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Variable winter moisture in the southwestern United States linked to rapid glacial climate shifts

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During the last glacial period, the climate of the Northern Hemisphere was characterized by rapid, large-amplitude temperature fluctuations through cycles lasting a few thousand years[1–3]. These fluctuations are apparent in Greenland temperature reconstructions[2,3], and corresponding temperature and hydrological variations have been documented throughout the Northern Hemisphere[4,5]. Here we present a record of precipitation in the southwestern United States from 56,000 to 11,000 yr ago, on the basis of $\delta^{18}O$ measurements of speleothem calcite from New Mexico. Our record shows that increased winter precipitation in the southwestern United States is associated with Northern Hemisphere cooling, which we attribute to a southward shift in the polar jet stream, which modulated the position of the winter storm track over North America. On the western side of the Pacific Ocean basin, decreases in summer monsoon precipitation are associated with Northern Hemisphere cooling, due to southward displacement of the intertropical convergence zone[4]. We conclude that cooling and warming excursions in the Northern Hemisphere lead to concurrent latitudinal displacement of both the intertropical convergence zone and the polar jet stream over the Pacific Ocean. Our data are consistent with modern evidence for a northward shift of the polar jet stream in response to global warming[6–8], which could lead to increasingly arid conditions in southwestern North America in the future.

During the last glacial, climate in the polar Northern Hemisphere was punctuated by rapid climate fluctuations known as Dansgaard–Oeschger (DO) events. These rapid oscillations are marked by rapid warming, followed by slow cooling. The most prominent coolings, known as Heinrich events (HEs), were associated with massive iceberg discharge into the North Atlantic Ocean[1]. These cycles are best expressed in the variations of the isotopic ratios of ice in the Greenland ice cores[5,9]. The climate of continental interiors during these rapid swings in polar climate may provide insight into how these regions will respond to future rapid climate change, such as that forced by anthropogenic greenhouse gases.

Climate in the Northern Pacific basin is partly modulated by the El Niño–Southern Oscillation on interannual timescales and the Pacific Decadal Oscillation on decadal timescales. On centennial to millennia timescales, it has been shown that the East Asian monsoon (EAM) responds to Northern Hemisphere climate-forcing through modulation of the intertropical convergence zone (ITCZ; ref. 4). Over longer, orbital timescales, it has been suggested that the high stands of lakes in western North America during the Last Glacial Maximum were associated with the southward shift of the polar jet stream[10,11]. The effect of centennial- to millennial-scale Northern Hemisphere climate modulation is less clear, in part owing to the lack of high-resolution proxies that can be absolutely dated. This is particularly true in arid regions, although speleothems have now provided new opportunities, especially with the advent of new multicollector inductively coupled plasma mass spectrometric techniques for the analysis of U-series isotopes in small samples[12].

For this study we collected a well-suited (high uranium and low detrital thorium concentrations) stalagmite from Fort Stanton Cave in central New Mexico (Fig. 1). The stalagmite, FS-2, was collected approximately 1 km into the cave, where the cave climate is exceptionally stable, with relative humidity at 100% through most of the year (Supplementary Fig. S1). We obtained 68 high-precision uranium-series dates using multicollector inductively coupled plasma mass spectrometry with typical age uncertainties of less than 1% (Supplementary Table S1), showing that stalagmite FS-2 grew continuously from 55.9 to 11.4 kyr. Coupled with the chronology, we measured 1209 $\delta^{18}O$ isotopic values along 122 mm of the axis of the sample, with an effective average resolution of 37 yr/subsample over this 44.5 kyr period (Supplementary Table S2). The $\delta^{18}O$ record has a large 6‰ range, from −11.52‰ to −5.50‰. Given 100% relative humidity in the cave and low correlation between $\delta^{13}C$ and $\delta^{18}O$ values ($R^2 = 0.07$, Supplementary Fig. S2), the large range in the isotopic values probably reflects changes in the isotopic composition of precipitation (rain and snow) that is transported through bedrock infiltration into the cave and minimally affected by kinetic isotope fractionation or evaporation during the slow growth of stalagmite FS2.

The $\delta^{18}O$ record of FS-2 is remarkably similar to other Northern Hemisphere climate records (Fig. 2) in both orbital and millennial timescales, including HEs and DO events. Our record includes the Younger Dryas (H0) and several HEs back to H5. The timings, within the chronologic uncertainties of the two records, and amplitudes of these events in our record and GISP II are exceptionally comparable. The large rapid shifts in $\delta^{18}O$ values seen in the GISP II icecore are transferred through atmospheric precipitation into the cave system, and preserved in speleothems as comparably fast climate transitions (3–6‰ shifts in less than 300 yr, that is, from −11.3 to −5.6‰ in 300 yr from 15.2 to 14.9 kyr). We take the speleothem $\delta^{18}O$ variations to be a near-direct proxy for variations in precipitation $\delta^{18}O$, which may reflect changes in air temperature, seasonality, amount of rainfall and other factors. The study area receives more than half of its annual precipitation during the summer months from the North American monsoon, which derives its moisture from the Gulf of Mexico and Gulf of California (Gulf) (data for New Mexico for the period 1895–2005 provided by the National Climatic Data Center at http://www.ncdc.noaa.gov). Although Pacific storms during the winter months constitute only a third of the amount of summer rains, they are likely to be an important source of recharge[13]. Summer precipitation is enriched in ^{18}O, with $\delta^{18}O$ values of about −2‰ whereas winter precipitation has low $\delta^{18}O$ values, on average around −11‰ (refs 14, 15). On the basis of modern speleothem

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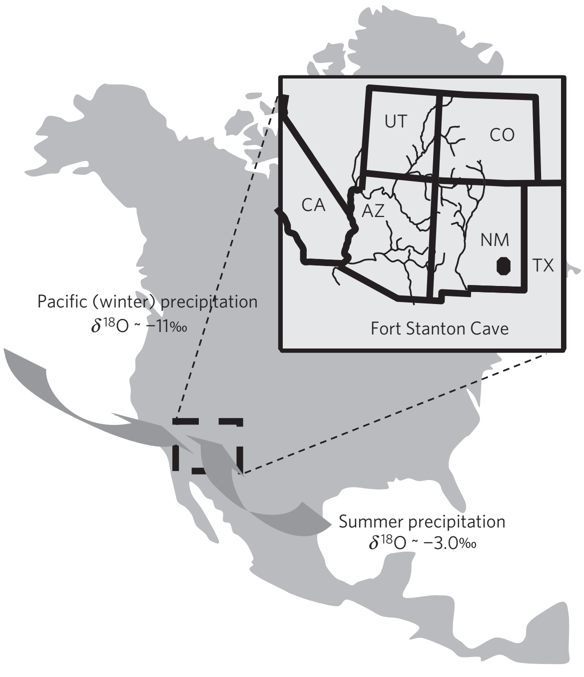

Figure 1 | Location map of Fort Stanton Cave, New Mexico, United States. The cave, typical of other parts of the southwestern United States, has two rainy seasons, consisting of summer North American monsoon rainfall, derived from the Gulf of Mexico, with $\delta^{18}O$ values in the range of −3‰, and Pacific-derived winter precipitation with low $\delta^{18}O$ values, in the range of −11‰ (refs 14, 15).

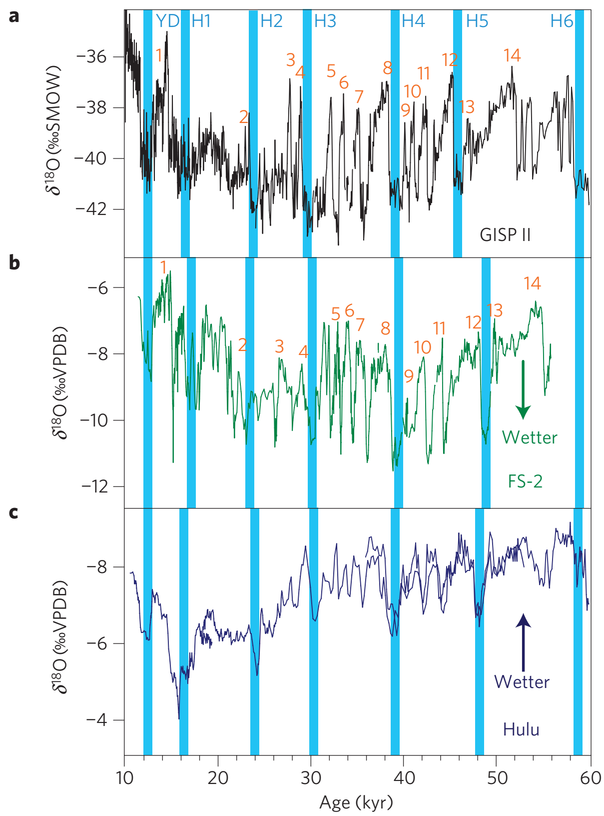

Figure 2 | Last glacial $\delta^{18}O$ variations. a, Greenland ice core (GISP II, black; ref. 2). **b**, Fort Stanton stalagmite (FS-2, green). **c**, Hulu Cave stalagmites (blue; ref. 4). The Younger Dryas (YD) and HEs (ref. 5) are shown as blue bars and blue numbers, whereas 14 DO events are shown in orange numbers[1–3,5]. In the FS-2 record, HEs correspond to increased Pacific (winter) contribution to regional precipitation, whereas DO events correspond to less Pacific (winter) contribution. Both FS-2 and Hulu capture the major swings in the GISP II record, but they have opposite response: increase in $\delta^{18}O$ (dry) in one record corresponds to decrease (wet) in the other (their axes are reversed in the figure). The ages for H5 in FS-2 and Hulu are within error of each other, but older than the age assigned in GISP II.

data (see Supplementary Information) the annual balance of effective moisture, precipitation–evaporation, between the two sources works out to be about 32% from Pacific-sourced, mostly winter, precipitation and 68% from summer North American monsoon precipitation (see Supplementary Information). Thus, a change in the balance between summer and winter precipitation is likely to be an important source of variability seen in our record.

At mid-latitude sites, such as the study area, the air temperature also influences the $\delta^{18}O$ of precipitation. The precise relationship between air temperature and $\delta^{18}O$ of precipitation can vary considerably, but is generally of the order of 0.5–0.69‰ $^{\circ}C^{-1}$ in temperate regions[16]. Any long-term temperature change that results in a change in $\delta^{18}O$ of precipitation, however, will also change the $\delta^{18}O$ of speleothem calcite by changing cave air temperatures. The temperature dependence of oxygen-isotope fractionation during calcite precipitation is −0.24‰ $^{\circ}C^{-1}$ (ref. 17). The net slope of the relationship between air temperature and speleothem calcite $\delta^{18}O$ will be of the order of 0.25–0.35‰ $^{\circ}C^{-1}$ in the study area. Thus, if due to temperature alone, the observed 6‰ range in speleothem $\delta^{18}O$ would require a 17–24 °C temperature change, which is more than three times the estimated 5–6 °C glacial/interglacial temperature change for the region[18,19]. Therefore, we attribute approximately half, or $\leqslant$3‰, of the observed $\delta^{18}O$ variability in our record to temperature, using 0.69‰ $^{\circ}C^{-1}$, the high end in the range of the $\delta^{18}O$/ air temperature gradient to be conservative, and the remainder to changes in the balance between winter (Pacific) and summer (Gulf) precipitation. For comparison, a speleothem from Oregon, northwest United States, with a single, continuous Pacific precipitation source[20], shows variability of about 3‰ during the Holocene–Pleistocene transition, a period in which the full 6‰ range in $\delta^{18}O$ is shown by FS-2. Using the Oregon record as a single-source end-member (Pacific), half of our 6‰ range is attributed to temperature, and the other half would therefore be attributed to moisture source, consistent with our temperature-effect calculations above.

In the modern North American regime the strength of winter storms is modulated by the position of the polar jet stream: colder-than-normal polar temperatures push the jet stream further south towards southwestern North America (ref. 11), which results in higher Pacific-dominated (winter) precipitation and higher annual precipitation[21], expressed as lower $\delta^{18}O$ values of mean annual rainfall[22]. Given ∼9‰ difference between summer and winter precipitation, a 3‰ change in calcite value during HEs and DO events translates to an approximately 0.33 fractional change in the contribution of winter precipitation (see Supplementary Section S2). Thus, during the lowest excursions, such as the time leading up to the Bølling–Allerød or during H4, the relative Pacific-source contribution to effective moisture must have been double its present value ($0.32 + 0.33 = 0.65$), or 65% of the annual precipitation–evaporation budget (see Supplementary Information).

Meridional oscillation in polar temperature and atmospheric circulation patterns should have implications for the positions of other regional and global climate modulators. Variations in the strength of the EAM during the last glacial period, as recorded in a speleothem from Hulu Cave, eastern China, have been attributed to changes in the position of the ITCZ as a direct response to polar Northern Hemisphere forcing[4]. There is a remarkable inverse

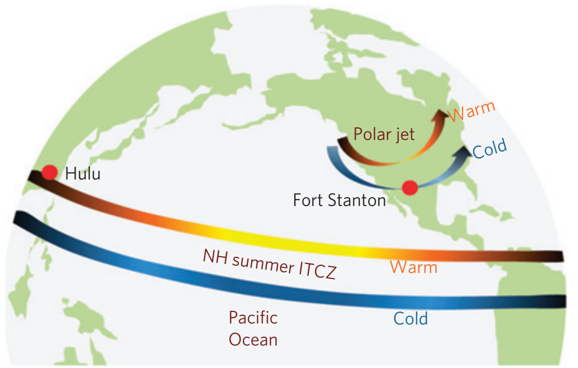

Figure 3 | Schematic representation of meridional shifts of the ITCZ and the polar jet stream. During DO events (warming swings), both the ITCZ and polar jet move northward, leading to drier conditions in SWNA and wetter conditions in the EAM regions. During HEs (cold swings), the ITCZ and the polar jets move southward, leading to wetter SWNA and drier EAM. Such a model is consistent with the responses (similar but opposite in sign) recorded in the F-2 (Fort Stanton, NM) speleothem and Hulu (China) speleothem (Fig. 2).

match between our FS-2 and the Hulu Cave record (Supplementary Fig. S3). This inverse relationship between EAM and SWNA climate seems to be a stable feature of the two climate regimes, even during the Holocene (Supplementary Fig. S3; ref. 23).

The Hulu Cave record, just like our FS-2 record, shows changes that correspond to HEs and DO events as seen in GISP II (Fig. 2). There is a better chronological match between the absolutely dated FS-2 and Hulu records than GISP II beyond 35 kyr ago. As previously suggested[4], and as our data also support, the small discrepancies between the speleothem-based records and GISP II are likely to be due to problems with the GISP II chronology and not an issue of lag or lead in climate response. For example, the timing of H5, on the basis of our record and the Hulu record (Fig. 2), is closer to 48 kyr rather than the previous age of ~45 kyr based on ice chronology[5]. The one noticeable difference between FS-2 and Hulu is the trend in the baseline signal between 15 and 30 kyr ago. Our record follows the GISP II trend whereas Hulu trends differently (Fig. 2). Overall, the coherence between FS-2 and Hulu is best explained by a meridional shift in climate zones in the Pacific Basin in response to changes in pole-to-Equator temperature gradient.

During warming episodes, the pole-to-Equator gradient decreases, shifting the polar jet stream and the Northern Hemisphere summer ITCZ further north. The opposite would happen during cold swings (Fig. 3). Analysis of later Holocene climate and historical data show that years of severe droughts are primarily the result of deficit in winter precipitation[22]. Given the rapid and synchronous response of the northern Pacific basin to changes in the pole-to-Equator temperature gradient, global warming may result in profound changes in precipitation of part of the hemisphere affected by the ITCZ and polar jet. This is particularly ominous for drought-sensitive regions, such as the western United States. Our projection is supported by numerical simulations of future climate under various greenhouse-warming scenarios, which find poleward shift of the jet streams[6]. Historical analysis of the variability of the position of jet streams (both the subtropical and polar jets) also seems to support our projection of the effect of global warming on regional precipitation[7,8]. The poleward shift during DO events occurred at a time when the earth was in a glacial state. An example of 'extra' warming during an interglacial, expressed as a +4 to +6 m rise in sea level relative to today, at the end of the last interglacial 125,000 yr ago has been reported[24]. Rapid DO-like warming due to greenhouse-gas forcing during the present interglacial stage could push SWNA into an even more arid phase, unseen since the early Holocene, or even go beyond this, into conditions not represented since 125,000 yr ago.

Methods

U-series isotope measurements were made at the Radiogenic Isotope Laboratory, University of New Mexico. Subsample powders (50–200 mg) were drilled and dissolved in nitric acid and spiked with a mixed ^{229}Th–^{233}U–^{236}U spike. U and Th were separated using conventional anion-exchange chromatography. Most of the U and Th measurements were made on a Neptune multicollector inductively coupled plasma mass spectrometer. In the spectrometer all U and Th isotopes were measured in a static mode using a mix of 10^{11}–10^{12} Ω resistors in conjunction with seven Faraday cup detectors and an ion-counting secondary electron multiplier detector, following the method described in ref. 12. Secondary electron multiplier–Faraday gain was established using a CRM-145 U standard for U and an in-house Th standard for Th analyses. Mass-fractionation correction was done using the ^{233}U/^{236}U ratio of 1.000 46 for U isotope analyses. For Th analyses standard-sample bracketing was used to correct for mass fractionation and instrument drift. The CRM-145 U isotope standard was measured with the samples, obtaining the conventionally accepted δ^{234}U value of -36.5 ± 0.5‰ (ref. 25). $\delta^{234}\mathrm{U} = [[^{234}\mathrm{U}/^{238}\mathrm{U}_{\mathrm{sample}}/^{234}\mathrm{U}/^{238}\mathrm{U}_{\mathrm{secular\ equilibrium}}]-1]\times10^3$, where $^{234}\mathrm{U}/^{238}\mathrm{U}_{\mathrm{secular\ equilibrium}} = \lambda_{238}/\lambda_{234}$ and λ is the decay constant[25]: $\lambda_{230} = 9.1577\times10^{-6}\ \mathrm{yr}^{-1}$, $\lambda_{234} = 2.8263\times10^{-6}\ \mathrm{yr}^{-1}$, $\lambda_{238} = 1.55125\times10^{-10}\ \mathrm{yr}^{-1}$. U and Th procedural blanks were in the range of 5–10 pg and therefore have no effect on ages. The analytical uncertainties are 2 σ of the mean. The age uncertainties include analytical errors and uncertainties in the initial ^{230}Th/^{232}Th ratios. A full discussion of the age model used for assigning ages to individual stable-isotope analyses is presented in Supplementary Information.

The δ^{18}O and δ^{13}C values were measured at the University of Massachusetts Stable Isotope Laboratory. Subsamples were drilled with a 0.5-mm-diameter bit along the stalagmite FS-2 growth axis at 0.1 mm intervals by moving the bit along the axis of the stalagmite. Stalagmite powders were reacted with a few drops of anhydrous phosphoric acid at 70 °C in a Finnigan Kiel-III automated carbonate-preparation device directly coupled to a Finnigan Delta Plus ratio mass spectrometer. Results are reported in standard permil (‰) notation with respect to Vienna Pee Dee Belemnite (VPDB). The internal precision is ~0.1% for δ^{18}O and δ^{13}C.

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Author contributions
Y.A. was principal investigator and V.J.P. was co-investigator. V.J.P. and Y.A. were responsible for U/Th dating and S.J.B. for oxygen isotopic analysis. V.J.P. was responsible for sample collection. Y.A. wrote the manuscript with contributions from V.J.P. and S.J.B.

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 Y.A.