Clim. Past Discuss., 10, 3397–3419, 2014 www.clim-past-discuss.net/10/3397/2014/ doi:10.5194/cpd-10-3397-2014 © Author(s) 2014. CC Attribution 3.0 License.



This discussion paper is/has been under review for the journal Climate of the Past (CP). Please refer to the corresponding final paper in CP if available.

Millennial meridional dynamics of Indo-Pacific Warm Pool during the last termination

L. Lo¹, C.-C. Shen¹, K.-Y. Wei¹, G. S. Burr^{1,2}, H.-S. Mii³, M.-T. Chen⁴, S.-Y. Lee⁵, and M.-C. Tsai¹

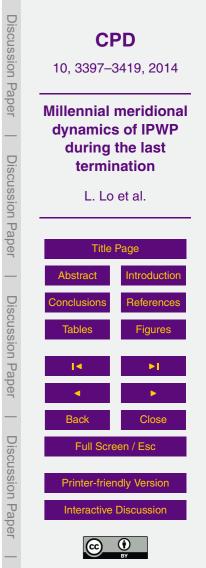
¹High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan ²NSF-Arizona Accelerator Mass Spectrometry Facility, Department of Physics, University of Arizona, Tucson, AZ 85721, USA

³Department of Earth Sciences, National Taiwan Normal University, Taipei 11677, Taiwan
 ⁴Institute of Applied Geosciences, National Taiwan Ocean University, Keelung 20224, Taiwan
 ⁵Research Center for Environmental Changes, Academia Sinica, Taipei 11529, Taiwan

Received: 5 July 2014 - Accepted: 14 July 2014 - Published: 21 August 2014

Correspondence to: C.-C. Shen (river@ntu.edu.tw)

Published by Copernicus Publications on behalf of the European Geosciences Union.



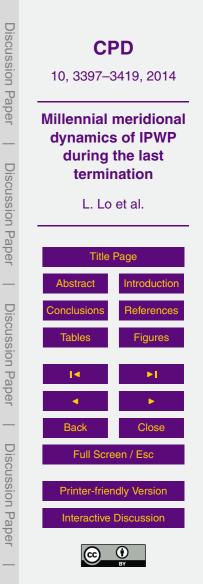
Abstract

To develop an in-depth understanding of the natural dynamics of the Indo-Pacific Warm Pool (IPWP) during the last deglaciation, stacked North- (N-) and South-IPWP (S-IPWP) thermal and hydrological records over the past 23-10.5 thousand years (ka) were built using planktonic foraminiferal geochemical data from a new core, MD05-2925 (9.3° S, 151.5° E, water depth 1661 m) in the Solomon Sea and eleven previous sites. Ice-volume corrected seawater $\delta^{18}O(\delta^{18}O_{SW-IVC})$ stacks show that S-IPWP $\delta^{18}O_{SW-IVC}$ values are indistinguishable from their northern counterpart through glacial time. The N-IPWP SST stacked record features an increasing trend of 0.5°C ka⁻¹ since 18 ka. Its S-IPWP counterpart shows an earlier onset of temperature increase 10 at 19 ka and a strong teleconnection to high-latitude climate in the Southern Hemisphere. Meridional SST gradients between N- and S-IPWP were 1.5°C during the Bølling/Allerød period and < 0.5 °C during both Heinrich event 1 and the Younger Dryas due to a warmer S-IPWP. A warm S-IPWP during the cold events snapshots may possibly weaken the southern hemispheric convection branch of the Hadley Cell and reduce 15 precipitation in the Asian Monsoon region.

1 Introduction

The Indo-Pacific Warm Pool (IPWP) is the largest warm water mass in the world, with an annual average sea surface temperature (SST) greater than 28 °C (Yan et al., 1992).

- ²⁰ Vigorous regional atmosphere circulation transports latent heat and water moisture from the IPWP to the middle and high latitudes (Yan et al., 1992). For the past five decades, the IPWP has experienced surface water freshening and a westward shift in precipitation, resulting in regional drought in East Africa and storm track changes in East Australia (Cravatte et al., 2009; Williams and Funk, 2011). Since the early
- ²⁵ 2000s, intensive paleoclimatological studies have been conducted to understand longterm thermal and hydrological changes in the IPWP, associated with glacial/interglacial



(G/IG) cycles, and to constrain the relationship between warm pool thermal and hydrological fluctuations to high latitude ice sheet and greenhouse gas concentrations during the late Pleistocene (e.g., Lea et al., 2000; Stott et al., 2002; Visser et al., 2003; Rosenthal et al., 2003; Stott et al., 2004; de Garidel-Thoron et al., 2005; Steinke et al., 2006; Levi et al., 2007; Xu et al., 2008; Linsley et al., 2010; Bolliet et al., 2011; Mothadi et al., 2014).

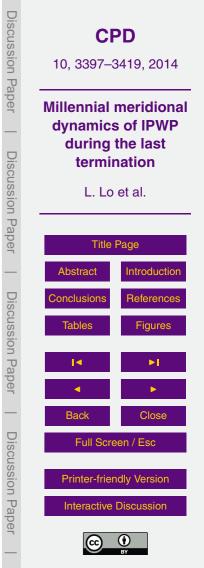
Stacked IPWP SST and seawater oxygen isotope ($\delta^{18}O_{SW}$) records from the last glacial to the Holocene clearly show a close link between the IPWP SST, the Asian-Australian Monsoon (AAM) system, and sea level (Stott et al., 2004; Oppo et al., 2009; Linsley et al., 2010). However, a complicated ocean–island configuration and regional

- ¹⁰ Linsley et al., 2010). However, a complicated ocean–island configuration and regional topography hinder the fidelity of using these records to describe past climate changes in detail (Griffiths et al., 2009; Mohtadi et al., 2011). In particular, little is known about the meridional thermal-hydrological dynamics between the N- and S-IPWP during the last termination.
- ¹⁵ Here we present new oceanic proxy-inferred SST and ice volume-corrected surface seawater oxygen isotope δ^{18} O ($\delta^{18}O_{SW-IVC}$) records from the Solomon Sea, Papua New Guinea (PNG) for the past 23–10.5 thousand years ago (ka, before 1950 AD, hereafter). New SST and $\delta^{18}O_{SW-IVC}$ stacked records since the last termination are built for both the N- and S-IPWP to understand regional thermal-hydrological changes and interhemispheric teleconnections.

2 Material and methods

25

Site MD05-2925 (9.3° S, 151.5° E, water depth 1661 m) is located at the northern slope of the Woodlark Basin in the Solomon Sea, which is the passage of surface and subsurface water masses between low- and middle-latitude South Pacific Ocean gyre and cross equatorial currents (Grenier et al., 2011; Melet et al., 2011) (Fig. 1). The seasonal precipitation in this region (Fig. 1) is dominated by the AAM system, coupled with the intertropical convergence zone (ITCZ) (Shiau et al., 2012, and references therein).



Tests of single species planktonic foraminifera, *Globigerinoides sacculifer* (> 500 μm, total amount of 2–6 mg), at 13 selected depths were picked for accelerator mass spectrometry (AMS) ¹⁴C dating. The AMS dates were calibrated using the CALIB 6.0.1 program (Remier et al., 2009; Stuvier et al., 2010; Table 1) to reconstruct an age model for a time interval from 23 to 10.5 ka.

Forty to sixty individuals of the planktonic foraminifera *Globigerinoides ruber* (white, s.s., 250–300 µm) were picked under the microscope. For Mg / Ca measurements, 20– 30 individuals were gently crushed and transported into a 1.5 mL Teflon vial. The cleaning procedure was as follows: (1) foraminiferal fragments were immersed in ethanol, (2) a 0.45 mL aliquot of 3 % H₂O₂, (3) NH₄Cl (0.45 mL, 1.0 N), (4) NH₂OH (0.45 mL, 0.01 N), and then (5) dilute nitric acid (1 mL, 0.005 N). A sector field inductive coupled plasma mass spectrometer (SF-ICP-MS), Thermo Electron Element II, housed at the High-Precision Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, was used to determine trace

10

Waelbroeck et al. (2002).

element / Ca ratios following the methodology developed by Shen et al. (2007). The detailed clean procedure and methodology are available in Lo et al. (2014). Two-year 1-sigma reproducibility of Mg / Ca analyses is ±0.21 % (Lo et al., 2014).

For oxygen stable isotope analysis, 7–10 individuals were immersed in methanol, ultrasonicated for 10 s, and then rinsed with deionized water 5 times. Samples were immersed afterward in a hyperchloride sodium (NaOCI) for 24 h, and then analyzed

²⁰ Immersed afterward in a hyperchloride sodium (NaOCI) for 24 h, and then analyzed with an isotopic ratio mass spectrometer (IRMS), Micromass IsoPrime, housed in the National Taiwan Normal University. Long-term 1-sigma precision is better than $\pm 0.05 \%$ (N = 701, Lo et al., 2013) with respect to Vienna Pee Dee Belemnite (V-PDB).

To extract seawater δ^{18} O (δ^{18} O_{SW}) values, we used a cultural based equation, 25 SST = 16.5–4.8×(δ^{18} O_C– δ^{18} O_{SW}) (Bemis et al., 1998) and a constant offset of 0.27‰ between carbonate VPDB and Vienna Standard Ocean Water (VSMOW) scales. Ice volume corrected δ^{18} O_{SW} (δ^{18} O_{SW-IVC}) was calculated using the method proposed by

CPD 10, 3397–3419, 2014 Millennial meridional dynamics of IPWP during the last termination L. Lo et al. **Title Page** Introduction Abstract Conclusions Reference Tables Figures Back Close Full Screen / Esc Printer-friendly Versior Interactive Discussion

Discussion Paper

Discussion Paper

Discussion Paper

Discussion Paper

The empirical orthogonal function (EOF) analysis of a modern SST dataset (1950–2004 AD, Reynolds et al., 2002) for a sector from 20° S– 20° N, and $100-180^{\circ}$ E was conducted (Fig. 2) to determine the boundary between N- and S-IPWP. With an equatorial border, the EOF1 factor (83.4%) clearly resolved different SST variation groups.

⁵ The EOF2 factor shows minor (9.7 %) but significant inter-annual zonal (ENSO) control on the SST patterns. EOF results show that the geographic equator is also the thermal equator between N-IPWP and S-IPWP (Fig. 2).

To build a stacked N- and S-IPWP record, we followed the suggestions by Leduc et al. (2010) and considered two criteria for this dataset: (1) sites with locations from

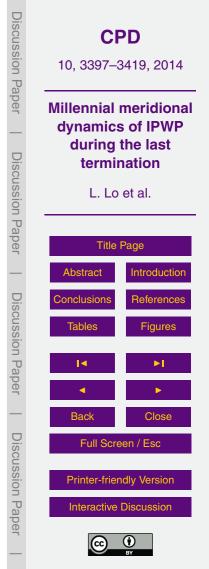
¹⁰ 12° N to 15° S, which is the main IPWP range (Yan et al., 1992; Gagan et al., 2004), and (2) usage of specific proxies, Mg / Ca-derived SST and $\delta^{18}O_{C}$ records of planktonic foraminifera, *G. ruber* (white, *s.s.*). Records from 12 sites were selected, including this study (Table 2). We adopted an age model for sites ODP806, MD97-2140, MD97-2141, MD98-2162, MD98-2170, MD98-2176, and MD98-2181. For records with avail-¹⁵ able original radiocarbon ages from sites, including MD01-2378, MD01-2390, MD98-2165, and MD06-3067, we recalculated the age models using the CALIB 6.0.1 program. The sea level change effect on $\delta^{18}O_{SW}$ was also corrected. We divided the total

gram. The sea level change effect on $\delta^{18}O_{SW}$ was also corrected. We divided the total data into 400 yr windows and calculated the mean and standard error of the mean for each time window.

20 3 Results and discussion

3.1 Geochemical proxy data at site MD05-2925

Planktonic foraminiferal geochemical proxy data for site MD05-2925 are shown in Fig. 3. *G. ruber* $\delta^{18}O_C$ varies from -1.0 to -2.3% and shows no significant millennial timescale variations. Mg / Ca ratios feature stable glacial values of ~ 3.5 mmol mol⁻¹ and rapid increasing transitions of 0.5–1.0 mmol mol⁻¹ at ~ 18.5, 16.5, 14.5, and



12.8 ka. The glacial–interglacial variation of calculated seawater $\delta^{18}O_{SW}$ changes is ~ 1‰. Two abrupt decreases of 0.6–0.8‰ are observed at 14.6 and 11.8 ka.

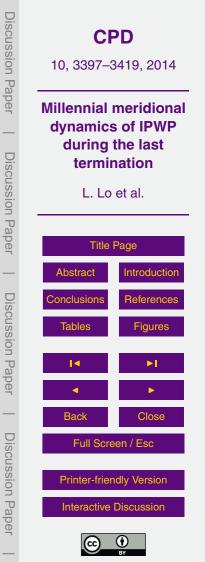
3.2 Solomon SST and $\delta^{18}O_{SW-IVC}$ records during the last termination

Mg / Ca SST records of the planktonic foraminifera *G. ruber* reveal a stable glacial thermal condition during the period 23.0–18.5 ka, with a variation < 1 °C and a glacial– interglacial difference of ~ 3 °C between the last glacial maximum (LGM) and the end of the Younger Dryas (YD) in the Solomon Sea (Fig. 4a). This record is characterized by (i) the end of glacial conditions at 18.5 ka, and (ii) rapid SST increases of 1–2 °C at 18.5–18.0, 17.0–16.0, 15.0–14.5, and 13.0–12.5 ka.

- ¹⁰ The onset of deglacial SST increases in this region is consistent with the timing of thermal changes in the Southern Ocean as inferred from Antarctic ice core δD records (Stenni et al., 2003) (Fig. 4a). This agreement indicates a strong synchronously climatic teleconnection between low- and high-latitude realms in the Southern Hemisphere (SH), as well as greenhouse gases (Mothadi et al., 2014). There are significant
- SST increases of 1–2°C during Heinrich event (H1) and the YD. Previous studies from the Eastern Equatorial and South Pacific reveal a mechanism characterized by early warming of South Pacific subtropical mode water (Pahnke et al., 2003; Lamy et al., 2004; Pena et al., 2008). This warm signal is transported along a gyre to the east equatorial Pacific and eventually to the west Pacific through ocean tunneling (Pena
- et al., 2008; Qu et al., 2013, Fig. 4a). Our new SST record is similar to those in the EEP (Pena et al., 2008) and eastern Indian Ocean records (Xu et al., 2008; Mothadi et al., 2014) for both termination timing (within dating error) and significant warming during the H1 and YD events.

The Solomon Sea $\delta^{18}O_{SW-IVC}$ record is given in Fig. 4b. It varies from -0.5 to 0.1 ‰

²⁵ during 23.0–10.5 ka. A relative stable condition with 1-sigma variability of 0.1‰ occurred from 23.0–16.0 ka. Two significant positive excursions with 0.2–0.5‰ enrichments in δ^{18} O are observed in the intervals 16.8–15.0, and 13.8–11.8 ka. Two sta-



ble periods with low $\delta^{18}O_{SW-IVC}$ of -0.4‰ occurred between 15.0–13.0 ka and after 11.8 ka.

The dramatic $\delta^{18}O_{SW-IVC}$ increases during H1 and the YD likely resulted from a weakening and/or southward shift of the ITCZ (Chiang and Bitz, 2005; Broccoli et al., 2006). Agreement of $\delta^{18}O$ sequences of Greenland NGRIP ice core and the Solomon Sea $\delta^{18}O_{SW-IVC}$ indicates an imprint from high Northern Hemisphere (NH) during the

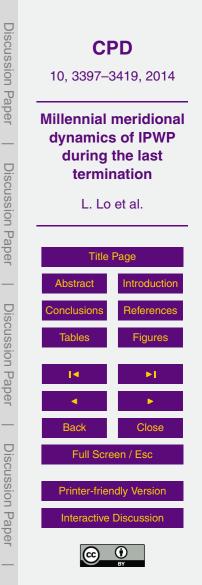
last termination period (Shakun and Carlson, 2010) (Fig. 4b).

3.3 Millennial timescale variations of N- and S-IPWP SST stacks

Both N- and S-IPWP stacked SSTs show the same difference of ~ 3 °C between the last
glacial and interglacial states (Fig. 5a). N-IPWP stacked SST values increased steadily since 18 ka through the termination at a rate of 0.5 °C ka⁻¹. Millennial timescale variability is absent in this record, which is similar to Linsley et al. (2010) and Stott et al. (2002). Although the resolution of ODP 806 and MD97-2140 are less than our request to solve millennial-timescale event, there is no significant difference with/without their records
in our N-IPWP stacks (not shown).

The onset of the termination at ~ 19 ka in the S-IPWP stack is consistent with temperature increases in Antarctica (Stenni et al., 2003), and occur about 1 ka earlier than in the N-IPWP stack (Fig. 5a). This timing is synchronously with EEP (Pena et al., 2008) and eastern Indian Ocean (Xu et al., 2008; Mothadi et al., 2014) SST records.

- Thus, our MD05-2925 and S-IPWP stacked SST may not severely controlled by the equatorial upwelling intensity. Instead of that, S-IPWP stacked SST represent broad SH equatorial region thermal conditions under upwelling/non-upwelling, E–W equatorial and even in the different ocean basin (Indian/Pacific Ocean). The S-IPWP stacked SST record is characterized by a warming trend during H1 and the YD periods, similar
- to Antarctic ice core temperature records (Stenni et al., 2003), and a steady thermal condition at ~ 27 °C during Bølling/Allerød (B/A), corresponding to the Antarctic Cold Reversal (ACR) (Fig. 5a).



The thermal gradient between N- and S-IPWP is around 1 $^{\circ}$ C during 23 to 19 ka. Due to the earlier S-IPWP warming, the thermal gradient dropped from 1 to 0.5 $^{\circ}$ C around 19–18 ka, and persisted to the end of the H1 event. The largest observed thermal gradient (1.5–2.0 $^{\circ}$ C) occurred during the B/A period, and was followed by a 1 $^{\circ}$ C drop during

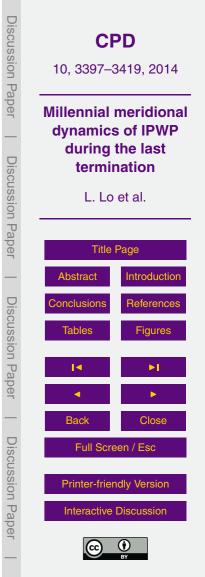
the YD. The meridional SST gradient between N- and S-IPWP over the last termination is attributed to the large thermal variability in the S-IPWP (Fig. 5a). Asynchroneity between persistent N-IPWP and fluctuating S-IPWP SST sequences (Fig. 5a) indicates a meridionally dynamic IPWP through the last termination period. This N–S SST gradient variability would also affect interhemispheric air flow and heat transport (Gibbons et al., 2014; McGee et al., 2014), providing a mechanism to explain heat transport between the hemispheres on a millennial timescale.

3.4 N- and S-IPWP $\delta^{18}O_{SW-IVC}$ records

Both N- and S-IPWP δ¹⁸O_{SW-IVC} records feature (i) high values of 0.8–1.2‰ during glacial times, and (ii) a decreasing trend after 17–16 ka (Fig. 5c). The gradient between N- and S-IPWP gradually increased from 0‰ to 0.2‰ through the termination (Fig. 5d). A similar pattern of δ¹⁸O_{SW-IVC} between N- and S-IPWP suggests that hydrological conditions in the two regions were governed by the same factor(s), probably related to Northern Atlantic cold perturbations (Shakun and Carlson, 2010). It has also been suggested that a major δ¹⁸O_{SW-IVC} increase in the IPWP region likely resulted from reduced precipitation and oceanic advection in both the N-IPWP and S-IPWP regions (Gibbsons et al., 2014; McGee et al., 2014).

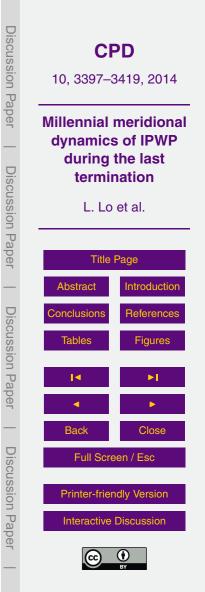
3.5 Meridional IPWP SST gradient and the southward-shifted ITCZ precipitation boundary

A striking feature of the stacked SST records is the warming in the S-IPWP during the H1 and YD periods (Fig. 5a). Modern observatory data over the past six decades (Fig. 12 of Feng et al., 2013) show that an equatorward shift of the NH convection



branch of the Hadley Cell (HC) could result from an oceanic warming lat $\sim 10^{\circ}$ S. This equatorward shift could induce a southward ITCZ shift of about 10° (Feng et al., 2013). Model simulations (Chiang and Bitz, 2005; Broccoli et al., 2006; Lee et al., 2011) suggest that this altered circulation is a powerful teleconnection between the NH and SH

- ⁵ climate systems through a coupled tropical ocean-atmosphere pathway, and is supported by marine and terrestrial hydrological proxy data (Wang et al., 2001, 2007; Lea et al., 2003; Griffiths et al., 2009; Shakun and Carlson, 2010; Mohtadi et al., 2011; Meckler et al., 2012; Ayliffe et al., 2013; Carolin et al., 2013; Gibbons et al., 2014; McGee et al., 2014, Fig. 6).
- ¹⁰ Distinctly different precipitation conditions across 8–10° S in the IPWP during the H1 and YD events are illustrated in Fig. 6. For example, enhanced terrestrial sediment flux into the Coral Sea is suggested by a marine sediment thorium isotopic proxy record at 11° S (Shiau et al., 2011). Lynch's crater records from northeastern Australia at 17° S (Muller et al., 2008) show strong Australian summer monsoonal conditions. Stalagmite
- 15 δ^{18} O records at Flores Island (8° S) also feature intense precipitation during H1 and the YD (Griffiths et al., 2009; Ayliffe et al., 2013). However, marine and stalagmite δ^{18} O evidence reveal conditions of reduced precipitation and increased salinity in the northern IPWP north of 8–10° S, including the South China Sea (12° N, Stenike et al., 2006), Sulu Sea (8° N, Rosenthal et al., 2003), Philippine Sea (6° N, Stott et al., 2002;
- Boillet et al., 2011), Java Island (8°S, Mohtadi et al., 2011), Solomon Sea (9°S, this study), and Borneo island (4°N, Meckler et al., 2012; Carolin et al., 2013) (Fig. 6). On the basis of previous terrestrial and marine hydrological records and our new data, as well as modern (Feng et al., 2013) and simulated (Chiang and Bitz, 2005; Broccoli et al., 2006) data, we speculate a sharp precipitation boundary between the maritime
- ²⁵ continents and Australia at about 8–10° S, extending from the Solomon Sea, Arafura Sea and Timor Sea, to the eastern Indian Ocean during H1 and the YD periods (Fig. 6). We propose that the west and east boundaries are between the Java-Flores islands (Griffiths et al., 2009; Mohtadi et al., 2011), and Solomon-Coral Seas, respectively (Shiau et al., 2011, this study).

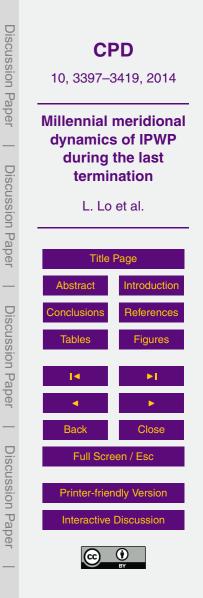


To sum up our geochemical and composite dataset in the IPWP region during the last terminations, we propose that the enlarged IPWP meridional SST gradient could result in an altered HC and reduced (increased) precipitation for the East Asian (Australia) monsoon territories during the H1 and YD periods (McGee et al., 2014). We also propose that variations in the meridional IPWP SST gradient during the termination period were mainly caused by the S-IPWP, which is closely linked to high-latitude climate systems.

4 Conclusions

5

- Our new MD05-2925 marine geochemical records and previous reports suggest that the meridional IPWP thermal conditions are strongly linked to interhemispheric highlatitude climate during the last deglaciation. Ice volume-corrected $\delta^{18}O_{SW}$ stacked records show an increasing salinity gradient between N- and S-IPWP over the last termination. Here we propose a new process of the thermal evolution of IPWP region, which meridional differences of its thermal gradient could amplify the signal from both
- ¹⁵ hemispheric climate event and greenhouse gas concentration. A hypothetical precipitation boundary around 8–10° S during H1 and the YD has also been proposed, which is most likely caused by the meridional IPWP SST gradient and HC circulation anomalies. More advanced high-resolution regional model simulations are required to clarify the role of IPWP meridional thermal-hydrological gradient to an altered HC and its re-
- ²⁰ lationship with regional and global climate systems during global climate perturbation events.



Acknowledgements. MD05-2925 site location was selected by Min-Te Chen and Meng-Yang Lee and collected during the IMAGES PECTEN Cruise, conducted by Luc Beaufort and Min-Te Chen. Chien-Ju Chou, Wan-Lin Hu, and Yu-Ting Hsiao helped to pick foraminifera samples. Yang-Hui Hsu helped to operate the climatological database and plotted figures. Thanks

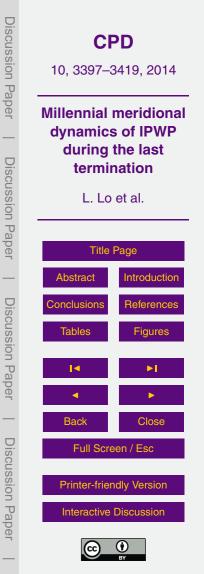
to Delia W. Oppo and Braddock K. Linsley for their generous offering of the non-overlapping method MatLab code. This research was funded by Taiwan ROC MOST (98-2811-M-002-129, 99-2611-M-002-005, 100-2116-M-002-009 to CCS, and 95-2611-M-002-019, 96-2611-M-002-019 to KYW), and National Taiwan University (101R7625 to CCS).

References

- Ayliffe, L. K., Gagan, M. K., Zhao, J.-X., Drysdale, R. N., Hellstrom, J. C., Hantoro, W. S., Griffiths, M. L., Scott-Gagan, H., Pierre, E. S., Cowley, J. A., and Suwargadi, B. W.: Rapid interhemispheric climate links via the Australasian monsoon during the last deglacialtion, Nat. Commun., 4, 2908, doi:10.1038/ncomms3908, 2013.
 - Bolliet, T., Holbourn, A., Kuhnt, W., Laj, C., Kissel, C., Beaufort, L., Kienast, M., Ander-
- 15 sen, N., and Garbe-Schönberg, D.: Mindanao Dome variability over the last 160 kyr: episodic glacial cooling of the West Pacific Warm Pool, Paleoceanography, 26, PA1208, doi:10.1029/2010PA001966, 2011.

Broccoli, A. J., Dahl, K. A., and Stouffer, R. J.: Response of the ITCZ to Northern Hemisphere cooling, Geophys. Res. Lett., 33, L01702, doi:10.1029/2005GL024546, 2006.

- ²⁰ Carolin, S. A., Cobb, K. M., Adkins, J. F., Clark, B., Conroy, J. L., Lejau, S., Malang, J., and Tuen, A. A.: Varied response of Western Pacific hydrology to climate forcings over the last glacial period, Science, 340, 1564–1566, 2013.
 - Chiang, J. C. H. and Bitz, C. M.: Influence of high latitude ice cover on the marine Intertropical Convergence Zone, Clim. Dynam., 25, 477–496, 2005.
- ²⁵ Cravatte, S., Delcroix, T., Zhang, D., McPhaden, M., and Leloup, J.: Observed freshening and warming of the western Pacific Warm Pool, Clim. Dynam., 33, 565–589, 2009.
 - de Garidel-Thoron, T., Rosenthal, Y., Bassinot, F., and Beaufort, L.: Stable sea surface temperatures in the western Pacific warm pool over the past 1.75 million years, Nature, 433, 294–298, 2005.



- Feng, J., Li, J., and Xie, F.: Long-term variation of the principal mode of boreal spring Hadley Circulation linked to SST over the Indo-Pacific Warm Pool, J. Climate, 26, 532–544, 2013.
- Gibbons, F. T., Oppo, D. W., Mohtadi, M., Rosenthal, Y., Cheng, J., Liu, Z., and Linsley, B. K.: Deglacial δ^{18} O and hydrological variability in the tropical and Indian Oceans, Earth Planet. Sc. Lett., 387, 240–251, 2014.

5

15

20

- Grenier, M., Cravatte, S., Blanke, B., Menkes, C., Joch-Larrouy, A., Durand, F., Melet, A., and Jeandel, C.: From the western boundary currents to the Pacific Equatorial Undercurrent: modeled pathways and water mass evolutions, J. Geophys. Res., 116, C12044, doi:10.1029/2011JC007477, 2011.
- ¹⁰ Griffiths, M. L., Drysdale, R. N., Gagan, M. K., Zhao, J.-X., Ayliffe, L. K., Hellstrom, J. C., Hantoro, W. S., Frisia, S., Feng, Y.-X., Cartwright, I., St. Pierre, E., Fischer, M., J., and Suwargadi, B. W.: Increasing Australian–Indonesian monsoon rainfall linked to early Holocene sealevel rise, Nat. Geosci., 2, 636–639, 2009.

Lamy, F., Kaiser, J., Ninnemann, U., Hebbeln, D., Arz, H. W., and Stoner, J.: Antarctic timing of surface water changes off Chile and Patagonian ice sheet response, Science, 304, 1959–1962, 2004.

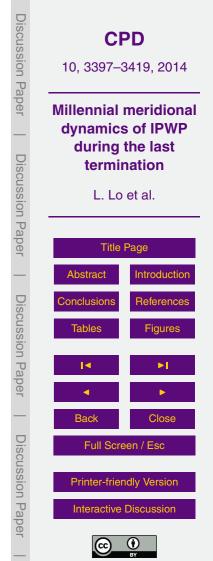
Lea, D. W., Pak, D. K., and Spero, H. J.: Climate impact of late Quaternary equatorial Pacific sea surface temperature variations, Science, 289, 1719–1724, 2000.

Lea, D. W., Pak, D. K., Peterson, L. C., and Hughen, K. A.: Synchroneity of tropical high-latitude Atlantic temperatures over the last glacial termination, Science, 301, 1361–1364, 2003.

Leduc, G., Schneider, R., Kim, J. H., and Lohmann, G.: Holocene and Eemian sea surface temperature trends as revealed by alkenone and Mg / Ca paleothermometry, Quaternary Sci. Rev., 29, 989–1004, 2010.

Levi, C., Labeyrie, L., Bassinot, F., Guichard, F., Cortijo, E., Waelbroeck, C., Caillon, N.,

- ²⁵ Duprat, J., de Garidel-Thoron, T., and Elderfield, H.: Low-latitude hydrological cycle and rapid climate changes during the last deglaciation, Geochem. Geophy. Geosy., 8, Q05N12, doi:10.1029/2006GC001514, 2007.
 - Linsley, B. K., Rosenthal, Y., and Oppo, D. W.: Holocene evolution of the Indonesian throughflow and the western Pacific warm Pool, Nat. Geosci., 3, 578–583, 2010.
- ³⁰ Lo, L., Lai, Y.-H., Wei, K.-Y., Lin, Y.-S., Mii, H.-S., and Shen, C.-C.: Persistent sea surface temperature and declined sea surface salinity in the northwestern tropical Pacific over the past 7500 years, J. Asian Earth Sci., 66, 234–239, 2013.



- Lo, L., Shen, C.-C., Lu, C.-J., Chen, Y.-C., Chang, C.-C., Wei, K.-Y., Qu, D., and Gagan, M. K.: Determination of element/Ca ratios in foraminifera and corals using cold- and hot-plasma techniques in inductively coupled plasma sector field mass spectrometry, J. Asian Earth Sci., 81, 115–122, 2014.
- ⁵ McGee, D., Donohoe, A., Marshall, J., and Ferreira, D.: Changes in ITCZ location and crossequatorial heat transport at the Last Glacial Maximum, Heinrich Stadial 1, and the mid-Holocene, Earth Planet. Sc. Lett., 390, 69–79, 2014.
 - Meckler, A. N., Clarkson, M. O., Cobb, K. M., Sodemann, H., and Adkins, J. F.: Interglacial hydroclimate in the tropical West Pacific through the late Pleistocene, Science, 336, 1301–1304, 2012.
 - Melet, A., Verron, J., Gourdeau, L., and Koch-Larrouy, A.: Equatorial pathways of Solomon Sea water masses and their modification, J. Phys. Oceanogr., 40, 810–826, 2011.

10

15

- Mohtadi, M., Oppo, D. W., Steinke, S., Stuut, J.-B. W., De Pol-Holz, R., Hebbeln, D., and Lückge, A.: Glacial to Holocene swings of the Australian–Indonesian monsoon, Nature Geosci., 4, 540–544, 2011.
- Mothadi, M., Prange, M., Oppo, D. W., De Pol-Holz, R., Merkel, U., Zhang, X., Stenike, S., and Lückge, A.: North Atlantic forcing of tropical Indian Ocean climate, Nature, 509, 76–80, 2014.

Muller, J., Kylander, M., Wüst, R. A. J., Weiss, D., Martinez-Cortizas, A., LeGrande, A. N.,

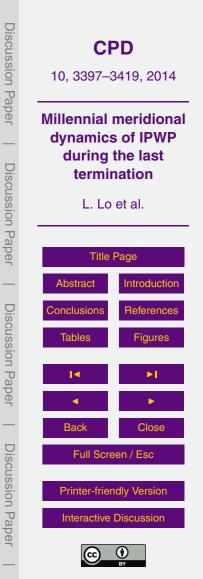
Jennerjahn, T., Behling, H., Andreson, W. T., and Jacobson, G.: Possible evidence for wet Heinrich phases in tropical Australia: the Lynch's Crater deposit, Quaternary Sci. Rev., 27, 468–475, 2008.

Northern Greenland Ice Core Project Members: High-resolution record of Northern Hemisphere climate extending into the last interglacial period, Nature, 431, 147–151, 2004.

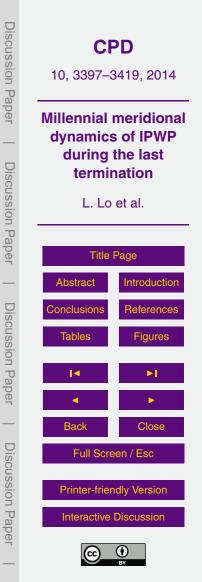
- ²⁵ Oppo, D. W., Rosenthal, Y., and Linsley, B. K.: 2,000-year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool, Nature, 460, 1113–1116, 2009.
 - Pahnke, K., Zahn, R., Elderfield, H., and Schulz, M.: 340,000-year centennial-scale marine record of Southern Hemisphere climatic oscillation, Science, 301, 948–952, 2003.

Pena, L. D., Cacho, I., Ferretti, P., and Hall, M. A.: El Niño–Southern Oscillation-like variabil-

- ³⁰ ity during glacial terminations and interlatitudinal teleconnections, Paleoceanography, 23, PA3101, doi:10.1029/2008PA001620, 2008.
 - Qu, T., Gao, S., and Fine, R. A.: Subduction of South Pacific tropical water and its equatorward pathways as shown by a simulated passive tracer, J. Phys. Oceanogr., 43, 1551–1565, 2013.



- Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Burr, G. S., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., McCormac, F. G., Manning, S. W., Reimer, R. W., Richards, D. A., Southon, J. R., Talamo, S.,
- Turney, C. S. M., van der Plicht, J., and Weyhenmeyer, C. E.: INTCAL09 and MARINE09 radiocarbon age calibration curves, 0–50,000 cal BP Radiocarbon, 51, 1111–1150, 2009.
 - Reynolds, R. W., Rayner, N. A., Smith, T. M., and Stokes, D. C.: An improved in situ and satellite SST analysis for climate, J. Climate, 15, 1609–1625, 2002.
 - Rosenthal, Y., Oppo, D. W., and Linsley, B. K.: The amplitude and phasing of climate change
- during the last deglaciation in the Sulu Sea, western equatorial Pacific, Geophys. Res. Lett., 30, 1428, doi:10.1029/2002GL016612, 2003.
 - Shakun, J. D. and Carlson, A. E.: A global perspective on Last Glacial maximum to Holocene climate change, Quaternary Sci. Rev., 29, 1801–1816, 2010.
 - Shakun, J. D., Clark, P. U., He, F., Marcott, S. A., Mix, A. C., Liu, Z., Otto-Bliesner, B., Schmit-
- tner, A., and Bard, E.: Global warming preceded by increasing carbon dioxide concentrations during the last deglacialtion, Nature, 484, 49–55, 2012
 - Shen, C.-C., Hasting, D. W., Lee, T., Chiu, C.-H., Lee, M.-Y., Wei, K.-Y., and Edwards, R. L.: High precision glacial–interglacial benthic foraminiferal Sr/Ca records from the eastern equatorial Atlantic Ocean and Caribbean Sea, Earth Planet. Sc. Lett., 190, 197–209, 2001.
- Shen, C.-C., Chiu, H.-Y., Chiang, H.-W., Chu, M.-F., Wei, K.-Y., Steinke, S., Chen, M.-T., Lin, Y.-S., and Lo, L.: High precision measurements of Mg / Ca and Sr/Ca ratios in carbonates by cold plasma inductively coupled plasma quadrupole mass spectrometry, Chem. Geol., 236, 339–249, 2007.
 - Shiau, L.-J., Chen, M.-T., Clemens, S. C., Huh, C.-A., Yamamoto, M., and Yokoyama, Y.: Warm
- pool hydrological and terrestrial variability near southern Papua New Guinea over the past 50k, Geophys. Res. Lett., 38, L00F01, doi:10.1029/2010GL045309, 2011.
 - Shiau, L.-J., Chen, M.-T., Huh, C.-A., Yamamoto, M., and Yokoyama, Y.: Insolation and crosshemispheric controls on Australian monsoon variability over the past 180 ka: new evidence from off shore southeastern Papua New Guinea, J. Quaternary Sci., 27, 911–920, 2012.
- Steinke, S., Chiu, H.-I., Yu, P.-S., Shen, C.-C., Erlenkeuser, H., Löwemark, L., and Chen, M.-T.: On the influence of sea level and monsoon climate on the southern South China Sea freshwater budget over the past 22,000 years, Quaternary Sci. Rev., 25, 1475–1488, 2006.



- Stenni, B., Jouzel, J., Masson-Delmotte, V., Röthlisberger, R., Castellano, E., Cattani, O., Falourd, S., Johnsen, S. J., Longinelli, A., Sachs, J. P., Selmo, E., Souchez, R., Steffensen, J. P., and Udisti, R.: A late-glacial high-resolution site and source temperature record derived from EPICA Dome C isotope records (East Antarctica), Earth Planet. Sc. Lett., 217, 183–195, 2003.
- ⁵ 183–195, 2003. Stott, L., Poulsen, C., Lund, S., and Thunell, R.: Super ENSO and global climate oscillations at millennial time scales, Science, 297, 222–226, 2002.
 - Stott, L., Cannariato, K., Thunell, R., Haug, G. H., Koutavas, A., and Lund, S.: Decline of surface temperature and salinity in the western tropical Pacific Ocean in the Holocene epoch, Nature, 431, 56–59, 2004.
- 10

20

- Stuiver, M., Reimer, P. J., and Reimer, R. W.: CALIB 6.0. (WWW program and documentation), 2010.
- Visser, K., Thunell, R., and Stott, L.: Magnitude and timing of temperature change in the Indo-Pacific warm pool during deglaciation, Nature, 421, 152–155, 2003.
- ¹⁵ Wang, X., Auler, A. S., Edwards, R. L., Cheng, H., Ito, E., Wang, Y., Kong, X., and Solheid, M.: Millennial-scale precipitation changes in southern Brazil over the past 90,000 years, Geophys. Res. Lett., 34, L23701, doi:10.1029/2007GL031149, 2007.
 - Wang, Y. J., Cheng, H., Edwards, R. L., An, Z. S., Wu, J. Y., Shen, C.-C., and Dorale, J. A.: A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China, Science, 294, 2345–2348, 2001.
 - Williams, A. P. and Funk, C.: A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa, Clim. Dynam., 37, 2417–2435, 2011.

Xu, J., Holbourn, A., Kuhnt, W., Jian, Z., and Kawamura, H.: Changes in ther thermocline

- structure of the Indonesian outflow during Terminations I and II, Earth Planet. Sc. Lett., 273, 152–162, 2008.
 - Yan, X.-H., Ho, C.-R., Zheng, Q., and Klemas, V.: Temperature and size variabilities of the western Pacific warm pool, Science, 258, 1643–1645, 1992.

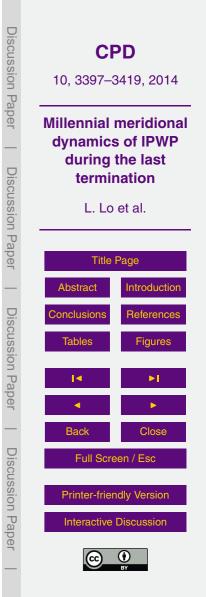


Table 1. AMS ¹⁴C dates of site MD05-2925.

Depth (cm)	¹⁴ C ages (years)	Error (years)	Cal. ages (years)	Error (years)
117	8823	50	9414	111
127*	10306	70	11 259	159
140	10441	30	11 333	80
147*	11 477	70	12854	110
157	12066	60	13 391	84
172*	13117	70	14973	309
180	13748	35	16283	453
192*	14080	74	16746	223
207*	15616	75	18201	175
217	16470	81	19083	90
262*	18985	94	22 167	181
272*	20960	150	24 41 1	167
292*	21 650	78	25 304	339

* Samples were measured in the NSF-Arizona AMS Laboratory of the University of Arizona (U. Arizona), Tucson, USA, and the others were measured in the Rafter Radiocarbon Laboratory, Institute of Geological and Nuclear Science (GNS), New Zealand.

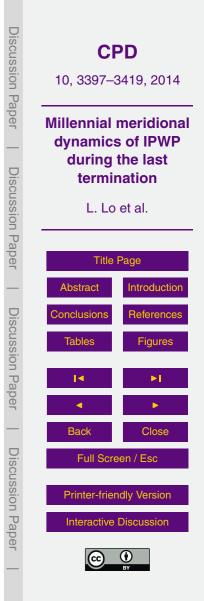
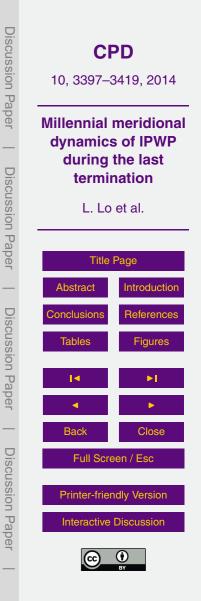


Table 2. Selected sites for stacked N- and S-IPWP records.

	Core	Location (Latitude and longitude)	References			
	North-IPWP group					
	(orange circles in Figs. 1 and 2)					
	ODP 806	0.3° N, 159.4° E	Lea et al. (2000)			
	MD97-2140	2.0° N, 141.7° E	de Garidel-Thoron et al. (2005)			
	MD98-2181	6.3° N, 125.83° E	Stott et al. (2002, 2004)			
	MD06-3067	6.5° N, 126.5° E	Bolliet et al. (2011)			
	MD97-2141	8.8° N, 121.3° E	Rosenthal et al. (2003)			
	MD01-2390	12.1° N, 113.24° E	Stenike et al. (2006)			
	South-IPWP group					
	(green circles and star in Figs. 1 and 2)					
	MD98-2162	4.4° S, 117.5° E	Visser et al. (2003)			
	MD98-2176	5.0° S, 133.4° E	Stott et al. (2004)			
	MD05-2925	9.3° S, 151.5° E	This Study			
	MD98-2165	9.7° S, 118.3° E	Levi et al. (2007)			
	MD98-2170	10.6° S, 125.4° E	Stott et al. (2004)			
_	MD01-2378	13.1° S, 121.7° E	Xu et al. (2008)			



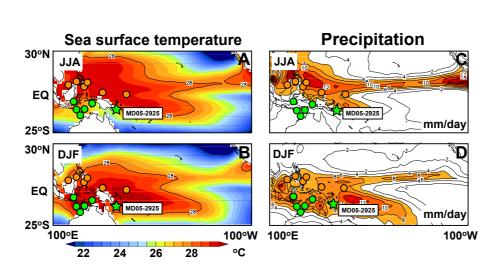
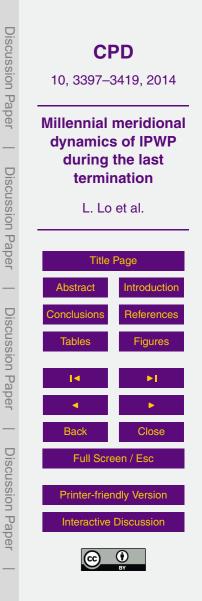


Figure 1. Climatological map of the Indo-Pacific Warm Pool (IPWP) sea surface temperature (SST, left) and precipitation (right) during 1950–2004 AD (Reynolds et al., 2002). Upper panels are June-July-August (JJA), and lower panels are December-January-February (DJF) averages of (**A**, **C**) SSTs and (**B**, **D**) precipitation distribution maps. SST and precipitation are at 0.5 °C and 2 mm day⁻¹ intervals. Our study site MD05-2925 is shown as the green star. Orange and green dots denote previous study sites in the IPWP region (Table 2) for reconstruction of meridional thermal and precipitation variations during the glacial/interglacial change.



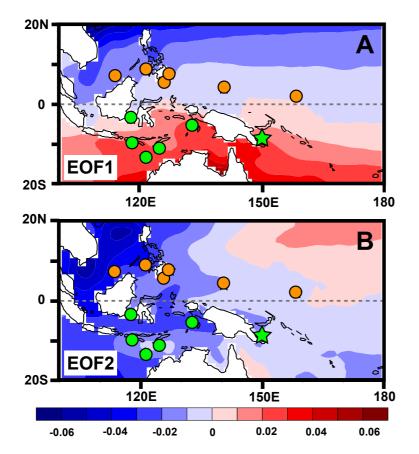
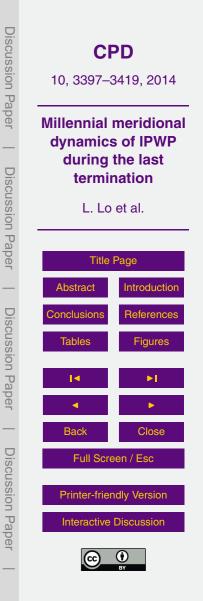
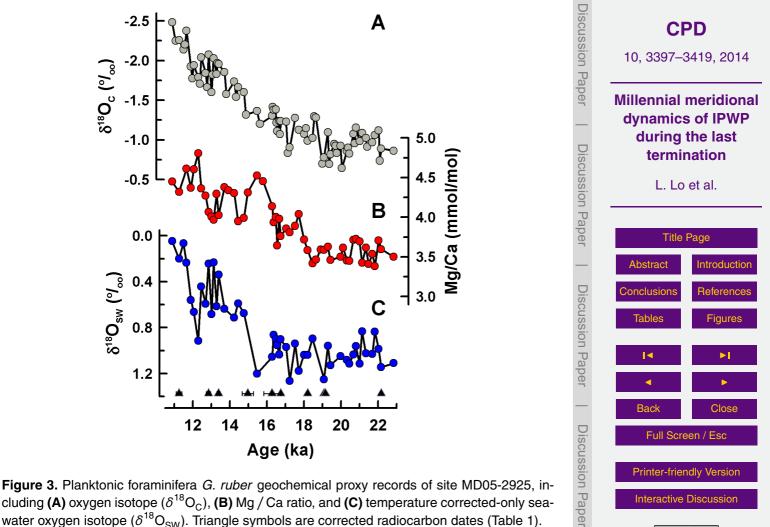


Figure 2. EOF analysis on SST (dataset from Reynolds et al., 2002) and selected sites (Table 2) used for stacked N- and S-IPWP records. **(A)** EOF1 explains 83.4 % of the total variance, which mainly represents intra-annual seasonality. **(B)** EOF2 shows a clear zonal pattern. Orange circles represent selected sites for the N-IPWP group and green ones for the S-IPWP group. The green star denotes the MD05-2925 site used in this study.





cluding (A) oxygen isotope ($\delta^{18}O_C$), (B) Mg / Ca ratio, and (C) temperature corrected-only seawater oxygen isotope ($\delta^{18}O_{SW}$). Triangle symbols are corrected radiocarbon dates (Table 1).

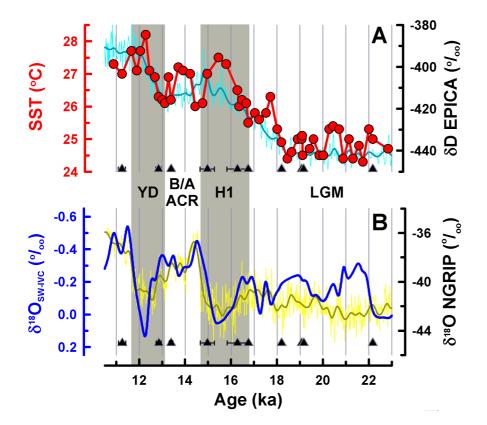
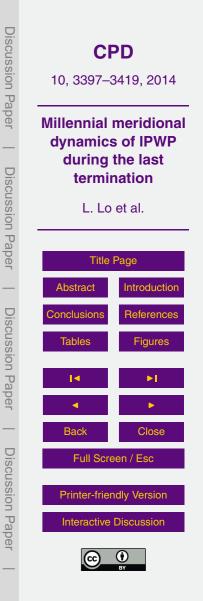


Figure 4. Geochemical proxy records of MD05-2925. **(A)** SST (red circles and line) and **(B)** $\delta^{18}O_{SW-IVC}$ (blue line) were reconstructed with *G. ruber* Mg / Ca ratios and $\delta^{18}O_{C}$. The cyan line denotes the Antarctica EPICA deuterium isotope record (Stenni et al., 2003), and the yellow line is the Greenland ice core NGRIP (Northern Greenland Ice Core Project Members, 2004) oxygen isotope record. The superimposed dark cyan and dark yellow lines are the 200 yr smoothed records, respectively. Black triangles are AMS ¹⁴C dates (Table 1). Vertical bars denote the H1 and YD periods.



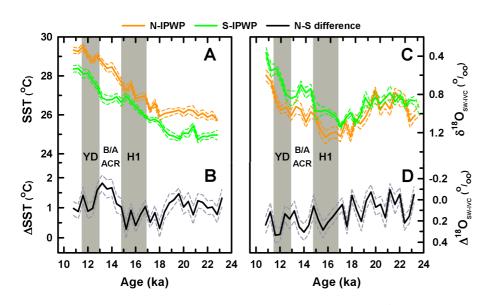
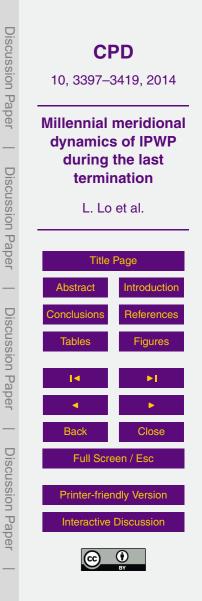


Figure 5. Four hundred-year non-overlapping binned **(A)** SST and **(C)** $\delta^{18}O_{SW-IVC}$ of N- (orange solid line) and S-IPWP (green solid line). Lower paneld show the differences in **(B)** SST and **(D)** $\delta^{18}O_{SW-IVC}$ between N- and S-IPWP. The compilations of N- and S-IPWP surface water thermal and hydrological records (Table 2) were calculated with the non-overlapping binned methods (Oppo et al., 2009; Linsley et al., 2010). All dashed lines represent 1-sigma uncertainty ranges. Gray bars show the H1 and YD events.



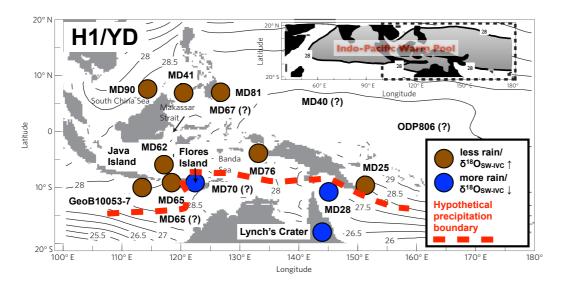


Figure 6. Hypothetical proxy-inferred precipitation boundary during the H1 and YD events (modified from the Linsley et al., 2010). Blue dots represent relatively increasing precipitation/ $\delta^{18}O_{SW}$ lighter condition, and brown ones a decreasing precipitation/ $\delta^{18}O_{SW}$ heavier condition. The segment between Java and Flores Islands of this sharp boundary (red dashed line) was proposed by Mohtadi et al. (2011), and the one between the Solomon and Coral Seas by this study. Black contours represent SST.

