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Enhanced upwelling in the eastern equatorial Pacific at the last five glacial terminations

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ABSTRACT

TEX^{H}_{86}- and $U^{K}_{37}{}'$-derived paleotemperatures, and isoprenoid glycerol dialkyl glycerol tetraether (GDGT), and alkenone concentrations were examined for ODP Site 1239 in the eastern equatorial Pacific (EEP) for the last 430 kyr. We propose that the difference between TEX^{H}_{86}- and $U^{K}_{37}{}'$-derived temperatures (ΔT) and the abundance ratio of GDGTs to alkenones (GDGT/alkenone ratio) are potential upwelling indices which show consistent results with other upwelling indices. The ΔT and GDGT/alkenone ratio were maximal during the last five deglaciations, suggesting intensified upwelling. The intensification of upwelling in the EEP coincided with those at the Peru margin and in the Southern Ocean. This coincidence suggests that the reorganization of the Southern Hemisphere atmospheric circulation induced the intensification of the subtropical high-pressure cell, causing stronger southeast trade winds along the west coast of South America and the southern westerlies over the Southern Ocean, enhancing upwelling in both regions.

1. Introduction

The eastern equatorial Pacific (EEP) is a region between subtropical gyres of the North and South Pacific and contains the eastern terminus of the equatorial current system of the Pacific (Kessler, 2006). This region is important for its roles in climate variability as a result of the El Niño-Southern Oscillation (ENSO) and its significance for global carbon cycle (Fiedler and Lavin, 2006).

Glacial–interglacial changes in the oceanic condition of the EEP have been reconstructed by various studies, including sea surface temperature (SST) (e.g., Lyle et al., 1992), salinity (e.g., Lea et al., 2000), export production (e.g., Lyle et al., 1988), and intermediate water properties (e.g., Ganeshram et al., 2000; Spero and Lea, 2002). These studies have provided evidence for an early response by the EEP to orbital forcing (e.g., Imbrie et al., 1992), and the EEP is thus thought to play an important role in amplifying climatic changes through positive feedback mechanisms.

ENSO-like variability has often been used to interpret changes in the oceanic condition of the EEP (e.g., Lea et al., 2000; Koutavas et al., 2002), but different proxy records have led to different conclusions. Some researchers, for instance, have suggested that the glacial EEP was El Niño-like based on foraminiferal Mg/Ca and $\delta^{18}O$ (e.g., Koutavas et al., 2002; Koutavas and Lynch-Stieglitz, 2003), but others have inferred a glacial La Niña-like condition (e.g., coccolith assemblages by Beaufort et al., 2001; foraminiferal assemblages by Martinez et al., 2003; alkenones by Rincon-Martínez et al., 2010). This disagreement has been attributed to differences in the behavior of different proxies (e.g., Dubois et al., 2009).

In this paper, we present temperature records derived from TEX^{H}_{86} and $U^{K}_{37}{}'$ for Ocean Drilling Program (ODP) Site 1239 and interpret the $U^{K}_{37}{}'$ and TEX^{H}_{86} records for the last 430,000 years. On the basis of this interpretation, we propose the difference between TEX^{H}_{86}- and $U^{K}_{37}{}'$-derived temperatures and the abundance ratio of glycerol dialkyl glycerol tetraethers (GDGTs) to alkenones as potential upwelling indices and discuss the response of the EEP upwelling system to orbital forcing.

1.1. Modern physical oceanography

The zonal surface current system in the eastern tropical Pacific (ETP) consists of westward- and eastward-flowing currents (Fig. 1). The main westward currents are the North Equatorial Current (NEC; 8° N and 20° N) and the South Equatorial Current (SEC; 3° N to 10° S). The SEC originates as a combination of the waters from the North Equatorial Counter Current (NECC), the Equatorial Undercurrent (EUC), and the Peruvian Undercurrent (Kessler, 2006) through equatorial upwelling, mixing and advection. Two main lobes of the SEC are observed at a latitude of about 3° S to just north of the equator. The NECC, an eastward current, flows just north of the equator and is centered at about 5° N (Wyrtki, 1967; Talley et al., 2011). This current transports warmer water from the western Pacific warm pool to the ETP region. Between the SEC and the NECC there is a narrow equatorial front (EF) that separates warm low-salinity waters in the north from cool high-salinity waters in the south (Fig. 1; Strub et al., 1998). This front is observable from July to September at about 2.5° N with a strong meridional SST gradient. In contrast, the EF position is unclear from January to April, when the southeast trade winds collapse and SST south of the equator increases owing to reduced upwelling. The condition of the EF is correlated with the displacement of the intertropical convergence zone (ITCZ) (e.g., Pak

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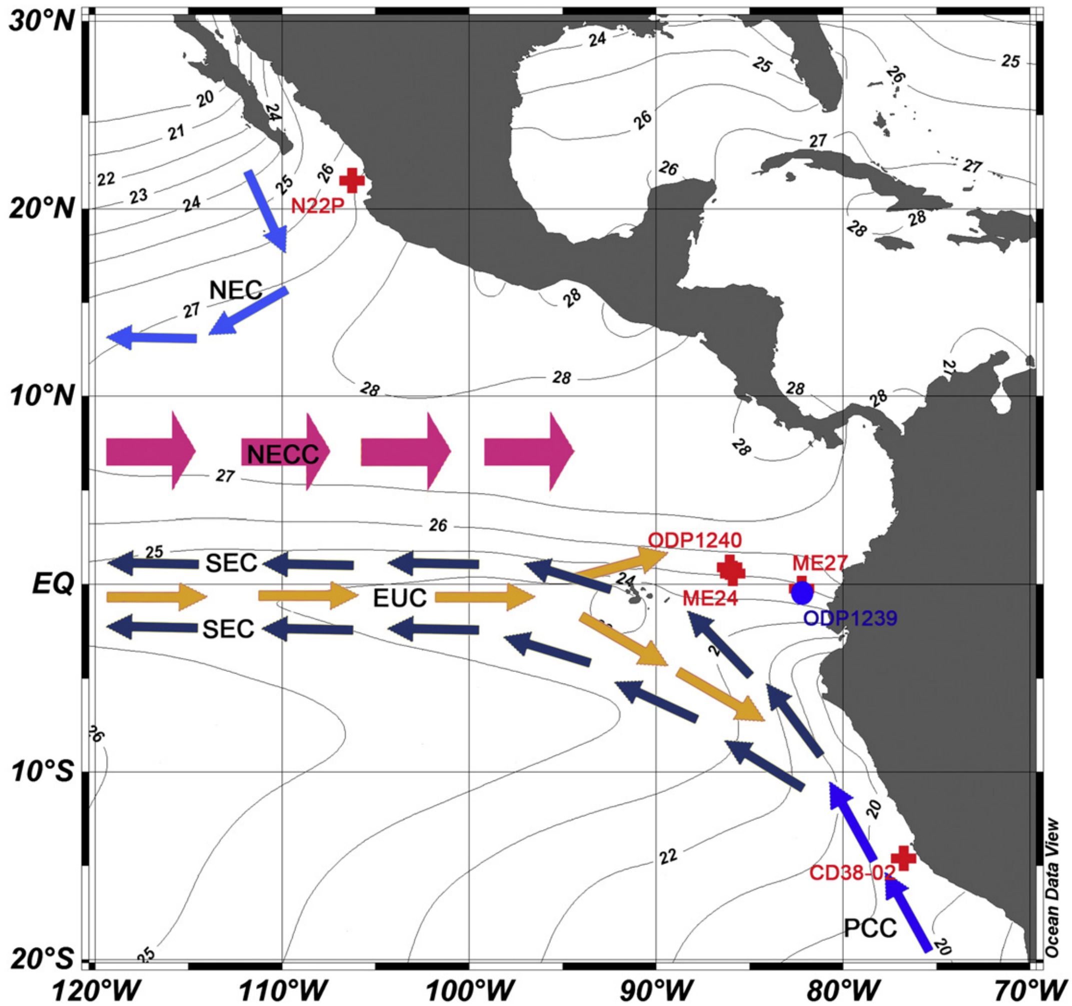

Fig. 1. Map showing mean annual SST (Locarnini et al., 2010), the location of ODP Site 1239 (this study), Sites 1240, ME24, ME27, N22P, CD38-02 and the surface and subsurface ocean currents in the EEP. SEC = South Equatorial Current, NEC = North Equatorial Current, EUC = Equatorial Undercurrent, NECC = North Equatorial Countercurrent. Modified after Kessler (2006) and Pennington et al. (2006).

and Zaneveld, 1974; Chelton et al., 2001; Raymond et al., 2004). The ITCZ reaches its northernmost extent in the month of August (~12° N) when southeast trade winds are stronger; the ITCZ is located closest to the equator in April (~2° N) when northeast trade winds are stronger (Waliser and Gautier, 1993).

The most influential subsurface current in this region is the EUC that flows eastward beneath the SEC. The EUC is fed by the saline New Guinea Coastal Undercurrent at its the western boundary (Talley et al., 2011) and flows within the equatorial thermocline and shoal as it approaches the Galapagos Islands (Kessler, 2006). When it reaches the Galapagos Islands, it splits into two branches (Steger et al., 1998) with the main branch flowing southward to merge with the Peruvian Undercurrent, which provides a source for the Peru coastal upwelling (Brink et al., 1983), the other branch continues to flow eastward, merging with the NECC (Wyrtki, 1967; Fiedler and Talley, 2006; Kessler, 2006).

The EEP is a region that has been impacted by coastal upwelling. Coastal upwelling in the EEP is driven by Ekman transport generated by southeast trade winds that blow along the west coast of South America (Wyrtki, 1981). The Ekman transport moves surface water offshore, away from the coastal boundary and replaces it with water from below the thermocline to maintain the mass balance. Seasonally, coastal upwelling is at its highest intensity when the strongest southeast trade winds blow over this region in boreal summer, and is reduced when southeast trade winds are relatively weak in boreal winter (Wyrtki, 1975, 1981; Kessler, 2006). The seasonal variability in the EEP is superimposed by interannual El Niño events (Wang and Fiedler, 2006), which occur every 2–7 years and last for 6–18 months (Pennington et al., 2006). Hydrological conditions that characterize El Niño (La Niña) phases in the EEP are a deeper (shallower) thermocline and a weaker (stronger) upwelling (Kessler, 2006).

Modern observation shows a clear seasonal and interannual SST variability in the EEP region (Fig. 2a). Seasonally, higher SST is recorded during boreal winter (February), and the lowest SST is recorded in boreal summer (August). The vertical temperature gradient is larger in boreal winter than that in boreal summer. Interannually, higher SST is observed in strong El Niño years and lower SST is observed in strong La Niña years (Fig. 2a). The thermocline depth at the study site is approximately 30–50 m (Fig. 2b).

2. Materials and methods

ODP Site 1239 (0° 40.32′ S, 82° 4.86′ W; 1414 m water depth) is located near the eastern crest of the Carnegie Ridge and ~120 km off the coast of Ecuador (Fig. 1). The sediments are dominated by light to dark olive gray foraminifera-nannofossil ooze with varying amounts of diatoms, clay, and micrite (Mix et al., 2003). The age-depth model of this core was established by Rincon-Martínez et al. (2010) based on correlation of the $\delta^{18}O$ record of the benthic foraminifera *Cibicidoides wuellerstorfi* with the LR04 global stack (Lisiecki and Raymo, 2005). In total, 236 samples were taken from 0.02 to 14.73 meters composite depth (mcd) at 2–10 cm intervals.