Strengthening of the Northeast Monsoon over the Flores Sea, Indonesia, at the time of Heinrich event 1

Joanne Muller[1]*, Jerry F. McManus[2], Delia W. Oppo[1], and Roger Francois[3]
[1]Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, 02540, USA
[2]Department of Earth and Environmental Sciences, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York 10964, USA
[3]Earth and Ocean Sciences, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada

ABSTRACT

Paleoclimate evidence from South America and Asia has been interpreted to indicate that tropical rainfall migrated southward during the Northern Hemisphere cooling associated with Heinrich stadial 1 (HS1), an event of massive iceberg discharge to the North Atlantic ca. 18–15 ka. Although arid conditions associated with such a shift are well documented in southern Asia, as far south as Borneo, debate still exists regarding the precipitation response in southern Indonesia and Australia during HS1. This study utilizes concentrations of the long-lived nuclide ^{232}Th as a proxy for detrital riverine input and ^{230}Th normalization to estimate the history of preserved fluxes reaching the seafloor in the Flores Sea, located between southern Sulawesi and the Lesser Sunda Islands, Indonesia. Because the only source of ^{232}Th to the ocean is continental minerals, this proxy is a robust indicator of continental weathering. The ^{230}Th normalized burial fluxes of lithogenic and biogenic matter demonstrate that both detrital and biogenic fluxes in the Flores Sea were higher during HS1 than any other period in the past 22 k.y. High detrital fluxes indicate enhanced precipitation runoff from surrounding landmasses during a period of maximum southward shift of the Intertropical Convergence Zone. This study further constrains the northern limit of enhanced rainfall associated with a southward shift of Australian monsoon-related rainfall at the time of HS1 and highlights the value of ^{232}Th as a proxy of continental input to deep-sea sediment records.

INTRODUCTION

The biannual Asian monsoon dominates the climate of tropical and subtropical regions, bringing a strong seasonal rainfall contrast in these areas. In the Australian and southern Indonesian regions, the Northeast Monsoon consists of northwesterly winds and heavy rain between November and March (Austral summer), while the dry season corresponds to the Southeast Monsoon period from May through September (Austral winter) (Spooner et al., 2005). The Intertropical Convergence Zone (ITCZ) is a key component of the monsoon system and usually is ~10°–15° north of the equator in the Austral winter and migrates south, dipping into northern Australia from January to March (Hobbs, 1998) (Fig. 1). Regional economies are heavily dependent on the predictability of monsoons, and better documenting of the links between the Asian-Australian monsoons and the global climate system is urgently needed to improve our predictions of future climate changes in this region (Meehl and Arblaster, 1998).

Paleoclimate records confirm that the tropical climate regime is quite sensitive to Northern Hemisphere high-latitude climate changes. Strong links are hypothesized between tropical precipitation regimes and North Atlantic glacial events of massive iceberg discharge, or Heinrich events (Jennerjahn et al., 2004; Kienast et al., 2006; Muller et al., 2008; Partin et al., 2007; Peterson et al., 2000; X. Wang et al., 2006; Y. Wang et al., 2001), which appear to have produced a significant reduction in the Atlantic meridional overturning circulation (AMOC) (Hemming, 2004; McManus et al., 2004). Modeling results suggest that the cooling of the northern Atlantic associated with Heinrich events results in a displacement of the ITCZ toward the warmer Southern Hemisphere (Broccoli et al., 2006; Chiang and Bitz, 2005). This is supported by drier conditions recorded in speleothems from China, as well as marine sediment studies from the Arabian Sea and the Cariaco Basin (Peterson et al., 2000; Schulz et al., 1998; Wang et al., 2001). In the Southern Hemisphere, speleothem records from southeast Brazil, and marine sediments from the Brazil margin and the eastern equatorial Pacific, show wet conditions, or a strengthening of monsoons, during Heinrich events, also consistent with this hypothesis (Jennerjahn et al., 2004; Kienast et al., 2006; Wang et al., 2004). These studies indicate a southward shift of the ITCZ in these regions during Heinrich events, as predicted by modeling studies for an AMOC reduction (Broccoli et al., 2006; Chiang and Bitz, 2005).

In the Australian and southern Indonesian region, however, the response is less clear. Speleothem records from northern Borneo indicate

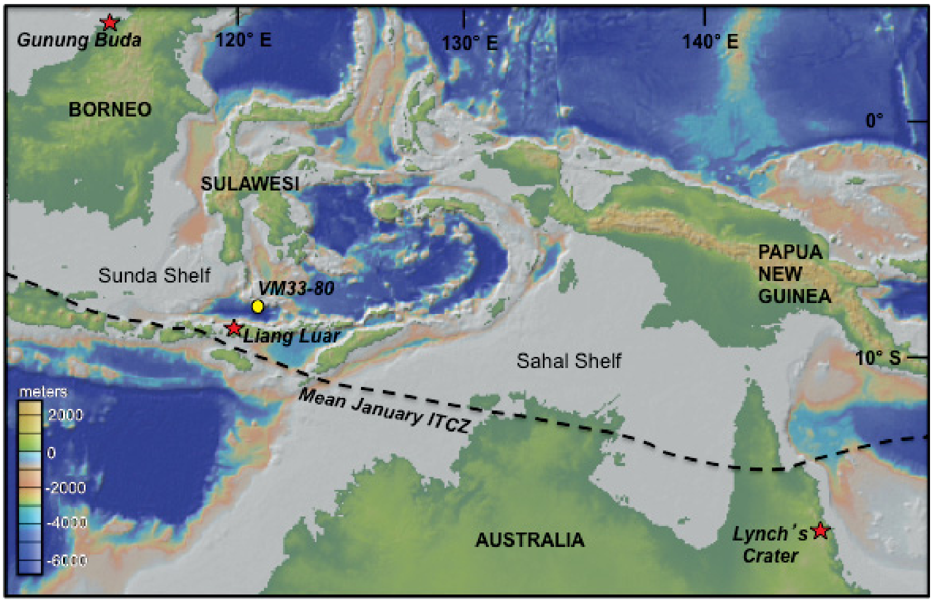

Figure 1. Location of sediment core VM33-80 in the Flores Sea, Indonesia (yellow circle). Present-day mean position of Intertropical Convergence Zone (ITCZ) during Southern Hemisphere summer (January). Also shown are locations of previous ITCZ studies (red stars), such as Lynch's Crater in northeast Australia (Muller et al., 2008), Gunung Buda, north Borneo (Partin et al., 2007), and Liang Luar, Flores (Griffiths et al., 2009).

---

*Current address: Department of Marine and Ecological Sciences, Florida Gulf Coast University, Florida 33965, USA.

GEOLOGY, July 2012; v. 40; no. 7; p. 635–638; doi:10.1130/G32878.1; 3 figures; Data Repository item 2012187.

dry conditions associated with Heinrich events (Partin et al., 2007), while biogenic silica recorded in peats from Lynch's Crater, northeast Australia, indicates the abrupt onset of wet conditions (Muller et al., 2008). Both studies imply a southward migration of the ITCZ as the likely mechanism for precipitation changes. These studies, however, contradict the interpretation of peat humification recorded in Lynch's Crater, concluding that dry conditions prevailed in this region during periods of AMOC reduction (Turney et al., 2004). Furthermore, modeling studies exhibit different responses in this region at times of decreased AMOC (e.g., Zhang and Delworth, 2005; Lewis et al. 2010). To further address these issues, we measured ^{232}Th concentrations, ^{230}Th normalized burial fluxes, authigenic uranium concentrations, and biogenic fluxes (opal and $CaCO_3$ fluxes) in a deep-sea core from the Flores Sea, located between southern Sulawesi and the Lesser Sunda Islands, Indonesia (Fig. 1).

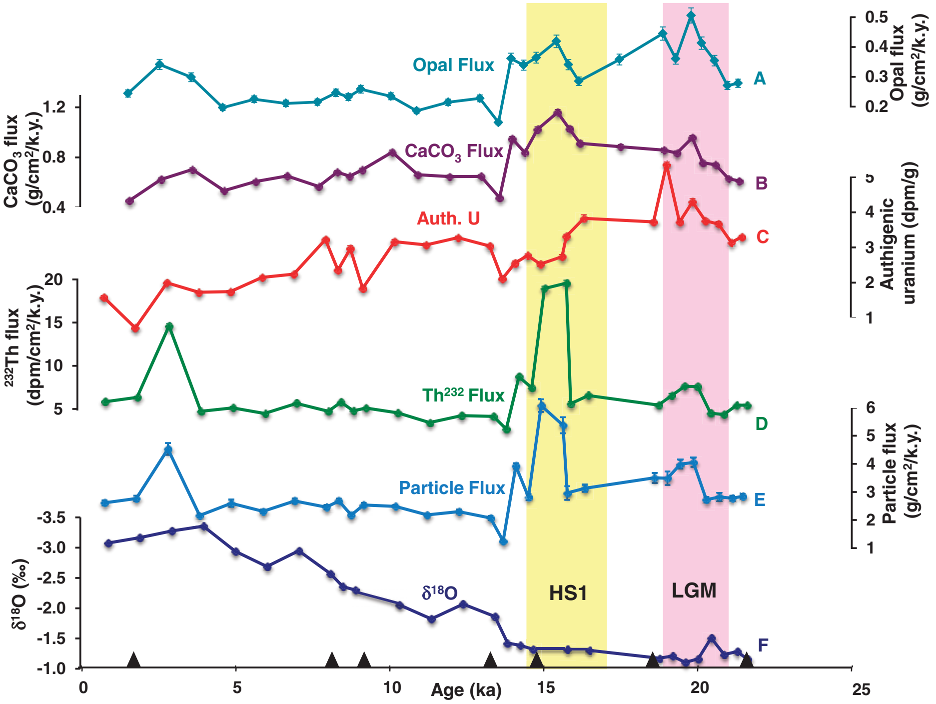

Figure 2. Biogenic, stable isotope, and radiochemical data from sediment core VM33-80 from Flores Sea (Indonesia). Arrows indicate ^{14}C age control points. Shading indicates significant climatic intervals. LGM—Last Glacial Maximum; HS1—Heinrich stadial 1. A: Opal fluxes. B: Calcium carbonate fluxes. C: Authigenic (Auth.) uranium concentrations. D: ^{232}Th fluxes. E: ^{230}Th-normalized particle fluxes. F: δ^{18}O from planktonic foraminifera (*Globigerinoides ruber*). Error bars on radiochemical data indicate standard deviation for each sample, and take into account corrections for regular standards, machine blanks, peak tailing, mass bias, counter gain, and drift.

METHODS

Piston core VM33-80 (lat 7°51.7′S, long 123°E) was recovered from 3164 m water depth in the Flores Sea (National Oceanic and Atmospheric Administration, http://www.ngdc.noaa.gov/geosamples). The mean sedimentation rate for VM33-80 is ~7.1 cm/k.y. The chronology was established with seven radiocarbon dates (analyzed at the National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole Oceanographic Institution, WHOI), and linear sedimentation rates were interpolated between the seven dates to establish an age curve (Fig. 2). Radiocarbon ages were calibrated to calendar years using the software CALIB 6.1.0 Marine 09 (Reimer et al., 2009). Calibrated age errors were between 80 and 360 yr (see Appendix DR1 in the GSA Data Repository[1]). The δ^{18}O stratigraphy (precision on samples was ±0.08) was established with *Globigerinoides ruber* on a Finnigan MAT253 mass spectrometer at the WHOI Micropaleontology Mass Spectrometry facility.

Uranium series nuclides (^{230}Th, ^{232}Th, and ^{238}U) were analyzed on a Finnigan MAT Element I single-collector, sector field, inductively coupled plasma–mass spectrometer (Choi et al., 2001). Reproducibility for replicate analyses (dissolution, chromatographic separation, and spectrometry) was usually <4% on the measured ^{230}Th, 1.2% on the measured ^{232}Th, and 0.7% on the measured ^{238}U. In this study we used ^{230}Th normalization (Bacon, 1984; Francois et al., 2004), a method that is used increasingly for calculating bulk and constituent sediment fluxes because it preserves the record of vertical particle fluxes regardless of whether sediment is subjected to postdepositional or syndepositional redistribution by bottom currents. For more details, see the methods discussion in Appendix DR1.

Opal content was measured by solution spectrophotometry following alkaline extraction of biogenic silica (Mortlock and Froelich, 1989) at the Lamont Doherty Earth Observatory (LDEO), Columbia University (uncertainties were <5% for biogenic opal). Bulk $CaCO_3$ was measured by coulometer at the LDEO (uncertainties were <2%). Residual detrital fluxes were calculated by first subtracting the proportion of all biogenic components (calcium carbonate, organic carbon, and opal) from 100 to get the percent residual detrital. This residual percentage (f_i) was then multiplied by the ^{230}Th-normalized bulk mass flux (F) at that depth interval ($F_i = f_i\, F$). To calculate ^{232}Th-derived detrital fluxes, we first determined the ^{230}Th-normalized flux of ^{232}Th at each depth interval in the core, and then divided this flux by the mean concentration of ^{232}Th in continental crust, 10 ppm (Taylor and McLennan, 1985), which is converted to 3.45 dpm/g.

$$^{232}\text{Th flux(dpm/cm}^2\text{/k.y.)} = (\text{production } ^{230}\text{Th} \times z) \times {}^{232}\text{Th}/{}^{230}\text{Th}. \qquad (1)$$

$$^{232}\text{Th-derived detrital flux (g/cm}^2\text{/k.y.)} = {}^{232}\text{Th flux/3.45 dpm/g}. \qquad (2)$$

RESULTS AND DISCUSSION

In the Flores Sea, the ^{230}Th-normalized bulk sediment (particle fluxes), biogenic silica (opal), calcium carbonate, and organic carbon fluxes, are all higher, on average, during the Last Glacial Maximum (LGM) (21.5–20 ka) than during the Holocene (Figs. 2 and 3). The higher particle and biogenic fluxes likely indicate enhanced surface ocean productivity during the LGM in the Flores Sea. This interpretation is indirectly supported by the higher concentrations of authigenic uranium, which is commonly precipitated in reducing sediments in response to in situ respiration of increased particulate organic carbon in the sediment, as well as decreases in oxygen concentration of bottom waters (Chase et al., 2001). Previous work on sediment from the Timor Sea indicates enhanced surface ocean productivity during the LGM (Holbourn et al., 2005; Müller and Opdyke, 2000), and this is further supported by modeling studies (Menviel et al., 2008). These works speculated that enhanced productivity was due to greater upwelling during the LGM, consistent with our results from the Flores Sea during the LGM (Fig. 2).

The most significant increase in total particle fluxes, indicated by the ^{230}Th-normalized

---

[1] GSA Data Repository item 2012187, Appendix DR1, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

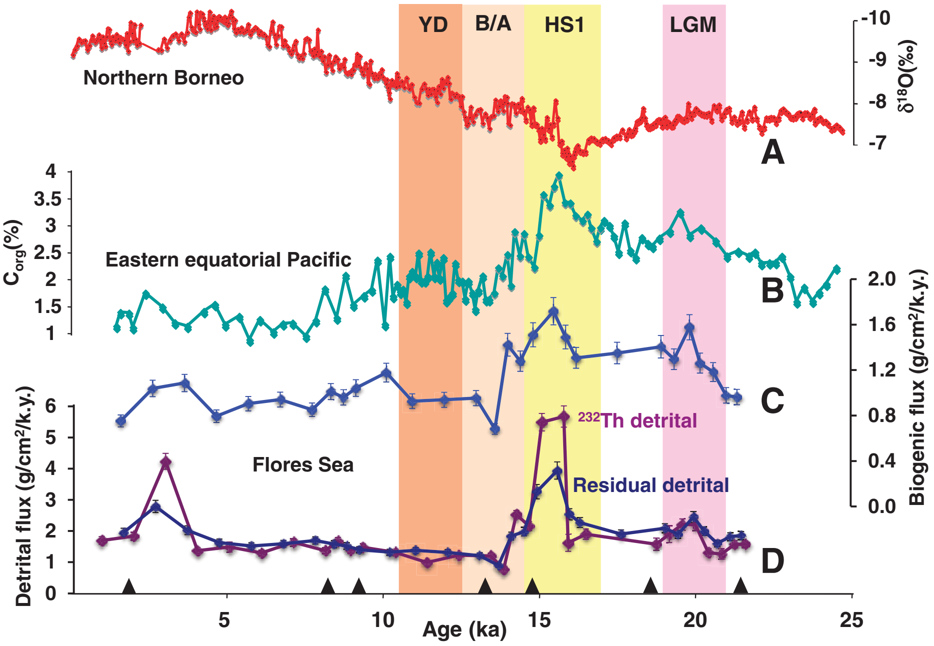

Figure 3. Comparison of Flores Sea records with other marine and terrestrial Intertropical Convergence Zone records. Arrows indicate ^{14}C age control points. Shading indicates significant climatic intervals. YD—Younger Dryas; B/A—Bølling-Allerød interstadial; HS1—Heinrich stadial 1; LGM—Last Glacial Maximum. A: δ^{18}O from Gunung Buda speleothem record (Partin et al., 2007). B: Percent organic carbon in eastern equatorial Pacific sediments (Kienast et al., 2006). C: Biogenic flux in Flores Sea sediments (see discussion of methods in text). D: Detrital fluxes from ^{232}Th and residual calculations in Flores Sea sediments (see discussion of methods in text).

fluxes, is centered at 16–14.5 ka (~6 g/cm^2/k.y. at 15 ka) (Fig. 2). This period of time spans the middle of Heinrich stadial 1 (HS1), an interval associated with evidence for reduced AMOC (McManus et al., 2004; Robinson and van de Flierdt, 2009), and ends with the onset of the Bølling-Allerød interstadial . The peak in ^{230}Th normalized flux is accompanied by an increase in the ^{232}Th-derived detrital input (Figs. 2 and 3). Because there is no seawater source for ^{232}Th, it provides a robust method for estimating detrital input at any location in the ocean either today or in the past, where the input of ^{232}Th at the sea surface equals the burial on the seafloor while at steady state (Robinson et al., 2008). The increase in ^{232}Th-derived detrital input also corresponds with an increase in residual detrital fluxes (Fig. 3) calculated by subtracting percent organic carbon, calcium carbonate, and biogenic silica from bulk fluxes. These calculations reveal that large amounts of detrital material were transported into the Flores Sea during HS1. One possible pathway for detrital material would be the many river systems flowing into the Flores Sea from the surrounding landmasses. Sediment-yield studies indicate that the Indonesian and Oceania regions represent the highest sediment yields (sediment load divided by drainage area) during prehistoric time (Syvitski et al., 2005). In addition, these areas receive the highest worldwide runoff (discharge divided by area) (Syvitski et al., 2005). An alternative explanation for the enhanced detrital input into the Flores Sea is increased sedimentation due to rapid deglacial sea-level rise on the Sunda Shelf; however, this explanation is not favored because sea-level curves for the Sunda Shelf indicate slow, rather than rapid, sea-level rise in the region at the time of HS1 (Hanebuth et al., 2000). Therefore, the likely source of detrital sediments entering the Flores Sea during HS1 is riverine. Since the *G. ruber* δ^{18}O record can be affected by variations in salinity, it might be expected that freshwater input, driven by precipitation, would decrease δ^{18}O values. However, we do not observe a significant change in δ^{18}O at the time of H1. It is possible that our δ^{18}O record does not have the resolution to pick up such freshwater events, or it might be that the δ^{18}O of the riverine runoff was close to that of the seawater δ^{18}O at that time.

In addition to enhanced detrital fluxes, we observe an increase in biogenic fluxes (opal and CaCO$_3$) during HS1 (Figs. 2 and 3). This increase points to enhanced biological productivity and was probably driven by the introduction of new river-sourced nutrients. It is possible that monsoon-driven upwelling also played a role in elevating productivity during this time; however, present-day studies indicate that highest upwelling in the Flores Seas coincides with northward migration of the ITCZ rather than southward migration (NASA Aqua satellite, moderate resolution imaging spectroradiometer, MODIS; http://oceancolor.gsfc.nasa.gov).

These results imply a time of significantly higher precipitation over the Flores Sea during HS1 that is consistent with several Southern Hemisphere paleorecords that demonstrate wet conditions during this period (Muller et al., 2008; Wang et al., 2006). At least one modeling study simulates increased precipitation in Kalimantan, southern Sumatra, Java, and parts of Sulawesi during periods of reduced AMOC (Lewis et al., 2010). These islands drain into the Flores Sea (Fig. 1), which would in turn increase the detrital sediment load to our site, supporting our interpretation of the ^{232}Th data. Together with evidence for dry conditions in northern Borneo (Fig. 1), the Flores Sea record further supports the hypothesis that a southward ITCZ shift characterized the tropical hydrological response during HS1 and the following years until the Bølling-Allerød period.

In contrast to the strong sedimentary signal during the early deglaciation, there is little or no evidence of a similar detrital response to the Younger Dryas (YD; ca. 13–11 ka) event in the Flores Sea particle flux profile (Fig. 2). This lack of a detrital signature may indicate a weaker hydrological response during the YD than during HS1. This explanation is consistent with evidence from Borneo (Partin et al., 2007) and the eastern equatorial Pacific (Kienast et al., 2006) suggesting that the response during the YD was weaker than during HS1. We favor this explanation because even though sea level was significantly higher (~50 m below present sea level) during the YD than during HS1, the Sunda Shelf would still have been largely exposed. Therefore, a significant precipitation increase during the YD should have caused a similar detrital response, as noted during HS1 in the Flores Sea. Work from the North Atlantic also supports this hypothesis, where an apparent drop in the rate of AMOC during the YD was less pronounced than during HS1 (McManus et al., 2004).

This study demonstrates that the Indonesian hydrological cycle is sensitive to high-latitude climate processes in the Northern Hemisphere. The work indicates greater precipitation over the Indonesian Seas during HS1 represented by increased riverine sediment fluxes. With previous work, our results provide strong evidence for a southward migration of the ITCZ during HS1 and a return northward during the Bølling-Allerød interstadial, highlighting the sensitivity of low-latitude rainfall patterns to abrupt climate change in the northern high latitudes.

ACKNOWLEDGMENTS

Contributions from Muller and McManus were supported in part by the Comer Science and Education Fund, the U.S. National Science Foundation (NSF), and the Woods Hole Oceanographic Institution (WHOI) Ocean Life Institute. Oppo's contribution was supported by the NSF. Muller acknowledges

Susan Brown-Leger (WHOI) and Maureen Soon (University of British Columbia) for assistance in the laboratory, and Candace Major and Sharon Hoffmann for helpful discussions. McManus acknowledges Pat Malone, who provided expert laboratory analysis at the Lamont-Doherty Earth Observatory. We thank reviewer Alex Thomas and one anonymous reviewer for helpful comments.

REFERENCES CITED

Bacon, M.P., 1984, Glacial to interglacial changes in carbonate and clay sedimentation in the Atlantic Ocean estimated from ^{230}Th measurements: Isotope Geoscience, v. 97, p. 97–111, doi.10.1016/0009-2541(84)90183-9.

Broccoli, A.J., Dahl, K.A., and Stouffer, R.J., 2006, Response of the ITCZ to Northern Hemisphere cooling: Geophysical Research Letters, v. 33, L01702, doi:10.1029/2005GL024546.

Chase, Z., Anderson, R.F., and Fleisher, M.Q., 2001, Evidence from authigenic uranium for increased productivity of the glacial subantarctic Ocean: Paleoceanography, v. 16, p. 468–478, doi:10.1029/2000PA000542.

Chiang, J., and Bitz, C., 2005, Influence of high latitude ice cover on the marine Intertropical Convergence Zone: Climate Dynamics, v. 25, p. 477–496, doi:10.1007/s00382-005-0040-5.

Choi, M., Francois, R., Sims, K., Bacon, M., Brown-Leger, S., Fleer, A., Ball, L., Schneider, D., and Pichat, S., 2001, Rapid determination of Th and Pa in seawater by desolvated-micronebulization inductively-coupled magnetic sector mass spectrometry: Marine Chemistry, v. 76, p. 99–112, doi:10.1016/S0304-4203(01)00050-0.

Francois, R., Frank, M., van der Loeff, M.M.R., and Bacon, M.P., 2004, ^{230}Th normalization: An essential tool for interpreting sedimentary fluxes during the late Quaternary: Paleoceanography, v. 19, PA1018, doi:10.1029/2003PA000939.

Griffiths, M., and 12 others, 2009, Increasing Australian-Indonesian monsoon rainfall linked to early Holocene sea-level rise: Nature Geoscience, v. 2, p. 636–639, doi:10.1038/ngeo605.

Hanebuth, T., Stattegger, K., and Grootes, P.M., 2000, Rapid flooding of the Sunda Shelf: A late glacial sea-level record: Science, v. 288, p. 1033–1035, doi:10.1126/science.288.5468.1033.

Hemming, S.R., 2004, Heinrich events: Massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint: Reviews of Geophysics, v. 42, p. 1–43, doi:10.1029/2003RG000128.

Hobbs, J.E., 1998, Climates of the southern continents: Present, past and future: West Sussex, UK, Wiley, p. 63–100.

Holbourn, A., Kuhnt, W., Kawamura, H., Jian, Z., Grootes, P., Elrlenkeuser, H., and Xu, J., 2005, Orbitally paced paleoproductivity variations in the Timor Sea and Indonesian Throughflow variability during the last 460 kyr: Paleoceanography, v. 20, PA3002, doi:10.1029/2004PA001094.

Mortlock, R.A., and Froelich, P.N., 1989, A simple method for the rapid determination of biogenic opal in pelagic marine sediments: Deep-Sea Research, v. 36, p. 1415–1426, doi:10.1016/0198-0149(89)90092-7.

Müller, A., and Opdyke, B.N., 2000, Glacial-interglacial changes in nutrient utilization and paleoproductivity in the Indonesian Throughflow sensitive Timor Trough, easternmost Indian Ocean: Paleoceanography, v. 15, p. 85–94, doi:10.1029/1999PA900046.

Muller, J., Kylander, M.E., Wust, R.A., Weiss, D.J., Martinez-Cortizas, A., LeGrande, A.N., Jennerjahn, T., Behling, H., Anderson, W., and Jacobson, G., 2008, Possible evidence for wet Heinrich phases in tropical NE Australia: The Lynch's Crater deposit: Quaternary Science Reviews, v. 27, p. 468–475, doi:10.1016/j.quascirev.2007.11.006.

Partin, J., Cobb, K., Adkins, J., Clark, B., and Fernandez, D., 2007, Millennial-scale trends in west Pacific warm pool hydrology since the Last Glacial Maximum: Nature, v. 449, p. 452–455, doi:10.1038/nature06164.

Peterson, L.C., Haug, G.H., Hughen, K.A., and Rohl, U., 2000, Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial: Science, v. 290, p. 1947–1951, doi:10.1126/science.290.5498.1947.

Reimer, P.J., and 27 others, 2009, IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP: Radiocarbon, v. 51, p. 1111–1150.

Robinson, L.F. and van de Flierdt, 2009, Southern Ocean evidence for reduced export of North Atlantic Deep Water during Heinrich event 1: Geology, v. 37, p. 195–198, doi:10.1130/G25363A.1.

Robinson, L.F., Noble, T., and McManus, J.F., 2008, Measurement of adsorbed and total ^{232}Th/^{230}Th ratios from marine sediments: Chemical Geology, v. 252, p. 169–179, doi:10.1016/j.chemgeo.2008.02.015.

Schulz, H., von Rad, U., and Erlenkeuser, H., 1998, Correlation between Arabian Sea and Greenland climate oscillations of the past 110,000 years: Nature, v. 393, p. 54–57, doi:10.1038/31750.

Spooner, M., Barrows, T., De Deckker, P., and Paterne, M., 2005, Palaeoceanography of the Banda Sea, and late Pleistocene initiation of the Northwest Monsoon: Global and Planetary Change, v. 49, p. 28–46, doi:10.1016/j.gloplacha.2005.05.002.

Syvitski, J., Vorosmarty, J., Kettner, A., and Green, P., 2005, Impact of humans on the flux of terrestrial sediment to the global coastal ocean: Science, v. 308, p. 376–380, doi:10.1126/science.1109454.

Taylor, S.R., and McLennan, S.M., 1985, The continental crust: Its composition and evolution: Oxford, UK, Blackwell, 312 p.

Turney, C.S.M., Kershaw, A.P., Clemens, S.C., Branch, N., Moss, P.T., and Fifield, L.K., 2004, Millennial and orbital variations of El Niño/Southern Oscillation and high-latitude climate in the last glacial period: Nature, v. 428, p. 306–310, doi:10.1038/nature02386.

Wang, X., Auler, A., Edwards, L., Cheng, H., Cristall, P., Smart, P.L., Richards, D.A., and Shen, C.-C., 2004, Wet periods in northeastern Brazil over the past 210 kyr linked to distant climate anomalies: Nature, v. 432, p. 740–743, doi:10.1038/nature03067.

Wang, X., Auler, A.S., Edwards, R.L., Cheng, H., Ito, E., and Solheid, M., 2006, Interhemispheric antiphasing of rainfall during the last glacial period: Quaternary Science Reviews, v. 25, p. 3391–3403, doi:10.1016/j.quascirev.2006.02.009.

Wang, Y.J., Cheng, H., Edwards, R.L., An, Z.S., Wu, J.Y., Shen, C.-C., and Dorale, J.A., 2001, A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China: Science, v. 294, p. 2345–2348, doi:10.1126/science.1064618.

Zhang, R., and Delworth, T., 2005, Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation: Journal of Climate, v. 18, p. 1853–1860, doi:10.1175/JCLI3460.1.

Manuscript received 29 September 2011
Revised manuscript received 8 February 2012
Manuscript accepted 8 February 2012

Printed in USA