Quaternary Science Reviews 192 (2018) 123–134

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Precession-paced thermocline water temperature changes in response to upwelling conditions off southern Sumatra over the past 300,000 years

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ARTICLE INFO

Article history:
Received 12 January 2018
Received in revised form
14 May 2018
Accepted 24 May 2018

Keywords:
Thermocline water temperature
Sea surface temperature
Precession cycle
Upwelling intensity
Sumatra

ABSTRACT

Modern variations of sea surface temperature (SST) and thermocline water temperature (TWT) off southern Sumatra are responding to local upwelling conditions which are controlled by the Australian-Indonesian winter monsoon. The relationships between SST, TWT and upwelling during the past glacial-interglacial cycles are less clearly understood. In this study, SST and TWT variabilities over the past 300 kyr are reconstructed by using foraminiferal Mg/Ca-paleothermometry in sediment core SO139-74 KL off southern Sumatra (6°32.6′S, 103°50′E; 1690 m water depth). Whereas SST shows a clear glacial-interglacial cycle, TWT displays a predominant cycle at the precession band. Generally, the TWT record varies with total organic carbon content, revealing that similar to today, TWT and upwelling intensity off southern Sumatra vary in concert during the past 300 kyr. The lack of glacial-interglacial variability in the TWT suggests a limited role of glacial boundary conditions, such as changing sea level and ice volume, on the upwelling intensity in this region. The vertical gradients of upper water $\delta^{18}O$ and temperature at this site also reveal precessional cyclicity. Our model simulation of air-sea interaction further supports the low TWTs during periods of enhanced upwelling and precession minimum.

1. Introduction

The physical process of upwelling is an important component of ocean-atmosphere system that brings cold water and nutrients to the sea surface and regulates sea-air exchange. In the eastern tropical Indian Ocean (ETIO), oceanic upwelling is coupled with reversed monsoonal wind directions (Schott et al., 2002; Schott and McCreary, 2001). During the southeast (SE) monsoon season (July to October), southeasterly wind blowing from Australia generates upwelling along the southern coasts of Java and Sumatra, but the upwelling is generally absent during the northwest (NW) monsoon (December to March) and the monsoon transition seasons (Fig. 1a).

Recently, many observational and model studies have revealed the multiple features of the upwelling system in the ETIO, including intensive easterly wind (e.g., Schott and McCreary, 2001; Webster et al., 1999), lower sea surface height (e.g., Clarke and Liu, 1993; Horii et al., 2016), increased marine biological productivity (e.g., Hendiarti et al., 2004; Iskandar et al., 2009; Susanto et al., 2006) and negative anomalies of upper ocean temperatures (e.g., Chen et al., 2016; Du et al., 2008; Qu et al., 2005). The interannual variability of the ETIO upwelling is not only modulated by the Australian-Indonesian winter monsoon (AIWM) but also by the Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO) (Saji et al., 1999; Susanto et al., 2001, Webster et al., 1999). In normal years, cooling induced by upwelling is largely counterbalanced by horizontal advection of warmer waters (Du et al., 2008). During the austral winter and spring (boreal summer and fall) of positive IOD (and/or El Niño) years, anomalous intensified easterly wind can enhance upwelling in the ETIO, and conditions are reversed for the negative IOD (and/or La Niña) years (Webster et al., 1999).

Since there are no robust indicators for reconstructing the variability of wind and sea surface height in the past, the upwelling intensity is mainly reconstructed by proxies of marine paleoproductivity and upper ocean thermal structure. Paleoproductivity

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https://doi.org/10.1016/j.quascirev.2018.05.035
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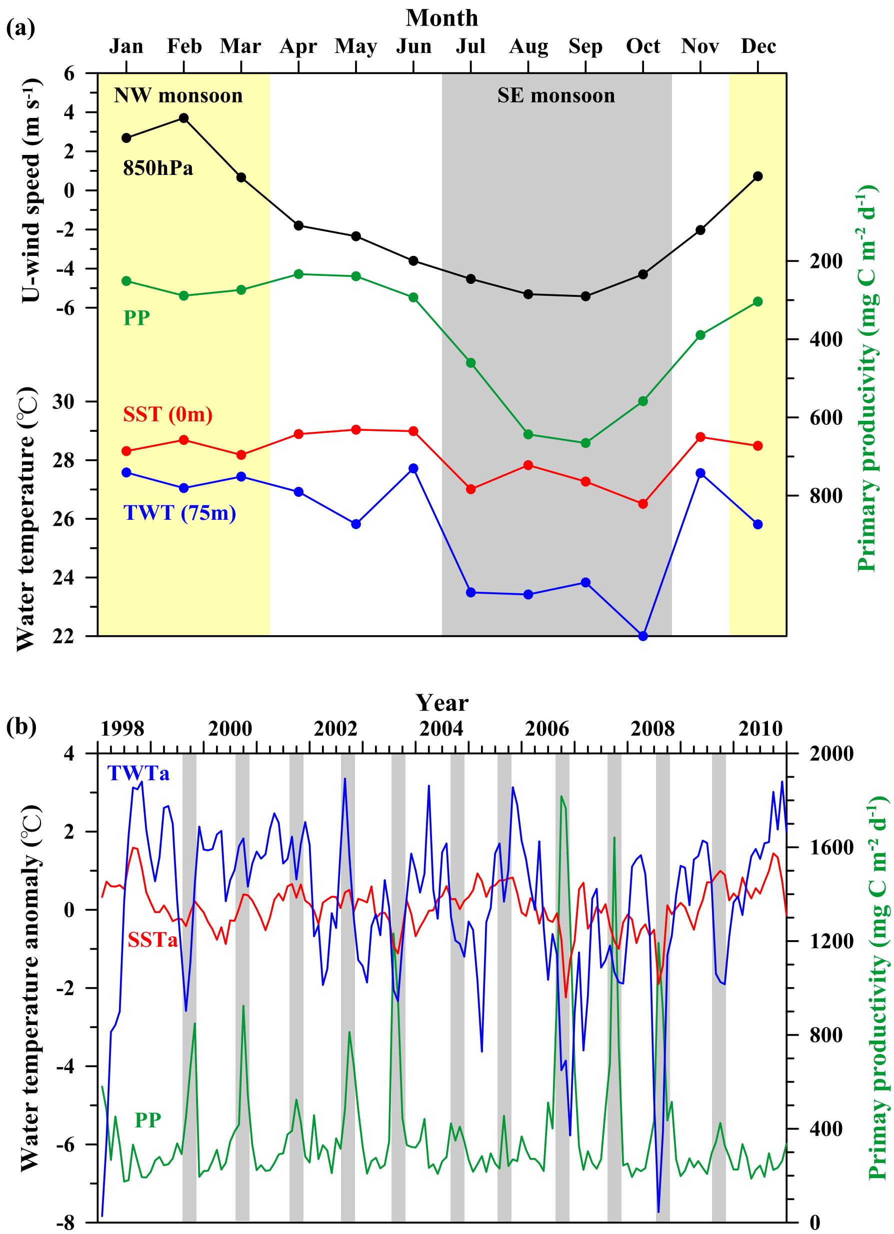

Fig. 1. (a) Monthly mean low-level zonal wind (850 hPa U-wind) off southern Sumatra (100–105°E/5–10°S) during the years 1948–1997 (black line) based on the NCEP reanalysis dataset (Kalnay et al., 1996). Monthly mean primary productivity from 103 to 103.5°E/6–6.5°S (green line, Behrenfeld and Falkowski, 1997, URL: http://www.science.oregonstate.edu/ocean.productivity/). Monthly water temperatures at 0 m (red line) and 75 m (blue line) from 103.5°E/6.5°S based on WOA01 dataset (Stephens et al., 2002). (b) Comparison of monthly primary productivity from 103 to 103.5°E 6–6.5°S (green line) during the years 1998–2010 (green line, Behrenfeld and Falkowski, 1997, URL: http://www.science.oregonstate.edu/ocean.productivity/) with sea surface temperature and thermocline water temperature anomalies from SODA (red and blue lines; Carton and Giese, 2008). Yellow and gray shaded vertical bars indicated the NW and SE monsoon seasons, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

off southern Sumatra during the past 300 kyr had been reconstructed by total organic carbon (TOC) content of core SO139-74 KL (Fig. 2), and was directly related to the strengthening of coastal upwelling during periods of increased Northern Hemisphere summer insolation and associated SE monsoon strength with a precessional cyclicity (Lückge et al., 2009). This finding was also confirmed by peak abundance of total coccolithophorid concentration in the same core (Andruleit et al., 2008) and total diatom concentration in neighboring core GeoB10038-4 (Romero et al., 2012). Mohtadi et al., (2010) found no glacial-interglacial variability in thermocline water temperature (TWT) off southern Sumatra during the past glacial-interglacial cycle and suggested remotely forced changes in mean annual temperature of the source water mass, the North Indian Water, instead of local seasonal upwelling intensity. In that study, thermocline depth derived from the vertical temperature gradient (ΔT, temperature difference between sea surface temperature, SST, and TWT) did not match the upwelling and East Asian summer monsoon (EASM) intensity. Other studies from southern Java and western Sumatra suggested that thermocline depth changes during the Holocene responded to upwelling intensity and could be correlated to the ENSO state (Steinke et al., 2014) and IOD state (Kwiatkowski et al., 2015), respectively. The records of upper ocean temperature especially TWT on glacial-interglacial scale in the upwelling region of the