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Indonesian Throughflow and monsoon activity records in the Timor Sea since the last glacial maximum

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ABSTRACT

Indonesian Throughflow (ITF) is known to play an important role in the heat exchange between the Pacific and the Indian Oceans. However, our understanding of the long-term evolution of the ITF and, in particular, the mechanism of heat transport is limited. Here, we present a high-resolution foraminifera-based multi-proxy study in the main ITF outflow area of the Timor Sea, to reconstruct the ITF variability and to understand the relationship between the ITF changes and monsoon activity from the last glacial maximum (LGM) to the Holocene. Our results show that when the strong surface water ITF occurs, high productivity is related to the mixing of the upper water column owing to the wind-driven upwelling rather than the shoaling of the depth of thermocline (DOT). By contrast, the DOT is affected more strongly by the ITF than by the monsoonal wind-driven upwelling in the Indonesian Seas. During the LGM (23–19 ka) and middle Holocene (8–6 ka), warm surface water ITF was dominated owing to the lowered sea level and (or) the higher steric height difference between the western Pacific and eastern Indian Oceans as a result of the strong southeast monsoon. During the early Holocene (11–8 ka) and late Holocene (last ~6 ka), because of the postglacial high sea level, the strong northwest monsoon and heavy rains, large amounts of freshwater flowed into the Java Sea from the South China Sea (SCS). The freshwater plug at the southern tip of the Makassar Strait blocked the warm surface flow, thus initiating the enhanced thermocline ITF. In the Timor Sea, the changes in the vertical profile of the ITF were influenced by the glacio-eustatic sea-level changes that have modified the geometry of the pathways within the Indonesian Seas, as well as by the monsoon activity which was modulated by the changes in the insolation with a precessional cyclicity.

1. Introduction

Today, the wind stress between the Pacific Ocean and the Indian Ocean maintains a sea-level height difference between these two oceans (Bray et al., 1996), as seen in the Indonesian Throughflow (ITF), a network of currents, surface and thermocline waters that are transported from the western equatorial Pacific Ocean into the Indian Ocean (Hirst and Godfrey, 1993; Linsley et al., 2010). The ITF is the only low-latitude connection along the return branch of the Great Conveyor Belt, which ultimately brings upper thermocline and surface waters from the Pacific to the North Atlantic (Gordon, 1986; Hirst and Godfrey, 1993; Bray et al., 1996; Gordon and Fine, 1996; Müller and Opdyke, 2000). The annual mean heat transport through the Indonesian Throughflow region (about 1.4×10^{15} W) represents a heat sink for the upper Pacific Ocean and is an important heat source for the Indian Ocean (Schiller et al., 1998; Ganachaud and Wunsch, 2000). However, modeling experiments and recent oceanographic measurements indicate that the modern ITF transport occurs mainly within the thermocline rather than at the sea surface (Gordon et al., 2003; Potemra et al., 2003; Song and Gordon, 2004; Gordon, 2005), and thus the net effect in terms of heat transport to the Indian Ocean could be negative instead of being positive.

The major component of the ITF is the Mindanao Current that originates from the upper thermocline of the North Pacific and is transported into the Indonesian Seas through the Makassar Strait (Gordon, 1986; Murray and Arief, 1988; Gordon and Fine, 1996) (Fig. 1). Within the Makassar Strait, the 680-m-deep Dewakang sill permits only the upper thermocline waters to enter the Flores Sea and flow eastward to the Banda Sea, or to directly exit into the Indian Ocean via the shallow Lombok Strait (Sprintall et al., 2009). Today, the ITF transport of warm, low-salinity water into the Indian Ocean averages ~16 Sv ($1\ \text{Sv} = 10^6\ \text{m}^3\ \text{s}^{-1}$) per year (Gordon and Fine, 1996; Schiller et al., 1998; Gordon et al., 2003). Mooring measurements show that only a small portion (~1.7 Sv) (Murray and Arief, 1988) of the waters flowing through the Makassar Strait across the Indonesian Seas directly enters the Indian Ocean via the Lombok Strait (with a sill depth of 350 m) between the islands of Bali and Lombok (Fig. 1). The largest part of these waters turns eastward into the Banda Sea and Flores Sea before spreading into the Indian

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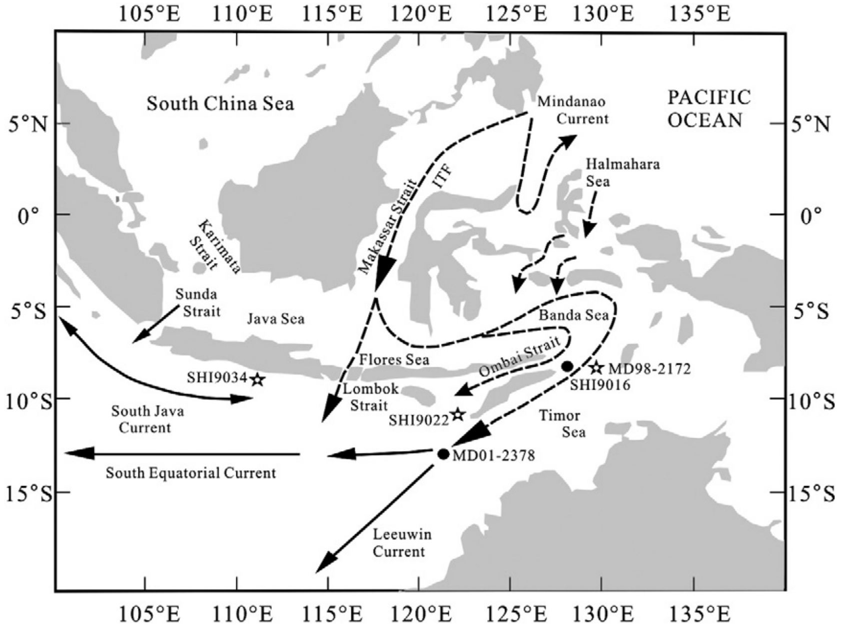

Fig. 1. Locations of core sites MD98-2172, SHI9034 and SHI9022 and those referred to in the text, with main oceanographic surface current (black line arrows), thermocline current (black dashed arrows) and main geographic locations mentioned in the text. Core SHI9016 was analyzed by Spooner et al. (2005) and core MD01-2378 by Xu et al. (2006).

Ocean through two main pathways: the Ombai Strait (with a sill depth of 3250 m and a yearly average flow of ~5.0 ± 1 Sv (Molcard et al., 2001)) and the Timor Sea (with a sill depth of 1890 m and a yearly average flow of 7.0 Sv (Creswell et al., 1993)) (Fig. 1). These ITF waters flow into the Indian Ocean as parts of the west-flowing South Java Current, the South Equatorial Current, and the south-flowing Leeuwin Current that runs along the western Australian margin (Gordon and Fine, 1996; Siedler et al., 2001) (Fig. 1).

The modern climate of the Indonesian Seas is dominated by bi-annual monsoonal shifts. Heavy rain accompanies northwesterly winds between November and March (Austral summer), during the Northwest (NW) Monsoon. The dry season corresponds to the Southeast (SE) Monsoon period from May to September (Austral winter) (Spooner et al., 2005).

The intertropical convergence zone (ITCZ), a pressure trough where the southeast and northeast trade winds meet, usually lies about 10°–15° north of the equator in the Austral winter and migrates southward, close to or over northern Australia in the Austral summer (Spooner et al., 2005). During the Austral summer, the NW Monsoon gathers large amounts of moisture while crossing the sea from the Asian high-pressure belt on its way to the ITCZ, which has shifted southward. At the ITCZ, the moisture-laden air rises, resulting in heavy rains (van der Kaars et al., 2000). During the Austral winter, the SE Monsoon originates from the Southern Hemisphere high-pressure belt and is relatively dry and cool (van der Kaars et al., 2000; Spooner et al., 2005).

The modern ITF is also closely related to the Asian monsoon dynamics. The main flow of the ITF in the key passages of the Makassar and Timor Straits shows a strong seasonal variability (Gordon et al., 1999; Potemra et al., 2003). During the NW Monsoon (Austral summer), a thermocline flow of relatively cool water dominates, as the warm surface flow becomes blocked by the development of a freshwater plug at the southern tip of the Makassar Strait, driven by monsoonal winds from the Java Sea (Gordon et al., 2003; Gordon, 2005). As a result, the tropical Indian Ocean is cooled rather than warmed by the ITF (Song and Gordon, 2004).

On the Milankovitch time scale, two main mechanisms may affect the ITF: (1) orbitally driven, low-latitude changes in insolation that affect monsoon dynamics and (2) glacio-eustatic sea-level changes that modify the geometry of the pathways within the Indonesian Seas. We have very limited understanding of the ITF evolution at this time scale. Using the records of the $\delta^{18}O$ and Mg/Ca of planktonic foraminifera, Linsley et al. (2010) suggested that the freshening of the surface ocean in the southern Makassar Strait 9.5 ka ago increased the northward pressure gradient and inhibited the flow of warmer surface-layer water into the Indian Ocean. Thus, 9.5 ka may have marked the initiation of the thermocline-enhanced cool ITF transport that is observed today. Xu et al. (2006, 2008) used a multi-proxy (planktonic foraminiferal census data and oxygen isotopic and Mg/Ca records) approach to reconstruct changes in the vertical profile of the ITF (depth of the thermocline and changes in sea surface and upper thermocline temperature), as well as monsoonal wind and precipitation variations in the Timor Sea during Terminations I and II. These studies indicated that the vertical structure of the ITF probably varied considerably over precessional and glacial–interglacial time scales, with the thermocline flow dominating during warm periods, i.e. the thermocline shoaled from the last glacial maximum (LGM) to the Holocene. However, through reconstructions of the vertical structure of the water column in the Banda Sea over the last ~80 ka using the abundance ratio of the planktonic foraminifera thermocline and mixed-layer dwellers, Spooner et al. (2005) showed that the mixed layer was thinner during the LGM, but thickened at the beginning of the Holocene. The latter may have been related to the strengthened surface water ITF in the early Holocene. Owing to the different climate proxies used in these studies, the existing data appear to be inconsistent.

A multi-proxy study in the main ITF outflow area and Java upwelling area is presented here, with the goal of comparing the results obtained using different climate proxies and reconstructing the ITF variations, hence improving our understanding on the relationship between the ITF changes and monsoon activity from the LGM to the Holocene. Our main objectives are to track changes of the ITF outflow during a period of extreme climate change and sea-level variations and to assess links between high- and low-latitude climate changes.

2. Materials and methods

Core MD98-2172 (8°31′S, 128°09′E) was obtained from the Timor Sea at a water depth of 1768 m during the International Marine Global Change Study (IMAGES) cruise IV of the R/V *Marion Dufresne* (Fig. 1). This Calypso giant piston core is 54 m long, but only work carried out on the upper 7.5 m of the core is discussed in this paper. Core MD98-2172 was sampled at 2 to 10-cm intervals for stable