Extrapolar climate reversal during the last deglaciation

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Large ocean-atmosphere and hydroclimate changes occurred during the last deglaciation, although the interplay between these changes remains ambiguous. Here, we present a speleothem-based high-resolution record of Northern Hemisphere atmospheric temperature driven polar jet variability, which matches the Greenland ice core records for the most of the last glacial period, except during the last deglaciation. Our data, combined with data from across the globe, show a dramatic climate reversal during the last deglaciation, which we refer to as the Extrapolar Climate Reversal (ECR). This is the most prominent feature in most tropical and subtropical hydroclimate proxies. The initiation of the ECR coincides with the rapid rise in CO2, in part attributed to upwelling in the Southern Ocean and the near collapse of the Atlantic Meridional Overturning Circulation. We attribute the ECR to upwelling of cold deep waters from the Southern Ocean. This is supported by a variety of proxies showing the incursion of deep Southern Ocean waters into the tropics and sub-tropics. Regional climate variability across the extrapolar regions during the interval previously referred to as the “Mystery Interval” can now be explained in the context of the ECR event.

The last deglaciation is characterized by large changes in SST1–3 ocean circulation4 and atmospheric CO25, 6 and regional hydroclimate7–10. Understanding the causal interplay between these changes, is vital for attribution of large-scale climate variability. The period following the Last Glacial Maximum (LGM) may be most accessible for detailed study because of the substantial number of proxies for upwelling6, 11–13, changes in CO2 concentration and temperature. Such records are primarily from ice cores and marine proxies and are linked to a period of dramatic change in tropical and subtropical hydroclimate.

Here we present a new δ18O time-series from a fast-growing, precisely dated stalagmite (FS-AH1), from Fort Stanton cave, New Mexico, USA (Figs 1 and 2A, Fig. S1), the same site from which stalagmite FS-2 was collected for our earlier work showing changes in the contribution of winter precipitation, driven by changes in the position of the polar jet stream7. The new δ18O time-series (Fig. 2A) is anchored by high-precision uranium (U)-series chronology (Fig. S2) facilitated by (1) the uninterrupted high-growth rate of stalagmite FS-AH1 (triple the rate of stalagmite FS-2), (2) new gains in efficiency in multi-collector inductively coupled mass spectrometry (MC-ICPMS Neptune Plus), (3) availability of new high-purity 233U-236U spikes and, (4) more precise determinations of the half-lives of 234U and 230Th14.

Stalagmite FS-AH1 was collected ~1.5 km into Fort Stanton Cave (Fig. S1), where current cave temperature is stable at 10 ± 0.55°C and relative humidity is near 100% perennially. We measured 45 U-series ages reported as years before 2000 AD (yr b2k) (Table S1) using minimal amount of powder (40–110 mg) to reduce errors related to drill-hole sizes. Our chronology shows that stalagmite FS-AH1 grew continuously from 48.4 ± 0.1 to 11.2 ± 0.1 kyr b2k. A robust age model with fully propagated errors (Fig. S2) was constructed using the program COPRA, that utilizes a Monte Carlo simulation and a translation procedure that allows for calculation of proxy time-series age uncertainties from radiometric date uncertainties15. The mean error across the full age range, back to 48 kyr b2k, is ±71 years (2−σ). Coupled with the high-precision chronology, we made 422 δ18O measurements. The δ18O data have a large range, from −10.8‰ to −5.3‰ (VPDB), and are within the range of values expected for equilibrium fractionation for summer and winter precipitation (see below). The lack of δ13C/δ18O covariation (R ~ 0.00) also supports minimal kinetic isotopic effects (Fig. S3).

The imprint of millennial-scale climate variability over the last glacial period was documented in the southwestern United States by abrupt and large changes in stalagmite δ18O, which were previously shown to reflect, in part, changes in the ratio of winter to summer precipitation forced by meridional shifts in the polar jet stream7, 16. The region has two rainy seasons, consisting of summer North American monsoon rainfall, derived from the Gulf of Mexico, which is open to atmospheric moisture from the tropics. The abrupt δ18O swings are interpreted as indicating a rapid increase in Northern Hemisphere temperature and are hypothesized to be the result of rapid warming of the tropical North Atlantic, and possibly enhanced feedback in the Eastern Pacific, driven by the Pacific Decadal Oscillation and enhanced deep-water formation in the North Atlantic16. The record from Fort Stanton Cave is consistent with a variety of proxies showing the incursion of deep Southern Ocean waters into the tropics and sub-tropics. Regional climate variability across the extrapolar regions during the interval previously referred to as the “Mystery Interval” can now be explained in the context of the ECR event.

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of Mexico and Gulf of California, with \( \delta^{18}O \) in the range of \(-3\%\)\(_o\), and Pacific-derived winter precipitation with low \( \delta^{18}O \), in the range of \(-11\%\)\(_o\). In addition to changes in the balance between winter and summer moisture, a fraction of the large range in precipitation and speleothem \( \delta^{18}O \) is attributed to temperature variability\(^7,17\), estimated to be 5–6 °C for the region\(^18\) from the LGM to the Holocene. The balance between winter and summer precipitation contribution to cave infiltration is modulated by changes in the meridional position of the Northern Hemisphere Polar Jet\(^19\). Concurrent changes in the Asian monsoon but with the opposite effect on \( \delta^{18}O \) was explained as reflecting changes in position of the intertropical convergence zone (ITCZ)\(^7\). Alternatively, it was also suggested that ITCZ displacement during North Atlantic stadials, leading to strengthening of winter time
18O data (WDC) 22 the Southern Hemisphere polar ice core West Antarctic Ice Sheet (WAIS) Divide ice core δ18O record. Whether the Greenland ice-core δ18O match between stalagmite FS-AH1 and NGRIP 18O for DO events, including the sharp stadial to interstadial δ18O and atmospheric 14C ages6, both attributed to increased upwelling in the Southern Ocean (Fig. 5). The excursion in large-scale hydrologic variability in the interval encompassing the ECR and HS1 coincides with the time of AMOC collapse6 (Fig. 4A) and a dramatic reduction in subtropical Atlantic SST8 (Fig. 4B). The beginning of the ECR is synchronous with the initiation of atmospheric CO2 rise8, and the steep decrease in the ventilation ages of deep water reservoirs of the Southern Ocean, derived from the offset between benthic foraminifera and atmospheric 14C ages8, both attributed to increased upwelling in the Southern Ocean (Fig. 5). The excursion of deep waters from the Southern Ocean are expressed very distally, for example in the north Pacific Ocean, based both on Δ14C data and the North Atlantic ocean, based on silica concentration data19. All these proxy data support continuous incursion of cold deep, Δ14C-depleted Southern Ocean waters in to the extrapolar oceans during the period of the ECR event. More directly, a potential teleconnection between Southern Ocean upwelling and changes in the tropical Pacific hydrology is suggested thorough changes in the flux

Figure 3. Detailed comparison of the Northern Hemisphere Greenland ice-core NGRIP δ18O time-series2 and the Southern Hemisphere polar ice core West Antarctic Ice Sheet (WAIS) Divide ice core δ18O data (WDC)22 against the FS-AH1 record. The secular trends in the three records are remarkably similar through the LGM, showing that the growth of Northern Hemisphere ice sheets and deglaciation took place in the background of concurrent bi-polar warming with only a slight change during the ECR in both poles. The two poles diverge during the Northern Hemisphere cooling associated with HS1 proper and the three records rapidly changing during the transition to the Bølling-Allerød. The largest shift in the AH1 occurs during ECR, which is also the case for many tropical and subtropical hydroclimate and SST proxies (Fig. 6).
of Antarctic Intermediate Water (AAIW). Changes in the SST gradients between the northern eastern tropical Pacific and southern eastern tropical Pacific follow the changes seen in our FS-AH1 record, the lowest gradient coinciding with the tropical and subtropical hydrology described below.

The fingerprint of the 18.6 kyr b2k climate transition is expressed prominently in many records around the globe, primarily in subtropical and tropical climate regimes (Fig. 6A,B), such as the SE Asian monsoon expressed in the Hulu record (Fig. 6A), the Cariaco tropical marine record (Fig. 6A) and the concurrent weakening of tropical Pacific convection (Fig. 6A). The hydroclimate changes during the ECR is the most prominent feature in most subtropical and tropical climate records. Lowering of tropical and subtropical SSTs (Fig. 4B) leading to decrease in net equatorial heat transport, with the slowdown of the AMOC (Fig. 4B) resulting in southward shift of the Asian Monsoon (Fig. 6A). Similarly southward displacement of the ITCZ during the ECR, would lead...
to strengthening of winter time North Pacific subtropical jet, and increased winter precipitation in the western United States20.

Although we showed that stalagmite FS-AH1 δ18O variability is coupled to changes in the meridional position of the polar jet stream7, the hydroclimatic response in extrapolar regions may also be linked to changes in the ITCZ position, because such variations appear to be decoupled from Greenland and Antarctic temperatures during this interval. It has been previously suggested that variability in the proportion of winter versus summer precipitation in the southwest USA, reflected by the stalagmite δ18O record, may be explained by changes in the position of the ITCZ20. The Cariaco record most resembles the FS-AH1 record to the extent that the ECR and HS1 are clearly resolved in both records due to their direct link to the AMOC9 (Fig. 6B). But there is also a difference in detail. The Cariaco record shows a rise in organic carbon content after initial rapid decrease, followed by another decrease during HS1 (Fig. 6B). The rise in organic carbon may reflect the infusion of nutrient-rich water due to upwelling.

The period covering the ECR and HS1 is expressed prominently by changes in tropical hydrology, including the collapse of western tropical Pacific rainfall8 (Fig. 6C) and changes in SST in the eastern tropical Pacific2, and narrowing of the gradient across it3. Although we suggest that the ECR and HS1 are two distinct events with different causes, the impact of these two events is similar across a range of tropical and subtropical regions and are most likely driven by changes in the long-term position of the ITCZ. Both models and proxy data in general20, 30 and for the western tropical Pacific in particular31, 32 show a southward shift of the mean ITCZ position during cold events and drier than normal conditions32, consistent with the patterns observed in western tropical Pacific rainfall (Fig. 6C).
Our analysis of proxy data in the context of the global SST and hydroclimate data show that Southern Ocean upwelling had a profound influence across the globe, providing a coherent framework for understanding large changes in hydroclimate during a period previously dubbed as the mystery interval

Methods

U-series isotope measurements were made at the Radiogenic Isotope Laboratory, University of New Mexico. Subsample powders (40–110 mg) were drilled and dissolved in nitric acid and spiked with a mixed 229Th-233U-234U spike. U and Th were separated using conventional anion-exchange chromatography. U and Th measurements were made on a Thermo Neptune plus configured multicollector inductively coupled plasma mass spectrometer (MC-ICPMS). The MC-ICPMS measurements were run in static mode using a mix of 10^-11 and 10^-12 Ω resistors in conjunction with five Faraday cup detectors and an ion-counting secondary electron multiplier detector, following the method described in ref. 35. The CRM-145 U isotope standard was measured with the samples, obtaining the conventionally accepted δ²³⁴U value of −38.5‰. U and Th procedural blanks were in the range of 5–10 pg and therefore have no effect on ages. The analytical uncertainties are 2σ of the mean. The age uncertainties include analytical errors and uncertainties in the initial ²³⁰Th/²³²Th ratios. Initial ²³⁰Th/²³²Th ratios were corrected using an empirical value of 30 ± 15 ppm, allowing for a range of contributions, from silicate to carbonate materials. The sample is very clean and thus not sensitive to initial ²³⁰Th correction, in addition to the fact that the samples are older than 10 kyrs.

Powders for δ¹⁸O analysis were sampled along the FS-AH1 growth axis at 1 mm intervals and were analyzed at the Las Vegas Isotope Science Lab (LVIS) of the University of Nevada, Las Vegas. Stalagmite powders were reacted with three drops of anhydrous phosphoric acid at 70 °C in a ThermoElectron Kiel-IV automated carbonate preparation device coupled to a Delta V Plus mass spectrometer. Values are reported in standard permil (‰) notation with respect to Vienna Pee Dee Belemnite (VPDB). Internal standard precision is better than 0.08‰ for δ¹⁸O.

Data accessibility. The AH-1 U-series data are included in the Supplemental Materials; the δ¹⁸O data are archived at the NOAA National Centers for Environmental Information website

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**Author Contributions**
Y.A. was principal investigator and wrote the manuscript, followed by revisions and inputs from V.J.P. and M.S.L. The U-series chronology was done by V.P. and Y.A., while M.S.L. performed the stable isotopic analysis. Field work and sample collection was done by Y.A. and V.J.P.

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