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Links between the East Asian monsoon and North Atlantic climate during the 8,200 year event

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An abrupt cooling event in the North Atlantic region 8,200 years ago affected climate throughout the Northern Hemisphere[1–3]. The event is well constrained in Greenland ice cores[3], but lack of resolution in records from other regions has challenged our understanding of the timing and nature of the associated teleconnections. Speleothem records from East Asia have suggested monsoonal changes associated with the 8,200 year event, but the nature of these changes remains controversial[1,2]. Here we assess changes in East Asian precipitation during the event from a sub-annually resolved stalagmite record from central China. Using $\delta^{18}O$ and Mg/Ca measurements of the speleothem carbonate, we show that climate dried significantly about 8,200 years ago. Based on our annual-layer-counted chronology, we show that the dry event lasted 150 years, with a central period of pronounced aridity that lasted 70 years. The duration and evolution of the event is indistinguishable from that observed in the Greenland ice cores. We therefore conclude that an effective and rapid atmospheric teleconnection exists between the North Atlantic and the monsoon system in warm climates similar to today's.

The 8.2 kyr event is an abrupt cold snap in the North Atlantic region[4] and is notable in Greenland ice-core records as the most pronounced climate event in the otherwise relatively stable Holocene period[3]. Ice-core records enable annual-resolution reconstruction of the event and indicate that it lasted for 160 years with a central extreme period of 69 years[3]. This centennial-scale cooling is thought to be caused by an abrupt change in Atlantic overturning circulation, probably initiated by flooding from an ice-dammed lake[5]. The 8.2 kyr event has attracted considerable attention because it demonstrates the potential for abrupt, high-amplitude climate change, even while climate is in a state close to that seen today.

The influence of abrupt 8.2 kyr cooling of the North Atlantic on climate in other regions of the globe has been widely studied[6,7], but there exist no other records with the annual resolution of the Greenland ice cores. This limits the ability to assess the teleconnections in the climate system that transmit climate change from the North Atlantic to other regions.

In the Asian monsoon region, the 8.2 kyr event has been elusive[6,8], often reflecting a lack of sufficient resolution in palaeoclimate records. Recent palaeomonsoon studies have, however, demonstrated a climate response at 8.2 kyr (refs 1,9,10), particularly from higher-resolution records captured in cave carbonates (Fig. 1). This response is generally interpreted as a drying during the 8.2 kyr event, which would mirror the weaker monsoon associated with cold North Atlantic conditions during unstable glacial climates[11].

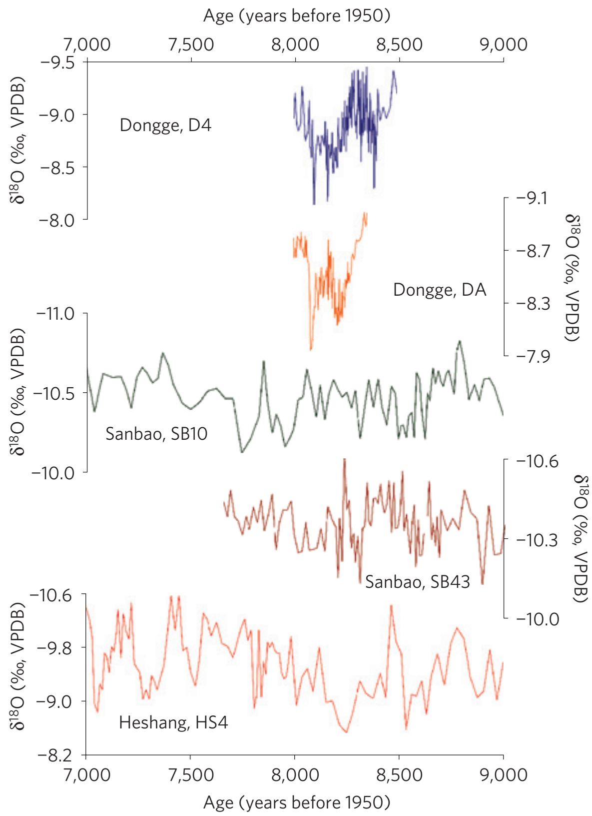

Figure 1 | Existing stalagmite $\delta^{18}O$ records from central China for the 8.2 kyr period. Dongge D4 (ref. 12) and DA (ref. 13) are plotted on the revised chronologies of ref. 1. The two Sanbao records are from ref. 14 and the Heshang record from ref. 10. VPDB, Vienna Pee Dee Belemnite.

However, the nature and structure of the 8.2 kyr event in the Asian monsoon is not well constrained. In the East Asian monsoon region, for instance (Fig. 1), two records from Dongge Cave[12,13] show a $\delta^{18}O$ anomaly but with different structure in two stalagmites; two lower-resolution records from Sanbao Cave[14] show no evidence for a $\delta^{18}O$ event; whereas a record from Heshang cave[10] shows evidence of a $\delta^{18}O$ increase at 8.2 kyr.

Heshang Cave (30° 27′ N, 110° 25′ E; 294 m) offers the potential to assess the response of the East Asian monsoon to North Atlantic cooling at 8.2 kyr at high resolution. The event is captured in a stalagmite with clear annual laminations (allowing precise

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chronology) and with very rapid growth rates averaging ≈0.3 mm a year (allowing high temporal resolution)[15]. These features allow reconstruction of the Asian monsoon at comparable resolution and temporal accuracy as observations in the Greenland ice cores. Heshang Cave has also been extensively monitored[16] so that the nature of the geochemical response to changing conditions is well understood[17]. Further details of the cave and the stalagmite used for this study (HS-4) are provided in the Supplementary Information.

Oxygen isotopes are by far the mostly commonly applied palaeoclimate proxy in stalagmites, but their interpretation is not straightforward. Stalagmite $\delta^{18}O$ is controlled not only by regional rainfall, but also by moisture source, atmospheric transport and mixing, atmospheric and cave temperatures, and regional and local evaporation[18,19]. Interpretation of Chinese $\delta^{18}O$ records therefore remains controversial[2,20] and may be controlled by a changing mixture of summer and winter rainfall, by changes in the source of moisture, or by changes in the pattern of rainfall in the broad region.

In this study we therefore augment $\delta^{18}O$ data with measurements of Mg/Ca—a proxy that responds to local rainfall. Stalagmite Mg/Ca increases slightly with increasing temperature but, to a much greater degree, with lower rainfall[21]. In Heshang Cave, stalagmite Mg/Ca is controlled by the removal of Ca from karst waters in the overlying aquifer (or on the surface of the stalagmite) by formation of calcite during transport before waters reach the measured stalagmite[17]. Such 'prior-calcite-precipitation' drives karst waters to higher Mg/Ca ratios owing to the exclusion of Mg relative to Ca during calcite growth. Lower rainfall, and therefore lower karst flow rates, provides more opportunity for prior-calcite-precipitation and leads to high Mg/Ca in stalagmites. Although not quantitative, Mg/Ca provides a robust indicator of rainfall at the site of Heshang cave. The response of this Mg/Ca proxy allows us to test, at this specific site, the common (but debated[2,20]) assumption that $\delta^{18}O$ is related to rainfall in the Asian monsoon region, and allows periods of past dry conditions to be clearly identified. Application of Mg/Ca, or another independent proxy for rainfall, could allow such tests in other well-understand caves to further test this linkage.

We construct a combined $\delta^{18}O$ and Mg/Ca record of the 8.2 kyr event at sub-annual resolution from the well-understood Heshang cave environment. $\delta^{18}O$ is measured on samples micromilled at 40 μm resolution, while Mg/Ca is measured by electron probe with a 10 μm resolution (see Supplementary Information for full analytical details). With annual layers ranging from 50 to 500 μm, this provides sub-annual resolution throughout the record. Absolute chronology is provided by 9 U/Th ages spanning 9 cm of stalagmite growth and an age range of 500 years. These ages provide a date for the onset of the event of 8.25 ± 0.10 kyr, with a substantial portion of the uncertainty due to a required initial ^{230}Th correction. The clear annual banding of the record allows a relative chronology to be hung on these U/Th ages. This provides an age model with annual resolution through the event so that the duration of changes can be constrained at close to annual precision for comparison with the layer-counted records in the Greenland ice cores.

Oxygen isotope values in the section of the HS-4 stalagmite forming at 8.2 kyr are higher than observed at any other part of the early Holocene (Fig. 2 and Supplementary Fig. S5). The anomalous $\delta^{18}O$ values at 8.2 kyr include a particularly high central portion (Fig. 3). To define the duration of the $\delta^{18}O$ event, we follow a similar approach to that used to define the 8.2 kyr event in Greenland Ice cores[3]. A long-term average $\delta^{18}O$ for the period 9–5 kyr is calculated from the lower-resolution portion of the HS-4 sample (ref. 10 and Fig. 2) as −9.59‰. The limits of the 8.2 kyr event are defined by depths where the observed $\delta^{18}O$ values fall consistently more than 1 s.d. away from this (that is, >−9.16‰), and the limits of a central extreme portion by values more than 2 s.d. away (that is, >−8.72‰; Fig. 3). Although other approaches might be used

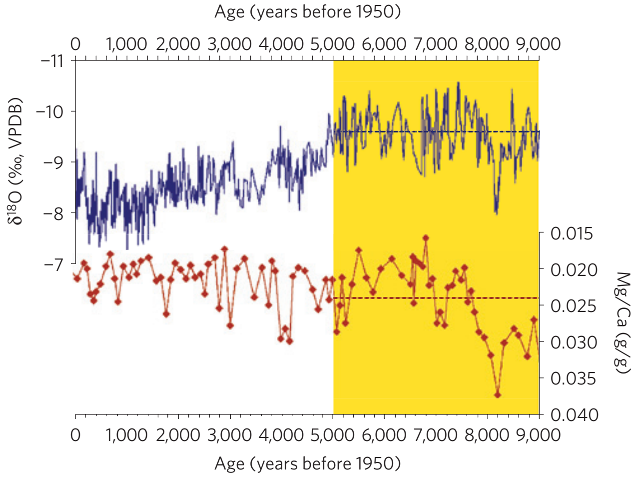

Figure 2 | Holocene $\delta^{18}O$ and Mg/Ca records from the HS-4 stalagmite. Note that both proxies are shown on inverted scales so that rainfall decreases down the graph. The $\delta^{18}O$ data and age model is from ref. 10, with the new data of this study inserted averaged at the same resolution as that earlier study (see Supplementary Fig. S5 for further details), while Mg/Ca is from this study. Yellow shading indicates the early Holocene (9–5 kyr), with dashed lines the average values for each proxy during that period (−9.59‰ for $\delta^{18}O$ with a standard deviation of 0.44‰). Note that the event at 8.2 kyr has the highest value for both $\delta^{18}O$ and Mg/Ca.

to define the event, use of an identical technique to that used in Greenland records ensures that the event can be readily compared. This approach indicates a climate event in Central China of 150 years duration, with a central extreme portion 70 years long.

Taken alone, the high $\delta^{18}O$ values observed at Heshang during this event might be caused by a variety of processes. Higher $\delta^{18}O$ has often been interpreted as reflective of decreased monsoon strength in this highly convective region, either owing to a change in the mixture of winter and summer monsoon strength[11] or to changes in the amount of rainfall along a moisture transport pathway[2,10]. But this change in $\delta^{18}O$ could also be explained by a decrease of mean annual temperature of only ≈2 °C (ref. 22) or by a change in the source of moisture.

The Mg/Ca record enables the various possible controls on $\delta^{18}O$ to be separated and provides strong support for the view that the event at 8.2 kyr represents a period of relative aridity. Mg/Ca reaches values of 0.06 during the 8.2 kyr portion of the stalagmite (Fig. 3) and is therefore higher than at any other point in the complete Holocene HS-4 record (Fig. 2). The duration of the high Mg/Ca values corresponds very closely to the high $\delta^{18}O$ values. Although reflecting a local rainfall control, the Mg/Ca data is consistent with the view that high $\delta^{18}O$ values reflect a regional decrease in rainfall at this time, rather than only a decrease in temperature or change in moisture source.

The thickness of annual layers also decreases during the event (from a Holocene average of 0.28 mm yr^{-1} to less than 0.10 mm yr^{-1}; Fig. 3); consistent with a decrease in rainfall. There are several controls on stalagmite growth rate, including drip rate, temperature, and Ca^{2+} concentration of the drip-waters (all three of which are positively correlated with growth rate[23,24]). At fast drip rates, such as those in Heshang, drip rate is not normally the major control on growth rate so, although the thinner layers are consistent with lower drip rates, the large change in thickness during the event may also suggest a coeval cooling.

The combined proxy data provides strong evidence for a drying in East Asia at 8.2 kyr, and enables a comparison of this drying with cooling in the North Atlantic region. The dry event in China lasts for 150 years, with a 70-year extreme portion (Fig. 3),

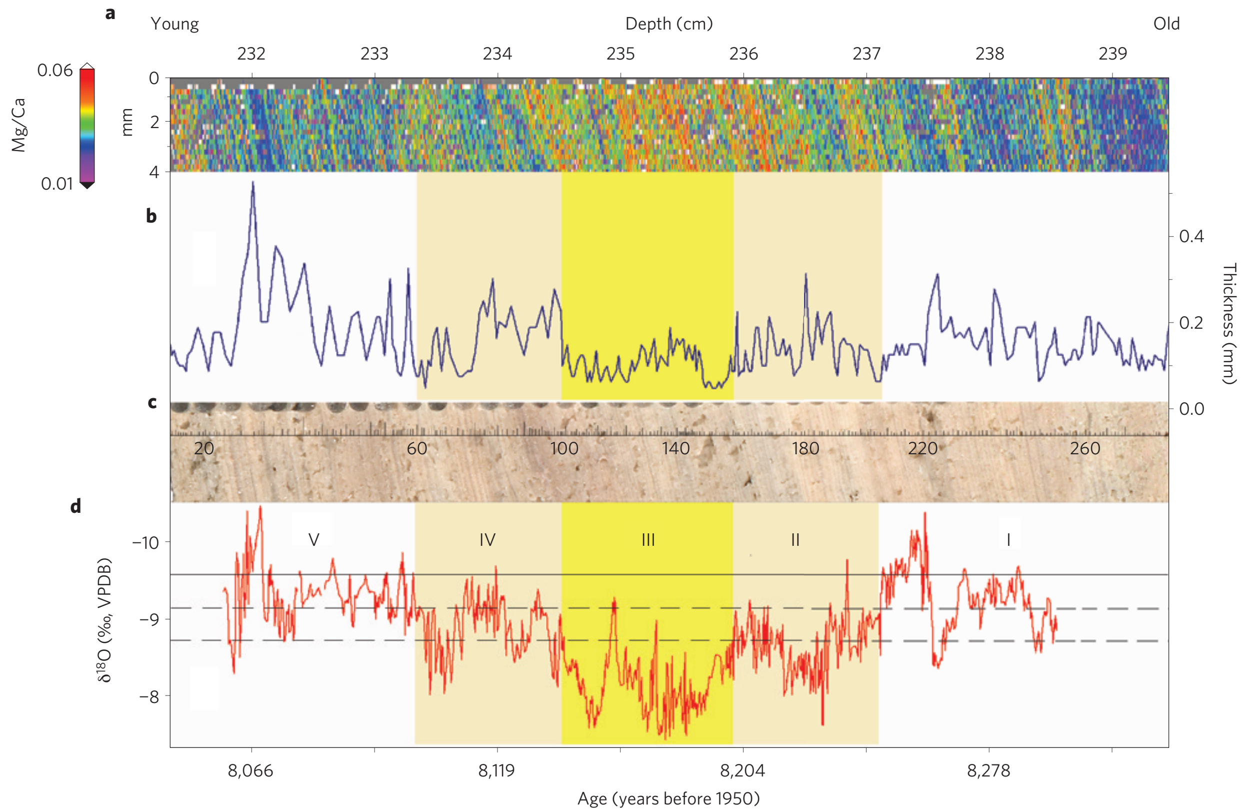

Figure 3 | The new high-resolution Heshang 8.2 kyr record plotted against depth and age. a, Electron-probe Mg/Ca data (g/g), with the orange and red colours representing higher values than at any other point in the Holocene. **b**, The blue line shows the thickness of the annual layers, with a pronounced decrease during the 8.2 kyr event. **c**, Photograph of the cut surface of the stalagmite with the annual layers visible, and their counting identified by tick marks and numbers. **d**, The red curve shows the ≈900 $\delta^{18}O$ value measured at 40 μm resolution. Horizontal lines across this record show the average, 1 s.d. and 2 s.d. bounds on $\delta^{18}O$ data outside the event and are used to identify the duration of the whole event (1 s.d., pale yellow band) and of the central portion (2 s.d., bright yellow band) following the approach used previously for Greenland ice core records[3]. Further details regarding identification of the limits of the event are provided in the Supplementary Information (for example, Supplementary Fig. S5).

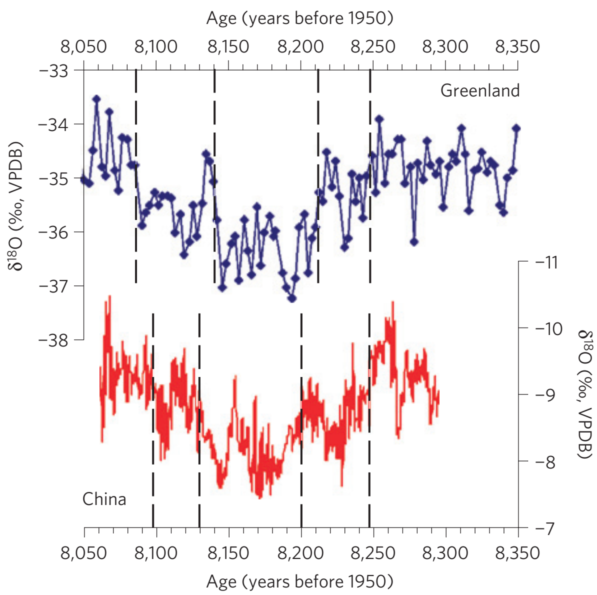

Figure 4 | Comparison of Greenland[3] and Central China (this study) $\delta^{18}O$ records. Both are plotted on their independent timescales and are relative to 1950. Uncertainty on the Heshang age scale is ≈100 years, and on the Greenland records ≈50 years. Both records are annually layer counted so that the durations of the event are robustly constrained.

compared to best estimates for the cooling of Greenland of 160 years with a central portion of 69 years[3] (Fig. 4). Given the noise in both climate records, these values are statistically indistinguishable (for example, another estimate of the duration in Greenland[25] places the duration at 150 yr). This indicates a broadly linear response of monsoon weakening to North Atlantic cooling, and suggests that the teleconnection between these regions operates on an annual timescale rather than with significant smoothing or an appreciable lag.

The rapid transmission of climate information from the North Atlantic to Asia supports an atmospheric teleconnection between the regions. Although changes in the North Atlantic propagate throughout the oceans owing to baroclinic adjustment in less than 20 years[26] these changes are damped by the time they reach Indian and Pacific oceans and not likely to generate the similarity in form observed for the 8.2 kyr event for China and Greenland. Similarly, combined atmospheric and ocean processes, in which changes to the ENSO system are initiated some years after a shut-down in North Atlantic circulation[27] to then influence the monsoon strength, are unlikely as an explanation for the one-to-one relationship between China and Greenland. This relationship is better explained by mechanisms that operate on an annual timescale, and therefore rely on atmospheric rather than oceanic processes. Prominent amongst these is the suggestion that changes in Eurasian[28] or high northern latitude[29,30] ice-cover reinforces Northern Hemisphere cooling, leading to a southwards displacement of the marine and terrestrial inter-tropical convergence zone, and hence to a weakening of the monsoon.

The proxy data from Heshang demonstrates that the 8.2 kyr event was a time of pronounced weakening of East Asian monsoon rainfall and indicates a rapid atmospheric teleconnection between abrupt North Atlantic temperature change and the monsoon, even in the relatively ice-free conditions of the Holocene. Future weakening of the Atlantic overturning circulation could lead to a slower rate of warming in the North Atlantic region, because the temperature effect of ocean circulation changes will be superimposed on the general global warming driven by CO_2 increase. The Heshang Cave data provide some indication of the impact that change in the North Atlantic might cause to East Asia—a region where more than a third of the world's population are influenced by the rains of the Asian monsoon system.

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Author contributions

C-Y.H. initiated work in Heshang Cave and recovered the HS-4 sample; G.M.H. conceived the high-resolution study of the 8.2 kyr event; Y-H.L. led the milling, measurement and interpretation, and contributed to all aspects of the study; A.J.M. led the U-Th measurements, and N.C. the electron probe measurement; the manuscript was written by Y-H.L. and G.M.H. with contributions from all authors.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to Y-H.L. or G.M.H.

Competing financial interests

The authors declare no competing financial interests.