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A long history of equatorial deep-water upwelling in the Pacific Ocean

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ABSTRACT

Cold, nutrient- and CO_2-rich waters upwelling in the eastern equatorial Pacific (EEP) give rise to the Pacific cold tongue. Quasi-periodic subsidence of the thermocline and attenuation in wind strength expressed by El Niño conditions decrease upwelling rates, increase surface-water temperatures in the EEP, and lead to changes in regional climates both near and far from the equatorial Pacific. EEP surface waters have elevated CO_2 concentrations during neutral (upwelling) or La Niña (strong upwelling) conditions. In contrast, approximate air–sea CO_2 equilibrium characterizes El Niño events. One hypothesis proposes that changes in physical oceanography led to the establishment of a deep tropical thermocline and expanded mixed-layer prior to 3 million years ago. These effects are argued to have substantially reduced deep-water upwelling rates in the EEP and promoted a "permanent El Niño-like" climate state. For this study, we test this supposition by reconstructing EEP "excess CO_2" and upwelling history for the past 6.5 million years using the alkenone-pCO_2 methodology. Contrary to previous assertions, our results indicate that average temporal conditions in the EEP over the past ~6.5 million years were characterized by substantial CO_2 disequilibrium and high nutrient delivery to surface waters — characteristics that imply strong upwelling of deep waters. Upwelling appears most vigorous between ~6.5 to 4.5 million years ago coinciding with high accumulation rates of biogenic material during the late Miocene – early Pliocene "biogenic bloom".

1. Introduction

The eastern equatorial Pacific (EEP) is one of the most dynamic regions in the world ocean. Wind-driven upwelling in the EEP brings cold, nutrient- and CO_2-rich deep-waters to the surface, setting up east–west gradients in a number of parameters including sea surface temperature (SST), export production and surface seawater CO_2 (Feely et al., 2002; Fiedler and Talley, 2006; Keeling, 1968). However, quasi-periodic (2–7 years) ocean–atmosphere perturbations of El Niño – Southern Oscillation (ENSO) significantly reduce deep-water upwelling in the EEP by deepening the thermocline, which impacts regional and global climates and the carbon cycle (McPhaden et al., 2006).

One supposition suggests that, prior to 3 million years ago (Ma), the equatorial Pacific Ocean maintained a negligible zonal temperature gradient similar to modern El Niño conditions, often referred to as the "permanent El Niño" hypothesis (Fedorov et al., 2013). During the "permanent El Niño-like" interval, the EEP is thought to have had a deep thermocline and near absence of deep-water upwelling (Fedorov et al., 2006; Philander and Fedorov, 2003). Subsequent global cooling and shoaling of the tropical thermocline would have promoted equatorial upwelling, the appearance of cold EEP sea surface temperatures (SSTs), and the eventual establishment of modern zonal temperature gradients (Fedorov et al., 2006; Philander and Fedorov, 2003). Evidence for near cessation of upwelling in the EEP region before 3 Ma is inferred from SST reconstructions that indicate substantially higher temperatures during the Miocene – Pliocene in many coastal and equatorial upwelling regions (Brierley et al., 2009; Rommerskirchen et al., 2011; Rosell-Mele et al., 2014), including the EEP (Dekens et al., 2007; Lawrence et al., 2006; Rousselle et al., 2013; Zhang et al., 2014). Recent biomarker-based temperature reconstructions indicate that the western equatorial Pacific (WEP) was also warmer, maintaining a zonal SST gradient in the tropical Pacific throughout the late Miocene – Pliocene (O'Brien et al., 2014; Zhang et al., 2014). However, the Pacific zonal temperature gradient was about ~3–4 °C during 12–3 Ma, reduced relative to the average late Quaternary

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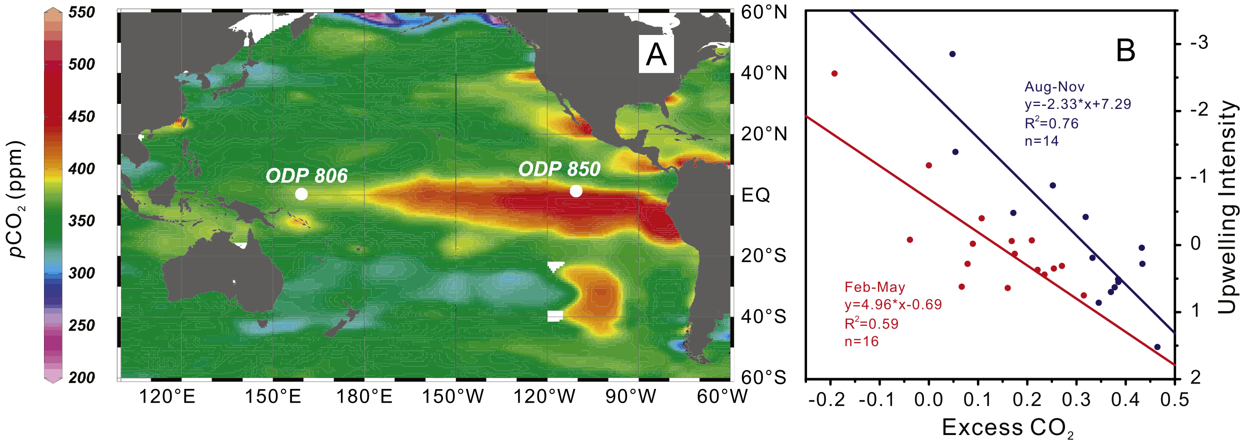

Fig. 1. Sample site locations and modern seawater pCO_2 relationships. (A), Surface seawater pCO_2 measurements collected 1957–2012 (Takahashi and Sutherland, 2012). Weighted-average gridding by Ocean Data View; ppm = parts per million. (B), Excess seawater CO_2 near ODP Site 850 relative to equilibrium conditions and "upwelling intensity" scaled by the Nino 3 index values. Regressions were performed using seasonal data from August to November and February to May. The t values for the two regressions are −4.8 and −6.5, respectively. At 0.05 level, both slopes are significant from zero. No data are available for December and January.

values (~5 °C) (Zhang et al., 2014). Importantly, the temporal resolution of deep-sea sediments does not allow the determination of the actual interannual climate variability, and new model simulation argues against using ENSO as analogs for long-term changes in tropical conditions (DiNezio et al., 2010).

Deep-sea sediment cores in the EEP consistently show that the mass accumulation rate (MAR) of biogenic components, such as carbonate and opal derived from marine microplankton, was significantly elevated during the late Miocene – early Pliocene, suggesting high export production in this region that probably links to the nutrient influx brought by deep-water upwelling (Farrell et al., 1995; Ma et al., 2015; Reghellin et al., 2015; Shackleton and Hall, 1995). The warm SSTs and high export production in the EEP during the "permanent El Niño-like" period appears to provide conflicting evidence for the strengths of equatorial upwelling.

It has been shown that the carbon cycle could be more sensitive to deep-water upwelling than temperature (Keller et al., 2015). Specifically, the outcrop of deep-water is usually associated with the outgassing of excess CO_2 accumulated from remineralization processes in seawater (Feely et al., 2002). In this study, we present surface seawater CO_2 levels in the western and eastern equatorial Pacific. Assuming the pCO_2 at WEP maintains approximate air–sea equilibrium, the WEP and EEP records are used together to compute the "excess CO_2" in the EEP, an independent proxy to probe the history of equatorial deep-water upwelling since the late Miocene.

2. Background

Deep-water upwelling in the EEP maintains air–sea CO_2 disequilibrium representing the world's largest ocean-to-atmosphere CO_2 flux (Takahashi et al., 2009) (Fig. 1). Pacific equatorial thermocline waters are sourced from the subduction of surface seawater in the extratropics — primarily in the Southern Hemisphere including Subantarctic Mode Water, but also in the Northern Hemisphere (O'Connor et al., 2002) — and are eventually transported by the Equatorial Undercurrent to the EEP. During neutral or La Niña conditions, pCO_2 in EEP surface waters can be ~50% higher than equilibrium conditions (Feely et al., 2002). During El Niño events, the thermocline deepens, surface water warms, and strong air–sea CO_2 disequilibrium quickly vanishes – a pattern that was revealed by the ship-board surveys during the 1994 and 1998 El Niño events (Feely et al., 2002). Long-term observations confirm the dominant influence of decadal-timescale ENSO phases on surface-seawater pCO_2, superimposed on the trend of anthropogenic CO_2 increase (Sutton et al., 2014). This implies that ancient pCO_2 levels recorded by sediments could be used to probe past deep-water upwelling strengths in this region (cf. Martinez-Boti et al., 2015; Palmer and Pearson, 2003).

Upwelling intensity in the equatorial Pacific is related to Ekman mass transport determined by the Coriolis parameter and wind stress, the history of which is lacking over the past several decades. Alternatively, wind stress, temperature and upwelling intensity are directly coupled on seasonal timescales in the EEP via the Bjerknes feedback (Bjerknes, 1969) which is captured in records of Nino 3 – an index that represents the magnitude of temperature anomalies in the EEP. Thus, the Nino 3 index acts as a proxy for upwelling intensity in the EEP on a seasonal timescale. Indeed, seawater pCO_2 measurements (Bakker et al., 2014) between years 1992 and 2007 in the vicinity of Ocean Drilling Program (ODP) Site 850 (Fig. S1) show that excess CO_2 (i.e., $[pCO_{2(sw)}/pCO_{2(air)}]-1$) and the degree of upwelling intensity, determined from Nino 3 values, are correlated (Fig. 1B). In contrast, the modern western Pacific warm pool is characterized by a deep mixed-layer and relative air–sea CO_2 equilibrium (Fig. 1A). Consequently, sea-surface pCO_2 offsets between the EEP (Site 850) and WEP (Site 806, Fig. 1A) provide a measure of excess CO_2 in the EEP through time.

We evaluated the magnitude of regional air–sea CO_2 disequilibrium across the equatorial Pacific Ocean for the past ~6.5 million years using the alkenone-CO_2 approach. Alkenones are long-chained (C_{37} to C_{39}) unsaturated ethyl and methyl ketones produced by haptophyte algae in the modern ocean (Conte et al., 1995). Alkenone-CO_2 reconstructions derive from the stable carbon-isotope composition of the di-unsaturated C_{37} methyl ketone ($\delta^{13}C_{37:2}$), planktonic foraminifera ($\delta^{13}C_{PF}$) and the total carbon isotope fractionation during algal growth ($\varepsilon_{p37:2}$). The magnitude of $\varepsilon_{p37:2}$ is a function of extracellular aqueous CO_2 concentration ($[CO_{2(aq)}]$), growth rate (μ), and cell geometry (i.e., the ratio of cellular volume to surface area), among other factors (Freeman and Pagani, 2005; Pagani, 2014). The phytoplankton physiological parameters such as growth rate and light availability are usually simplified to a single term '*b*', estimated from the concentration of reactive soluble phosphate ($[PO_4^{3-}]$) (Bidigare et al., 1997) or export productivity (Seki et al., 2010). We adopt the phosphate-*b* relationship from the global or regional survey of suspended particles to estimate modern *b* value at both sites. $\varepsilon_{p37:2}$ values were established at Site 850, while an existing Pliocene record (Pagani et al., 2010) was extended to the late Miocene at Site 806 (Fig. 2A, S2).