PERSPECTIVE

Hydrologic impacts of past shifts of Earth's thermal equator offer insight into those to be produced by fossil fuel CO_2

Wallace S. Broecker[a] **and Aaron E. Putnam**[a,b,1]

[a]*Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964; and* [b]*Climate Change Institute, University of Maine, Orono, ME 04469*

Edited by John C. H. Chiang, University of California, Berkeley, CA, and accepted by the Editorial Board August 31, 2013 (received for review February 3, 2013)

Major changes in global rainfall patterns accompanied a northward shift of Earth's thermal equator at the onset of an abrupt climate change 14.6 kya. This northward pull of Earth's wind and rain belts stemmed from disintegration of North Atlantic winter sea ice cover, which steepened the interhemispheric meridional temperature gradient. A southward migration of Earth's thermal equator may have accompanied the more recent Medieval Warm to Little Ice Age climate transition in the Northern Hemisphere. As fossil fuel CO_2 warms the planet, the continents of the Northern Hemisphere are expected to warm faster than the Southern Hemisphere oceans. Therefore, we predict that a northward shift of Earth's thermal equator, initiated by an increased interhemispheric temperature contrast, may well produce hydrologic changes similar to those that occurred during past Northern Hemisphere warm periods. If so, the American West, the Middle East, and southern Amazonia will become drier, and monsoonal Asia, Venezuela, and equatorial Africa will become wetter. Additional paleoclimate data should be acquired and model simulations should be conducted to evaluate the reliability of this analog.

hydroclimate | deglaciation | global warming | Intertropical Convergence Zone

As Earth warms in response to the continuing buildup of fossil fuel CO_2, there will be a northward shift in the location of its thermal equator (1). This shift will be the consequence of a difference in the extent of warming in each hemisphere. Model simulations suggest that the Northern Hemisphere, because of its continents, will heat up twice as fast as the Southern Hemisphere, because of its oceans (2–4). For example, with differential heating of the polar hemispheres, if the extent of global warming was to reach 3.6 °C, then that in the north would be 4.8 °C and that in the south 2.4 °C. Attendant differential reduction of sea ice coverage in the Arctic and Antarctic (5) could amplify this process (6).

The paleo-hydrologic record bears witness to past shifts in the position of the thermal equator that led to significant geographic alterations in hydrology. These shifts were driven by a seesawing of sea ice cover between the polar hemispheres (7). When the ice cover expanded in the northern Atlantic, it shrunk in the Southern Ocean and vice versa. Evidence for these shifts comes from the abrupt changes that punctuated the last deglaciation (Fig. 1). The largest and best documented of these occurred 14.6 kya at the end of the Mystery Interval. This transition marks the abrupt onset of the Bølling/Allerød warm episode in the Northern Hemisphere and the onset of the Antarctic Cold Reversal in the Southern Hemisphere. The cause of this abrupt change is thought to have been a rejuvenation of deep water formation in the northern Atlantic (8). The consequence of this rejuvenation was to eliminate the extensive winter sea ice cover in the northern Atlantic (7) and to increase it in the Southern Ocean. Documentation of the latter comes from the cessation of the deposition of opal-rich sediment in the Southern Ocean (9) and the pause in the buildup of atmospheric CO_2 (10, 11). The steepened interhemispheric thermal gradient imposed by these shifts in sea ice extent caused the thermal equator to move northward (12).

This northward shift of Earth's thermal equator created major hydrologic changes across the globe (Figs. 1 and 2). The most convincing evidence comes from the regions surrounding the Amazon rain forest (Fig. 3). In the now very dry southern portion of Bolivia's Altiplano, Lake Tauca, which during the latter part of the Mystery Interval had a size three times that of present-day Lake Titicaca, underwent a desiccation (13, 14). In now-dry eastern Brazil, rivers that just before 14.6 kya delivered large amounts of sediment to the continental margin had shrunk to a trickle (15). In the same region, a millennial-duration pulse of stalagmite growth in a now-dry cave came to a halt 14.6 kya (16). By contrast, at the same time, the discharge of river-borne debris into the Caribbean's Cariaco Basin increased (Fig. 1), and Central America became considerably wetter (17), both attesting to the northward shift of the Amazonian rain belt (18).

A second piece of evidence is the rejuvenation 14.6 kya of Africa's Lake Victoria, which was totally dry during the latter part of the Mystery Interval (19). Documentation for this rejuvenation comes from radiocarbon dating of lake sediments that rest on a grass-covered soil. A seismic survey demonstrated that reflections from this soil extend to the deepest part of the lake. A switch from dry to wet conditions across much of Africa at the Mystery Interval–Bølling/Allerød transition has also been documented from a number of other hydrologic indicators, such as the signature of leaf-wax deuterium from the sediments of Lake Tanganyika (20) and decreased dust input into the Atlantic Ocean off of northwest Africa (21).

A third piece of evidence is a pronounced increase in the ^{18}O to ^{16}O ratio in Chinese stalagmites thought to represent an increase in the strength of the Indian monsoon (22, 23). This record is reinforced by the

---

Author contributions: W.S.B. and A.E.P. designed research, performed research, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. J.C.H.C. is a guest editor invited by the Editorial Board.

[1] To whom correspondence should be addressed. E-mail: aputnam@ldeo.columbia.edu.

www.pnas.org/cgi/doi/10.1073/pnas.1301855110

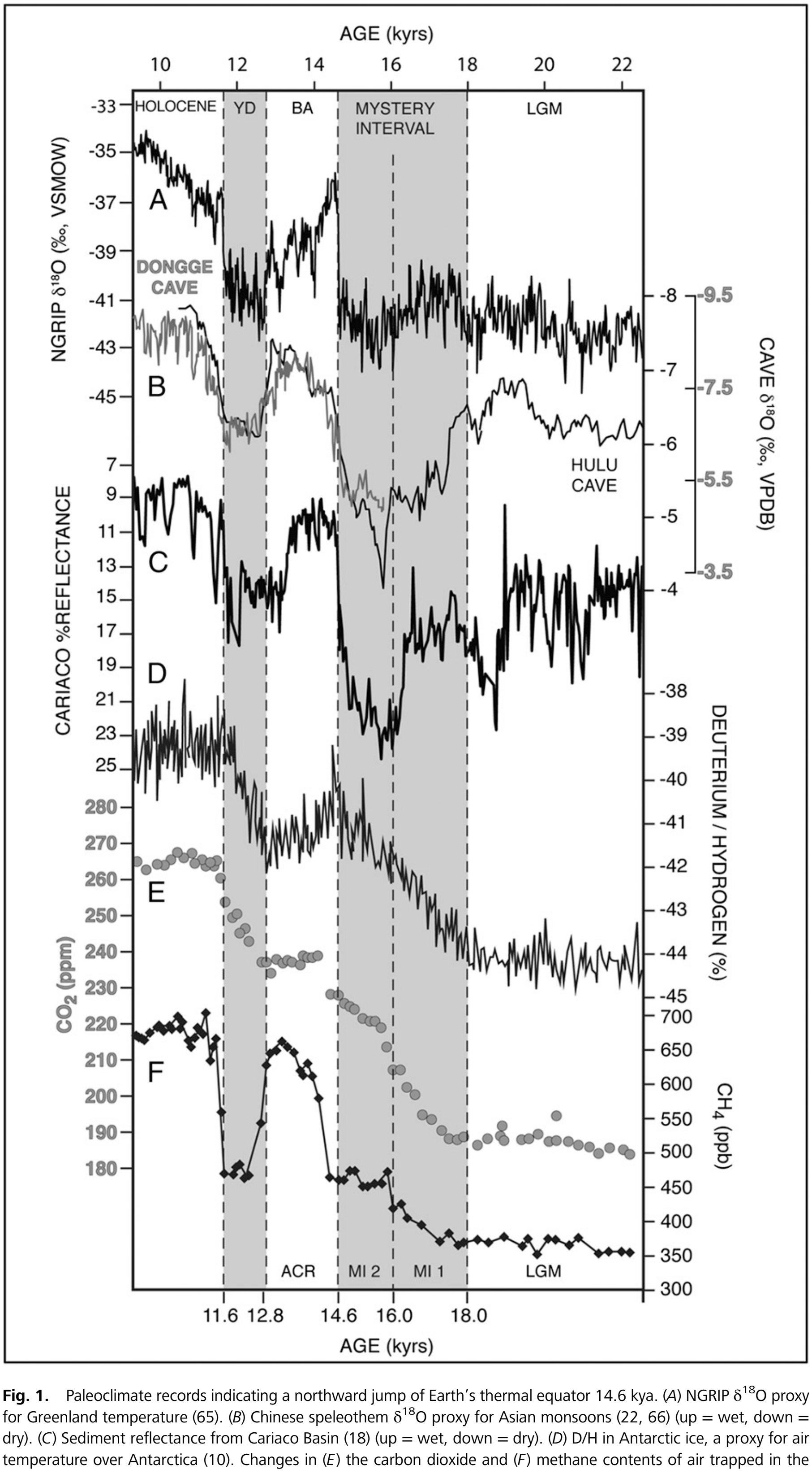


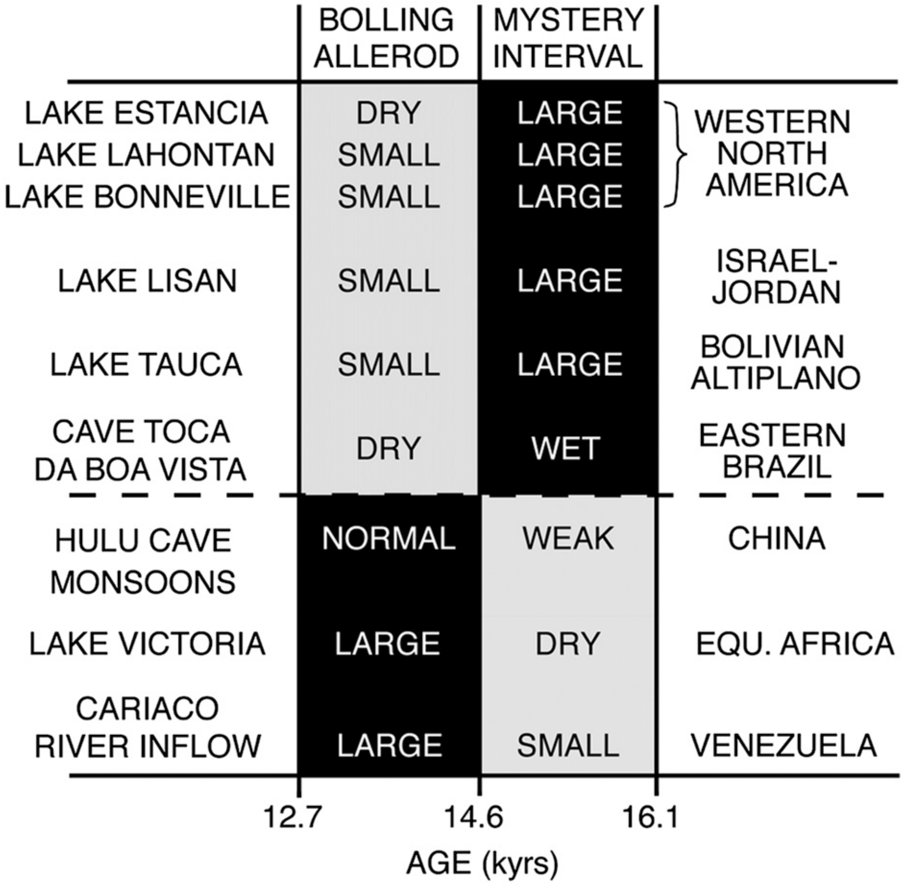
Fig. 1. Paleoclimate records indicating a northward jump of Earth's thermal equator 14.6 kya. (*A*) NGRIP $\delta^{18}O$ proxy for Greenland temperature (65). (*B*) Chinese speleothem $\delta^{18}O$ proxy for Asian monsoons (22, 66) (up = wet, down = dry). (*C*) Sediment reflectance from Cariaco Basin (18) (up = wet, down = dry). (*D*) D/H in Antarctic ice, a proxy for air temperature over Antarctica (10). Changes in (*E*) the carbon dioxide and (*F*) methane contents of air trapped in the section of an Antarctic ice core record for the last period of deglaciation. Unlike the pattern of D/H and CO_2 increase during the mystery interval (MI), CH_4 undergoes only a small rise. Then, CH_4 increases sharply at 14.6 kya, marking the elimination of extensive MI sea ice cover that warmed our planet's northern cap, thereby boosting CH_4 production in boreal wetlands. At the same time, there appears to have been an increase in Southern Ocean sea ice cover (9), which squelched CO_2 release and cooled the Antarctic continent. BA, Bølling/Allerød; YD, Younger Dryas; ACR, Antarctic Cold Reversal.

signature of $\delta^{18}O$ in O_2 trapped in polar ice, which indicates enhanced monsoon activity throughout the Northern Hemisphere (24).

Although stalagmite and ice core ^{18}O and sediment $CaCO_3$ serve only as qualitative hydrologic recorders, the size of closed-basin lakes is a direct measure of drainage basin runoff (25). In this regard, closed basin lakes in the western United States achieved their largest recorded sizes during the Mystery Interval (26). Then with the onset of the Bølling/Allerød, they underwent a major desiccation (27). Although it is not clear how desiccation of the American West is linked to the northward shift of the thermal equator, a likely candidate is a northward jump of the moisture-bearing winter storm tracks associated with the Northern Hemisphere's westerly wind belt (1, 7, 9, 26–28). By this mechanism, a northward migration of the intertropical convergence zone could have stimulated a weakening of the Northern Hemisphere winter Hadley cell and an attendant northward shift of the midlatitude boreal jet (29). Lake Lisan in Israel-Jordan also appears to have experienced a desiccation at the onset of the Bølling/Allerød (30).

In addition to the evidence that north-south shifts of the thermal equator occurred during the course of the last deglaciation, there are hints that smaller-scale shifts may have accompanied the Medieval Warm (800–1200 AD)–Little Ice Age (1300 AD to 1850 AD)–Industrial Warm (1850 AD to present) climate oscillation (Figs. 4 and 5). Although tree line, snowline, sea ice, and ice core records make clear that the northern cap of our planet underwent a warm-cold-warm cycle of amplitude of about 1 °C, indications from the Southern Hemisphere are murky. However, recent glacier reconstructions from the New Zealand Southern Alps (31, 32) hint that southern glacier snowlines may have been out of step with those in the north. For example, Southern Alps snowlines registered colder than present conditions during Medieval times and gradual warming during the northern Little Ice Age (31, 32). If this is correct, then interhemispheric asynchrony in glacier extent is consistent with Earth's thermal equator having maintained a northern position during Medieval time and a southern position during Little Ice Age time. Whether Late Holocene conditions in New Zealand were representative of the entire southern middle latitudes awaits resolution.

There is evidence for a hydrologic response to the Medieval Warm–Little Ice Age–Industrial Warm oscillation of Earth's thermal equator. For example, in accordance with



	BOLLING ALLEROD	MYSTERY INTERVAL	
LAKE ESTANCIA	DRY	LARGE	WESTERN NORTH AMERICA
LAKE LAHONTAN	SMALL	LARGE	
LAKE BONNEVILLE	SMALL	LARGE	
LAKE LISAN	SMALL	LARGE	ISRAEL-JORDAN
LAKE TAUCA	SMALL	LARGE	BOLIVIAN ALTIPLANO
CAVE TOCA DA BOA VISTA	DRY	WET	EASTERN BRAZIL
HULU CAVE MONSOONS	NORMAL	WEAK	CHINA
LAKE VICTORIA	LARGE	DRY	EQU. AFRICA
CARIACO RIVER INFLOW	LARGE	SMALL	VENEZUELA

Fig. 2. The northward shift of the thermal equator 14.6 kya led to a major reorganization of global rainfall. Some areas profited, whereas others lost. Monsoonal Asia, Venezuela, and equatorial Africa were among the winners, and Brazil, Bolivia, Israel-Jordan, and the American West were among the losers. Will differential heating of the hemispheres during the global warming transient produce similar changes?

the summary by Seager and colleagues (33), Medieval hydroclimate was characterized by dry conditions in the western United States (34, 35), wet conditions at the northern edge of the tropics (36, 37), and drought at the southern edge of the South America tropics (38). This spatial pattern of hydroclimate has been attributed to "La Niña–like" conditions in the tropical Pacific during Medieval times (33, 39, 40) and may have also involved an attendant northward displacement of the boreal jet streams (33, 35, 41, 42).

The transition from Medieval Warm to Little Ice Age conditions may have involved a southward shift of the thermal equator, with corresponding hydroclimatic changes. On the basis of lake sediment lithologies and hydrogen isotope compositions, Sachs and colleagues (43) made a case that small islands in the equatorial Pacific experienced shifts from wet conditions when the rain belt lay overhead to dry conditions when it shifted to the north or the south of the island. Their conclusion was that the narrow rain belt lay 500 km south of its present location during the Little Ice Age. Further evidence for a southward excursion of the tropical rain belt during the Little Ice Age comes from the tropical Andes of South America and monsoonal Asia (Fig. 4). Little Ice Age cooling in the North Atlantic region coincided with drying in Venezuela (36) and an increase in monsoon rainfall in Peru (38). At the same time, weakening of monsoon rainfall led to drought and societal instability in Southeast Asia (37, 44–46). Altogether, hydrologic data straddling the tropics suggest that a southward shift of Earth's thermal equator accompanied northern Atlantic cooling and sea ice expansion during the transition into the Little Ice Age (Fig. 5).

There is evidence that changes in thermohaline circulation accompanied this cycle. Reconstruction of the slope of isopycnal horizons across the Florida Straits suggest an ∼20% weakening of the Atlantic's meridional overturning (i.e., conveyor) circulation during the time of the Little Ice Age (47). In addition, Keigwin (48) has shown that the thin tongue of bottom water of Antarctic origin that currently extends to 35°N in the western Atlantic was absent during the Little Ice Age but present during the Medieval Warm. This evidence for a reduction in North Atlantic overturning during the Little Ice Age is consistent with the record of persistent sea ice cover around Iceland (48). The number of months in each year that Icelandic fishermen were able to get through the ice was much smaller than present during the Little Ice Age. Although the evidence in hand is insufficient to allow the exact nature of the change to be articulated, there is a suggestion that in addition to a Little Ice Age slowdown of the conveyor, there was a change in the density contrast between deep waters formed in the Southern Ocean and those formed in the northern Atlantic, with an attendant expansion of North Atlantic sea ice.

For a detailed discussion of the effect of interhemispheric temperature differences on global atmospheric circulation, the reader is referred to the excellent review by Chiang and Friedman (12). If indeed hydrologic shifts to be induced by the differential hemispheric warming generated by fossil fuel CO_2 turn out to be similar to those that occurred at the onset of the Bølling/Allerød (Figs. 1 and 5) and opposite to those registered during the Medieval Warm to Little Ice Age transition (Figs. 4 and 5), then we should expect the following impacts: (*i*) a northward shift in the location of Amazonia, which would lead to decreased rainfall for the Altiplano and eastern Brazil and increased rainfall in Venezuela; (*ii*) a strengthening of monsoon rainfall in South Asia; (*iii*) drying of the American West; (*iv*) increased East African rainfall and discharge of the Nile River; and (*v*) a decrease in Middle East rainfall.

As the planet has warmed during the industrial age, the Northern Hemisphere continents have warmed faster than the Southern Hemisphere oceans, and sea ice has diminished faster in the Arctic than in the Southern Ocean (2, 5). The thermal inertia of the Southern Ocean has played a large role in the evolution of the differential thermal gradient (49). Accordingly, there are tentative indicators that a northward shift of Earth's thermal equator could already be underway (3, 4). For example, drought in the American West (34) and in southern Amazonia (50) is consistent with a northward migration of Earth's thermal equator. However, we admit that our prediction is subject to a number of challenges. Among these are the following: (*i*) forcing of the hydrological

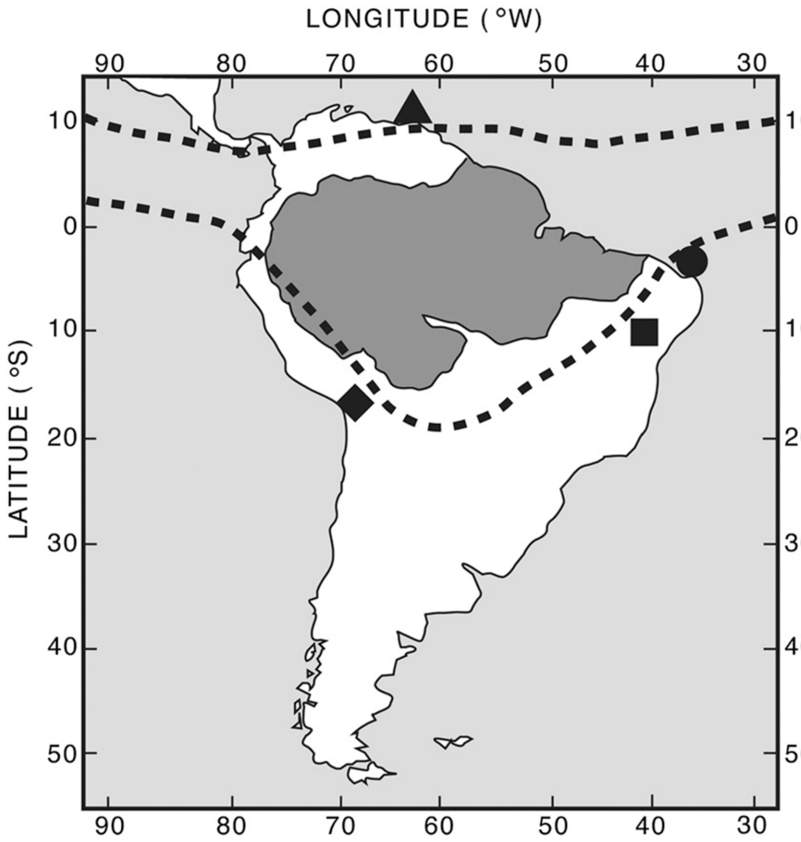


Fig. 3. Evidence supporting a major northward shift of Amazonia 14.6 kya comes from four locations: Cariaco Basin (▲) (18), Offshore eastern Brazil (●) (15), Brazilian caves (■) (16), and Lake Tauca, southern Altiplano (◆) (13). The dashed lines show the seasonal limits of today's tropical rain belt and the gray area is today's Amazonia.

cycle during deglaciation was dominated by thermal contrasts associated with an interhemispheric seesawing of polar sea ice cover rather than differential interhemispheric warming caused by atmospheric CO_2 rise; (*ii*) during the millennial-duration Mystery Interval and Bølling/Allerød, the ocean had adequate time to reach a steady state (this will not be the case during the century-long CO_2 transient); (*iii*) unlike the present day, large ice sheets still covered much of northern North America and Scandinavia during deglacial time, and the background climate state was colder during Bølling/Allerød time than today (therefore, consequent shifts of the thermal equator during deglaciation were likely to have been of a larger magnitude than those that might occur with future warming; this is, in part, our reason for also examining the Medieval Warm–Little Ice Age transition, which took place under similar boundary conditions as industrial-age warming); (*iv*) the CO_2 transient will not create a change in ocean thermohaline circulation comparable to that which occurred at the onset of the Bølling/Allerød interstadial [it has been suggested instead that CO_2-induced warming might weaken North Atlantic overturning; however, any cooling that may result from weakened North Atlantic overturning will be countered by the warming and reduction in sea ice due to radiative effects of increased atmospheric CO_2 concentrations (51, 52)]; and (*v*) aerosol-induced cooling of the Northern Hemisphere (4, 53) could suppress the temperature contrast between the polar hemispheres. Furthermore, aerosol loading might also explain why the South Asian monsoons have not strengthened over the latter part of the 20th century (54). However, these impacts will diminish as CO_2 rises and aerosol loading flattens or decreases.

We do not think that a shift in Earth's thermal equator will be the only hydrological consequence of CO_2-induced planetary warming. For example, Held and Soden (55) suggested on the basis of a number of model experiments that with global warming, Earth's subtropics will become drier, and precipitation in tropical regions will increase. Such a change in atmospheric circulation may also have taken place during the global transition from glacial to interglacial conditions (56) and may occur in the future (55, 57). Neelin et al. (57) showed that redistributions of tropical and subtropical moisture might also occur in the zonal sense. Therefore, we think that a reasonable expectation of future changes in Earth's hydrology involves a northward shift in Earth's thermal equator superimposed on the "rich get richer and poor get poorer" hydrological scenarios proposed by Held and Soden (55) and Neelin et al. (57). Amazonia could provide a natural test of the relative dominance of each of these models. For example, if Earth's thermal equator migrates northward, as we suggest, southern Amazonia should become progressively more arid and northern

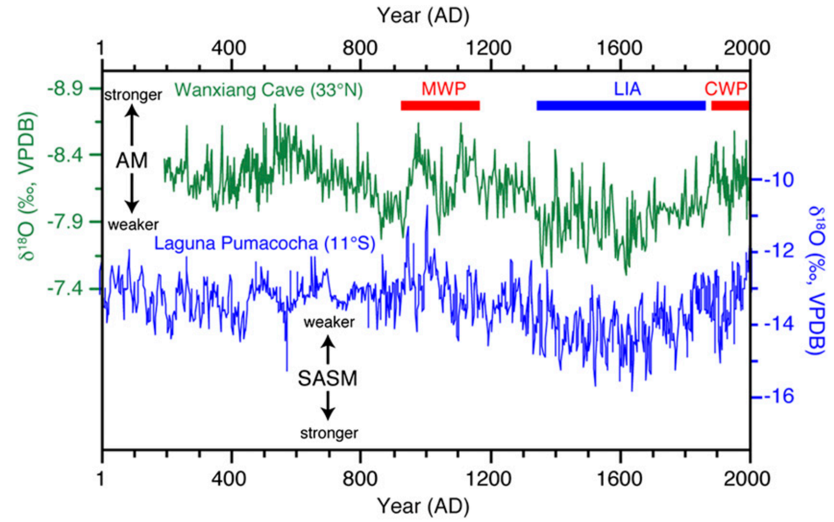


Fig. 4. Speleothem and lacustrine isotope records of the Asian Monsoon (AM; green curve) (37) and South American Summer Monsoon (SASM; blue curve) (38), respectively, during the Medieval Warm (MWP)–Little Ice Age (LIA)–Current Warm Period (CWP) oscillation. During the LIA, the AM weakened while the SASM strengthened, consistent with a southward migration of Earth's thermal equator during that time (43).

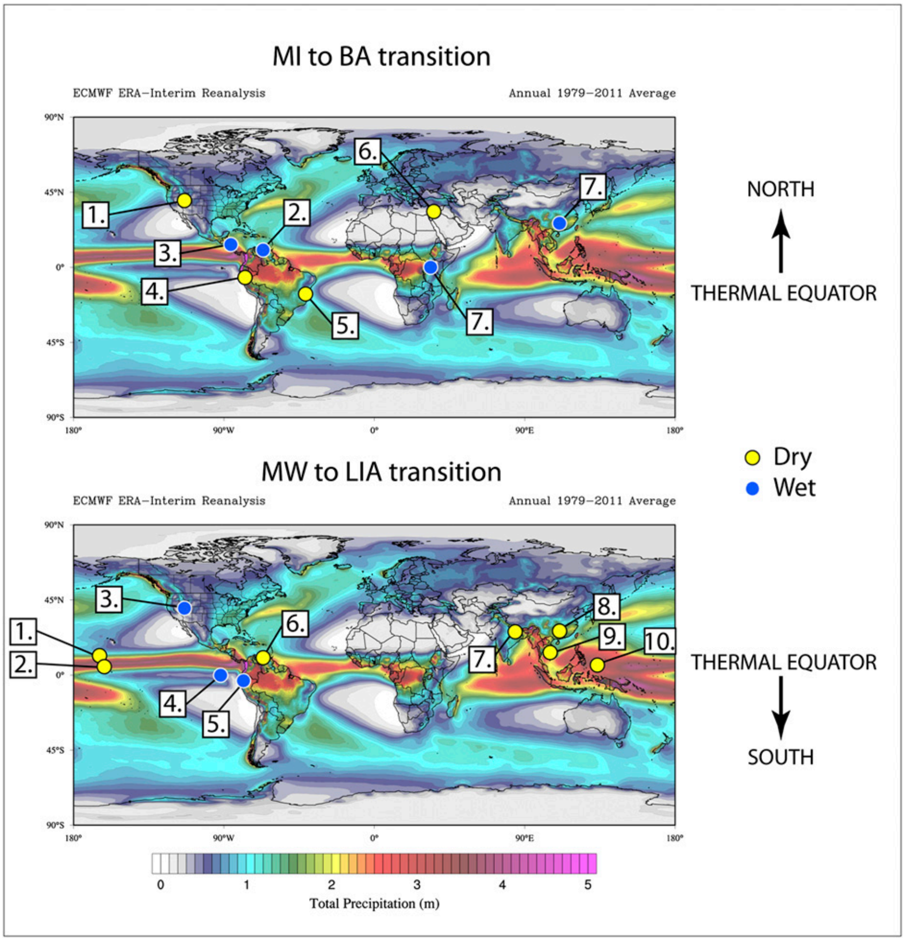


Fig. 5. Maps showing the locations of pertinent paleoclimate records discussed in text. Color scheme depicts mean annual precipitation for the period spanning the years AD 1979 and AD 2011 (see legend, *Inset*). (*Upper*) Data sets recording hydrologic changes during the Mystery Interval (MI)–Bølling/Allerød (B/A) transition: (1) Great Basin (25–27); (2) Venezuela (18); (3) Central American lowlands (17); (4) Lake Tauca, Bolivian Altiplano (13, 14); (5) Eastern Brazil (15, 16); (6) Lake Lisan (30); (7) East African lakes (19, 20); (8) Hulu Cave, China (22). (*Lower*) Data sets recording hydrologic changes during the Medieval Warm (MW) to Little Ice Age (LIA) transition: (1) Washington Island (43); (2) Christmas Island (43); (3) Great Basin (34, 35); (4) Galapagos Islands (43); (5) Laguna Pumacocha, Peru (38); (6) Venezuela (36); (7) Monsoonal Asia (45); (8) Wanxiang Cave, China (37); (9) Cambodia (44); (10) Western Tropical Pacific (39, 43). Blue dots indicate regions that became wet, and yellow dots are regions that became dry during each of these transitions. Precipitation data are derived from ECMWF ERA-Interim reanalysis (67). Background images generated by the Climate Reanalyzer (http://cci-reanalyzer.org).

Amazonia should become wetter. On the other hand, if the model of Held and Soden (55) dominates, then all of Amazonia should become wetter. Finally, if the Neelin et al. (57) model dominates, then all of Amazonia should dry.

We acknowledge that some paleoclimate records, when taken at face value, do not fit our conceptual model of north-south shifts of Earth's thermal equator during the past climate changes. For example, isotopes measured from Borneo stalagmites record a monotonic increase in rainfall during the last deglaciation (58), with no evidence for abrupt changes registered in many other tropical hydrological records. Such a discrepancy might reflect the added influence of sea level on Indo-Pacific hydrological records (59). Records of East African hydroclimate afford another such example, where in addition to the position of the thermal equator (60), Indian Ocean sea-surface temperatures also modulate rainfall on land (61). Increased Indian Ocean temperatures during Bølling/Allerød time boosted precipitation throughout equatorial Africa, thereby reinforcing the wetting effects of northward intertropical convergence zone (ITCZ) migration in the northern African tropics but counteracting expected drying in the southern African tropics (20). Other examples include various tropical lacustrine proxy records interpreted to reflect rainfall variability but, at face value, exhibit regionally conflicting patterns during late Holocene time (43, 62).

We consider that the best ways to evaluate the utility of our paleo analog are as follows. First, continued development of robust paleo-hydroclimate records on a global scale will help to refine spatiotemporal patterns of how Earth's hydrological system evolved with past climate. Combining physical geomorphological evidence for past water availability with continuous biological and geochemical records will afford deconvolution of climate dynamics and assessment of the principle climatic controls on water resources. Such an approach is necessary not only to test the mechanisms proposed here but also to help reconcile regionally conflicting reconstructions.

Second, a quantitative relationship between interhemispheric meridional temperature differences and shifts in the ITCZ has yet to be firmly established and is a welcome direction for future research. Simulations of future hydroclimatic responses to globally asymmetric warming should be conducted using models capable of reproducing changes documented from the Bølling/Allerød transition and during the more recent Medieval Warm–Little Ice Age transition. Indeed, there is already progress on this front. For example, predictive models featured in the Intergovernmental Panel on Climate Change Fourth Assessment report (63) feature some (but not all) of the future hydrologic changes predicted in our analysis. In addition, global warming experiments that use slab-ocean models have shown that, for models that exhibit greater warming in the Northern Hemisphere compared with the Southern Hemisphere, there is indeed a northward migration of the tropical rain belt (1, 64).

Although paleo-hydrologic reconstructions are, for the most part, restricted to relatively small geographic regions, those based on models are robust only for large geographic regions. However, because north and south shifts of the thermal equator at the onsets of the Bølling/Allerød and Little Ice Age, respectively, led to pronounced and widespread changes in hydroclimate, we predict that Earth is indeed capable of undergoing rapid adjustments in response to future differential heating between the hemispheres. In particular, we anticipate that with current and future global warming, Earth's rain and desert belts will respond by shifting northward, giving rise to changes in water availability around the globe.

ACKNOWLEDGMENTS. We are grateful to the Comer Science and Education Foundation, the Quesada Family Fund, and the Columbia Earth Institute Climate Center for support. We thank G. H. Denton and S. Bordoni for thoughtful discussion. Four anonymous reviewers provided constructive criticisms that greatly improved the paper. This is Lamont-Doherty Earth Observatory contribution no. 7724.

1 Ceppi P, Hwang Y-T, Liu X, Frierson DMW, Hartmann DL (2013) The relationship between the ITCZ and Southern Hemispheric eddy-driven jet. *J Geophys Res* 118(11):5136–5146.

2 Xu Y, Ramanathan V (2012) Latitudinally asymmetric response of global surface temperature: Implications for regional climate change. *Geophys Res Lett* 39(13):L13706.

3 Drost F, Karoly D, Braganza K (2012) Communicating global climate change using simple indices: An update. *Clim Dyn* 39(3-4): 989–999.

4 Friedman AR, Hwang Y-T, Chiang JCH, Frierson DMW (2013) Interhemispheric temperature asymmetry over the 20th century and future projections. *J Clim* 26(15):5419–5433.

5 Tareghian R, Rasmussen P (2012) Analysis of Arctic and Antarctic sea ice extent using quantile regression. *Int J Climatol* 33(5): 1079–1086.

6 Flohn H (1982) Climate change and an ice-free arctic ocean. *Carbon Dioxide Review*, ed Clark WC (Oxford Univ Press, New York), pp 145–179.

7 Denton GH, et al. (2010) The last glacial termination. *Science* 328(5986):1652–1656.

8 Barker S, Knorr G, Vautravers MJ, Diz P, Skinner LC (2010) Extreme deepening of the Atlantic overturning circulation during deglaciation. *Nat Geosci* 3(8):567–571.

9 Anderson RF, et al. (2009) Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO$_2$. *Science* 323(5920): 1443–1448.

10 Monnin E, et al. (2001) Atmospheric CO$_2$ concentrations over the last glacial termination. *Science* 291(5501):112–114.

11 Parrenin F, et al. (2013) Synchronous change of atmospheric CO$_2$ and Antarctic temperature during the last deglacial warming. *Science* 339(6123):1060–1063.

12 Chiang JCH, Friedman AR (2012) Tropical cooling, interhemispheric thermal gradients, and tropical climate change. *Annu Rev Earth Planet Sci* 40(1):383–412.

13 Blard P-H, et al. (2011) Lake highstands on the Altiplano (Tropical Andes) contemporaneous with Heinrich 1 and the Younger Dryas: New insights from ^{14}C, U-Th dating and δ^{18}O of carbonates. *Quat Sci Rev* 30(27-28):3973–3989.

14 Placzek C, Quade J, Patchett PJ (2006) Geochronology and stratigraphy of late Pleistocene lake cycles on the southern Bolivian Altiplano: Implications for causes of tropical climate change. *Geol Soc Am Bull* 118(5-6):515–532.

15 Arz HW, Patzold J, Wefer G (1998) Correlated millennial-scale changes in surface hydrography and terrigenous sediment yield inferred from last-glacial marine deposits off northeastern Brazil. *Quat Res* 50(2):157–166.

16 Wang XF, et al. (2004) Wet periods in northeastern Brazil over the past 210 kyr linked to distant climate anomalies. *Nature* 432(7018):740–743.

17 Escobar J, et al. (2012) A ∼43-ka record of paeoenvironmental change in the Central American lowlands inferred from stable isotopes of lacustrine ostracods. *Quat Sci Rev* 37:92–104.

18 Peterson LC, Haug GH, Hughen KA, Röhl U (2000) Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial. *Science* 290(5498):1947–1951.

19 Johnson TC, et al. (1996) Late Pleistocene Desiccation of Lake Victoria and Rapid Evolution of Cichlid Fishes. *Science* 273(5278): 1091–1093.

20 Tierney JE, et al. (2008) Northern hemisphere controls on tropical southeast African climate during the past 60,000 years. *Science* 322(5899):252–255.

21 McGee D, deMenocal PB, Winckler G, Stuut JB, Bradtmiller LI (2013) The magnitude, timing and abruptness of changes in North African dust deposition over the last 20,000 yr. *Earth Planet Sci Lett* 371–372:163–176.

22 Wang YJ, et al. (2001) A high-resolution absolute-dated late Pleistocene Monsoon record from Hulu Cave, China. *Science* 294(5550):2345–2348.

23 Pausata FSR, Battisti DS, Nisancioglu KH, Bitz CM (2011) Chinese stalagmite 18O controlled by changes in the Indian Monsoon during a simulated Heinrich event. *Nat Geosci* 4(7):474–480.

24 Severinghaus JP, Beaudette R, Headly MA, Taylor K, Brook EJ (2009) Oxygen-18 of O$_2$ records the impact of abrupt climate change on the terrestrial biosphere. *Science* 324(5933):1431–1434.

25 Broecker WS (2010) Long-term water prospects in the western United States. *J Clim* 23(24):6669–6683.

26 Munroe JS, Laabs BJC (2013) Temporal correspondence between pluvial lake highstands in the southwestern US and Heinrich Event 1. *J Quaternary Sci* 28(1):49–58.

27 Benson L, Kashgarian M, Rubin M (1995) Carbonate deposition, Pyramid Lake Subbasin, Nevada. 2. Lake levels and polar-jet stream positions reconstructed from radiocarbon ages and elevations of carbonates (tufas) deposited in the Lahontan Basin. *Palaeogeogr Palaeoclimatol Palaeoecol* 117(1-2):1–30.

28 Asmerom Y, Polyak VJ, Burns SJ (2010) Variable winter moisture in the southwestern United States linked to rapid climate shifts. *Nat Geosci* 3(2):114–117.

29 Li C, Battisti DS, Bitz CM (2010) Can North Atlantic Sea Ice Anomalies Account for Dansgaard-Oeschger Climate Signals? *J Clim* 23(20):5457–5475.

30 Schramm A, Stein M, Goldstein SL (2000) Calibration of the ^{14}C time scale to >40 ka by ^{234}U-^{230}Th dating of Lake Lisan sediments (last glacial Dead Sea). *Earth Planet Sci Lett* 175(1-2):27–40.

31 Schaefer JM, et al. (2009) High-frequency Holocene glacier fluctuations in New Zealand differ from the northern signature. *Science* 324(5927):622–625.

32 Putnam AE, et al. (2012) Regional climate control of glaciers in New Zealand and Europe during the pre-industrial Holocene. *Nat Geosci* 5(9):627–630.

33 Seager R, et al. (2007) Blueprints for Medieval hydroclimate. *Quat Sci Rev* 26(19-21):2322–2336.

34 Cook ER, Woodhouse CA, Eakin CM, Meko DM, Stahle DW (2004) Long-term aridity changes in the western United States. *Science* 306(5698):1015–1018.

35 Stine S (1994) Extreme and Persistent Drought in California and Patagonia During Medieval Time. *Nature* 369(6481):546–549.

36 Haug GH, Hughen KA, Sigman DM, Peterson LC, Röhl U (2001) Southward migration of the intertropical convergence zone through the Holocene. *Science* 293(5533):1304–1308.

37 Zhang PZ, et al. (2008) A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. *Science* 322(5903):940–942.

38 Bird BW, et al. (2011) A 2,300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes. *Proc Natl Acad Sci USA* 108(21):8583–8588.

39 Newton A, Thunell R, Stott L (2006) Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium. *Geophys Res Lett* 33(19):L19710.

40 Graham NE, et al. (2007) Tropical Pacific — mid-latitude teleconnections in medieval times. *Clim Change* 83(1-2):241–285.

41 Graham NE, Ammann CM, Fleitmann D, Cobb KM, Luterbacher J (2011) Support for global climate reorganization during the "Medieval Climate Anomaly" *Clim Dyn* 37(5-6):1217–1245.

42 Bond G, et al. (2001) Persistent solar influence on North Atlantic climate during the Holocene. *Science* 294(5549):2130–2136.

43 Sachs JP, et al. (2009) Southward movement of the Pacific intertropical convergence zone AD 1400-1850. *Nat Geosci* 2(7): 519–525.

44 Buckley BM, et al. (2010) Climate as a contributing factor in the demise of Angkor, Cambodia. *Proc Natl Acad Sci USA* 107(15): 6748–6752.

45 Cook ER, et al. (2010) Asian monsoon failure and megadrought during the last millennium. *Science* 328(5977):486–489.

46 Sinha A, et al. (2011) A global context for megadroughts in monsoon Asia during the past millennium. *Quat Sci Rev* 30:47–62.

47 Lund DC, Lynch-Stieglitz J, Curry WB (2006) Gulf Stream density structure and transport during the past millennium. *Nature* 444(7119):601–604.

48 Denton GH, Broecker WS (2008) Wobbly ocean conveyor circulation during the Holocene? *Quat Sci Rev* 27(21-22):1939–1950.

49 Zelinka MD, Hartmann DL (2012) Climate feedbacks and their implications for poleward energy flux changes in a warming climate. *J Clim* 25(2):608–624.

50 Cox PM, et al. (2008) Increasing risk of Amazonian drought due to decreasing aerosol pollution. *Nature* 453(7192):212–215.

51 Gregory JM, et al. (2005) A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO2 concentration. *Geophys Res Lett* 32(12):L12703.

52 Hu A, Meehl GA, Washington WM, Dai A (2004) Response of the Atlantic thermohaline circulation to increased atmospheric CO2 in a coupled model. *J Clim* 17(21):4267–4279.

53 Mitchell JFB, Johns TC (1997) On modification of global warming by sulfate aerosols. *J Clim* 10(2):245–267.

54 Turner AG, Annamalai H (2012) Climate change and the South Asian summer monsoon. *Nature Climate Change* 2(8):587–595.

55 Held IM, Soden BJ (2006) Robust responses of the hydrological cycle to global warming. *J Clim* 19(21):5686–5699.

56 Quade J, Broecker WS (2009) Dryland hydrology in a warmer world: Lessons from the Last Glacial period. *Eur Phys J Spec Top* 176(1):21–36.

57 Neelin JD, Münnich M, Su H, Meyerson JE, Holloway CE (2006) Tropical drying trends in global warming models and observations. *Proc Natl Acad Sci USA* 103(16):6110–6115.

58 Partin JW, Cobb KM, Adkins JF, Clark B, Fernandez DP (2007) Millennial-scale trends in west Pacific warm pool hydrology since the Last Glacial Maximum. *Nature* 449(7161):452–455.

59 DiNezio PN, Tierney JE (2013) The effect of sea level on glacial Indo-Pacific climate. *Nat Geosci* 6(6):485–491.

60 Tierney JE, Russell JM (2007) Abrupt climate change in southeast tropical Africa influenced by Indian monsoon variability and ITCZ migration. *Geophys Res Lett* 34(15):L15709.

61 Tierney JE, Smerdon JE, Anchukaitis KJ, Seager R (2013) Multidecadal variability in East African hydroclimate controlled by the Indian Ocean. *Nature* 493(7432):389–392.

62 Conroy JL, Overpeck JT, Cole JE, Shanahan TM, Steinitz-Kannan M (2008) Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. *Quat Sci Rev* 27(11-12):1166–1180.

63 Solomon S, et al. (2007) *IPCC Fourth Assessment Report: Climate Change 2007: Climate Change 2007: Working Group I: The Physical Science Basis* (Cambridge Univ Press, New York).

64 Frierson DMW, Hwang JS (2012) Extratropical Influence on ITCZ shifts in slab ocean simulations of global warming. *J Clim* 25(2):720–733.

65 NGRIP Members (2004) High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature* 431(7005):147–151.

66 Dykoski CA, et al. (2005) A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. *Earth Planet Sci Lett* 233(1-2):71–86.

67 Dee DP, et al. (2011) The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q J R Meteorol Soc* 137(656):553–597.