LETTERS
PUBLISHED ONLINE: 10 JANUARY 2010 | DOI: 10.1038/NGEO707

nature geoscience

Moisture variability in the southwestern United States linked to abrupt glacial climate change

J. D. M. Wagner[1], J. E. Cole[1,2]*, J. W. Beck[1,3], P. J. Patchett[1], G. M. Henderson[4] and H. R. Barnett[1]

Many regions of the world experienced abrupt climate variability during the last glacial period (75–15 thousand years ago[1,2]). These changes probably arose from interactions between Northern Hemisphere ice sheets and circulation in the North Atlantic Ocean[3], but the rapid and widespread propagation of these changes requires a large-scale atmospheric response whose details remain unclear[4–7]. Here we use an oxygen isotope record from a speleothem collected from the Cave of the Bells, Arizona, USA, to reconstruct aridity in the southwestern United States during the last glacial period and deglaciation. We find that, during this period, aridity in the southwestern United States and climate in the North Atlantic region show similar patterns of variability. Periods of warmth in the North Atlantic Ocean, such as interstadials and the Bølling–Allerød warming, correspond to drier conditions in the southwestern United States. Conversely, cooler temperatures in the high latitudes are associated with increased regional moisture. We propose that interstadial warming of the North Atlantic Ocean diverted the westerly storm track northward, perhaps through weakening of the Aleutian Low, and thereby reduced moisture delivery to southwestern North America. A similar response to future warming would exacerbate aridity in this already very dry region.

In the Southwest US, human and ecological systems depend critically on water resources that are expected to diminish as climate warms[8]. Understanding past changes in regional hydroclimate, and their global climate associations, offers the opportunity to better anticipate future changes. Although extensive tree-ring reconstructions document the past one to two millennia of drought variability[9], longer records are scarce. Lake-based and palaeovegetation records indicate wetter, cooler conditions during the Last Glacial Maximum (LGM; 25–17 thousand years (kyr) BP; refs 10, 11), but these generally lack the chronological precision and resolution to describe in detail the history of deglaciation or abrupt stadial–interstadial changes, as seen in Greenland ice cores[12–14] and other records worldwide[2,5–7,15]. We have developed a new record of climate variability based on a record of speleothem oxygen isotope ratios (δ^{18}O) from Cave of the Bells, Arizona, that reveals an unprecedented history of changes in aridity strongly coupled to North Atlantic variability during the deglacial and marine isotope stage 3 (MIS3). Our results support a strong link between North Atlantic variability and the influx of moisture from the Pacific into southwestern North America.

The southwestern US receives about half its annual precipitation (and virtually all groundwater recharge) from westerly storms in the winter half-year (October–March) and about half from the summer North American monsoon (late June–early September). Intense evaporation and runoff during the hot summer means that nearly all water entering our cave site derives from winter precipitation, according to oxygen isotopic data from modern precipitation and cave dripwaters (Supplementary Figs S1 and S2). In winter, the isotopic content of local precipitation depends mainly on precipitation amount, with negligible temperature influence. We cannot completely discount the potential influence of temperature on our records, but the significant correlation of precipitation amount and δ^{18}O, along with the opposite effects of temperature on the δ^{18}O of calcite and precipitation, lead us to describe our results in terms primarily of moisture (see Supplementary Discussion). Thus we interpret speleothem isotopic changes as representing primarily changes in winter moisture from westerly storms: high δ^{18}O values correspond to relatively dry conditions and low δ^{18}O to relatively moist.

Modern climate relationships show strong linkages between southwestern US precipitation and both Pacific and Atlantic Ocean variability[16,17]. Pacific Ocean sea surface temperature (SST) influences winter precipitation in part by modulating the position of westerly storm tracks; when the tropical Pacific Ocean is warm (El Niño conditions), a southward-shifted storm track enhances winter moisture delivery to the southwestern US (ref. 16). Atlantic Ocean conditions also have a role; above-normal SST in the North Atlantic Ocean correlates with drier conditions across the Southwest US (ref. 17). A recent modelling study describes a mechanism for this correlation: when North Atlantic Ocean SST is warm, storm tracks in both the North Atlantic and North Pacific oceans move poleward and weaken, associated with stronger northward oceanic heat flux and a weaker Aleutian Low[18]. These responses lead to reduced winter precipitation in the Southwest US when the North Atlantic Ocean is warm (Fig. 1).

We present a new, absolutely dated oxygen-isotope record of climate variability from a stalagmite that formed in Cave of the Bells (COB), Arizona (see Supplementary Methods and Fig. S3). Sixty-two uranium-series measurements, nearly continuous in depth, indicate that the sample dates from 53 kyr to approximately 8 kyr BP (Supplementary Table S1 and Fig. S4). We identify two hiatuses between ∼11.5–10.0 and 29.8–23.3 kyr BP, on the basis of the U-series dating and on two thin cloudy bands that we interpret as indicating growth cessation. We rule out substantial kinetic influences through comparison of oxygen- and carbon-isotope data (Supplementary Discussion and Fig. S5).

Oxygen isotope values from COB show distinct patterns of deglacial and millennial variability similar to those seen in Greenland ice cores (Fig. 2; refs 12–14). We removed the global ice volume component of the δ^{18}O record to clarify local/regional climatic influences (Supplementary Methods). After this correction, δ^{18}O values during the extreme LGM (23–21 kyr BP) lie about 1.4‰below expected modern values (−12.0‰ LGM

[1]Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA, [2]Department of Atmospheric Sciences, University of Arizona, Tucson, Arizona 85721, USA, [3]Department of Physics, University of Arizona, Tucson, Arizona 85721, USA, [4]Department of Earth Sciences, University of Oxford, Oxford, OX13PR, UK. *e-mail: jecole@email.arizona.edu.

© 2010 Macmillan Publishers Limited. All rights reserved.

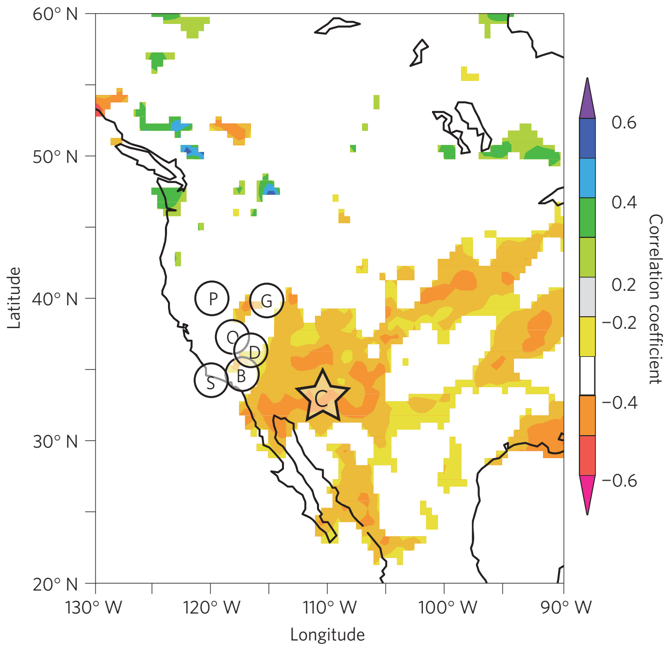

Figure 1 | Correlation of winter precipitation with Atlantic SST. The map illustrates simultaneous correlation of winter (October–March) precipitation with a detrended index of North Atlantic SST (HadISST AMO: SST anomalies over 25°–60° N, 7°–75° W, global mean temperature signal removed) over the 1951–2003 period. Palaeoclimate sites include Cave of the Bells (star with C; this study), Pyramid Lake (P; ref. 22), Owens Lake (O; ref. 22), Goshiute Cave (G; ref. 20), Baldwin Lake (B; ref. 23), Devil's Hole (D; ref. 21) and Santa Barbara Basin (S; ref. 19). Yellow-orange colours indicate that North Atlantic warmth correlates with winter aridity; blue-green colours indicate the opposite relationship. Coloured areas are significant at ≥90%. (Created at Climate Explorer (http://climexp.knmi.nl) on 13 May 2008.)

versus −10.6‰ expected modern, defined on the basis of dripwater $\delta^{18}O$ and cave temperature). On the basis of modern calibrations, this difference most likely indicates wetter winter conditions at the LGM than today. Summer precipitation, isotopically heavier by 4‰ relative to winter, does not strongly influence cave dripwaters today. Lower $\delta^{18}O$ during the LGM therefore does not reflect altered precipitation seasonality, as this would require a shift towards even smaller proportions of summer precipitation.

The deglacial transition occurs in steps (Fig. 2A). Beginning at 15.3 kyr BP, speleothem $\delta^{18}O$ increases rapidly to high values, which persist until 13.1 kyr BP, punctuated by a small decrease between 14.1 and 13.8 kyr BP, and falls again to lower values between 13.0 and 11.5 kyr BP. The timing of these isotopic shifts closely resembles that in Greenland ice-core records[14]. In those records, the Bølling/Allerød warming midpoint occurs around 14.7 kyr ago, compared with our midpoint date of 15.1 kyr BP. A wetter/cooler interval spans 13.0–11.5 kyr BP in the COB record; the upper date is uncertain as it borders the younger hiatus. This event is comparable in timing and duration to the Younger Dryas in Greenland ice-core records (12.9–11.7 kyr BP). Our record agrees with other regional deglacial reconstructions[11] and with the pattern of SST warming seen off Baja California (but not that in the California current region and Santa Barbara basin, where initial warming may occur earlier[19]).

The portion of our record older than the lower hiatus (spanning 54–30 kyr BP) shows millennial variability that corresponds closely to North Atlantic records during MIS3 (Fig. 3). Warm interstadials in the North Atlantic Ocean co-occur with higher $\delta^{18}O$ values in our speleothem, reflecting drier conditions relative to the wetter

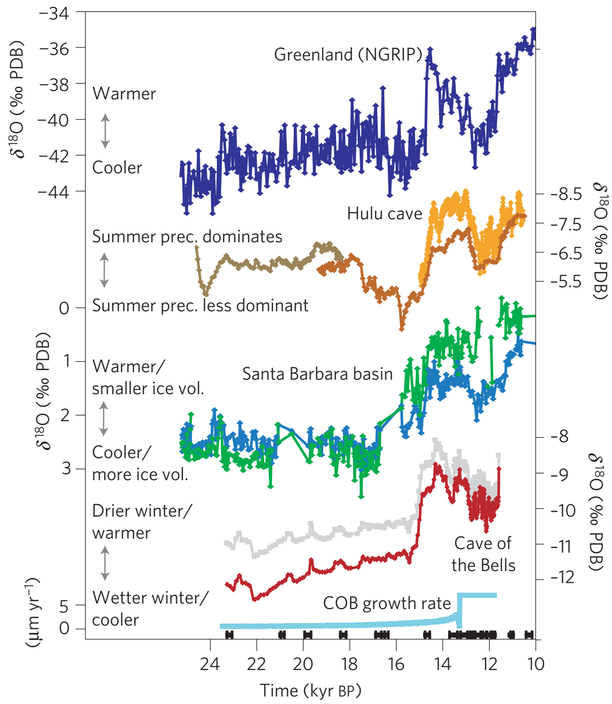

Figure 2 | Comparison of deglacial COB record with other records. The ice-volume-corrected COB record is shown in red (grey is uncorrected), with speleothem growth rate below. We show U/Th dates along the X axis with 2σ analytical precision. From the top, the other records are a $\delta^{18}O$ curve from the North GRIP (Greenland) ice core, plotted on age model GICC05 (ref. 14); isotopic data from Hulu cave, China[7] (dark orange = core PD, light orange = core HB2, brown = core MSD; negative $\delta^{18}O$ anomalies occur when summer moisture predominates over winter); planktonic foraminiferal $\delta^{18}O$ records from Santa Barbara basin[19], indicating a mix of SST, local seawater $\delta^{18}O$ and ice-volume changes (green = *Globigerina bulloides*; blue = *Neogloboquadrina pachyderma*). Interpretations based on original references are indicated on the left (prec. is precipitation). PDB, PeeDee Belemnite.

stadials. Our record tracks the pattern of millennial variability seen in diverse locations throughout the Northern Hemisphere between 54 and 30 kyr BP (ref. 2); dry conditions in Arizona co-occur with a stronger summer Asian monsoon[7] and warmer ocean temperatures off Southern California[19] (Fig. 3), along with a northward-displaced intertropical convergence zone in both the Pacific and Atlantic[4,5]. Slight age model offsets are apparent among these data, but major interstadial warmings agree in age within the chronological precision of the records.

Other records from the southwestern US and Great Basin support our contention that this region experienced substantial millennial variability in hydroclimate during the last glacial cycle (Fig. 1), but they generally lack either the continuity or temporal resolution and precision to define a coherent picture. Nevada speleothem data from three brief, discrete intervals between 83 and 103 kyr BP suggest more positive $\delta^{18}O$ values during interstadials, analogous to our record[20]. The Devil's Hole, Nevada, speleothem record does not reveal millennial features during MIS3, probably owing to the long (about 2,000 yr) transit time of groundwater recharge to deposition site[21]. Lake-based records north and west of our site show millennial variations during MIS3 whose timing and phasing are not precisely constrained, but that imply wetter conditions during interstadials[22,23]—in contrast to our site. Today, the correlation between North Atlantic Ocean SST and winter precipitation in the western US weakens west of ~115° W (Fig. 1), suggesting that moisture palaeorecords from the Pacific Ocean coast

© 2010 Macmillan Publishers Limited. All rights reserved.

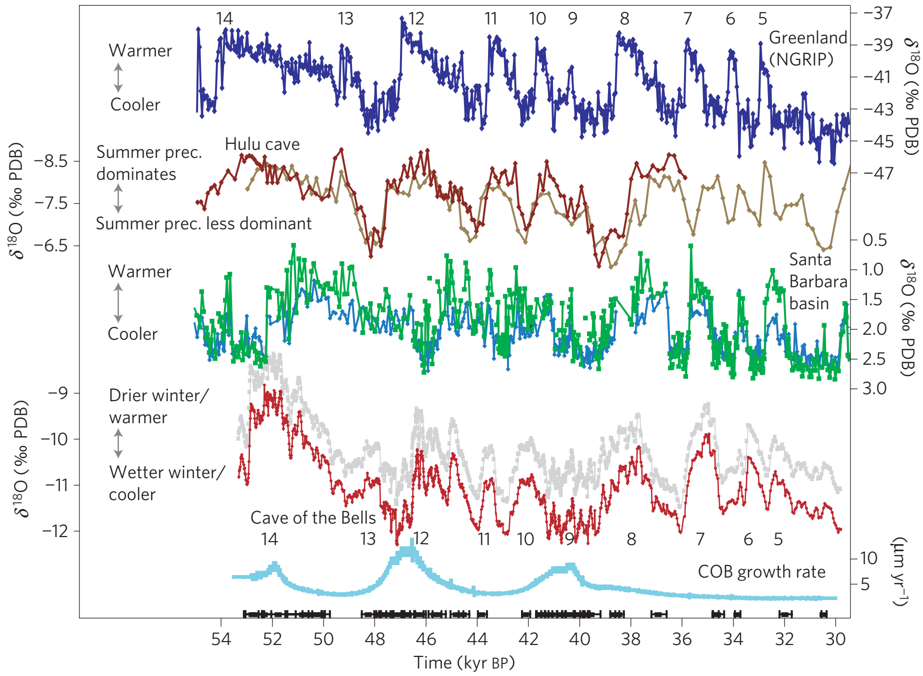

Figure 3 | Comparison of COB record during MIS3 with other records of millennial variability. The ice-volume-corrected COB $\delta^{18}O$ is shown in red (grey is uncorrected) at the bottom, with speleothem growth rate and U/Th dates as in Fig. 2. From the top, we also show the North GRIP (Generaland) ice core $\delta^{18}O$ data plotted against the GICC05 age model[14] in dark blue, and the Hulu cave $\delta^{18}O$ records[7] plotted in light brown (core MSD) and dark brown (core MSL), indicating a stronger summer monsoon (negative $\delta^{18}O$) during interstadials. The Santa Barbara basin SST records[19] (blue and green) are plotted as in Fig. 2. Numbers indicate interstadial stages in the Greenland and COB records. Interpretations based on original references are indicated on the left (prec. is precipitation). PDB, PeeDee Belemnite.

and Great Basin may not respond as strongly to changes in Atlantic SST. Warmer Pacific Ocean SST during interstadials[19] may have a more important role in these areas.

How do our results bear on inferred mechanisms of millennial climate variability? A leading hypothesis for the origin of millennial variability during MIS3 is that meltwater pulses in the North Atlantic weaken the ocean's meridional overturning circulation, cool regional SST and lead to sea ice expansion; these cold stadials are followed by a recovery to stronger meridional overturning circulation and North Atlantic Ocean warming[3]. Climate model experiments forced by freshwater input to the North Atlantic Ocean ('hosing') suggest that the atmospheric circulation response to North Atlantic SST variability can influence moisture delivery at our site. In a comparison of four coupled models forced by freshwater hosing, all showed a North Pacific Ocean response that included a stronger winter Aleutian Low during stadials[24]. Observations link a deeper Aleutian Low with wetter conditions in the Southwest US and a southward-shifted storm track during modern El Niño events[25]. Thus a deeper Aleutian Low during stadials would be consistent with our inference of wetter conditions at COB. The global impact of North Atlantic Ocean SST variations has also been explored using simulations and observations of the Atlantic Multidecadal Oscillation. These results point to atmospheric circulation responses that align with the hosing experiments. A colder North Atlantic Ocean leads to a southward shift in the westerly storm tracks in the Pacific Ocean[18] and increased precipitation at our site (Fig. 1).

Atmospheric circulation responses to North Atlantic Ocean variability can explain the co-occurrence of anomalies in disparate regions. In climate-model studies, North Atlantic Ocean cooling leads to a southward shift of the Atlantic intertropical convergence zone (ref. 26), a deeper Aleutian Low[18,24] and weaker East Asian summer monsoons[27]. These simulated responses are consistent with a growing suite of well dated palaeoclimate records, including our new record from the southwestern US. New ice-core analyses indicate that such atmospheric circulation responses precede even Greenland temperature during stadial–interstadial transitions and can occur within a few years[28]. These results highlight the critical role of atmospheric processes in propagating abrupt change globally. Our speleothem record clearly indicates that the hydroclimate of the southwestern US is sensitive to atmospheric circulation changes that most likely initiated in the North Atlantic Ocean.

Studies of recent drought in the Southwest US often invoke variability in the El Niño–Southern Oscillation (ENSO) system, which strongly controls moisture in the Southwest US today. If we interpret our data in an ENSO framework, we would infer El Niño-like conditions from increased moisture during stadials. However, stadials are cool in the Santa Barbara basin[19], the opposite of what we would expect during El Niño conditions. Other Pacific-based palaeoclimate studies disagree on whether interstadials resemble La Niña-like or El Niño-like conditions[6,15]. Broad patterns of stadial–interstadial change do not conform to patterns associated with modern ENSO teleconnections[2,29]. Nonetheless, millennial variability clearly engages elements of tropical Pacific Ocean climate[4,6,15]. Modelling studies suggest a linkage between stadials (forced by North Atlantic freshwater hosing) and either El Niño or enhanced ENSO variability in several models, although specific physical responses are model dependent[26]. In these studies, a southward shift of the intertropical convergence zone during stadials, well documented from palaeoclimatic records[4,5,29], mediates the response of the tropical Pacific Ocean to North Atlantic Ocean variations. Our results indicate that North Atlantic variability ultimately influences the position of the Pacific Ocean storm track, but we cannot yet disentangle extratropical atmospheric effects from those mediated through tropical interactions.

Multidecadal North Atlantic Ocean variability may provide a basis for anticipating climate variability in coming decades[30]. Our work suggests a strong connection between Atlantic Ocean SST

© 2010 Macmillan Publishers Limited. All rights reserved.

and winter precipitation in the Southwest US that could be used to improve long-term predictions of regional water resources. The net effect of the Atlantic Ocean and other influences (for example, Pacific Ocean and annular modes) on Southwest US precipitation as climate warms under human influence will have profound consequences for water resources, and thus for human and natural systems, in this rapidly growing region.

Received 15 June 2009; accepted 2 November 2009; published online 10 January 2010

References

1. Alley, R. B. *et al.* Abrupt climate change. *Science* **299,** 2005–2010 (2003).
2. Overpeck, J. T. & Cole, J. E. Abrupt change in Earth's climate system. *Ann. Rev. Environ. Res.* **31,** 1–31 (2006).
3. Broecker, W. S. Abrupt climate change: causal constraints provided by the paleoclimate record. *Earth Sci. Rev.* **51,** 137–154 (2000).
4. Leduc, G. *et al.* Moisture transport across Central America as a positive feedback on abrupt climatic changes. *Nature* **445,** 908–911 (2007).
5. Peterson, L. C., Haug, G. H., Hughen, K. A. & Rohl, U. Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial. *Science* **290,** 1947–1951 (2000).
6. Stott, L., Poulsen, C., Lund, S. & Thunell, R. Super ENSO and global climate oscillations at millennial timescales. *Science* **297,** 222–226 (2002).
7. Wang, Y. J. *et al.* A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, China. *Science* **294,** 2345–2348 (2001).
8. Barnett, T. P. *et al.* Human-induced changes in the hydrology of the western United States. *Science* **319,** 1080–1083 (2008).
9. Cook, E. R., Seager, R., Cane, M. A. & Stahle, D. W. North American drought: Reconstructions, causes, and consequences. *Earth Sci. Rev.* **81,** 93–134 (2007).
10. Anderson, R. S., Betancourt, J. L., Mead, J. I., Hevly, R. H. & Adam, D. P. Middle- and late-Wisconsin paleobotanic and paleoclimatic records from the southern Colorado Plateau, USA. *Paleogeogr. Paleoclimatol. Paleoecol.* **155,** 31–57 (2000).
11. Pigati, J. S., Bright, J. E., Shanahan, T. M. & Mahan, S. A. Late Pleistocene paleohydrology near the boundary of the Sonoran and Chihuahuan deserts, southeastern Arizona, USA. *Quat. Sci. Rev.* **28,** 286–300 (2009).
12. Dansgaard, W. *et al.* Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* **364,** 218–220 (1993).
13. Johnsen, S. J. *et al.* Irregular glacial interstadials recorded in a new Greenland ice core. *Nature* **359,** 311–313 (1992).
14. Svensson, A. *et al.* A 60 000 year Greenland stratigraphic ice core chronology. *Clim. Past* **4,** 47–57 (2008).
15. Turney, C. S. M. *et al.* Millennial and orbital variations of El Nino/Southern Oscillation and high-latitude climate in the last glacial period. *Nature* **428,** 306–310 (2004).
16. Cayan, D. R., Redmond, K. T. & Riddle, L. G. ENSO and hydrologic extremes in the western United States. *J. Clim.* **12,** 2881–2893 (1999).
17. Enfield, D. B., Mestas-Nunez, A. M. & Trimble, P. J. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophys. Res. Lett.* **28,** 2077–2080 (2001).
18. Zhang, R. & Delworth, T. L. Impact of the Atlantic multidecadal oscillation on North Pacific climate variability. *Geophys. Res. Lett.* **34,** L23708 (2007).
19. Hendy, I. L. & Kennett, J. P. Dansgaard–Oeschger cycles and the California Current System: Planktonic foraminiferal response to rapid climate change in Santa Barbara Basin, Ocean Drilling Program hole 893A. *Paleoceanography* **15,** 30–42 (2000).
20. Denniston, R. F. *et al.* Synchronous millennial-scale climatic changes in the Great Basin and the North Atlantic during the last interglacial. *Geology* **35,** 619–622 (2007).
21. Winograd, I. J. *et al.* Devils Hole, Nevada, δO-18 record extended to the mid-Holocene. *Quat. Res.* **66,** 202–212 (2006).
22. Benson, L., Lund, S., Negrini, R., Linsley, B. & Zic, M. Response of North American Great Basin Lakes to Dansgaard–Oeschger oscillations. *Quat. Sci. Rev.* **22,** 2239–2251 (2003).
23. Kirby, M. E., Lund, S. P. & Bird, B. W. Mid-Wisconsin sediment record from Baldwin Lake reveals hemispheric climate dynamics (Southern CA, USA). *Paleogeogr. Paleoclimatol. Paleoecol.* **241,** 267–283 (2006).
24. Okumura, Y., Deser, C., Hu, A., Timmermann, A. & Xie, S. P. North Pacific climate responses to freshwater forcing in the subarctic North Atlantic: Oceanic and atmospheric pathways. *J. Clim.* **22,** 1424–1445 (2009).
25. Liu, Z. & Alexander, M. Atmospheric bridge, oceanic tunnel, and global climatic teleconnections. *Rev. Geophys.* **45,** R62005 (2007).
26. Timmermann, A. *et al.* The influence of a weakening of the Atlantic meridional overturning circulation on ENSO. *J. Clim.* **20,** 4899–4919 (2007).
27. Lu, R. Y., Dong, B. W. & Ding, H. Impact of the Atlantic multidecadal oscillation on the Asian summer monsoon. *Geophys. Res. Lett.* **33,** L24701 (2006).
28. Steffensen, J. P. *et al.* High-resolution Greenland Ice Core data show abrupt climate change happens in few years. *Science* **321,** 680–684 (2008).
29. Wang, X. F. *et al.* Millennial-scale precipitation changes in southern Brazil over the past 90,000 yr. *Geophys. Res. Lett.* **34,** L23701 (2007).
30. Keenlyside, N. S., Latif, M., Jungclaus, J., Kornblueh, L. & Roeckner, E. Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature* **453,** 84–88 (2008).

Acknowledgements

We appreciate constructive comments from T. Ault, T. Broccoli, K. Dahl, I. Hendy, J. Overpeck and J. Quade, and useful critiques from two anonymous reviewers. Dripwater collection has been sustained by D. Hoburg, and permission to work at the Cave of the Bells was facilitated by J. Trout, US Forest Service. C. Eastoe and A. Long provided the Tucson precipitation isotopic data. This work was supported by the US National Science Foundation (Earth system history 03-18480), the University of Arizona (Faculty Small Grant program and Geosciences Department) and the Geological Society of America.

Author contributions

J.E.C., J.W.B. and P.J.P. conceived the study. J.D.M.W., P.J.P. and G.M.H. implemented the U/Th analyses. J.D.M.W., H.R.B. and J.E.C. implemented the stable isotopic analyses. All authors participated in data discussion and interpretation. J.E.C. and J.D.M.W. wrote the initial manuscript, and all authors provided substantial comments and editorial revisions to the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to J.E.C.

© 2010 Macmillan Publishers Limited. All rights reserved.