Variability of the throughflow at its exit in the Indian Ocean

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[1] The hydrological properties and circulation along the TIP (Transport Indian Pacific) section between Java and Australia in September 2000 at the end of the southeast monsoon season are described. It is a reoccupation of the JADE (Java Australia Dynamic Experiment) sections carried out in August 1989 and in February 1992, which encompass the throughflow between the Pacific and the Indian oceans. The net geostrophic transport in September 2000 is of the same order as the August 1989 estimate. The results from the three occupations reveal that the seasonal and inter-annual variability is predominant and during the three cruises the transport evaluations capture the largest variability of the throughflow. **Citation:** Fieux, M., R. Molcard, R. Morrow, A. Kartavtseff, and A. G. Ilahude (2005), Variability of the throughflow at its exit in the Indian Ocean, *Geophys. Res. Lett.*, *32*, L14616, doi:10.1029/2005GL022836.

1. Introduction

[2] Observational and theoretical studies have demonstrated the climatic importance of the oceanic link (called the "throughflow") between the Pacific Ocean and the Indian Ocean, which carries warm and fresh waters from the Pacific to the Indian Ocean [*Gordon*, 1986; *Wyrtki*, 1987; *Masumoto and Yamagata*, 1993; *Gordon and Fine*, 1996; *Godfrey*, 1996; *Chong et al.*, 2000; *Ganachaud*, 2003]. A difficulty to approach the estimation of the throughflow transport is that the area undergoes several types of climatic variability: seasonal variability due to the reversal of the monsoon winds (SE winds in June–September and NW winds during November–March) and the reversal of the Java Current [*Quadfasel and Cresswell*, 1992; *Sprintall et al.*, 1999, 2002]; inter-annual variability related to the El Nino-Southern Oscillation (ENSO) which increases or decreases the sea level differences between the Pacific Ocean and the Indian Ocean [*Clarke and Liu*, 1993; *Meyers et al.*, 1995; *Meyers*, 1996]; short term variability due to transient eddies [*Feng and Wijffels*, 2002]. After the JADE 1 section in August 1989 [*Fieux et al.*, 1994; *Molcard et al.*, 1994] and the JADE 2 section in February 1992 [*Fieux et al.*, 1996a, 1996b; *Molcard et al.*, 1996] between Java and Australia (WOCE IR06 section), repeated hydrological stations were carried out along this same section during the TIP cruise, in September 2000, on board the French R/V Marion Dufresne of the Institut Polaire Français Paul Emile Victor (Figure 1). The location of the section was chosen to be close to the exits of the "throughflow" into the eastern Indian Ocean (i.e. Lombok, Sumba and Savu straits and Timor Passage) and to encompass the whole of it.

2. The TIP Data

[3] Between East Java and the continental shelf of northwest Australia, 27 $CTDO_2$ hydrological casts were conducted down to the bottom. Station intervals were less than 55 km and further reduced near the Indonesian coast.

[4] The CTD probe was a Seabird 9 system. The CTD was mounted with a rosette sampler fitted with 24 12l-bottles. The rms of the difference between the salinity measured by the CTD and the calibration measurements with a Guildline salinometer (with a 0.003 uncertainty) is 0.003; for oxygen, the rms is 1.5 μmol/kg (calibration with the Winkler method with a 0.5 μmol/kg uncertainty). The maximum difference between the temperature given by the CTD and the calibrated temperature is less than 0.0002°C, with an absolute uncertainty of ±0.003°C. The rms of the difference between the pressure given by the CTD and the calibration data is 0.23 db.

3. Comparison Between the Three Sections

[5] Different water masses enter the region:

[6] (i) Pacific waters are modified through the Indonesian Seas into:

[7] - Indonesian Water (IW) in the surface layer, characterized by low salinity (S < 34.5)

[8] - Intermediate Indonesian Water (IIW) in the thermocline layer down to around 1300 db, characterized by a homogeneous salinity slightly less than 34.60

[9] (ii) Waters coming from the Indian Ocean:

[10] - the North Indian Intermediate Water (NIIW), close to the Indonesian islands of Sumatra, Java and Bali, is characterized by low oxygen content and higher salinity than the IIW (core around 500 db with salinity > 34.65)

[11] - the Subtropical Water (STW), coming from the south Indian Ocean, is characterized by a high salinity (core around 250 db, S > 34.75)

[12] - the Central Water-Subantarctic Mode Water (CW-SAMW), is characterized by a high oxygen content (core around 400 db, O_2 > 3.5 ml/l)

[13] - at depth, the Indian Ocean Deep Water (IDW), a mixture of North Atlantic Deep Water, Antarctic Circumpolar Deep Water and Red Sea Deep Water, is characterized by a salinity maximum around 2400 db.

[14] These water masses have been described in several papers [*Rochford*, 1969; *Fieux et al.*, 1994; *Ffield and Gordon*, 1992; *Fieux et al.*, 1996a; *Bray et al.*, 1997;

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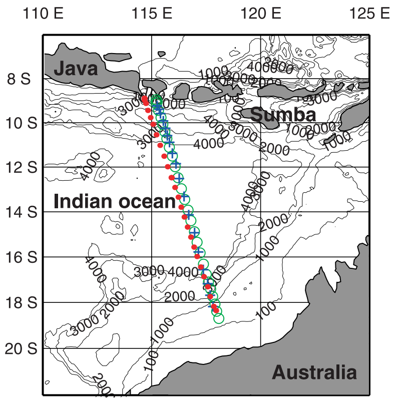

Figure 1. Map of the throughflow sections (JADE 1: blue crosses, JADE 2: green circles, TIP: red points).

Coatanoan et al., 1999; *Jean-Baptiste et al.*, 1997; *Jeandel et al.*, 1998; *Wijffels et al.*, 2002].

[15] The surface distributions (Figure 2) show the strong seasonal differences between TIP and JADE 1 (respectively in September and in August, at the end of the SE monsoon season which is the dry season) and JADE 2 in February (NW monsoon season which is the wet season). Higher salinity waters are found in the surface layer during JADE 2 (Figure 2b), contrary to what would have been expected during the wet season. Indeed, the throughflow (which transports low salinity waters from the Pacific) is stronger during the SE monsoon and stronger during the La Nina episodes (Meyers, 96), which correspond to the TIP and JADE 1 cruises and therefore overwhelms the local fresh water seasonal variation. With higher surface temperature in February (Figure 2a), the thermocline is much sharper than during the other seasons. Close to the Indonesian coast, the cooler slightly saltier surface waters (Figure 2a) and the slopes of the isohalines (Figure 3) reveal an upwelling in August and September down to 300 db which corresponds to the westward Java Current at that season. This is also noticeable on the oxygen content distributions (Figure 4). In contrast, in February (JADE 2, Figure 3) there is a coastal downwelling corresponding to the reversed eastward Java Current in the surface layers (0–120 db) carrying low salinity coastal waters. During TIP, the low salinity surface waters extended closer to the Australian shelf than in 1989 (Figure 3) and were particularly thick between 11°30S and 13°30S. JADE 2, in February 1992, is the only situation when the hydrological front reaches the surface at 13°30S, where there is a net separation between the high salinity in the south and the low salinity in the north (Figure 3).

[16] The lower temperature and slightly higher salinity signals observed between 10°S and 12°S during JADE 2 (Figure 2) correspond to the effect of a cyclone encountered at that time which mixed the upper layer, lowering the surface temperature and increasing the surface salinity.

[17] The hydrological front is found at 12°S during TIP, extending from the surface layer down to around 700 db. It separates the high salinity STW and the oxygen rich CW-SAMW (which is ventilated in the south-eastern Indian Ocean), on the southern side, and the lower oxygen-lower salinity IIW coming from the Indonesian seas, on the northern side. The cores of the STW and the CW are more intense during TIP and they extend further north than in 1989 and 1992 (Figure 3), perhaps due to the presence of a large anti-cyclonic eddy (sea level anomaly map, not shown), which deflected the position of the subsurface hydrological front to the north.

[18] The upper part of the IIW is found between the subsurface hydrological front and the NIIW core trapped along the Indonesian coast. In 2000, its horizontal extension is reduced due to the northern position of the front (Figures 3 and 4). Below 700 db, the extent of the lower part of the IIW is also reduced compared to 1989 and 1992.

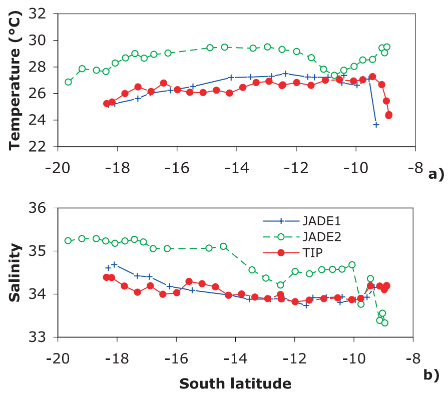

Figure 2. (a) Temperature and (b) salinity sea surface distributions for JADE 1 (August 1989), JADE 2 (February 1992) and TIP (September 2000) cruises.

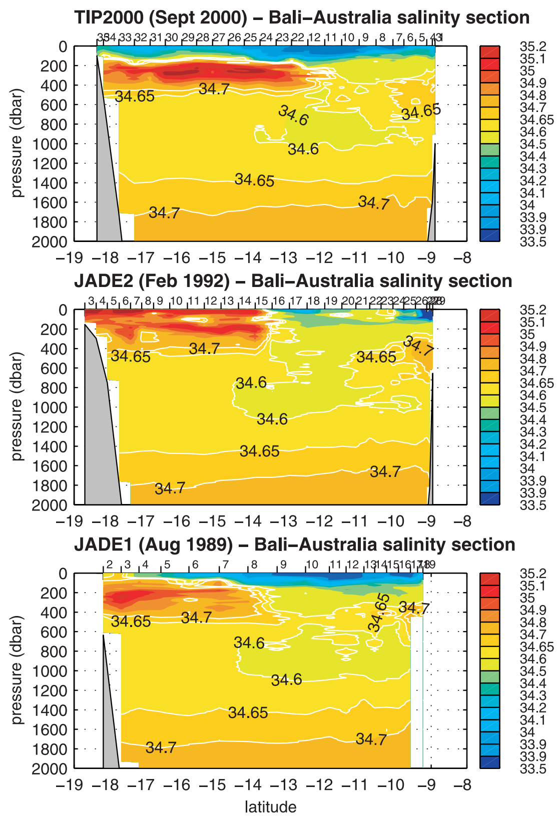

Figure 3. Salinity sections for JADE 1, JADE 2 and TIP cruises (the 34.65 isohaline denotes the NIIW).

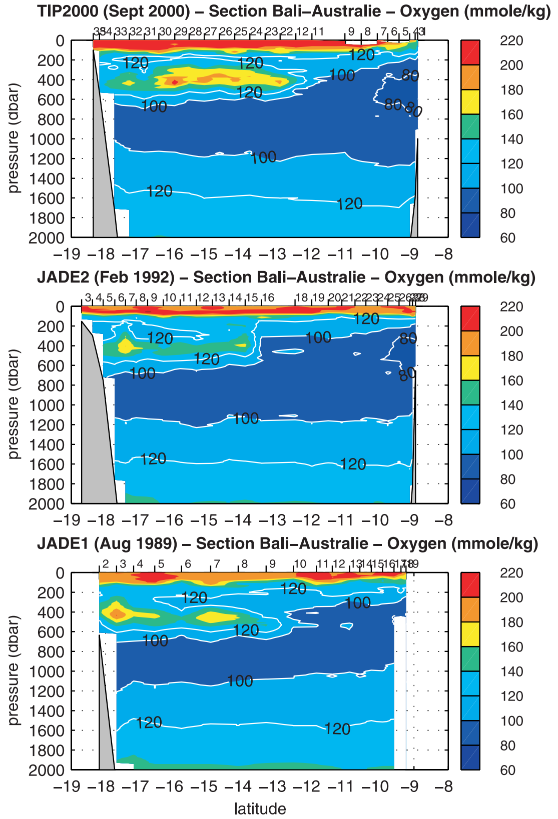

Figure 4. Oxygen sections for JADE 1, JADE 2 and TIP cruises.

[19] The comparison between the different cruises shows that the intermediate NIIW eastward flow, between 200 and 700 db, presents a maximum in February during the NW monsoon (Figures 3 and 4). It is noticeable that when there is a strong eastward NIIW in the north, there is a weak eastward input of STW-CW in the south, and vice versa.

4. Transports

[20] To calculate the geostrophic transports the reference level is chosen at 1300 db. This level is the common lowest passage through the Indonesian sills between the Pacific Ocean and the Indian Ocean and it corresponds to the transition between IIW coming from the east and IDW coming from the west [see *Fieux et al.*, 1994, 1996a, 1996b]. If we chose 1500 db, which is the extreme limit of the influence of the IIW on that section, the transports are very similar. ADCP measurements (JADE 2 and TIP, not shown) show the same features as the geostrophic transport distribution.

[21] The strong westward cores induced by the throughflow, corresponding to the stems of the South Equatorial Current (SEC), are always north of 12°S during all seasons, i.e. north of the hydrological front. Large transport differences are located near the Indonesian coast, in the Java Current (Figure 5). During the SE monsoon season (JADE 1, TIP), the Java Current flows strongly westward. In contrast, during the NW monsoon season (JADE 2), the Java Current flows strongly eastward down to 120 db, entraining low salinity coastal waters. The cumulative transport curves for the 3 cruises (Figure 5) show that the JADE 2 curve is shifted eastward due to the eastward reversal of the Java Current during that season. During TIP, the Java Current is westward, but a very narrow eastward current is present close to the Java eastern coast.

[22] The net cumulative geostrophic transports along the 3 sections, from north to south, highlights the large variability (Figure 5). The JADE 1 section in August 1989, and the TIP section in September 2000, were both carried out during the SE monsoon season, and show large westward net transports, between 0–1300 db, of respectively 20 Sv and 18 Sv. In comparison, JADE 2 in February 1992 showed a small net eastward transport of around 1 Sv within the incertitude estimate of ±7 Sv [*Fieux et al.*, 1996b]. Some slight differences with the values given by *Sprintall et al.* [2002] come from the smoothing of the data and the different reference levels.

[23] During the 3 cruises, transient eddies are characteristic of the circulation in that region [*Feng and Wijffels*, 2002]. They were particularly strong during TIP with large reversals near the Indonesian coast.

5. Discussion

[24] The seasonal effect of the monsoon reversal, enhanced by the inter-annual ENSO effect, is very important in the transport variability: during JADE 1 and TIP (SE monsoon season) the invasion of low salinity surface throughflow waters from the Indonesian seas (IW) destroyed the upper part of the hydrological front, whereas this front reached the surface only during JADE 2 (NW monsoon season). This front separates the high salinity in the south, due to strong evaporation effect, and the low salinity in the north, due to the IW throughflow.

[25] The comparison of net transports across the section for the 3 cruises does not distinguish either the Java Current or the SEC variability, or the depth distribution. Between 0 and 500 db, the Java Current has a westward transport of −14 Sv during TIP and −18 Sv during JADE 1; during JADE 2, it reverses eastward with a transport of 15 Sv. The transport of the westward SEC, between 0 and 500 db, ranges from −13 Sv (TIP) to −18 Sv (JADE 1 and 2). The lower transport of the SEC during TIP is perhaps due to the presence of the large eddy, which crosses the section and reduced the extension of the SEC.

[26] The inter-annual variability linked to ENSO phenomenon also affects the intensity of the throughflow

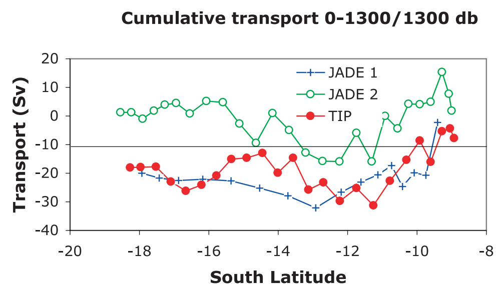

Figure 5. Cumulative net geostrophic transports for the 3 cruises from Indonesia to Australia (positive eastward, reference level 1300 db; first value = transport between first and second stations).

[*Meyers*, 1996]: during an El Nino episode, the Pacific trade winds are weaker and the sea level lower on the western Pacific side which tends to decrease the throughflow. JADE 2 took place during an El Nino episode and during the NW monsoon which both tend to decrease the transport between the Pacific and the Indian Ocean. On the contrary, JADE 1 and TIP took place at the end of La Nina episodes (the opposite of El Nino) and also during the season when the action of the SE monsoon winds tends to increase the throughflow, so both seasonal and inter-annual variability tend to increase the throughflow transport during these two cruises.

[27] Due to these extreme climatic characteristics (seasonal as well as inter-annual), our evaluation of the net transport range from the three 1989–1992–2000 cruises (1 Sv eastward to 20 Sv westward) captures the largest variability of the throughflow.

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