LETTERS

# Eastern Pacific cooling and Atlantic overturning circulation during the last deglaciation

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**Surface ocean conditions in the equatorial Pacific Ocean could hold the clue to whether millennial-scale global climate change during glacial times was initiated through tropical ocean–atmosphere feedbacks or by changes in the Atlantic thermohaline circulation[1]. North Atlantic cold periods during Heinrich events and millennial-scale cold events (stadials) have been linked with climatic changes in the tropical Atlantic Ocean and South America[2–4], as well as the Indian and East Asian monsoon systems[5,6], but not with tropical Pacific sea surface temperatures[7]. Here we present a high-resolution record of sea surface temperatures in the eastern tropical Pacific derived from alkenone unsaturation measurements. Our data show a temperature drop of 1 °C, synchronous (within dating uncertainties) with the shutdown of the Atlantic meridional overturning circulation during Heinrich event 1, and a smaller temperature drop of 0.5 °C synchronous with the smaller reduction in the overturning circulation during the Younger Dryas event. Both cold events coincide with maxima in surface ocean productivity as inferred from $^{230}$Th-normalized carbon burial fluxes, suggesting increased upwelling at the time. From the concurrence of equatorial Pacific cooling with the two North Atlantic cold periods during deglaciation, we conclude that these millennial-scale climate changes were probably driven by a reorganization of the oceans' thermohaline circulation, although possibly amplified by tropical ocean–atmosphere interaction as suggested before[8].**

Heinrich events are anomalous occurrences of ice-rafted detritus in the North Atlantic between 70 and 10 kyr before present (BP; ref. 9), and there is growing consensus that these events were associated with substantial perturbations of the Atlantic meridional overturning circulation (AMOC)[10]. For example, based on the sedimentary $^{231}$Pa/$^{230}$Th ratio, a novel kinematic proxy for the vigour of the AMOC, it has been suggested[10] that the meridional overturning was nearly, or completely, eliminated during Heinrich event 1 (H1).

Recent studies support a link between Heinrich events in the North Atlantic and changes in the environmental conditions of the tropical Atlantic Ocean and South America[2,3]. Consistent with modelling studies[11], these palaeorecords suggest that a slowdown of the AMOC during H1 is accompanied by a southward displacement of the Intertropical Convergence Zone (ITCZ). Similarly, millennial-scale variability of the Indian and East Asian monsoon systems has been shown to be closely linked to climate change in the North Atlantic[5,6]. The orchestrated response of the tropical Atlantic and the East Asian monsoon during the last glacial–interglacial transition has led to speculation[12] that the similarity in the deglacial evolution of climate in these distant regions is linked to shifts in the mean position of the ITCZ. Whereas linkages between low and high northern latitude climate change are well established for the tropical Atlantic[4] and the Indian[5] and Asian[6] monsoon systems, the interaction of the tropical Pacific Ocean with millennial-scale changes during the deglaciation observed elsewhere is still largely unknown. Thus, none of the few open oceanic Pacific sea surface temperature (SST) records available to date displays any obvious response to the reduction of the AMOC and/or the reorganization of atmospheric circulation during H1 and the Younger Dryas[7].

Here we present a multi-proxy record of surface ocean conditions from the eastern equatorial Pacific (EEP) north of the Equator. Core ME0005A-24JC was recovered at 0° 1.3′ N, 86° 27.8′ W from 2,941 m water depth. According to the radiocarbon chronology (see Supplementary Information), sedimentation rates range between 23 and 29 cm kyr$^{-1}$, for the first time allowing resolution of centennial-scale changes in the EEP during the glacial–interglacial transition. Temperature estimates based on alkenone unsaturation (Supplementary Information) yield average values of 22.8 °C during the Last Glacial Maximum (19–23 kyr BP), about 2–3 °C below average latest Holocene (~25 °C from 2–4 kyr BP) or modern annual average (24.4–25.2 °C, World Ocean Atlas (WOA)) values (Fig. 1). The glacial–interglacial transition is punctuated by a cooling starting at ~18 kyr BP, with the coldest SST estimates (21.4–22.2 °C) between 16.5 and 14.5 kyr BP. Following this cooling event, alkenone unsaturation index $U_{37}^{K'}$ temperature estimates rise rapidly to 22.7–23.1 °C at ~14 kyr BP (Fig. 1). Within the acknowledged uncertainties of radiocarbon chronologies, the primary cold spell during the deglaciation is coeval with the H1 reduction of the AMOC (~17.5–14.5 kyr BP; ref. 10). The smooth rise of estimated SST to maximum values at the core surface is interrupted by a second cold event between 12.5 and 11.5 kyr BP, coeval with the Younger Dryas interval, with temperatures ~0.5 °C below the preceding and following time intervals (Fig. 1). Before the deglaciation (ages > 21 kyr BP), there is no obvious correlation to cooling events in the North Atlantic. However, uncertainties in our chronology before 21 kyr BP (Supplementary Information) preclude us from ruling out a linkage between the cold period in the EEP centred at 26.5 kyr BP (Fig. 1) and Heinrich events 2 (~24 kyr BP) or 3 (~29 kyr BP).

The higher sedimentation rates at this site are in part the result of sediment focusing (Supplementary Information), which has the potential to substantially bias alkenone-derived SST estimates[13]. It is therefore important to assess whether or not alkenone-derived EEP SST estimates presented here record local or regional surface ocean conditions or whether their variability is influenced by sediment advection and redeposition. Two sets of observations argue against a

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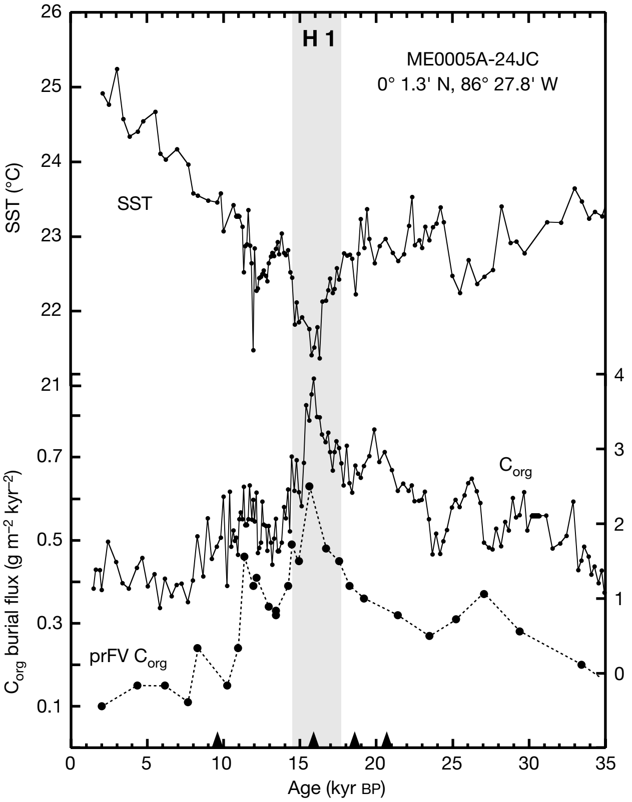


**Figure 1 | Time series of data from site ME0005A-24JC in the eastern equatorial Pacific north of the Equator.** Shown are estimated SST (based on alkenone unsaturation, $U_{37}^{K'}$), percentage organic carbon ($C_{org}$) and $^{230}$Th-normalized organic carbon burial flux (prFV $C_{org}$). The vertical bar marks the time period of the shut-down of the Atlantic meridional overturning circulation during Heinrich event 1[10]. Triangles on the bottom axis mark $^{14}$C age control points.

significant sedimentological bias of the alkenone-based SST estimates. (1) Although $^{230}$Th-normalization indicates significant sediment focusing during the Holocene (Supplementary Information), the average SST estimates of the topmost three samples (~25 °C) agree very well with the annual mean SST at this site (~25.2 °C, WOA). Likewise, the glacial–interglacial range of alkenone SST estimates presented here is in agreement with the range of glacial–interglacial SST variability obtained from lower-sedimentation-rate cores from this region; this latter range is based on Mg/Ca ratios (2.5 °C at site TR163-19; ref. 14) and species assemblages (1 to 3°C at a number of EEP sites[15]) of planktonic foraminifera, which are less prone to redistribution by bottom currents than finer-grained sediments hosting the alkenones. Also, there is no correlation between periods of maximum focusing and minimum SSTs, or vice versa. (2) Detailed bathymetric maps and high-resolution chirp sub-bottom profiles[16,17] show that core site ME0005A-24JC is located in a narrow east–west-trending trough in a region of abyssal hills, bordered by the Cocos–Nazca rise in the north and the Carnegie ridge to the south. Assuming that any potential sediment redistribution is topographically steered and bottom-current driven[18], the source region for laterally advected sediments (including alkenones) is thus restricted to less than 100 km in the north–south direction. Within this general region, modern SSTs range through ~2.3 °C (from 23.8 °C 1.5° south of the Equator, to 26.1 °C 1.5° north of the Equator, noting that WOA temperature gradients may be substantially smoothed relative to synoptic gradients), and glacial temperature gradients may have been either larger[19] or smaller[20,21]. To explain temperature changes of ~0.5–1.0 °C exclusively in terms of sediment redistribution would require ~30–100% (depending on whether one adopts a typical synoptic gradient or the local WOA gradient, respectively) of the alkenone signal during the cooling to have been reworked from the crest of the Carnegie ridge. Although the reworking hypothesis is not entirely impossible, we assume that the alkenone record presented here records local/meridional SST variability throughout the past 35 kyr despite evidence for substantial sediment focusing in this region (Supplementary Information).

Understanding the cause of the H1 cooling of the eastern tropical North Pacific will offer important insights into the mechanistic linkage between this region and the AMOC during this time interval. Two scenarios are entertained. A first mechanism that has been inferred to cause cooling of the EEP is increased advection of colder waters from the Peru Current[22,23]. Two lines of reasoning, however, argue against advection of colder water masses as the principal driver of decreased SSTs in the EEP during H1. First, advection of colder waters to site ME0005A-24JC should also affect SSTs off the Galapagos Islands. However, foraminiferal Mg/Ca SST estimates from core V21-30 (ref. 21), which has high enough sedimentation rates to allow resolution of millennial-scale SST variability, do not show any cooling associated with this time interval. In addition, SST and palaeoproductivity records off Peru suggest an early warming of the Peru Current starting at ~20 kyr BP (ref. 22), without interruption during the H1 or Younger Dryas time intervals[24]. A second possible explanation for cooling in the EEP north of the Equator is increased wind-driven upwelling (or upwelling of colder source waters). This scenario is supported by evidence for a close link between SST and marine primary production, as recorded by organic carbon percentage and $^{230}$Th-normalized fluxes at our study site (Fig. 1).

The data presented here suggest that surface ocean conditions in the EEP varied synchronously (within the uncertainties of radiocarbon chronologies) with a slowdown of the AMOC during the time interval of H1 and the Younger Dryas. Two competing scenarios have been offered to explain abrupt climate changes, including H1 and the Younger Dryas event during the last deglaciation (see ref. 1 for a recent review). One attributes such changes to variations in the ocean's thermohaline circulation[25]. The alternative view suggests that ocean–atmosphere interactions in the tropics, analogous to the present-day El Niño/Southern Oscillation (ENSO) dynamics, affect climate worldwide (see Supplementary Information, and ref. 26), possibly even through feedbacks on the AMOC[8].

Perturbations to the ocean–atmosphere system of the tropical Pacific have the demonstrated potential to affect climate throughout the globe[27], suggesting that the tropical origin hypothesis has merit. However, a response of the tropical Pacific to orbital forcing as simulated by the Zebiak and Cane model cannot explain the presence of maximum productivity or minimum SSTs in the EEP coincident with both H1 and the Younger Dryas events[28]. Although this highly idealized model shows that ENSO physics can abruptly lock to the seasonal cycle, thus leading to shutdowns of ENSO (that is, a mean state of the tropical Pacific resembling a La Niña event), the orbital configurations necessary for this to happen only recur on an approximately 11-kyr timescale, possibly synchronous with the Younger Dryas and Heinrich event 2, but not at the time of H1. On the other hand, newly developed global ocean–atmosphere models[29,30] simulate significant changes in the tropical Pacific triggered by a southward displacement of the ITCZ associated with a slowdown of the AMOC, thus offering a number of potential (and non-exclusive) explanations for the observations presented here. In the models, a slowdown of the AMOC strengthens the northeast trade winds. Although the intensified trade winds north of the Equator could explain the decreased SSTs via latent cooling, the associated increase in mixing may not be enough to account for the significant increase in organic carbon flux at our site (Fig. 1). On the other hand, the close association of enhanced marine primary production with decreased SSTs could be indicative of increased equatorial upwelling driven by increased Ekman divergence caused by the intensified northeast trades. The inference of increased equatorial upwelling in the EEP,

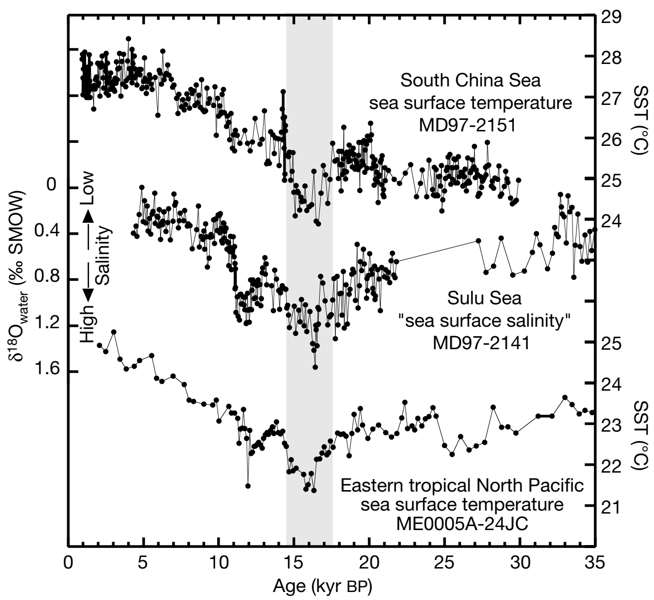


**Figure 2 | Comparison of the SST evolution at site ME0005A-24JC to data from the Sulu Sea and the South China Sea.** Shown are sea surface salinity ($\delta^{18}O_{water}$) estimates from the Sulu Sea[31] and $U_{37}^{K'}$ SST estimates from the South China Sea[32] on independent timescales. The vertical bar highlights climatic response to Heinrich event 1.

however, is not necessarily borne out by the recent coupled general circulation models[29,30], suggesting that the effect of intensified northeast trades on equatorial upwelling may be offset by weakened mean southeasterly cross-equatorial winds.

Finally, Zhang and Delworth[29] suggest that the intensified southward winds produced in their model in response to a shutdown of the AMOC induce coastal upwelling adjacent to central and south America (north of the Equator), leading to cooling of up to 0.5 °C in the eastern tropical Pacific north of the Equator owing to propagation of the upwelling signal with Ekman drift. South of the Equator, the anomalous southward winds induce coastal downwelling, translating to a warming of ~0.5 °C there. Our study site is essentially at the hinge point between these cool and warm anomalies in the model, which has a meridional resolution of the tropical ocean of 1/3° and a latitudinal resolution of the atmosphere of 2°. These authors speculate[29] that a higher-resolution model could produce larger anomalies. For this model to explain the equatorial cooling and increased carbon flux during H1 and the Younger Dryas, we must assume that our site is dominated by the effects of the Northern Hemisphere coastal upwelling, and that our record from a single site is representative of the larger region of the EEP north of the Equator. This scenario could thus be confirmed by analysing additional high resolution cores in the region. The model predictions of Zhang and Delworth[29] are also in accord with lower SST and higher sea surface salinity reconstructions from the South China Sea and the Sulu Sea, respectively (Fig. 2), suggesting a close coupling of the position of the ITCZ, the tropical Pacific atmosphere–ocean circulation, and the East Asian monsoon (see also ref. 30).

Given the fact that the Zebiak and Cane model only accounts for changes due to variable insolation forcing, ignoring other forcings such as $CO_2$ or ice sheet extent, it might be premature to discount ENSO-related dynamics as the principal driver of abrupt climate change in the past. However, the records presented here lend support to the hypothesis that millennial-scale global climate change, at least during H1 and the Younger Dryas, is initiated by a reorganization of the ocean's thermohaline circulation, albeit potentially amplified by orbitally induced ENSO-related freshwater perturbations in the tropics (such amplification is considered in ref. 8).

**Received 10 January; accepted 22 August 2006.**

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**Supplementary Information** is linked to the online version of the paper at www.nature.com/nature.

**Acknowledgements** The manuscript benefited from discussions with A. Clement, T. Delworth, D. Lea and A. Timmermann. Laboratory assistance by M. Soon, D. Montluçon, A. Fleer and S. Brown-Leger is acknowledged. This work was supported by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), the Natural Sciences and Engineering Research Council (NSERC) of Canada, the National Science Foundation (NSF), the WHOI postdoctoral fellowship programme (M.K. and G.M.) and a fellowship of the Canadian Institute for Advanced Research (CIAR; M.K.).

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