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Temperature correlations between the eastern equatorial Pacific and Antarctica over the past 230,000 years

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ABSTRACT

Tropical sea surface temperatures (SSTs) warmed and cooled in step with the Pleistocene ice age cycles, but the mechanisms are not known. It is assumed that the answer must involve radiative forcing by CO_2 but SST reconstructions have been too sparse for a conclusive test. Here I present a 230,000-yr tropical SST stack from the eastern equatorial Pacific (EEP) using two new Mg/Ca reconstructions combined with three earlier ones. The EEP stack shows persistent covariation with Antarctic temperature on orbital and millennial timescales indicating tight coupling between the two regions. This coupling however cannot be explained solely by CO_2 forcing because in at least one important case, the Marine Isotope Stage (MIS) 5e–5d glacial inception, both regions cooled ∼5–6.5 thousand years before CO_2 decreased. More likely, their covariation was due to advection of Antarctic climate signals to the EEP by the ocean. To explain the MIS 5e–5d event and glacial inception in general the hypothesis is advanced that the cooling signal spreads globally from the Northern Hemisphere with an active ocean circulation – first from the North Atlantic to the Southern Ocean with a colder North Atlantic Deep Water, and then to the Indian and Pacific Oceans with cooler Antarctic deep and intermediate waters.

1. Introduction

Milankovitch theory postulates that ice-age cycles are driven by changes in Earth's orbit, with boreal summer insolation serving as the critical control for the growth and decay of northern ice sheets (Hays et al., 1976; Imbrie and Imbrie, 1979; Milankovitch, 1930). This concept however fails to explain why glacial periods are synchronous in the Northern and Southern Hemispheres (NH and SH) or how the vast tropical oceans cool and warm during glacial inceptions and terminations. The discovery that atmospheric CO_2 covaries with Antarctic temperature and global ice volume (Lorius et al., 1990; Lüthi et al., 2008; Petit et al., 1999) has propelled CO_2 to the forefront as climatic "globalizer". However, the processes governing CO_2 variability are themselves poorly understood, and likely require an oceanic/climatic trigger in the first place (Adkins, 2013; Ferrari et al., 2014; Sigman et al., 2010). Antarctic ice core records are furthermore ambiguous with regard to the causal relationship between CO_2 and temperature. Phase relationships show CO_2 lagging behind temperature in the obliquity band (Jouzel et al., 2007) and across some major transitions (Caillon et al., 2003; Fischer et al., 1999; Kawamura et al., 2007; WAIS Divide Project Members, 2013), most prominently during the Marine Isotope Stage (MIS) 5e–5d boundary, i.e. the last glacial inception. Antarctic cooling at this time was associated with a major Milankovitch signal, and appears to have transpired almost entirely before the change in CO_2 concentration. It remains unclear whether the temperature lead was restricted to Antarctica or was broader. During the last glacial cycle reconstructed tropical Pacific and Indian Ocean SSTs covary with Antarctic temperature on orbital timescales (Kiefer et al., 2006; Lea, 2004; Lea et al., 2000; Saraswat et al., 2005) raising the question of whether tropical ocean cooling also led CO_2 during the MIS 5e–5d glaciation, a rather major question for understanding the mechanisms of tropical SST variability. However, due to the sparseness and low resolution of tropical SST records a clear picture has yet to emerge. Here the relationship between tropical SSTs, Antarctic temperature and CO_2 is addressed with two new Mg/Ca reconstructions and a new SST stack from the eastern equatorial Pacific (EEP) for the past 230 thousand years before present (ky BP).

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2. Oceanographic setting

The EEP is a nexus of important thermodynamic and biogeochemical processes with wide implications for Earth's climate. Energetically, it is a region of strong downward heat flux into the ocean (Boccaletti et al., 2004). Heat gained here is advected west with the mean equatorial flow contributing to the heat budgets of the Western Pacific and Indian Oceans via the Indonesian Through Flow (ITF). Heat transport into the South Atlantic via the Agulhas Leakage, and finally into the North Atlantic from where heat is lost to the atmosphere, serves to balance the heat gained in the EEP. Oceanographically the EEP represents a confluence of cool waters from the eastern boundary Peru–Chile Current, from coastal upwelling along the Peru Margin, and from equatorial upwelling (Kessler, 2006). Cool temperatures of 18–24 °C prevail south of the equator but give way to warmer waters (28–29 °C) northward as convergent winds push surface waters against the Central American landmass forming the Northeastern Pacific Warm Pool. Fueled by warm SSTs, convection here drives heavy rainfall, low salinity and enhanced stratification. Cross-equatorial North-South gradients in SST, salinity, stratification, and nutrients are evident in maps of annual mean properties, but are seasonally and interannually modulated by the annual cycle and by ENSO. Such modulations are governed by coupled ocean–atmosphere dynamics responding to external forcing (the annual solar cycle) or internal variability (for example ENSO). Due to the brevity of observational datasets, it is not known whether similar dynamical processes operate on longer timescales, and if so whether they are externally forced or internally generated.

On timescales of 10^3–10^5 yrs global climate undergoes major orbitally paced glacial–interglacial cycles, punctuated by millennial-scale Dansgaard/Oeschger (D/O) oscillations and Heinrich Stadials (HS), whose origins are not fully understood (Jouzel et al., 2007). The role of the tropical Pacific in these cycles is unclear. Tropical SSTs warmed and cooled by ~2–4 °C during the major 100-ky glacial cycles (Lea et al., 2000), but it is not clear whether these cycles involved dynamical effects, e.g. altered SST gradients, thermocline depth or tilt, ENSO variability, etc. (Koutavas et al., 2002; Koutavas and Joanides, 2012; Lea et al., 2000; Pena et al., 2008). In the case of the millennial events it is similarly unclear whether they impacted tropical Pacific SSTs, and if so whether they followed a Greenland or Antarctic temperature pattern. Within this framework the most fundamental question appears to remain unanswered: how did tropical SSTs cool and warm during the ice-age cycles?

3. Material and methods

δ^{18}O and Mg/Ca of *Globigerinoides ruber* foraminifera were measured in cores V28-134 (6°54′N, 85°25.98′W, 2434 m) and V19-28 (2°22′S, 84°39′, 2720 m) (Fig. 1 and Fig. 2). Analysis of large numbers of individual shells (Rustic et al., 2015) indicates that *G. ruber* is present throughout the year and the Mg/Ca data here are interpreted to represent annual mean conditions. *G. ruber* were picked from the 250–355 μm size fraction without discriminating between *sensu stricto* and *sensu lato* morphotypes. δ^{18}O was measured on whole-shell or crushed samples split in two or more aliquots for paired δ^{18}O and Mg/Ca. The number of shells per sample varied from as low as 5 to >100 (Fig. 2) but was generally between 10 and 30. Replicate δ^{18}O and Mg/Ca analyses in both cores showed good reproducibility regardless of sample size. Core V19-28 had sections where *G. ruber* were sparse or absent due to excessive dissolution resulting in gaps, especially in Mg/Ca.

δ^{18}O and δ^{13}C were measured with a Micromass VG Optima isotope ratio mass spectrometer at Lamont-Doherty Earth Observatory (LDEO) calibrated to VPDB via the NBS-19 carbonate standard,

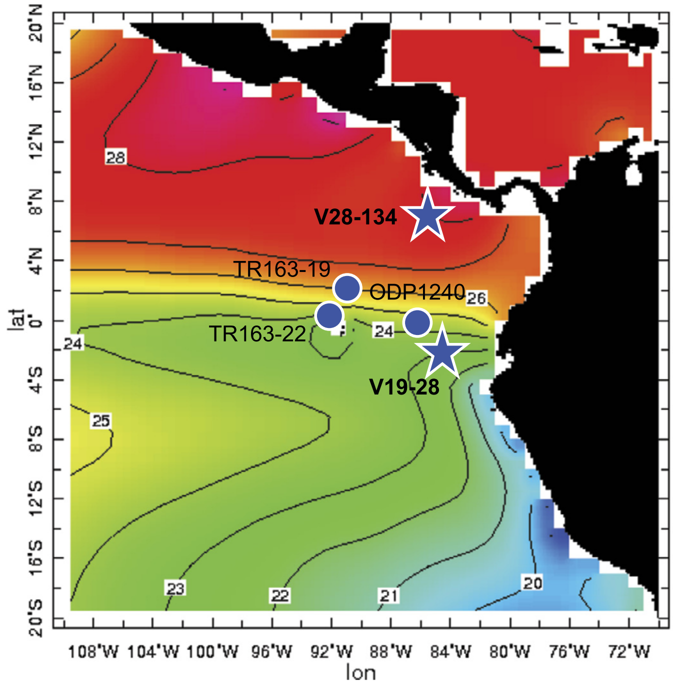

Fig. 1. Map of eastern equatorial Pacific annual mean SST, indicating cores used in this study. Stars denote the new Mg/Ca records from V19-28 and V28-134. Circles are sites with previously published Mg/Ca records.

with analytical precision of 0.06‰ for δ^{18}O and 0.04‰ for δ^{13}C. Sample splits for Mg/Ca underwent clay removal followed by oxidative and reductive cleaning to remove authigenic oxides and sulfides, and were analyzed on a Jobin-Yvon Panorama-V ICP-OES at LDEO. Al/Ca and Fe/Ca ratios were measured concurrently with Mg/Ca to assess possible sediment contamination. Samples with Al/Ca or Fe/Ca greater than 0.1 mmol/mol were rejected. The vast majority of samples were below this threshold. Analytical precision for Mg/Ca expressed as the pooled standard deviation of sample replicates is equivalent to ~0.2 °C. Temperature (T, in °C) was calculated with the equation Mg/Ca $= 0.38^{*}e^{0.09T}$ where Mg/Ca is given in mmol/mol (Anand et al., 2003). The standard error of the calibration is approximately ±1 °C.

Age models for the cores were constructed by ^{14}C dating between 0–30 ky BP (Table S1), and by correlation of *G. ruber* δ^{18}O with the Lisiecki and Raymo (2005) benthic δ^{18}O stack (LR04) in older sections. Using planktonic δ^{18}O for stratigraphic correlation with LR04 is not ideal given the possibility that local changes in surface temperature and hydrology can overprint the global ice volume signal. However, in two EEP cores where both planktonic and benthic δ^{18}O have been measured (TR163-19 and TR163-22) (Lea et al., 2006) there are no significant differences in δ^{18}O stratigraphy suggesting that both would yield similar age models. Average sedimentation rates are 3.8 cm/ky in V19-28, and 4.2 cm/ky in V28-134.

4. Results

4.1. $\delta^{18}O$

V28-134 and V19-28 are on opposites sides of the cross-equatorial front of the EEP (Fig. 1) and are separated by a mean SST difference of 5 °C. The data show the δ^{18}O gradient between them to stay relatively constant over the past 230 ky (Fig. 3A) indicating that a front comparable to today was present at most times within data resolution. One exception appears to be the Last Glacial Maximum (LGM), 18–24 ky BP, when the N–S gradi-