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# Holocene centennial-scale changes of the Indonesian and South China Sea throughflows: Evidences from the Makassar Strait

Weijia Fan [a,*], Zhimin Jian [a], Franck Bassinot [b], Zhihui Chu [a,c]

[a] State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China
[b] Laboratoire des Sciences du Climat et de l'Environnement, UMR 8212 CEA-CNRS-UVSQ (LSCE), Gif-sur-Yvette 91198, France
[c] CNOOC (China) Co., Ltd. Shanghai branch, Shanghai 200030, China

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ABSTRACT

The Indonesian throughflow (ITF), as one of the key links of the global thermohaline circulation in the tropics, influences the large-scale redistribution of ocean heat and freshwater between the Pacific and the Indian Oceans. The ITF interacts with the low-salinity South China Sea throughflow (SCSTF) in the Makassar Strait at the pace of El Niño Southern Oscillation (ENSO). In this paper, variation of the throughflows via the Makassar Strait over the past 12 ka is reconstructed according to the seawater $\delta^{18}O_{sw}$ differences (indicating salinity gradients), which were determined based on paired measurements of $\delta^{18}O$ and magnesium/calcium ratio (Mg/Ca) of *Globigerinoides ruber* obtained from two sediment cores from the northern and the southern ends of the Makassar Strait respectively. Furthermore, thermal structure variation of the upper water column in the upstream ITF is retrieved on the basis of the temperature difference between the sea surface (*G. ruber*) and the thermocline (Mg/Ca of *Pulleniatina obliquiloculata*). It is shown that the surface ITF might have become stronger during the intervals 0.6–1.2, 3–3.6 and 7.2–8 ka BP. It also turns out that the SCSTF/ITF system and the upper ocean thermal structure co-vary with each other, and are likely linked with ENSO-like variation of the tropical Pacific. During El Niño-like periods, such as 1.2–3, 3.8–4.6, 5.2–7, and 8–9.6 ka BP, the depth of thermocline in the Celebes Sea shoaled and the transport of SCSTF was enhanced, meanwhile the surface warm water transport of the ITF was reduced. An opposite evolution was reconstructed during La Niña-like periods.



## 1. Introduction

The Indonesian throughflow (ITF), which connects the tropical Pacific and Indian oceans through the mazy passages in the archipelago between Asia and Australia, influences the large-scale redistribution of ocean heat and freshwater, and may have significant impacts on the tropical climate and the Asian–Australian monsoon system (Gordon, 1986; Godfrey, 1996; Gordon, 2005). The total transport via the ITF is estimated by 10–15 Sv (1 Sv $= 10^6$ $m^3$ $s^{-1}$). About 70–80% of the ITF is transported through the Makassar Strait (Gordon, 2005), where it interacts with the northward low-salinity surface flow originating from the South China Sea (SCS) via the Karimata Strait (Fig. 1), according to Qu et al. (2005). The excess heat and freshwater received by the SCS can only be balanced by horizontal advection, with an inflow of Western Pacific cold and salty water through the Luzon Strait, and an outflow of warm and freshwater to the Makassar Strait, which was named as the South China Sea throughflow (SCSTF) (Qu et al., 2006, 2009). Influenced by the interplay between ITF and SCSTF, changes of the surface flow through the Makassar Strait mainly depend on the density gradient variability along the strait not only on seasonal cycles (Gordon et al., 2003) but also on the pace of the El Niño-Southern Oscillation (Qu et al., 2006).

According to mooring observations, there is a substantial increase (about 38%) in the annual mean transport observed during the 2004–2006 INSTANT period relative to the period of the strong 1997/1998 El Niño event (Ffield et al., 2000; Susanto et al., 2012). However, the observations during the 2004–2009 INSTANT period indicate a more complex relationship between the El Niño Southern Oscillation (ENSO) and ITF, perhaps due to mixed influence factors (e.g. Asian monsoon and Indian Ocean Dipole) and none strong ENSO warm or cold event within the time span of the observations (Susanto et al., 2012). In spite of the discrepancy of the observations, many simulation studies have revealed that the transport volume of the ITF that varied on inter-annual timescales might be in association with ENSO. During the La Niña (El Niño) periods, the strengthened (relaxed) easterly trade wind and the intensified (reduced) Pacific–Indian Ocean sea surface height gradient might be favorable to promote (reduce) the ITF in numerous modeling studies (Potemra et al., 1997; Wajsowicz et al., 2003; Sprintall et al., 2009). Besides, El Niño condition might induce a stronger SCSTF, which would go back to the western tropical Pacific via Makassar Strait and

* Corresponding author at: State Key Laboratory of Marine Geology, Tongji University, Siping Rd. 1239, Shanghai 200092, China. Tel.: +86 65988808.
*E-mail addresses:* jwfan.jeffrey@gmail.com (W. Fan), Jian@tongji.edu.cn (Z. Jian), Franck.Bassinot@lsce.ipsl.fr (F. Bassinot), woshichuzhihui@163.com (Z. Chu).

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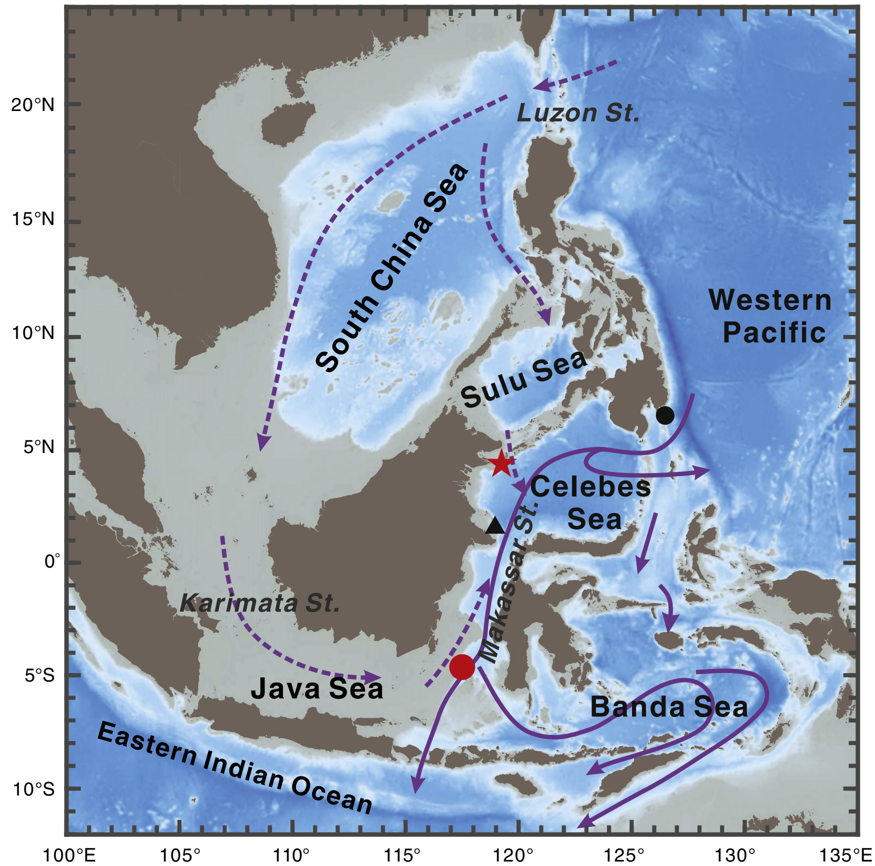


**Fig. 1.** Map of the study region and the locations of the study sites. Pathways of the ITF (purple solid arrow) and the SCSTF (purple dashed line) are sketched. Major straits for the circulation system are indicated in italic labels. The study sites are shown by a red circle (MD98-2161) and a red star (MD98-2178), respectively. Sites MD98-2177 (Newton et al., 2011) and MD06-3067 discussed in the text are marked with black triangle and black dot, respectively. Core MD98-2160 (Newton et al., 2011) is too close to MD98-2161 to be plotted in the map.

Celebes Sea and hence would reduce the southward transport of the ITF (Qu et al., 2009). It was also speculated that during a climate shift which occurred in 1976, with a change in the background state of the ENSO, the associated cooling of the main thermocline and weakening of easterly trade winds across the Pacific may also necessitate a weaker ITF (Wainwright et al., 2008). Through the reconstruction of density gradient, Newton et al. (2011) reconstructed the variation of surface ITF over the past 2000 yrs and ascribed that mainly to the past ENSO variability, which should induce dramatic variability in the thermal structure of the tropical Pacific as it does today.

It might be an approach to reconstruct both the variations of the ITF and its thermal structure to find out whether or not the ENSO-like variability played an important role on the changes of the ITF. Here, we do this over the course of Holocene when the Karimata Strait was inundated due to global sea level rise and the modern ITF/SCSTF system was established. We present two multi-decadal resolved upper ocean hydrological records MD98-2161 and MD98-2178, from the key regions of the ITF, the northern and the southern ends of the Makassar Strait, to explore the main control of the ITF through investigating its behavior during the millennial-to-centennial-scale climate shifts during the Holocene. Based on paired measurements of $\delta^{18}O$ and Mg/Ca of two species of planktonic foraminifera with different habitat water depth, the sea surface water $\delta^{18}O$ ($\delta^{18}O_{sw}$) gradient (indicating salinity gradients) along the Makassar Strait is reconstructed to explore the variability of the ITF/SCSTF system and the vertical temperature gradient is calculated to capture the variability of the thermal structure of the upper water column. Then the relationship between the ITF and its thermal structure over the course of the Holocene is discussed.

## 2. Materials and methods

Two Calypso cores, MD98-2178 (3.62 °N,118.70 °E,water depth 1984 m) and MD98-2161 (05 °12.6′S,117 °28.8′E,water depth 1185 m), were recovered from the northwestern Celebes Sea and the south end of the Makassar Strait, respectively, during IMAGES IV cruise of the R/V Marion Dufresne. Carbonate in the sediment of the two cores is preserved well and abundance of pteropod shells can be found in the sediment from MD98-2161. The age model of MD98-2178 was established on the basis of linear interpolation from 9 AMS$^{14}$C dated points, and that of MD98-2161 based on 10 AMS$^{14}$C determinations (Table 1). The average sedimentation rates of the cores are both >50 cm/ka. As sampled with 2 cm intervals, the sample resolution of MD98-2178 varies from 13 to 50 yrs and that of MD98-2161 20–75 yrs.

All the materials for AMS$^{14}$C dating were shells of *Globigerinoides ruber*, ~10 mg carbonate for each sample. AMS$^{14}$C analyses for MD98-2178 were performed in the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research and for MD98-2161in LSCE.

To reconstruct the surface water temperature (SST) and the subsurface water temperature, two species of planktonic foraminifera, *G. ruber* and *Pulleniatina obliquiloculata*, were chosen due to their habitat depth. *G. ruber* is mixed-layer-dwelling and *P. obliquiloculata* is thermocline-dwelling, the calcification depth of whom was reported as ~100 m below the sea surface (Xu et al., 2006; Zuraida et al., 2009; Dang et al., 2012).

Mg/Ca ratios were measured on the tests of *G. ruber* (*sensu stricto*, 30–35 individuals from 250–350 μm size fraction) and *P. obliquiloculata* (15–18 individuals from 350–440 μm size fraction).