America beyond speleothem δ¹⁸O evidence, however a trace element record from Botuverá Cave (Brazil)29 suggests wetter conditions during the event (Fig. 3b;29), consistent with the negative δ¹⁸O anomalies in the region. Drier conditions are inferred over central America by Morrill et al.13, whereas the speleothem isotope signals show a more mixed signal.

Discussion
The prominence of the 8.2 ka event in Greenland records is perhaps unsurprising, given that it was forced by a large change in freshwater flux to the North Atlantic11,30,31. Its prominence in the speleothem records shows that this change was sufficient to trigger a global reorganisation of the climate system. We have shown that the 8.2 ka event shows remarkable global coherency with respect to timing, duration, magnitude and spatial pattern. The coeval timing of the event in regions both close and far from the north Atlantic (Europe and the Mediterranean versus Asia) supports the indirect evidence of global synchronicity from Greenland ice core methane records32.
which reflect hydrological changes over methane producing regions, mainly tropical wetlands. The 8.2 ka methane excursion is coeval (within 4 years) with changes in δ¹⁸O (which reflects changes in local temperature) in Greenland, indicating that the North Atlantic and global climate response to the 8.2 ka freshwater influx is indeed synchronous. The Greenland ice core δ¹⁸O record and a sub-annual resolution speleothem record from Heshang Cave, China were found to be statistically indistinguishable, supporting a rapid (annual) teleconnection between these regions. Furthermore, a comparison of eight speleothem records from China, Oman and Brazil showed the event occurred at the same time in all the records, within the dating uncertainties. Oceanic teleconnections operate on decadal to centennial timescales. Since lags on these timescales are not observed (even within uncertainties) between near (Europe) and far (Asia) regions, our study supports the idea that the transmission of the 8.2 ka event occurred through suitably rapid atmospheric processes.

One atmospheric mechanism for the transmission of the North Atlantic signal globally is a southward shift in the mean position of the intertropical convergence zone (ITCZ), in response to cooler sea-surface temperatures (SSTs) in the North Atlantic. Such a shift in the mean position of the ITCZ is supported by the spatial patterning of the speleothem isotope signals (Fig. 4a). The antiphase pattern of positive signals in the northern hemisphere tropics of Asia and negative signals in the southern hemisphere tropics of America and southern Africa is consistent with the weakening of northern hemisphere monsoons and strengthening of southern hemisphere monsoons in response to a shift in the ITCZ. Negative (positive) speleothem isotope signals in the monsoon regions have been interpreted as reflecting a stronger (weaker) monsoon, via a combination of processes, including regional precipitation and atmospheric circulation changes driving moisture transport changes and climate variability in the region, with ocean feedbacks playing a significant role. Over central America, the mixed speleothem isotope signal contrasts with the drying signal inferred from lake records and simulated by climate models. It is possible that the negative δ¹⁸O anomalies observed in the northern sites reflect lower δ¹⁸O of seawater in the north of the Gulf of Mexico, observed in a marine δ¹⁸O record. However, the age uncertainties of these speleothem records are larger than most records (Fig. 3) and there are other δ¹⁸O excursions at around this time. In the study documenting the Dos Anas and Santo Tomas records, an earlier positive δ¹⁸O anomaly is tentatively suggested as reflecting the 8.2 ka event. More high-resolution speleothem records of the 8.2 ka event are needed in this region to understand the climate response in the central America region better.

The negative speleothem isotope anomalies over Europe are consistent with the widespread cooling observed in numerous palaeoclimatic records. Quantitative temperature estimates suggest a cooling of between 1 and 1.5 °C. Based on the observed and modelled temperature/δ¹⁸Oprecipitation gradients of 0.17‰ to 0.9‰ °C⁻¹, and an equilibrium isotope fractionation between drip water and calcite of −0.18 to −0.23‰ °C⁻¹, the regional δ¹⁸O speleothem anomaly of 0.4‰ could be fully explained by the regional temperature decrease. The oxygen isotopic composition of moisture delivered to Europe was also likely lower during the 8.2 ka event, further contributing to negative isotope anomalies in the region. Lower δ¹⁸O of seawater (of −0.4‰) in the North Atlantic region and cooler SSTs (of −1 °C) would deliver moisture that is ~0.5‰ more depleted. Other studies have emphasised other possible causes of the depleted δ¹⁸O values in the region, including changes in solar irradiance or volcanicity (or both) and which have also been considered as a manifestation of internal (unforced) climate variability. The lack of a significant 4.2 ka event in our speleothem analysis could reflect the complexity of the event: records of the event do not always show a well-constrained timing or a signal with an amplitude larger than the noise of the record. Furthermore, the signal of this event sometimes consists of several oscillations rather than one straightforward excursion. However, it seems more likely that this event was not of global extent. There is no regional 4.2 ka event in the north Atlantic region and even in the Mediterranean region, where evidence of the event is clearest, there are numerous palaeoclimate records that do not show the event.
Conclusion

We have shown that the 8.2 ka event is the most prominent abrupt climate event in the Holocene. The event shows a globally extensive, coherent and synchronous climate response. The coherency of the regional δ¹⁸O anomalies indicates that the freshwater pulse at 8.2 ka triggered a widespread reorganisation of climate systems. The synchronicity of isotope signals globally suggests that the North Atlantic freshening was transmitted via rapid atmospheric teleconnections. We have provided the first global speleothem isotope synthesis of the 8.2 ka event, that can be used to test the ability of climate models to simulate the impacts of ice sheet melting and ocean circulation changes.

Methods

Holocene abrupt event detection analysis. We determine the presence and timing of abrupt events during the Holocene using a global dataset of speleothem δ¹⁸O records from the SISAL (Speleothem Isotopes Synthesis and Analysis) version 2 database. We identify abrupt events during a moving 1000-year window (with 50% overlap). For each window, we select speleothem records using the following criteria:

- They have a mean sampling resolution of < 30 years within the window;
- They have a minimum length within the window of 500 years;
- They have a mean temporal resolution of < 30 years within the period;
- They are at least 300 years long within the period.

This resulted in the selection of 275 speleothem records from 170 sites for this analysis (Fig. 1). The choice of a minimum resolution of < 30 years gives a minimum of five data points for abrupt events of ~150 years duration and ensures that there are sufficient records included in the analysis to identify a global signal.

To detect abrupt events within a window objectively, we carried out breakpoint analysis using the Strucchange package in R. The method detects significant shifts in speleothem δ¹⁸O data using a dynamical programming approach. The optimal number of breakpoints (and location) is determined using a Bayesian Information Criterion. Where two breakpoints occur within <300 years, it suggests an abrupt event, whereby there is a rapid shift in δ¹⁸O values, which are maintained for at least a few years, then a shift back. To prevent the breakpoint analysis from detecting changes in δ¹⁸O values that relate to long-term changes, the speleothem records are first individually detrended and normalised by fitting a linear regression through each record across the 1000-year window, then subtracting the predicted δ¹⁸O values from the linear model from the observed δ¹⁸O values.

We calculate the number of records within 300-year bins across the Holocene that show >2 breakpoints (Fig. 2), given as a percentage of the total records in that bin (thereby ensuring plotted values do not reflect the changing number of records through the Holocene). 300-year bins are chosen to examine the presence of abrupt events because they are sufficiently short to exclude multi-centennial scale variability but long enough to capture the full length of an abrupt event. As a further step, we determined which bins were statistically significant above randomly generated noise. This was important because speleothem δ¹⁸O records often have a high degree of autocorrelation, which can cause statistically spurious breakpoints to be detected. We therefore carried out the same breakpoint analysis on randomly generated records with the same sampling resolution and autocorrelation as the speleothem records, using the arima.sim function in R. We carried out these steps 1000 times and calculated the mean percentage of randomly generated records with >2 breakpoints within a bin. Bins where the actual speleothem records have a higher percentage than the randomly generated noise are considered statistically significant.

8.2 ka anomalies. To identify the presence of the 8.2 ka event, and characterise the timing, duration and magnitude of speleothem oxygen isotope anomalies at the event, we selected speleothem records from SISAL version 2 covering the interval 7.8 to 8.4 ka. Records were selected using the following criteria:

- They have a mean temporal resolution of < 30 years within the period;
- They are at least 300 years long within the period.

This resulted in the selection of 67 speleothem records from 48 sites for this analysis (Fig. 1). We added a further 6 records (from 6 sites), that are not available in SISALv2 (Table S1). Although we used a mean temporal resolution of < 30 years to select the records for this analysis, 95% of records have a mean resolution of < 20 years and 67% have a mean resolution of < 10 years (Table S1).

We detected abrupt shifts in δ¹⁸O values by carrying out breakpoint analysis over each individual, detrended record. Where a speleothem record shows < 1 breakpoint, there is no significant δ¹⁸O excursion (Fig. 5a). Where a speleothem record shows 2 breakpoints, the record shows one simple δ¹⁸O excursion (Fig. 5b). If a record shows >2 breakpoints (i.e. an excursion can be separated into segments, or there are several significant fluctuations), we determine which segments are significantly different from the base period (before and after the event). If all significant segments have the same sign anomaly (relative to the base period), this suggests they represent an event with a more complex evolution (Fig. 5c). If significant segments show a changing sign of anomaly, this suggests that the record shows numerous fluctuations and therefore the record does not show one clear 8.2 ka excursion (Fig. 5d).

The oldest breakpoint is defined as the start of the excursion and the youngest breakpoint defined as the end (Fig. 5b). We calculate the event duration in each individual record as the difference between the start and the end of the event. Anomalies are calculated as the mean δ¹⁸O between the start and the end of the event, minus the mean δ¹⁸O of before and after the event (Fig. 5).
To ensure no spurious results related to the record noise are included in our synthesis, we removed any records where the amplitude of the ~8.2 ka δ¹⁸O anomaly is smaller than one standard deviation of the base period (before and after the event), to minimise the impact of noise in the records which might result in spurious event detection.

We also examined the age uncertainties associated with the 8.2 ka δ¹⁸O excursions using age uncertainty data available in the SISAL v2 database. The database contains chronologies from seven different age-depth modelling approaches26. Age uncertainties were calculated from the spread of individual ensembles in six modelling approaches (linear interpolation, linear regression, Bchron, Bacon, OxCal, COPRA). Age uncertainties were obtained in the seventh model (StalAge) through a Monte Carlo approach, but individual ensembles were not preserved. SISAL v2 age-depth models were screened to ensure reliability. The models had to meet several criteria to be included in the database, including: (a) having no age reversals, (b) flexibly following clear growth rate changes and (c) showing greater uncertainties between dates and near growth hiatuses. No age-depth model is successful for all speleothem records. The ages (and uncertainties) were extracted at the breakpoint locations using all available age-depth modelling approaches for each record, thereby assessing uncertainty associated with the choice of model. This demonstrated whether a δ¹⁸O excursion could plausibly have occurred at ~8.2 ka. Where age uncertainties are too large and therefore the timing of the 8.2 ka isotope excursion too poorly constrained, we excluded the entity from our analysis.

Data availability
The Speleothem Isotopes Synthesis and AnaLysis (SISAL) database version 2 is available through the University of Reading Data Archive, at https://doi.org/10.17864/1947.256.62. The dataset generated in this study is available in a GitHub repository, available at https://doi.org/10.5281/zenodo.5871176. We use R for analyses66. The code used to run the analyses and generate the figures in this study are also available at https://doi.org/10.5281/zenodo.5871176.

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