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LETTERS

Moisture transport across Central America as a positive feedback on abrupt climatic changes

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Moisture transport from the Atlantic to the Pacific ocean across Central America leads to relatively high salinities in the North Atlantic Ocean[1] and contributes to the formation of North Atlantic Deep Water[2]. This deep water formation varied strongly between Dansgaard/Oeschger interstadials and Heinrich events—millennial-scale abrupt warm and cold events, respectively, during the last glacial period[3]. Increases in the moisture transport across Central America have been proposed to coincide with northerly shifts of the Intertropical Convergence Zone and with Dansgaard/Oeschger interstadials, with opposite changes for Heinrich events[4]. Here we reconstruct sea surface salinities in the eastern equatorial Pacific Ocean over the past 90,000 years by comparing palaeotemperature estimates from alkenones and Mg/Ca ratios with foraminiferal oxygen isotope ratios that vary with both temperature and salinity. We detect millennial-scale fluctuations of sea surface salinities in the eastern equatorial Pacific Ocean of up to two to four practical salinity units. High salinities are associated with the southward migration of the tropical Atlantic Intertropical Convergence Zone, coinciding with Heinrich events and with Greenland stadials[5]. The amplitudes of these salinity variations are significantly larger on the Pacific side of the Panama isthmus, as inferred from a comparison of our data with a palaeoclimate record from the Caribbean basin[6]. We conclude that millennial-scale fluctuations of moisture transport constitute an important feedback mechanism for abrupt climate changes, modulating the North Atlantic freshwater budget and hence North Atlantic Deep Water formation.

Paleotemperatures recorded in Greenland indicate that rapid climatic changes occurred on a millennial timescale during Marine Isotope Stage 3 (MIS3[5,7], between 59 and 25 kyr BP) and were intimately linked to the process of North Atlantic Deep Water (NADW) formation[2,3] (the Dansgaard–Oeschger[5] and Heinrich events[7], H-DO variability). The H-DO features are also observed in tropical areas sensitive to summer monsoon fluctuations, which were linked to latitudinal shifts of the Intertropical Convergence Zone (ITCZ)[4,8,9]. To explain the existence of H-DO features at different latitudes, we need to understand how climatic teleconnections are set up between high and low latitudes and/or different ocean basins[10,11].

In modern climatology, the interoceanic freshwater transfer from the Atlantic to the Pacific Oceans maintains the high Atlantic salinity required for NADW formation[1]. This is achieved by the combination of strong easterly winds and increased atmospheric humidity within the Caribbean region[12], which occurs mainly during the boreal summer when the ITCZ is shifted northward (Supplementary Information). Modelling studies imply that the modern interoceanic vapour flux ranges from 0.13 Sv (ref. 1) to 0.45 Sv (ref. 13) ($1\ \mathrm{Sv} = 10^6\ \mathrm{m^3\ s^{-1}}$).

For the Last Glacial Maximum (LGM), different models show either an increased[14] or a decreased[15] water vapour export from the Atlantic Ocean. Recent work on marine sequences covering the last deglaciation suggested that cross-isthmus vapour transport was not strongly affected by glacial boundary conditions[16]. Rather, the interoceanic vapour transport and the interbasin salt contrast seem to have been influenced by ITCZ dynamics, which contributed to the hydrological variability in the Eastern Equatorial Pacific (EEP) region[16]. From this point of view, the EEP appears to be a key climatic crossroad involved in rapid climatic changes. To understand better how the ITCZ dynamics and the moisture transfer changes across Central America evolved with respect to the H-DO variability, it is crucial to gather observations covering the entire MIS3, and in particular at the prominent six Heinrich events. Since the EEP sea surface salinities (SSS) are intimately linked to the intensity of the ITCZ and its mean latitudinal position (Fig. 1), reconstructing past EEP SSS fluctuations allows us to track variations in moisture transport across the Panama isthmus (Supplementary Information).

Here we present a multi-proxy record of past EEP hydrological characteristics from the sediment core MD02-2529 (08° 12.33′ N, 84° 07.32′ W, 1,619 m water depth) (Fig. 2). The $\delta^{18}O$ values for the surface-dwelling foraminifer *Globigerinoides ruber* ($\delta^{18}O_{G.\ ruber}$) are about −3‰ for the Holocene and decrease by about 2‰ between the MIS2 and the late Holocene (Fig. 2a). Rapid $\delta^{18}O_{G.\ ruber}$ variations of 0.5 to 1‰ occurred on a millennial timescale during MIS2 and the late part of MIS3. Two longer cycles with saw-tooth shapes are recorded between 40 and 46 kyr BP and between 46 and 53 kyr BP. From 58 to 90 kyr BP, fluctuations are observed with longer wavelengths and weaker amplitudes than the $\delta^{18}O_{G.\ ruber}$ shifts during MIS2 and 3.

The $U^{k'}_{37}$ sea surface temperatures ($U^{k'}_{37}$-SST) reconstruction agrees well with the record of the Mg/Ca-SST measured on *G. ruber*, except between 20 and 25 kyr BP (Fig. 2b, Supplementary Information). The mean Holocene SST of 28 °C (Fig. 2b) is within the range of modern SST values (Supplementary Information). A long-term 3 °C increase occurred between 25 and 10 kyr BP in $U^{k'}_{37}$-SST. The SST record for MIS3, 4 and 5 varies between 24.5 and 28 °C with minima and maxima centred at 30, 43 and 65 kyr BP, and at 38, 57 and 85 kyr BP, respectively. Therefore the EEP SST appear to vary independently from the millennial-scale variability of $\delta^{18}O_{G.\ ruber}$ (Fig. 2a, b), and the $\delta^{18}O$ of sea water ($\delta^{18}O_{sw}$) clearly indicates that the large-amplitude millennial-scale $\delta^{18}O_{G.\ ruber}$ fluctuations are driven by $\delta^{18}O_{sw}$ variations (Fig. 2a, c and Supplementary Information).

After the removal of the global $\delta^{18}O_{sw}$ linked to sea-level variations (ref. 17), rapid fluctuations in $\Delta\delta^{18}O_{sw}$ (a proxy for regional SSS) persist throughout the sequence (Fig. 3c). For the modern climate, a northern position of the ITCZ during the boreal summer leads to increased net precipitation in the EEP region (Fig. 1). Indeed, about half of the EEP precipitation originates from the Caribbean[18] and is brought to the Pacific side through zonal atmospheric transport

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across Central America, mainly during the wet summer season[12] (Supplementary Information). The salinity record based on $\Delta\delta^{18}O_{sw}$ can therefore be used as an indicator of rainfall and, in connection with similar records, of cross-isthmus moisture transport. Time intervals with low $\Delta\delta^{18}O_{sw}$ should correspond to periods of intensified moisture fluxes across the Panama isthmus.

The high-resolution reflectance record of the Cariaco Basin (Fig. 1) results from high/low productivity and terrigenous input associated with the northward/southward shifts of the ITCZ over the last glacial period[4]. The northern position of the ITCZ appears to be in phase with DO interstadials[4], while southward migrations of the ITCZ are in phase with Heinrich events and DO stadials (Fig. 3a, b). The MD02-2529 $\Delta\delta^{18}O_{sw}$ and Cariaco Basin reflectance data indicate that the northward migration of the ITCZ in the Cariaco Basin is associated with EEP SSS minima, and so to enhanced moisture export from the Atlantic, when the ITCZ was aligned with the Central America low-level mountain channels[4] (Fig. 3b, c). Therefore, the Equatorial Atlantic and the EEP are efficiently linked through atmospheric teleconnection.

Maximum EEP SSS occurred during H events and DO stadials (Fig. 3c). This is compatible with a southward migration of the ITCZ accompanied by a decrease in water vapour transport to the Pacific Ocean. The ITCZ displacements are also documented in northeastern Brazil at 10° S by well-dated growth phases of speleothems during the prominent H events, indicating wet climate at these periods[19] (Fig. 3d). The modern distribution of precipitation over South America in March (Fig. 1) implies a southward migration of the ITCZ over the Amazon Basin at the times of H events (Fig. 3d). These enhanced rainfall time intervals correspond to periods of increased runoff to the tropical Atlantic, as is clearly recorded in shallow sediments along the northeastern Brazilian coast[20] (Figs 1 and 3d). The orogenic blocking by the Andes prevented the export of water vapour from the Atlantic to the Pacific, and probably induced the recirculation of freshwater within the Atlantic Ocean during H events and DO stadials, mainly via the Amazon River outflow.

We consider similar records obtained from cores retrieved on the other side of the Panama isthmus in order to better constrain the EEP hydrological changes and to further study the moisture transport from the Atlantic to the Pacific. Recent work on a Caribbean sediment core (Fig. 1) has recorded regional SSS maxima during Heinrich events and the Younger Dryas[6], indicating that both sides of the isthmus were strongly influenced by north–south shifts of the ITCZ (Fig. 1), making the Atlantic and the Pacific salinity records in phase for their main features. However, a second-order antiphase pattern is superimposed on these first-order variations, and is linked to cross-isthmus moisture transport. Evidence for this second-order antiphase is seen when the respective amplitudes of salinity changes

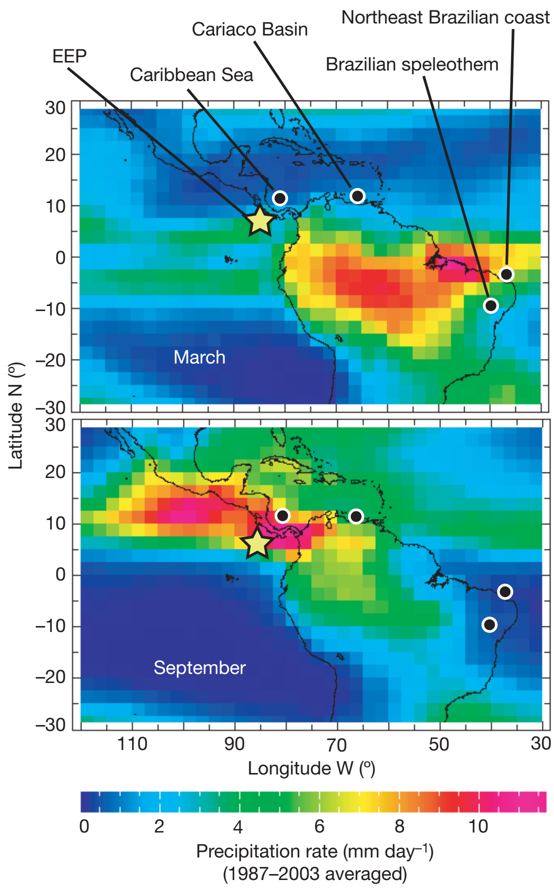

Figure 1 | Averaged precipitation rates over South America for March and September for the period AD 1987–2003. Black dots indicate locations of palaeoclimatic archives discussed in the text, that is, the comparison of the EEP (core MD02-2529, yellow star, this study) to the sedimentary sequences of the Cariaco Basin (ODP hole 1002C)[4], of the Caribbean Sea (core VM28-122 and ODP hole 999A)[6] and of the northeastern Brazilian margin (core GeoB3104-1/3912-1)[20] as well as the northeastern Brazil speleothem growing phases[19]. Rainfall data were retrieved from the International Research Institute for Climate Prediction and are available at http://iri.ldeo.columbia.edu.

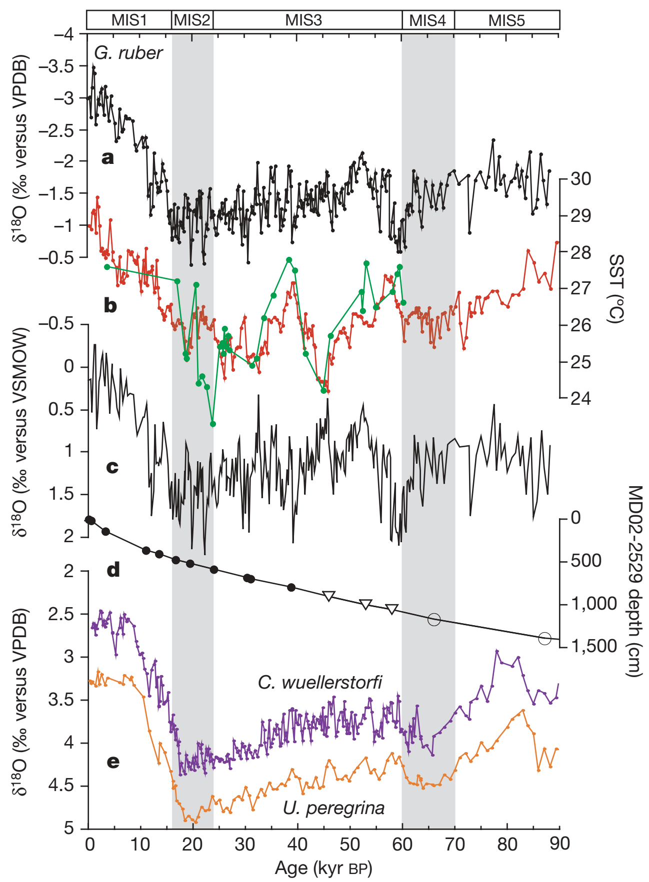

Figure 2 | Records of MD02-2529 versus age for the last 90 kyr BP. **a,** $\delta^{18}O$ record of the surface-dwelling planktonic foraminifer *G. ruber*. **b,** Comparison of $U_{37}^{k'}$-SST (red curve) and Mg/Ca-SST (green curve). **c,** Calculated $\delta^{18}O_{sw}$. **d,** Age–depth relationship based on radiocarbon measurements (black dots) and benthic foraminifera stratigraphy tuned to Byrd (open triangles) and to a benthic $\delta^{18}O$ stack (open circles) (see Supplementary Information for the age model construction). **e,** $\delta^{18}O$ records of the benthic species *Cibicidoides wuellerstorfi* (blue curve) and *Uvigerina peregrina* (orange curve). VPDB, Vienna Pee-Dee Belemnite standard; VSMOW, Vienna Standard Mean Ocean Water.

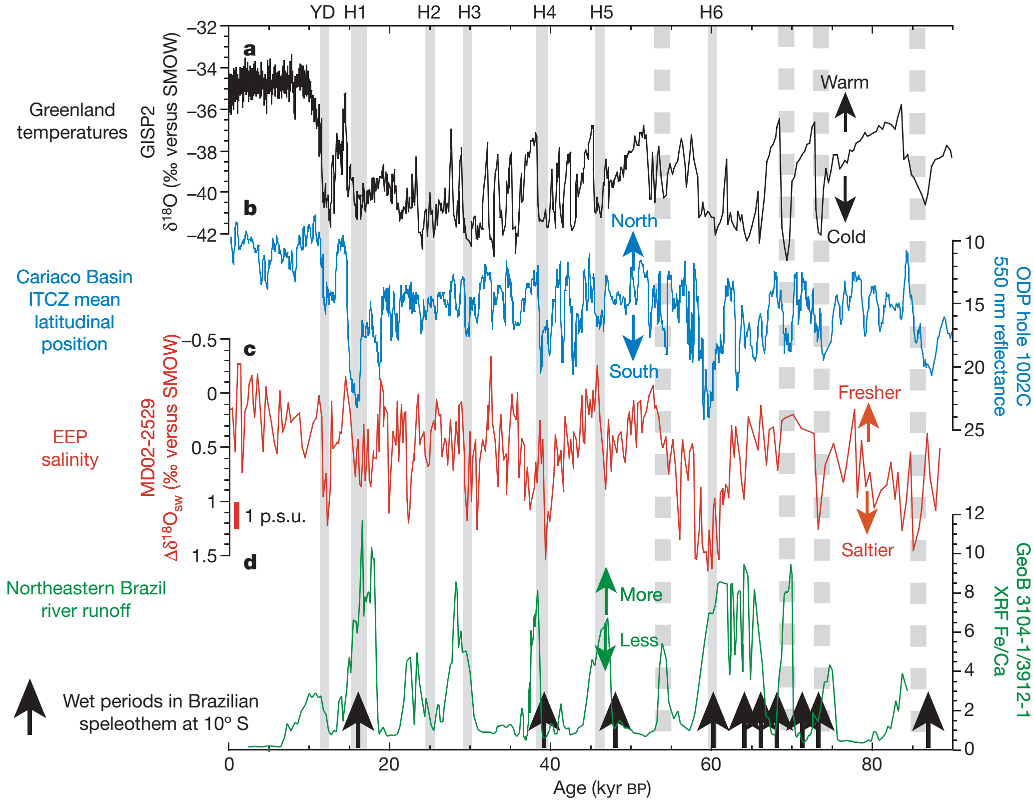

Figure 3 | Temporal variations of the calculated $\Delta\delta^{18}O_{sw}$ of MD02-2529 compared to other palaeoclimatic records. The data are presented on their published original timescales without further tuning. **a**, Greenland GISP2 palaeotemperature record[5]. **b**, Cariaco basin sediment reflectance, monitoring the latitudinal mean position of the ITCZ in the northwestern equatorial Atlantic[4]. **c**, $\Delta\delta^{18}O_{sw}$ of MD02-2529. **d**, Fe/Ca measurements, a proxy for riverine input, performed on sediments retrieved off Brazil[20]; black arrows indicate time intervals of the ITCZ southward expansion over Brazil based on well-dated speleothem growth intervals[19]. Grey vertical bars mark the North Atlantic H events. See Fig. 1 for the localization of tropical palaeoclimatic archives. YD, Younger Dryas; H1–H6, Heinrich events.

in the Caribbean and the EEP are considered (Supplementary Information). Our observations demonstrate that for all Heinrich events and the Younger Dryas the salinity increases are about two to three times larger on the Pacific side than on the Atlantic side of the isthmus (Supplementary Information). Our interpretation is that the salinity increases on both sides of the isthmus are modulated by the southward ITCZ shifts, whereas the signature of decreased interoceanic moisture flux is less salinity increase on the Atlantic side and more salinity increase on the Pacific side. This is precisely the anti-phased pattern of cross-isthmus moisture transport changes.

The MD02-2529 $\Delta\delta^{18}O_{sw}$ values imply that a northerly location of the ITCZ allowed enhanced moisture transport across the Panama isthmus, potentially leading to the build-up of salt in North Atlantic surface waters. By contrast, a southerly ITCZ position led to the orogenic blocking of moisture transport by the Andes[4]. This fresh water returned preferentially into the Atlantic Ocean, in particular through the Amazon basin drainage[20]. Inevitably, this must have lowered the salinity of low-latitude currents in the Atlantic Ocean, such as the North Brazil current, the Guyana current and the Caribbean current feeding the Gulf Stream.

The deuterium excess record from GRIP ice cores in Greenland shows that changes in their source temperature reflect southward shifts of the geographical location of moisture sources during stadials, presumably associated with southward displacements of the ITCZ[21]. This provides additional evidence for the key role played by the atmospheric water cycle and its related cross-isthmus moisture transport with respect to the H-DO variability. Some modelling studies attempted to reproduce the H-DO variability related to the formation of NADW by applying small freshwater anomalies of 0.03 Sv to the North Atlantic surface water[22] that are one order of magnitude smaller than the modern cross-isthmus vapour transport[1,13,14,18]. In the modern North Atlantic, low-salinity anomalies initially located at river mouths[23] are then advected in the Nordic Seas after a delay of several years with a probable influence on NADW formation[24]. If the ITCZ latitudinal cycles were indeed able to modulate the interoceanic salt contrast at the millennial timescale, then they could have contributed to the freshwater flux forcing applied in modelling experiments[22]. It is also possible that further north in the North Atlantic gyre other feedbacks could operate in a different manner[25]. The combined palaeoceanographic evidence and all identified feedback effects should be considered in modelling these events, that may enlighten our understanding of the modulation of NADW formation process and its related climatic effects.

We speculate that the moisture transport across Central America acts as a positive feedback on abrupt climatic changes. If true, the tropical climate variability is not limited to a passive response to the abrupt climatic changes observed in the North Atlantic region. Further tests of the implications of observed latitudinal and longitudinal hydrological shifts should be performed with models coupling atmosphere and ocean processes at the seasonal scale, and using highly resolved representations of Central and South-America in order to simulate realistic runoff fluxes.

METHODS

We estimated the regional SSS over the last 90 kyr BP by measuring $\delta^{18}O_{G. ruber}$ coupled with alkenone-based (using $U^{k'}_{37}$) and *G. ruber* Mg/Ca-based (using the cleaning method including the reductive step) sea surface palaeotemperatures data (Supplementary Information). To convert the $U^{k'}_{37}$ and the Mg/Ca into temperatures, we have used the calibration of refs 26 and 27, respectively. The lower Mg/Ca temperatures of the 20–25 kyr BP time interval might be caused by foraminiferal test dissolution (Fig. 2b, Supplementary Information). The $\delta^{18}O$ of sea water ($\delta^{18}O_{sw}$) was estimated by combining the $\delta^{18}O_{G. ruber}$ and $U^{k'}_{37}$-SST (Fig. 2c, Supplementary Information). To reconstruct past EEP salinities

($\Delta\delta^{18}O_{sw}$, Fig. 3c) we also removed the effect of global ice volume changes (ref. 17) from $\delta^{18}O_{sw}$. In the modern EEP, a $\delta^{18}O_{sw}$ drop of 1‰ corresponds to a salinity decrease of about 4 p.s.u. (ref. 18), remaining highly significant with respect to the typical error on salinity reconstructions[28] (Supplementary Information). The age model is constrained by a series of radiocarbon ages and by isotopic stratigraphy using the $\delta^{18}O$ temporal variations measured on two benthic foraminifer species (Fig. 2d, e; see Supplementary Information).

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1. Zaucker, F. & Broecker, W. S. The influence of atmospheric moisture transport on the fresh water balance of the Atlantic drainage basin: General circulation model simulations and observations. *J. Geophys. Res.* **97,** 2765–2773 (1992).
2. Broecker, W. S., Bond, G., Klas, M., Bonani, G. & Wolfli, W. A salt oscillator in the glacial Atlantic? 1. The concept. *Paleoceanography* **5,** 469–477 (1990).
3. Bard, E. Climate shock: Abrupt changes over millennial time scales. *Phys. Today* **55,** 32–37 (2002).
4. Peterson, L. C., Haug, G. H., Hughen, K. A. & Röhl, U. Rapid changes in the hydrologic cycle of the tropical Atlantic during the Last Glacial. *Science* **290,** 1947–1951 (2000).
5. Stuiver, M. & Grootes, P. M. GISP2 oxygen isotope ratios. *Quat. Res.* **53,** 277–284 (2000).
6. Schmidt, M. W., Spero, H. J. & Lea, D. W. Links between salinity variation in the Caribbean and North Atlantic thermohaline circulation. *Nature* **428,** 160–163 (2004).
7. Bond, G. *et al.* Correlations between climate records from North Atlantic sediments and Greenland ice. *Nature* **365,** 143–147 (1993).
8. Wang, Y. J. *et al.* A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China. *Science* **294,** 2345–2348 (2001).
9. Ivanochko, T. S. *et al.* Variations in tropical convection as an amplifier of global climate change at the millennial scale. *Earth Planet. Sci. Lett.* **235,** 302–314 (2005).
10. Broecker, W. S. Does the trigger for abrupt climate change reside in the ocean or in the atmosphere? *Science* **300,** 1519–1522 (2003).
11. Vidal, L. & Arz, H. in *Past Climate Variability Through Europe And Africa* (eds Battarbee, R. W. *et al.*) 31–44 (Springer, Dordrecht, 2004).
12. Liu, W. T. & Tang, W. Estimating moisture transport over oceans using space-based observations. *J. Geophys. Res.* **110,** D10101, doi:10.1029/2004JD005300 (2005).
13. Manabe, S. & Stouffer, R. J. Two stable equilibria of a coupled ocean-atmosphere model. *J. Clim.* **1,** 841–866 (1988).
14. Hostetler, S. W. & Mix, A. C. Reassessment of ice-age cooling of the tropical ocean and atmosphere. *Nature* **399,** 673–676 (1999).
15. Schmittner, A., Meissner, K. J., Eby, M. & Weaver, A. J. Forcing of the deep ocean circulation in simulations of the Last Glacial Maximum. *Paleoceanography* **17,** 1015, doi:10.1029/2001PA000633 (2002).
16. Benway, H. M., Mix, A. C., Haley, B. A. & Klinkhammer, G. P. Eastern Pacific Warm Pool paleosalinity and climate variability: 0–30 kyr. *Paleoceanography* **21,** PA3008, doi:10.1029/2005PA001208 (2006).
17. Waelbroeck, C. *et al.* Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. *Quat. Sci. Rev.* **21,** 295–305 (2002).
18. Benway, H. M. & Mix, A. C. Oxygen isotopes, upper-ocean salinity, and precipitation sources in the eastern tropical Pacific. *Earth Planet. Sci. Lett.* **224,** 493–507 (2004).
19. Wang, X. *et al.* Wet periods in northeastern Brazil over the past 210 kyr linked to distant climate anomalies. *Nature* **432,** 740–743 (2004).
20. Arz, H. W., Pätzold, J. & Wefer, G. Correlated millennial-scale changes in surface hydrography and terrigenous sediment yield inferred from last-glacial marine deposits off northeastern Brazil. *Quat. Res.* **50,** 157–166 (1998).
21. Masson-Delmotte, V. *et al.* GRIP deuterium excess reveals rapid and orbital-scale changes in Greenland moisture origin. *Science* **309,** 118–121 (2005).
22. Ganopolski, A. & Rahmstorf, S. Rapid changes of glacial climate simulated in a coupled climate model. *Nature* **409,** 153–158 (2001).
23. Masson, S. & Delecluse, P. Influence of the Amazon river runoff on the tropical Atlantic. *Phys. Chem. Earth B* **26,** 137–142 (2001).
24. Mignot, J. & Frankignoul, C. Interannual to interdecadal variability of sea surface salinity in the Atlantic and its link to the atmosphere in a coupled model. *J. Geophys. Res.* **109,** C04005, doi:10.1029/2003JC002005 (2004).
25. Schmidt, M. W., Vautravers, M. J. & Spero, H. J. Rapid subtropical North Atlantic salinity oscillations across Dansgaard-Oeschger cycles. *Nature* **443,** 561–564 (2006).
26. Sonzogni, C. *et al.* Temperature and salinity effects on alkenone ratios measured in surface sediments from the Indian Ocean. *Quat. Res.* **47,** 344–355 (1997).
27. Lea, D. W., Pak, D. K. & Spero, H. J. Climate impact of Late Quaternary equatorial Pacific sea surface temperature variations. *Science* **289,** 1719–1724 (2000).
28. Schmidt, G. A. Error analysis of paleosalinity calculations. *Paleoceanography* **14,** 422–429 (1999).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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