

# The amplitude and phasing of climate change during the last deglaciation in the Sulu Sea, western equatorial Pacific

Yair Rosenthal,<sup>1</sup> Delia W. Oppo,<sup>2</sup> and Braddock K. Linsley<sup>3</sup>

Received 15 November 2002; accepted 19 February 2003; published 22 April 2003.

[1] Variations in tropical sea surface temperature patterns and the phasing relative to climate change in higher-latitudes provide insight into the mechanisms of climate change on both orbital and shorter time-scales. Here, we present well-dated, high-resolution records of planktonic foraminiferal  $\delta^{18}\text{O}$  and Mg/Ca-based SST spanning the last deglaciation from the Sulu Sea, located in the western equatorial Pacific. The results indicate that the last glacial maximum was  $2.3 \pm 0.5^\circ\text{C}$  cooler than present in the Sulu Sea with a concomitant decrease in sea surface salinity. The similarity between variations in surface salinity in the Sulu Sea, the western and eastern equatorial Pacific, and the Greenland ice-core record suggests that the observed changes in salinity reflect large-scale rearrangement of atmospheric patterns, which were coherent and synchronous throughout the Northern Hemisphere. The results suggest that the glacial equatorial Pacific climate was strongly influenced by both tropical, and extra-tropical forcing, although it is not clear whether interannual (ENSO) variability is a good analogue of glacial-interglacial climate change. **INDEX TERMS:** 4267 Oceanography: General: Paleooceanography; 4522 Oceanography: Physical: El Niño. **Citation:** Rosenthal, Y., D. W. Oppo, and B. K. Linsley, The amplitude and phasing of climate change during the last deglaciation in the Sulu Sea, western equatorial Pacific, *Geophys. Res. Lett.*, 30(8), 1428, doi:10.1029/2002GL016612, 2003.

## 1. Introduction

[2] Under current conditions, interannual variations in the distribution of equatorial sea surface temperature (SST) related to the El Niño-Southern Oscillation (ENSO) exert a major effect on atmospheric circulation and global climate. Longer-term changes of SST patterns in the equatorial Pacific might also have had large consequences for extra-tropical climate during the last glacial maximum (LGM). Model simulations suggest that decreased seasonality associated with reduced summer insolation would favor a shift in the mean climate state of the equatorial Pacific to more El Niño-like conditions during the LGM relative to the modern climate state [Clement *et al.*, 1999]. Other model studies have suggested a more uniform cooling of tropical SST in response to extra-tropical forcing [Andreasen *et al.*, 2001].

The paleoceanographic evidence is, however, controversial. For example, Lea *et al.* [2000] showed similar cooling during the LGM in cores from the eastern and western equatorial Pacific. Based on  $\delta^{18}\text{O}_{\text{water}}$  reconstructions that indicate glacial freshening of the Ontong Java Plateau region in the western equatorial Pacific (WEP) relative to the eastern equatorial Pacific (EEP), Lea *et al.* [2000] argued in favor of more La Niña-like conditions. Subsequent studies, however, countered that the tropical Pacific was not more La Niña-like on broader spatial scales [Andreasen *et al.*, 2001; Oppo *et al.*, 2003], whereas others propose that the glacial tropics were more El Niño-like than today. This argument was made based on glacial reconstructions of weaker zonal and meridional SST gradients in the equatorial Pacific [Koutavas *et al.*, 2002] and relatively salty conditions in the Mindanao Sea in the WEP [Stott *et al.*, 2002]. Here we assess the amplitude and phasing of climate change in a high-resolution sediment record from the Sulu Sea, a semi-enclosed shallow-silled basin located between South China Sea and the western equatorial Pacific (Figure 1), and discuss the implications to glacial tropical climatology.

[3] Surface and subsurface waters from the South China Sea enter the Sulu Sea from the northwest side through the  $\sim 420$  m deep Mindoro Strait. Shallower passages connect the Sulu Sea to the Sulawesi Sea ( $\sim 250$  m) and through the Philippine archipelago (110 and 65 m) to the WEP. The modern climatology of the Sulu Sea is strongly influenced by the combined effects of the East Asian monsoon and ENSO. Mean annual SST is  $28.7^\circ\text{C}$ , varying seasonally by less than  $2^\circ\text{C}$ . Sea surface salinity (SSS) in the Sulu Sea reflects its intermediate position between the relatively salty WEP and the low salinity South China Sea. During low sea level stands, however, the relative contribution of surface water from South China Sea was greatly enhanced due to the hydraulic constraints on the influx of Pacific surface water.

[4] A record of temporal variations in  $\delta^{18}\text{O}$  and Mg/Ca of the mixed-layer planktonic foraminifer *Globigerinoides ruber*, was generated from Sulu Sea IMAGES core MD972141 ( $8.8^\circ\text{N}$ ,  $121.3^\circ\text{E}$ , 3633 m water depth) located near the site of ODP769A [Linsley, 1996]. Here we discuss the high resolution results (2-cm sample interval representing  $\leq 200$  years/sample) from the uppermost part of the core spanning 4.5 to 22 ky. The analytical methods and other aspects of core MD972141 have been discussed elsewhere [Dannenmann *et al.*, 2003; Oppo *et al.*, 2003].

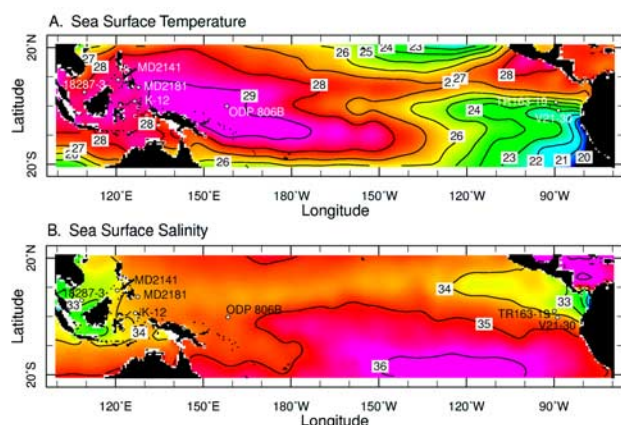
## 2. Results and Discussion

[5] The planktonic  $\delta^{18}\text{O}_{\text{ruber}}$  record from the Sulu Sea shows a 1‰ LGM to Holocene negative shift (Figure 2; LGM is defined as the interval of 18–24 ky B.P.), which is

<sup>1</sup>Institute of Marine and Coastal Sciences, and Department of Geology, Rutgers, The State University, New Brunswick, New Jersey, USA.

<sup>2</sup>Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.

<sup>3</sup>Department of Earth and Atmospheric Sciences, University at Albany-SUNY, Albany, New York, USA.



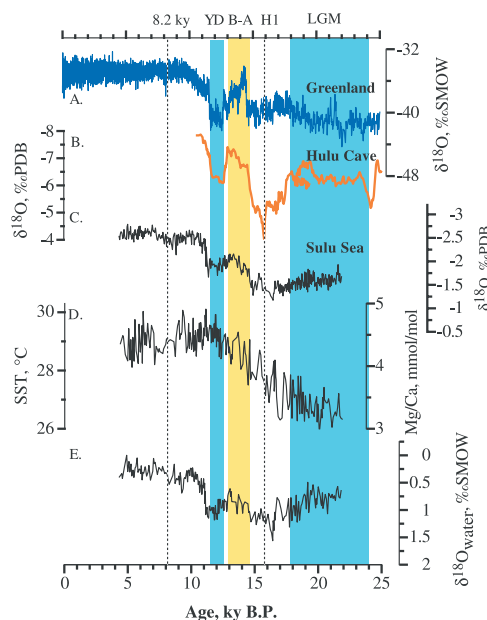
**Figure 1.** A. Equatorial Pacific mean annual SST; B. Mean annual SSS. Marked on the panels are the locations of the equatorial Pacific records discussed in the text [Levitus and Boyer, 1994].

similar to the global ice volume effect [Schrage *et al.*, 1996]. The LGM-Holocene  $\Delta\delta^{18}\text{O}_{\text{ruber}}$  amplitude is consistent with earlier results from ODP site 769A [Linsley, 1996]. Concomitantly, the Mg/Ca ratio in *G. ruber* shells shows an LGM-Holocene increase of about  $0.9 \text{ mmol mol}^{-1}$ , suggesting that Sulu Sea SST was significantly colder during the LGM than at present. Carbonate preservation in the Sulu Sea is much better than in the open Pacific Ocean. The high planktonic foraminiferal preservation in the basin results in relatively high Mg/Ca. This yields unreasonably high SST values when using open-ocean calibrations, because the latter were calibrated for more dissolved foraminifera [Lea *et al.*, 2000] (e.g. estimated core top SST =  $30^\circ\text{C}$  and LGM SST =  $27.6^\circ\text{C}$ ). Instead, we apply the preservation-dependent calibration of Rosenthal and Lohmann [2002]; using the average, core-top shell weight (212–300  $\mu\text{m}$  size fraction) of 6.74  $\mu\text{g}$ , the Mg-temperature relationship for the Sulu Sea is,  $(\text{Mg/Ca})_{\text{ruber}} = 0.28\text{Exp}(0.095\text{SST})$ . Applying this equation to the average core top value of  $\text{Mg/Ca} = 4.32 \text{ mmol mol}^{-1}$  we calculate SST of  $28.9^\circ\text{C}$ , in agreement with modern mean annual value of  $28.7^\circ\text{C}$  at the Sulu Sea (note however that the core top age is  $\sim 4.5 \text{ ky}$ ). Applying the equation to the LGM data we estimate glacial cooling of  $2.3 \pm 0.5^\circ\text{C}$  in the Sulu Sea.

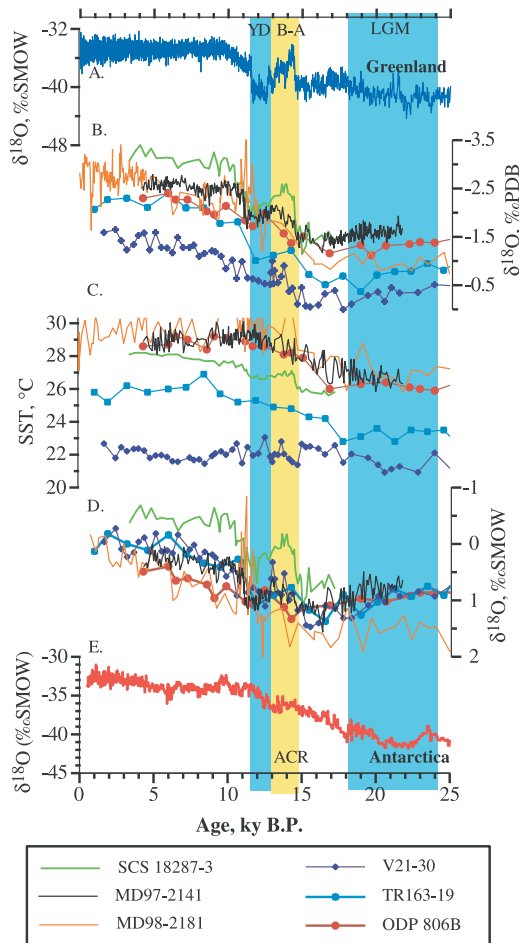
[6] The small LGM-Holocene  $\Delta\delta^{18}\text{O}_{\text{water}}$  amplitude ( $\sim 0.5\text{‰}$ ) in the Sulu Sea, reconstructed from paired  $\delta^{18}\text{O}_{\text{ruber}}$  and Mg/Ca-derived SST, indicates that the glacial cooling in the Sulu Sea was associated with significant surface water freshening. As discussed elsewhere [Oppo *et al.*, 2003] and elaborated on below, we believe that both hydraulic and climatic factors influenced the SSS of the Sulu Sea. To gain further insight into the spatial significance of these changes, we compare  $\delta^{18}\text{O}_{\text{ruber}}$ , SST, and  $\delta^{18}\text{O}_{\text{water}}$  records from the Sulu Sea and other equatorial sites including the southern South China Sea (core 18287-3 at  $5^\circ 39'\text{N}$   $110^\circ 39'\text{E}$ ; [Kienast *et al.*, 2001]), Mindanao Sea off the southeastern coast of the Philippines (MD98-2181 at  $6^\circ 3'\text{N}$   $125^\circ 83'\text{E}$ ; [Stott *et al.*, 2002]), Ontong Java Plateau (ODP 806B at  $0^\circ 19'\text{N}$   $159^\circ 22'\text{E}$ ), and two cores from the eastern equatorial Pacific, TR163-19 ( $2^\circ 16'\text{N}$   $90^\circ 57'\text{W}$  [Lea *et al.*, 2000]) and V21-30 in the cold tongue ( $1^\circ 13'\text{S}$   $89^\circ 41'\text{W}$

[Koutavas *et al.*, 2002]). We also compare the Sulu Sea record with a continental record of East Asian monsoon variability based on the U-Th dated stalagmite  $\delta^{18}\text{O}$  record of the Hulu Cave ( $33.5^\circ\text{N}$ ) in China [Wang *et al.*, 2001].

[7] The  $\delta^{18}\text{O}_{\text{water}}$  values extracted from sediment records at two western equatorial Pacific sites, the Sulu Sea and the Ontong Java Plateau near the core of today's western Pacific warm pool, become progressively heavier between 22 and 16.5 ky, suggesting increasing SSS just as sea level began to rise (Figure 3). The increasing trend in SSS in the Sulu Sea may partly be attributable to the decrease in summer/winter precipitation ratio in the East Asian monsoon as suggested from the Hulu Cave record [Wang *et al.*, 2001]. However, similar trends in the Ontong Java Plateau and both EEP sites indicate that a post-glacial increase in SSS is a broad spatial feature of the equatorial Pacific, thereby suggesting a large-scale rearrangement of atmospheric patterns. The similarity in surface water  $\delta^{18}\text{O}_{\text{water}}$  composition at the Ontong Java Plateau and EEP sites during the LGM suggests a reduction in the zonal salinity gradient of the equatorial Pacific relative to the present, primarily due to glacial freshening of the WEP [Lea *et al.*, 2000]. Unlike today, the records also show that the  $\delta^{18}\text{O}_{\text{water}}$  composition of the Sulu Sea was virtually identical to that of the South China Sea during the LGM and significantly different than observed in the Ontong Java Plateau. These observations suggest that in addition to climatological changes, hydraulic controls due to



**Figure 2.** A comparison of the last deglaciation records from Greenland, eastern continental China, and the Sulu Sea. A)  $\delta^{18}\text{O}$  record from GISP II; B) Stalagmite  $\delta^{18}\text{O}$  record of East Asian monsoon intensity from the Hulu Cave-eastern China. [Wang *et al.*, 2001]; C)  $\delta^{18}\text{O}$  records of planktonic foraminiferal *G. ruber* (212–300  $\mu\text{m}$  size-fraction of the white form) from the Sulu Sea (MD97-2141); D) Mg/Ca-based SST records from the Sulu Sea; E) Surface  $\delta^{18}\text{O}_{\text{water}}$  records from the Sulu Sea and Mg-derived SST. MD97-2141 chronology is based on 15 accelerator mass spectrometry radiocarbon age dates [de Garidel-Thoron *et al.*, 2001].



**Figure 3.** Comparison of records from the equatorial Pacific sites of Sulu Sea, southern South China Sea, Mindanao Sea, Ontong Java Plateau core ODP806B, TR163-19, and V21-30. A)  $\delta^{18}\text{O}$  record from GISP II; B) Planktonic foraminiferal  $\delta^{18}\text{O}$  records; C) SST records; D) Surface  $\delta^{18}\text{O}_{\text{water}}$ ; E) Antarctic, Byrd ice core isotopic record.

lower sea level limited the inflow of saltier equatorial Pacific surface water relative to inflow of fresher South China Sea waters, which enhanced the freshening of the glacial Sulu Sea. The Mindanao Sea record [Stott *et al.*, 2002] is the only exception to this pattern: of the five sites with records extending into the LGM, it is the only one that does not show the post-glacial increase in SSS suggesting that it was more saline than the other sites during the LGM and early stage of deglaciation.

[8] The glacial cooling of  $2.3 \pm 0.5^\circ\text{C}$  in the Sulu Sea is matched by similar cooling of  $2\text{--}3^\circ\text{C}$  observed in western (Ontong Java Plateau, Mindanao) and northeastern (TR163-19) equatorial Pacific records. In contrast, V21-30 exhibits a much smaller glacial cooling of  $\sim 1.2^\circ\text{C}$  [Koutavas *et al.*, 2002]. Because V21-30 records conditions in the cold tongue of the eastern equatorial Pacific, the new records suggest both reduced zonal equatorial SST gradient as well as lower meridional SST gradient within the eastern equatorial Pacific during the LGM relative to the present. Koutavas *et al.* [2002] proposed that the LGM reduction

in the equatorial Pacific east-west SST gradient and contraction of the cold tongue are consistent with a persistent El Niño-like pattern in the tropical Pacific, a corollary consistent with model studies [Clement *et al.*, 1999]. Similarly, based on evidence of relatively salty conditions in the Mindanao Sea, Stott *et al.* [2002] proposed super-El Niño conditions for the LGM, and argued that this is consistent with the reduced zonal salinity gradient inferred from  $\delta^{18}\text{O}_{\text{water}}$  records. It is important to note, however, that the observed decreases in equatorial Pacific SST gradients during the LGM are significantly smaller than the anomalies between the eastern and western Pacific SST observed during modern El Niño events. For example, at the LGM the zonal SST gradient was  $\sim 1^\circ\text{C}$  smaller than the Holocene gradient, compared to the  $3\text{--}4^\circ$  anomalies during the historical El Niño events. In fact, such small variations occur seasonally, with the warming of the cold tongue during the winter months of February and March. The analogy of El Niño-like conditions also implies weaker Walker circulation and trade winds, and therefore reduced equatorial upwelling in the EEP during the LGM. Recent evidence suggesting a decrease in productivity and nutrient concentrations in the south equatorial current, is consistent with reduced upwelling along the Peru margin [Loubere, 2002]. In contrast, there is evidence for higher glacial productivity further north and south of the equator, which is interpreted to reflect a general enrichment in surface water nutrient concentrations [Loubere, 2002]. The paleorecords also suggest that the change in tropical Pacific SST patterns during the LGM was superimposed on an overall cooling of tropical SST, likely in response to extra-tropical forcing [Andreassen *et al.*, 2001].

[9] The Sulu Sea record exhibits millennial-scale oscillations both in  $\delta^{18}\text{O}$  and SST superimposed on the deglacial trends. Most notably, the  $\delta^{18}\text{O}$  oscillations parallel climate oscillations in Greenland. However, the new high-resolution record from the Sulu Sea reveals the strong coherence with the Greenland ice core record in greater detail. For example, the heaviest  $\delta^{18}\text{O}$  values between 16 and 16.5 ky B.P. are most likely associated with the Heinrich event (H1). The rapid decrease in foraminiferal  $\delta^{18}\text{O}$  at about 14.8 ky B.P. coincides with the Bølling Transition (B-A) and the pronounced  $\delta^{18}\text{O}$  excursion between  $\sim 12.8$  and  $11.0$  ky B.P. correlates with the Younger Dryas (Y-D). The Sulu Sea  $\delta^{18}\text{O}$  record also shows a significant positive excursion centered at about 8.5 ky B.P., likely associated with the 8.2 ky cooling event, known from the Greenland ice core. In contrast with  $\delta^{18}\text{O}$ , the Mg/Ca-based SST record shows (within the error of our analyses of  $\pm 0.5^\circ\text{C}$ ) no discernible variations during these millennial events. The absence of significant SST change in the Sulu Sea during these events indicates that millennial-scale variability in the  $\delta^{18}\text{O}_{\text{ruber}}$  record is primarily driven by changes in SSS. We interpret the strong correlation among  $\delta^{18}\text{O}_{\text{water}}$  records from the South China Sea, Sulu Sea, Mindanao Sea and the speleothem record of changes in East Asian monsoon intensity from the Hulu Cave (Figure 2) to indicate that suborbital variability in Sulu Sea hydrography is coupled to changes in the intensity of the East Asian monsoon, whereby relatively fresh surface waters in the Sulu Sea coincide with greater net precipitation associated with higher intensity of the summer monsoon. It appears that



suborbital variations in  $\delta^{18}\text{O}_{\text{water}}$  are also coherent and synchronous with variations in the cold tongue (V21-30), suggesting that these changes were part of a wider tropical climatic response. It is also noteworthy that under present conditions a weaker boreal winter monsoon is often associated with El Niño events, possibly reflecting a teleconnection between climate conditions in East Asia and SST anomalies in the equatorial Pacific [Wang *et al.*, 2000]. It is possible therefore, that the positive covariation in  $\delta^{18}\text{O}_{\text{water}}$  and by inference salinity, between the western and eastern equatorial Pacific indicates that similar extratropical-tropical interactions also occurred on millennial time-scales.

[10] Studies of SST change in tropical regions since the LGM suggest a spatially inhomogeneous initiation of rapid deglacial warming. Whereas SST appears to rise synchronously with the Northern Hemisphere Bølling warming in the South China Sea [Kienast *et al.*, 2001], the timing of warming in the open tropical Pacific is more ambiguous. Post LGM surface water warming in the Sulu Sea began at 20 ky B.P., about 3.5 ky before the abrupt deglacial shift in  $\delta^{18}\text{O}_{\text{ruber}}$  but synchronous with the warming inferred from records from the Mindanao Sea, TR163-19 and core V21-30, in the western and eastern equatorial Pacific, respectively. The offset between Sulu Sea SST and  $\delta^{18}\text{O}_{\text{ruber}}$  is consistent with observations from other equatorial Pacific sites and reflects changes in hydrology. Within dating uncertainty, the equatorial warming began synchronously with the beginning of global sea level rise [Hanebuth *et al.*, 2000], and the gradual early warming of both Greenland and Antarctica [Grootes *et al.*, 2001]. The Sulu Sea Mg/Ca-based SST record, however, displays none of the well-known North Atlantic millennial-scale oscillations like the Bølling warming or Younger Dryas cooling. In fact, Sulu Sea SST reaches modern values ( $\sim 29^\circ\text{C}$ ) during the Younger Dryas, which is accompanied by the positive shift in  $\delta^{18}\text{O}_{\text{ruber}}$ , suggesting that deglacial changes in the WEP hydrology continued for  $\sim 1000$  years after surface water reached Holocene temperatures. The same pattern of warming is also found in other equatorial Pacific records. The difference in timing between the South China Sea site, on the one hand, and the open Pacific sites on the other hand, indicates that the marginal sea record of South China Sea is more strongly affected by continental climate than the open ocean sites and therefore shows greater similarity to the Greenland ice core record. The absence of Northern Hemisphere millennial variability in SST in open ocean equatorial Pacific sites may reflect the integrated effects of changes in heat transfer and the associated tropical SST patterns driven by tropical dynamics and background cooling driven by global climate change. These variations likely had major implications for global climate change.

[11] **Acknowledgments.** We thank the IMAGES Program for allowing access to core MD97-2141. This project has been funded by NSF Awards #OCE 9987060 to YR, #OCE 9710097 to DWO, and #OCE

9710156 to BKL. We also acknowledge the support of French MENRT, TAAF, CNRS/INSU and IFRTP to the Marion Dufresne and the IMAGES program. This is WHOI contribution number 10850.

## References

- Andreasen, D. J., A. C. Ravelo, and A. Broccoli, Remote forcing at the last glacial maximum in the tropical Pacific Ocean, *J. Geophys. Res.*, 106, 879–897, 2001.
- Clement, A. C., M. Cane, and R. Seager, Orbital controls on the tropical climate, *Paleoceanography*, 14, 441–456, 1999.
- Dannenmann, S., B. K. Linsley, D. W. Oppo, Y. Rosenthal, and L. Beaufort, East Asian Monsoon Forcing of Suborbital variability in the Sulu Sea during Marine Isotope Stage 3: Link to Northern Hemisphere Climate, *Geochemistry, Geophysics, Geosystems*, 4, doi:10.1029/2002GC000390, 2003.
- de Garidel-Thoron, T., L. Beaufort, B. K. Linsley, and S. Dannenmann, Millennial-scale dynamics of the East Asian winter monsoon during the last 200,000 years, *Paleoceanography*, 16, 491–502, 2001.
- Grootes, P. M., E. J. Steig, M. Stuiver, E. D. Waddington, and D. L. Morse, The Taylor Dome Antarctic  $^{18}\text{O}$  record and globally synchronous changes in climate, *Quat. Res.*, 56, 289–298, 2001.
- Hanebuth, T., K. Stattegger, and P. M. Groot, Rapid flooding of the Sunda Shelf: A late-glacial sea-level record, *Science*, 288, 1033–1035, 2000.
- Kienast, M., S. Steinke, K. Stattegger, and S. E. Calvert, Synchronous tropical south China Sea SST change and Greenland warming during deglaciation, *Science*, 291, 2132–2134, 2001.
- Koutavas, A., J. Lynch-Stieglitz, T. M. Marchitto, and J. P. Sachs, El Niño - Like Pattern in Ice Age Tropical Pacific Sea Surface Temperature, *Science*, 297, 226–230, 2002.
- Lea, D. W., D. K. Pak, and H. J. Spero, Climate impact of late Quaternary equatorial Pacific sea surface temperature variations, *Science*, 289, 1719–1724, 2000.
- Levitus, S., and T. P. Boyer, World ocean atlas 1994 volume 4: Temperature, NOAA Atlas NESDIS 4. U.S. Department of Commerce, Washington DC, 117 pp., 1994.
- Linsley, B. K., Oxygen-isotope record of sea level and climate variations in the Sulu Sea over the past 150,000 years, *Nature*, 380, 234–237, 1996.
- Loubere, P., Remote vs. local control of changes in eastern equatorial Pacific bioproductivity from the last glacial maximum to the Present, *Global Planet. Change*, 35, 113–126, 2002.
- Oppo, D. W., B. K. Linsley, Y. Rosenthal, S. Dannenmann, and L. Beaufort, Orbital and suborbital climate changes in the western tropical Pacific, *Geochemistry, Geophysics, Geosystems*, 4, doi:10.1029/2002GC000260, 2003.
- Rosenthal, Y., and G. P. Lohmann, Accurate estimation of sea surface temperatures using dissolution-corrected calibrations for Mg/Ca paleothermometry, *Paleoceanography*, 17, doi:10.1029/2001PA000749, 2002.
- Schrag, D. P., G. Hampt, and D. W. Murray, Pore fluid constraints on the temperature and isotopic composition of the glacial ocean, *Science*, 272, 1996.
- Stott, L., C. Poulsen, L. Lund, and R. C. Thunell, Super ENSO and Global Climate Oscillations at Millennial Time Scales, *Science*, 297, 222–226, 2002.
- Wang, B., R. Wu, and X. Fu, Pacific-East Asian teleconnection: How does ENSO affect East Asian Climate?, *J. Climate*, 13, 1517–1536, 2000.
- Wang, Y. J., et al., A high-resolution absolute-dated late Pleistocene Monsoon record from Hulu Cave, China, *Science*, 294, 2345–2348, 2001.

Y. Rosenthal, Institute of Marine and Coastal Sciences, and Department of Geology, Rutgers, The State University, 71 Dudley Road, New Brunswick, NJ 08901-8521, USA.

D. W. Oppo, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA.

B. K. Linsley, Department of Earth and Atmospheric Sciences, ES 351, University at Albany-SUNY, 1400 Washington Ave., Albany, NY 12222, USA.