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Holocene variations of thermocline conditions in the eastern tropical Indian Ocean

Cornelia Kwiatkowski [a, *], Matthias Prange [a], Vidya Varma [a, b], Stephan Steinke [a], Dierk Hebbeln [a], Mahyar Mohtadi [a]

[a] *MARUM – Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany*
[b] *Dept. of Meteorology, Stockholm University, SE-10691 Stockholm, Sweden*

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ABSTRACT

Climate phenomena like the monsoon system, El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are interconnected via various feedback mechanisms and control the climate of the Indian Ocean and its surrounding continents on various timescales. The eastern tropical Indian Ocean is a key area for the interplay of these phenomena and for reconstructing their past changes and forcing mechanisms. Here we present records of upper ocean thermal gradient, thermocline temperatures (TT) and relative abundances of planktic foraminifera in core SO 189-39KL taken off western Sumatra (0°47.400′ S, 99°54.510′ E) for the last 8 ka that we use as proxies for changes in upper ocean structure. The records suggest a deeper thermocline between 8 ka and ca 3 ka compared to the late Holocene. We find a shoaling of the thermocline after 3 ka, most likely indicating an increased occurrence of upwelling during the late Holocene compared to the mid-Holocene which might represent changes in the IOD-like mean state of the Indian Ocean with a more negative IOD-like mean state during the mid-Holocene and a more positive IOD-like mean state during the past 3 ka. This interpretation is supported by a transient Holocene climate model simulation in which an IOD-like mode is identified that involves an insolation-forced long-term trend of increasing anomalous surface easterlies over the equatorial eastern Indian Ocean.

1. Introduction

Presently, the Indonesian climate is mainly controlled by the seasonal migration of the Intertropical Convergence Zone (ITCZ), the Australian-Indonesian monsoon and the El Niño – Southern Oscillation (ENSO). The Indian Ocean Dipole (IOD) which is a coupled ocean–atmosphere phenomenon also exerts a significant control on the climate variability over western Indonesia (Saji et al., 1999; Webster et al., 1999; Abram et al., 2007). Negative IOD events are characterized by positive rainfall anomalies over western Indonesia accompanied by dry conditions over East Africa and eastward surface wind anomalies over the eastern Indian Ocean. On the other hand a positive IOD event is characterized by sea surface cooling (Fig. 1) and increased productivity off Sumatra due to enhanced upwelling in the eastern Indian Ocean accompanied by strong easterlies over the central Indian Ocean, dry conditions in West Indonesia and higher-than-normal rainfall over East Africa (Webster et al., 1999).

Behera et al. (2006) suggest that the IOD is initiated by processes internal to the Indian Ocean and, might be additionally affected and amplified by other climatic phenomena as e.g. ENSO. Saji et al. (1999) suggest the IOD being independent of ENSO but model simulations imply that ENSO has a strong influence on the periodicity, strength, and formation processes of the IOD in years of co-occurrences (Behera et al., 2006). However, since the occurrence of three positive IOD events in the years 2006–2008 it is obvious that ENSO is not the only triggering factor (Behera et al., 2006).

Previous studies on the IOD mainly focus on its present-day behavior, but only little is known about its past variability beyond the instrumental record. So far, there exist only three studies from the eastern Indian Ocean investigating the IOD variability during the Holocene; two are based on SST anomaly reconstructions from coraline Sr/Ca ratios off Sumatra (Abram et al., 2007, 2009) and one is based on precipitation changes derived from δD and $\delta^{13}C$ of plant waxes (Niedermeyer et al., 2014). Two studies investigate the IOD variability in the western Indian Ocean by using a multi-proxy

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* Corresponding author.
E-mail address: ckwiatkowski@marum.de (C. Kwiatkowski).

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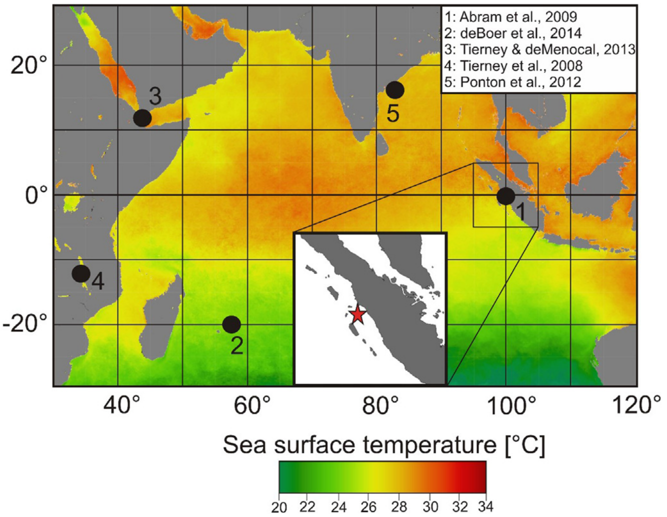

Fig. 1. Map of SST in the Indian Ocean indicating the surface cooling caused by the upwelling of cold subsurface water in autumn 2006 during a positive IOD event (http://oceancolor.gsfc.nasa.gov). The red star indicates the core site of SO 189-39KL, sites from other studies relevant for this work are numbered serially.

reconstruction from the Mauritian lowlands (de Boer et al., 2014) and δD from Lake Tanganyika sediments (Tierney et al., 2008).

Abram et al. (2007) hypothesize that observed SST anomalies are related to IOD events and suggest the Asian monsoon and ENSO being capable of triggering positive IOD events. They state a close relationship between the Asian monsoon system and IOD implied by a longer duration of positive IOD events during times of strong Asian summer monsoon and argue that sea surface cooling during a positive IOD event is constrained by the cross-equatorial wind reversal at the end of the Asian summer monsoon season resulting in an abrupt termination of Ekman upwelling along the coast of Sumatra (Abram et al., 2007). Furthermore, they assume that the monsoonal wind reversal controlling the timing of peak cooling during positive IOD events to be a consistent feature during the Holocene. The close relationship between the monsoon system and IOD is further supported by the study of Abram et al. (2009). Niedermeyer et al. (2014) investigate regional precipitation patterns over Sumatra in comparison to precipitation patterns from East Africa and Southeast India and find a general agreement with the reconstructed IOD variability by Abram et al. (2009).

The study of de Boer et al. (2014) suggests an anti-phased relationship of climate dynamics between the Mauritian lowlands and western tropical Australia during the middle Holocene reflecting a prolonged configuration of a negative mode of the IOD, which is partly inconsistent with the findings of Abram et al. (2009).

In order to understand the underlying mechanisms and the interaction between the IOD and other climate phenomena, e.g. the monsoon or ENSO continuous long-term data series are essential.

In this study we use a continuous sediment archive recovered from the northern Mentawai Basin off western Sumatra, close to the site published by Abram et al. (2009), in order to estimate variations in upper water column temperature and thermal gradient (i.e. depth of thermocline), and investigate the planktic foraminiferal assemblage to reconstruct the upper water column structure during the past 8 ka. We compare our results to orbital-forced model simulations and other climatic records from the Indian Ocean region in order to better assess possible forcing mechanisms of the upper water column variations off western Sumatra.

2. Study area

Aldrian and Susanto (2003) show that under modern conditions, SST and precipitation off western Sumatra are neither controlled by ENSO nor by the monsoonal system but by the seasonal migration of the ITCZ. At present, upper water column temperature and sea surface salinity anomalies in the study area are mainly controlled by the IOD (Yu et al., 2005; Qiu et al., 2012). This is also evident from several SST and TT datasets (e.g. SODA 2.2.4) in comparison to the Dipole Mode Index (DMI) introduced by Saji et al. (1999). Previous studies have shown that the western coast of Sumatra is one of the most sensitive areas for the development of the IOD (e.g. Abram et al., 2007). During positive IOD events, observational data of the last decades have shown that a decrease in SST is accompanied by a decrease in precipitation off Sumatra (Webster et al., 1999). Oceanic thermocline variations associated with IOD are confined to the region north of 6°S (Yu et al., 2005). Large-scale surface and subsurface circulation of the Indian Ocean might not affect the hydrography of the Mentawai Basin due to the topographic situation in which the fore-arc islands impede a direct influence of the open ocean (Mohtadi et al., 2014). Thus, paleoenvironmental archives from this area might record changes related to IOD variability. Seasonal changes are weak in the study area (Mohtadi et al., 2014) except for variations related to the IOD, which peaks in the September–October–November (SON) season (Saji et al., 1999). During extreme positive IOD events a SON SST decrease of >2 °C off Sumatra is one of the most significant signals observed presently (Webster et al., 1999; Abram et al., 2007; Du et al., 2008). This surface cooling in the eastern basin of the Indian Ocean is caused by unusually strong upwelling along the equator and off Sumatra. Furthermore, strong precipitation in the eastern Indian Ocean during normal years results in the development of a barrier layer, a layer separating the thermocline and the mixed layer, which impedes the upward movement of subsurface water masses (Spintall and Tomczak, 1992; Du et al., 2005; Qu and Meyers, 2005). During positive IOD events, the reduced warm water advection to the eastern equatorial Indian Ocean (Murtugudde et al., 2000) and the missing barrier layer in the water column due to decreased precipitation allow upwelling of cooler, nutrient-rich subsurface waters to the sea surface (Murtugudde et al., 2000; Du et al., 2008). However, Qiu et al. (2012) and Saji and Yamagata (2003) show that changes in SON SST are relatively small (<1 °C) during most positive IOD events and that temperature changes at the thermocline are much more prominent than changes at the sea surface (cf. Fig. 2). Zhao and Nigam (2015) show that the temperature dipole structure of the IOD occurs at the subsurface whereas the SST field shows a monopole structure over the Indian Ocean. Hence, when using foraminiferal Mg/Ca for the reconstruction of past IOD variations, the depth of thermocline and TT in the eastern Indian Ocean appear to be most suitable to characterize a possible IOD-like mean state – periods characterized either by stronger and/or more frequent positive IOD events (positive IOD-like mean state; upwelling; shallowing of the thermocline) or by weaker and/or less frequent positive IOD events (negative IOD-like mean state; deepening of the thermocline).

3. Material and methods

3.1. *Sample material*

Piston core SO189-39KL was recovered from the northern Mentawai Basin off western Sumatra (0°47.400′ S, 99°54.510′ E, 1350 cm core length, 517 m water depth) during the R/V Sonne 189 – SUMATRA expedition in 2006 (Wiedicke-Hombach et al., 2007; Fig. 1). Here we study the upper 2.7 m of this core representing the