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Inter-hemispheric asymmetry in the early Pleistocene Pacific warm pool

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[1] The position of the southern boundary of the Pacific warm pool is shown to have been stable since the early Pleistocene, based upon a planktic foraminiferal Mg/Ca-derived reconstruction of subtropical sea surface temperature in the Coral Sea. This contrasts with previous reconstructions showing warm pool contraction from the north and east and means that the early Pleistocene warm pool was more hemispherically asymmetric than its present configuration. The latter was not established until ~1Ma, supporting a strengthening of the northern Hadley Cell, which was not replicated in its southern counterpart, prior to the Mid-Pleistocene Transition. **Citation:** Russon, T., M. Elliot, A. Sadekov, G. Cabioch, T. Corrège, and P. De Deckker (2010), Inter-hemispheric asymmetry in the early Pleistocene Pacific warm pool, *Geophys. Res. Lett.*, *37*, L11601, doi:10.1029/2010GL043191.

1. Introduction

[2] As the largest body of warm water on the planet, the Pacific warm pool is a key source of both heat and moisture to the atmosphere, which acts to transport those properties polewards. Temporal variability in these fluxes plays an important role in global climate on time-scales ranging from the seasonal to the geological [*Koutavas et al.*, 2002; *Ravelo et al.*, 2004]. The modern extent of the warm pool, defined here as the region for which mean annual Sea Surface Temperature (SST) exceeds 28°C, is limited to the western Pacific and eastern Indian Ocean. Within the Pacific it is hemispherically asymmetric, extending between ~20°N and ~15°S (Figure 1). Variability in the meridional extent of the past warm pool implies changes not only to meridional heat and moisture fluxes but also to the wider tropical ocean/atmosphere system, as the subtropics are a significant source for the cool waters upwelling in the modern eastern Pacific [*Brierley et al.*, 2009]. The extent of past inter-hemispheric warm pool asymmetry is also important as the relative strength of the two branches of the meridional atmospheric Hadley circulation is a function of the latitudinal position of maximum atmospheric convergence in the tropics which is sensitive to the extent of extra-tropical SST asymmetry [*Broccoli et al.*, 2006].

[3] Reconstructions of Pliocene SST distributions in the Pacific show substantially reduced zonal equatorial [*Wara et al.*, 2005] and equatorial-subtropical [*Brierley et al.*, 2009] gradients, implying a significantly expanded warm pool and a permanent El Niño state at that time [*Wara et al.*, 2005; *Fedorov et al.*, 2006]. Since 3Ma the planet has experienced a general global cooling, intensification of northern hemisphere glaciation and warm pool contraction [*Ravelo et al.*, 2004; *Wara et al.*, 2005; *Jia et al.*, 2008]. The timing of these various changes was not, however, synchronous. Continuous down-core reconstructions of Plio-Pleistocene SST from the equatorial Pacific show that, by ~1Ma, the modern tropical SST distribution was broadly established with an equatorial gradient of 4–5°C between the Western Equatorial Pacific (WEP) and the cooler upwelled waters of the Eastern Equatorial Pacific (EEP) (Figure 1) [*Wara et al.*, 2005; *Lawrence et al.*, 2006; *Dekens et al.*, 2008]. The associated onset of significant zonal atmospheric Walker Circulation is thought to have occurred during the early Pleistocene [*Ravelo et al.*, 2004]. In contrast, the last significant period of deep-water cooling [*Sosdian and Rosenthal*, 2009] and ice expansion [*Mudelsee and Schulz*, 1997] occurred during the early part of the Mid-Pleistocene Transition (MPT) at 0.8–1.2Ma. The relative timing of these changes has led to the suggestion that the tropical system may have played an important role in the timing of the MPT [*McClymont and Rosell-Mele*, 2005].

[4] The evaluation of this hypothesis relies upon reconstruction of meridional as well as zonal SST gradients. The evolution of the SST gradient between the equator and the northern subtropics in the western Pacific has been shown to resemble that of the zonal equatorial gradient, including a rapid increase prior to ~1.0Ma [*Jia et al.*, 2008]. As modeling studies suggest that increasing equatorial-subtropical SST gradients lead to reductions in air temperature and increases in precipitation over North America [*Brierley and Fedorov*, 2010], this supports a potential tropical control for MPT ice-sheet expansion. The mechanism for such a connection relates to the positive correlation between underlying meridional SST gradients and Hadley Cell strength [*Rind and Perlwitz*, 2004; *Brierley et al.*, 2009].

[5] The present study seeks to establish whether the early Pleistocene phase of warm pool contraction was hemispherically symmetric and what impact any such changes may have had on poleward heat and moisture transport prior to the MPT. In order to achieve this, SST in the southern subtropical western Pacific was reconstructed over the past 1.6Ma from measurements of planktic foraminiferal Mg/Ca. The core site used lies to the south of the modern warm pool such as to be sensitive to past fluctuations in the southern extent of warm pool influence.

2. Study Site, Materials and Methods

[6] Sediment core MD06-3018 was recovered from 2470m water depth in the eastern side of the New Caledonia Trough (23°00′S, 166°09′E), southeastern Coral Sea. The core site is ~60km from the main island of New Caledonia but located on a broad bathymetric high that generally

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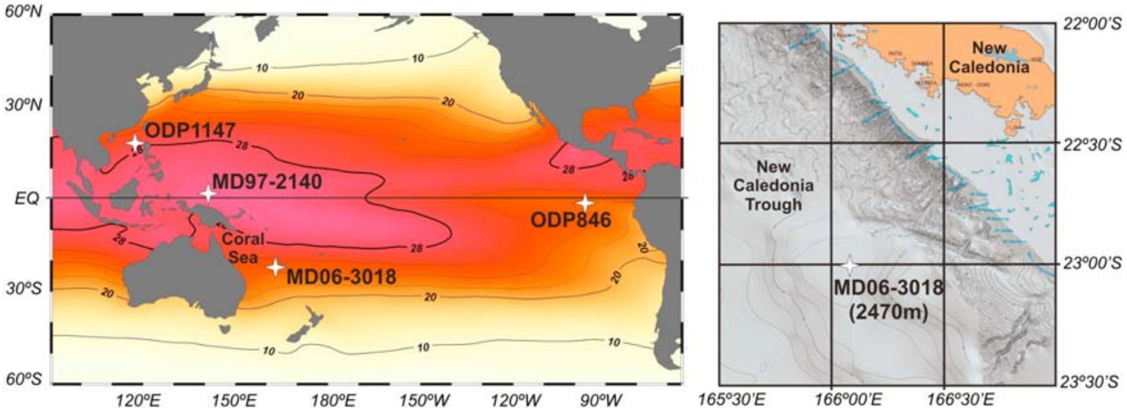

Figure 1. Map of Pacific mean annual SST distribution from World Ocean Atlas data [*Locarnini et al.*, 2006] plotted using the Ocean Data View software (R. Schlitzer, Ocean Data View, 2007, http://odv.awi.de) and location of MD06-3018 core-site, bathymetry from the Zonéco program.

shelters the site from significant down-slope transport of shallow-water material (Figure 1). The core is 24.5m in length and composed of homogenous calcareous ooze dominated in the >150μm size fraction by planktic foraminifera of a tropical/subtropical assemblage. The MD06-3018 core age model is based on orbital tuning of the $\delta^{18}O_{benthic}$ record to the LR04 stack [*Lisiecki and Raymo*, 2005], one biostratigraphic datum and four paleomagnetic polarity events [*Russon et al.*, 2009].

[7] Mg/Ca ratios were measured on samples of thirty-five to forty individuals of the surface dwelling foraminifera *Globigerinoides ruber* picked from the 250-315μm size fraction. The present study follows established cleaning methods [*Barker et al.*, 2003] and the intensity-ratio calibration method [*de Villiers et al.*, 2002]. Samples were analyzed using a Varian VISTA Pro ICP-OES (Axial) in the School of Geosciences, University of Edinburgh. To monitor residual contamination samples with a Fe/Mg ratio exceeding 1 mol/mol [*Barker et al.*, 2003], or Al/Ca or Mn/Ca ratios >3σ above the background level were rejected. Long-term reproducibility was monitored through repeated measurements of carbonate reference material ECRM-521. Over the period of analysis the measured Mg/Ca value for this standard was 3.762 mmol/mol ± 2σ = 0.0352 mmol/mol (n = 162), consistent with existing studies [*Greaves et al.*, 2005]. Short-term reproducibility was assessed through four down-core repeated (n≥5, including full replication of picking and cleaning stages) foraminiferal measurements and was always better than 2σ = 0.52mmol/mol.

[8] The Mg/Ca record is calibrated to SST using a sediment-trap based *G. ruber* calibration for the 250-350μm size fraction without a pre-assumed partition coefficient [*Anand et al.*, 2003]. This calibration function is preferred as it is based on a similar size fraction and the same cleaning method used in the present study. No correction for dissolution is applied as the core location lies well above the modern lysocline [*Martinez*, 1994]. Seasonal biases in the flux of *G. ruber* shells to the sediment in subtropical regions can potentially bias Mg/Ca-derived SST away from the mean annual value. The MD06-3018 core-top Mg/Ca value, based on seven repeated measurements, is 4.60 ± 2σ = 0.52mmol/mol. This yields a calibrated late Holocene Mg/Ca-derived SST value of 25.5 ± 2σ = 1.0°C in comparison to the modern World Ocean Atlas mean annual value for 0m depth at the core-site of 24.4°C [*Locarnini et al.*, 2006]. These values are nearly within the sample reproducibility error and well within the calibration function error. Furthermore, the amplitude of Last Glacial Maximum to Holocene SST change seen in the MD06-3018 reconstruction is consistent with previous regional reconstructions based on transfer function methods [*Barrows and Juggins*, 2005]. Past variations in Mg/Ca-derived SST should therefore reflect those in mean annual SST.

3. Results

[9] The MD06-3018 SST reconstruction shows glacial-interglacial variability across the Pleistocene in the range 2–3°C (Figure 2a). The "long-term mean" is defined here as the 200kyr running box-car average, so as to remove all glacial-interglacial variability. This term varies by less than ±0.5°C around an average value of 23.9°C (with a Standard Error on the Mean (SEM) of $\pm 2\sigma_{SEM}$ = 0.3°C) over the past 1.5Ma. The apparent trend towards warmer values seen prior to 1.0Ma lies within the uncertainty range associated with different assumptions regarding past $Mg/Ca_{(sw)}$ for this time interval [*Medina-Elizalde et al.*, 2008] and is not statistically different from a constant value.

[10] To place the southeastern Coral Sea record in a Pacific context it is compared to existing SST reconstructions from the WEP (MD97-2140 [*de Garidel-Thoron et al.*, 2005]), South China Sea (ODP 1147 [*Jia et al.*, 2008]) and EEP (ODP 846 [*Lawrence et al.*, 2006]) (Figures 1 and 2). Whereas the Coral Sea and WEP SST reconstructions are based on Mg/Ca paleothermometry, the South China Sea and EEP reconstructions are based on alkenone saturation indices. Whilst the two proxy systems involve different assumptions, they have been shown to be in agreement regarding first-order trends in EEP SST over the past 5Ma [*Dekens et al.*, 2008]. In the case of the South China Sea record, there is no available Mg/Ca record for comparison, but transfer function studies [*Wang*, 1994] show similar patterns of variability to those seen in the alkenone reconstructions [*Jia et al.*, 2008].

[11] The WEP record shows a similar lack of variability in the long-term mean to that from the Coral Sea but with an

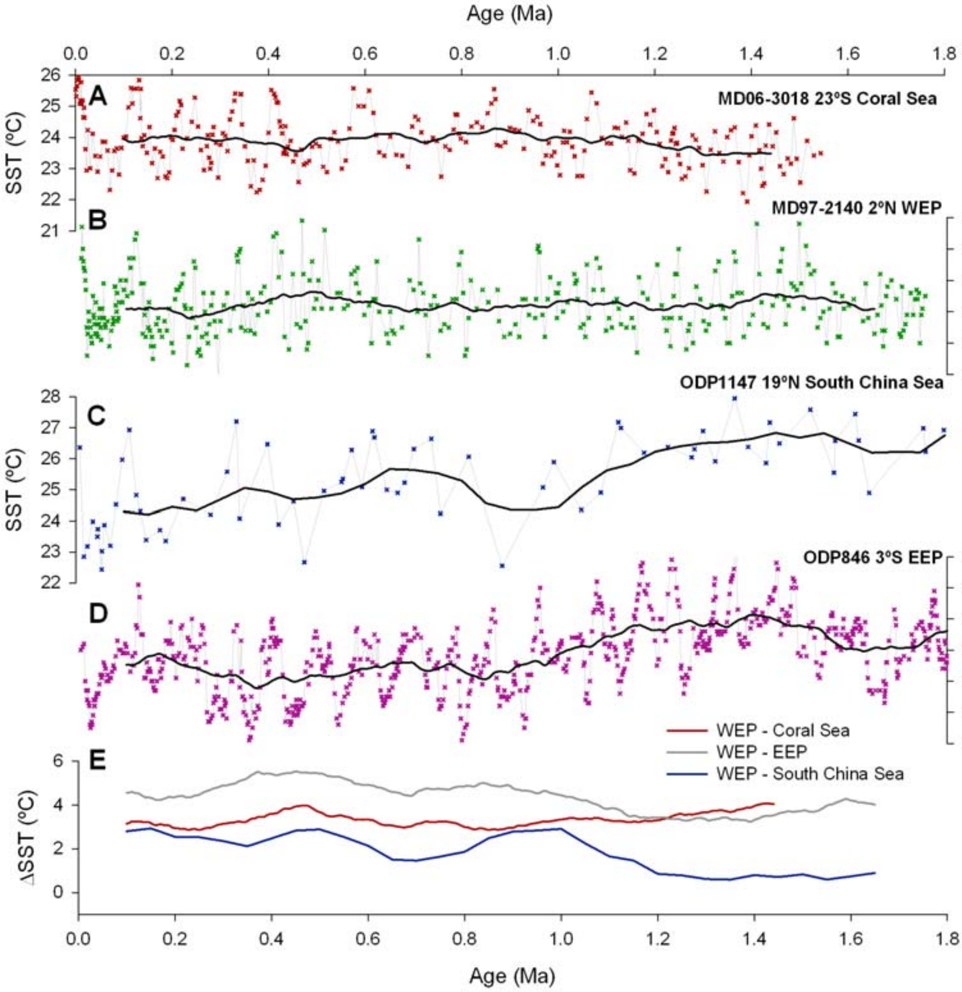

Figure 2. Pleistocene SST reconstructions from the core locations shown in Figure 1. (a) Southern Coral Sea core MD06-3018 (present study), (b) WEP core MD97-2140 [*de Garidel-Thoron et al.*, 2005], (c) South China Sea core ODP1147 [*Jia et al.*, 2008] and (d) EEP core ODP846 [*Lawrence et al.*, 2006]. Bold lines show 200kyr running means, calculated after 5kyr smoothing (through linear interpolation) of all records except ODP1147, which was smoothed to 50kyr resolution. All records are presented on published core age models. (e) Calculated SST gradients between the running means.

average value of 27.4°C (Figure 2b). The reconstructed SST gradient between the WEP and the southeastern Coral Sea, a measure of the equator-southern subtropical gradient, thus remains within $\pm 2\sigma_{\mathrm{SEM}} = 0.4$°C (the MD06-3018 reproducibility error is assumed for all reconstructions) of 3.5°C across the past 1.5Ma (Figure 2e). In contrast to the Coral Sea and WEP, both the EEP and South China Sea records show significant cooling trends during the early Pleistocene (Figures 2c and 2d). The reconstructed zonal equatorial SST gradient consequently increased by ~1.5°C over the interval 0.9–1.2Ma before remaining near to its modern value of ~4.5°C over the past 0.9Ma (Figure 2e). The reconstructed WEP-South China Sea SST gradient, a measure of the equatorial-northern subtropical gradient, increased by ~2.0°C over the interval 1.0–1.2Ma before remaining near to its modern value of ~2.5°C over the past 1.0Ma (Figure 2e).

[12] The difference between the WEP-South China Sea and WEP-Coral Sea SST gradient reconstructions provides a first-order proxy for the extent of inter-hemispheric SST asymmetry between the northern and southern subtropics in the western Pacific. Over the past ~1Ma, the two gradients remain within 2°C of each other with the latter always the more positive (Figure 2e), consistent with the existing inter-hemispheric SST asymmetry in the western Pacific. Prior to ~1Ma, however, they diverge indicating an increasing degree of asymmetry with age during the early Pleistocene.

4. Discussion and Conclusions

[13] Reconstructed southeastern Coral Sea SST shows no significant long-term variability over the past 1.6Ma. This climatic stability requires the corresponding stability of the southern boundary of the warm pool on this time-scale. Whilst the MD06-3018 record does not extend that far, the middle Pliocene (~3Ma) PRISM project SST reconstructions show southwestern Pacific subtropical values similar to the modern [*Dowsett and Robinson*, 2009], suggesting that the climatic stability of the region probably extends across at least the past 3Ma.

[14] From the middle Pliocene to ~1Ma both the eastern [*Wara et al.*, 2005; *Lawrence et al.*, 2006] and northern [*Jia*

et al., 2008] boundaries of the warm pool were generally contracting. This contraction is thought to be driven by the upwelling of cooler thermocline waters in the former case [*Philander and Fedorov*, 2003] and may be related to inferred changes in the vigor of the Kuroshio Current system [*Dowsett et al.*, 1996] in the latter. The present study demonstrates that the southern boundary of the warm pool did not follow this pattern and remained stable at least during the early Pleistocene. Consequently, the early Pleistocene warm pool, whilst expanded relative to its modern configuration, was also more hemispherically asymmetric. Recent ocean/atmosphere models for the Pliocene have assumed a meridionally symmetric configuration for the expanded Pacific warm pool [*Barreiro et al.*, 2006; *Brierley et al.*, 2009]. However, if the early Pleistocene trends documented here can be extrapolated to the Pliocene then the present reconstruction questions this choice of boundary conditions and is instead more consistent with the PRISM reconstructions [*Dowsett et al.*, 1996; *Dowsett and Robinson*, 2009].

[15] The latitudinal position of atmospheric inter-tropical convergence and hence the relative strength of the northern and southern branches of the Hadley circulation is partly controlled by the extent of inter-hemispheric extra-tropical SST asymmetry [*Broccoli et al.*, 2006]. This principle is supported on the glacial-interglacial time-scale by proxy reconstructions showing a southward shift of the Pacific inter-tropical convergence during periods of northern hemisphere cooling [*Koutavas and Lynch-Stieglitz*, 2004]. On the longer time-scales of interest here, a reduction in inter-hemispheric SST asymmetry from the early to the late Pleistocene implies southward migration of maximal atmospheric convergence and the relative strengthening of the northern Hadley Cell. It also implies a corresponding weakening of the southern Hadley Cell, but the relative stability of the equatorial-southern subtropical SST gradient suggests that any such changes were very limited.

[16] An increase in the strength of the northern Hadley Cell from the early to the late Pleistocene is in the same sense as proposed changes based on the equatorial-northern subtropical SST gradients [*Jia et al.*, 2008]. However, the equatorial-subtropical SST gradient approach may overestimate changes in Hadley Cell strength as it does not allow for migration of the ascending limb between the two core locations over the period of the reconstruction. Future modeling studies including enhanced, rather than reduced, inter-hemispheric SST asymmetry in the western Pacific are needed to evaluate whether this effect leads to significant changes in extra-tropical heat and moisture export prior to the MPT.

[17] The processes driving the observed decrease in inter-hemispheric subtropical Pacific SST asymmetry from the early to the late Pleistocene may be tropical or high-latitude in origin. In the former case, the tectonic arrangement of the western Pacific region and corresponding changes in the Indonesian throughflow were largely completed during the Pliocene [*Jochum et al.*, 2009] and are unlikely to have influenced the early Pleistocene changes. However, upstream changes in the north and south equatorial current systems could have affected the relative strength of oceanic heat transport to the northern and southern subtropics. Such variability could be closely linked to the enhanced warm pool asymmetry as the southern subtropics were probably more important, relative to their northern counterpart, as a source of thermocline waters to the EEP under such conditions. Alternatively, the decrease in inter-hemispheric subtropical Pacific SST asymmetry could have resulted from the differential cooling of the northern and southern high-latitudes across the Plio-Pleistocene. Within this scenario, the probable Hadley Cell response discussed above would have acted as a positive feedback, rather than a driving mechanism, for northern hemisphere glaciation during the MPT. The Hadley Cell response may have also acted to reinforce the East Asian Winter Monsoon system at the expense of the Summer Monsoon [*Jia et al.*, 2008], consistent with Plio-Pleistocene continental records of monsoon variability and acting as a further positive feedback on glaciation [*Xiong et al.*, 2003].

[18] The present study demonstrates that meridional SST gradients in both hemispheres are important in understanding past variability in poleward heat and moisture fluxes and that greater than modern inter-hemispheric symmetry in the extent of the paleo-warm pool cannot be safely assumed.

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