Indonesian Throughflow

Introduction

The Indonesian Throughflow (ITF) is the only low-latitude oceanic connection between the major ocean basins of today (Schneider, 1998), due to which it plays an integral role in the global thermohaline circulation and directly impacts the basin heat and freshwater budgets of both the Pacific and Indian Oceans (Byrden and Imawaki, 2001; Sprintall and Liu, 2005). It transports heat and freshwater from the Pacific Ocean to the Indian Ocean. The mass transport of the throughflow affects the thermocline of the Indian Ocean and is in part responsible for anomalous deep thermocline and lack of cold upwelling off the western coast of Australia (Godfrey and Golding 1981; Schneider, 1998). The heat transported by the ITF removes a significant amount of the surface heat flux from the Pacific Ocean received in the tropics and transfers it to the Indian Ocean thereby raising the SST. The ITF has a very important role in determining the SST and upper-layer heat storage in the Pacific and Indian Oceans (Hirst and Godfrey, 1993; Verschell *et al*., 1995; Murtugudde *et al*., 1998), as has been simulated in a number of models. The Indian and Pacific Oceans would have been completely different from what they are today if the ITF would have been zero (MacDonald, 1993). The effect of zero ITF would raise the sea level in the Pacific Ocean and lower in the Indian Ocean by 2-10 cm (Maes, 1998) and would stop the shift of warmest SST and associated atmospheric convective region towards the west (Schneider, 1998).

The Indonesian Throughflow rises from the western continuation of the Western Pacific Warm Pool (Yan et al., 1992; You and Tomczak, 1993; Gordon and Fine, 1996), which (WPWP) plays a key role in regulating the heat budget of the Earth (Bjerknes, 1969; Wyrtki, 1981, 1987; Bastacov, 1996; Patrick and Thunell, 1997; Webb et al., 1997).

The ITF is regarded as one of the major switchboards in the global thermohaline circulation, and its variability influences the global climate on short term (ENSO related) and long-term timescales (Schott and McCreary, 2001; Gordon et al., 2003; Kuhnt et al, 2004).

Route of the ITF

The Indonesian Archipelago is a combination of numerous islands, with narrow straits that connect a series of large, deep ocean basins within the Indonesian seas, providing a winding route for the ITF (Sprintall, 2009). ITF waters are drawn from the North Pacific thermocline as well as the South Pacific thermocline through the Mindanao and Halmahera eddies respectively (Gordon et al,), the South Pacific waters being more saline than the North Pacific. The ITF source water (North Pacific versus South Pacific) depends upon land geometry and the tropical Pacific wind fields (Nof, 1996; Morey *et al.*, 1999; Wajsowicz, 1999). The main route drives North Pacific water through the Sulawesi Sea and the Makassar Strait, and exits through the Lombok and Ombai Straits and through the Timor Passage (Koch-Larrouy et al., 2007; Fine, 1985; Ffield and Gordon, 1992; Gordon, 1995; Gordon and Fine, 1996; Sprintall, 2009). The Makassar Strait, westernmost deep channel, carries the bulk of the ITF water (Wajsowicz, 1996). The Dewakang Sill (680 m deep) (Sprintall et al., 2009) in the Makassar Strait turns most of the upper thermocline Makassar Strait Throughflow eastward within the Flores Sea to enter the Banda Sea before entering the Indian Ocean (Gordon and Fine, 1996), while some of it exits the Indonesian Sea through the Lombok Strait (Murray and Arief, 1988). The lower thermocline waters of the Banda Sea are dominated by the higher salinity South Pacific water, which dominates the deeper layers through density-driven overflow (Van Aken et al., 1988; Gordon and Fine, 1996; Hautala et al., 1996; Ilahude and Gordon, 1996). About 90% of the ITF thermocline water flows through this main route with an estimated transport of 10 ± 5 Sv (1 Sv = 10^6 m^3/s) (Gordon, 2005; Koch-Larrouy et al., 2007). The second route transfers the lower thermocline water of South Pacific origin through the Maluku Sea and the Lifamatola Strait. It has a transport of 1.5 – 3 Sv (Van Aken et al., 1988; Gordon et al., 2003). South Pacific waters, characterized by higher salinity maximum, flow through the last route passing by the Halmahera, Seram and Banda Seas (Gordon and Fine, 1996). This route advects about 10% of the thermocline water, amounting to ~1-2 Sv, inferred from the balance between the exit and the entrance (Gordon, 2005).

From the Banda Sea, the ITF enters the southeast Indian Ocean along the Nusa Tenggara island chain via the Timor Passage (1250 m sill depth at the eastern end and 1890 m at the western end), or through Ombai Strait and then through the Savu Sea to Sumba Strait. The ITF waters form a relatively narrow fresh jet across the tropical South Indian Ocean within the westward South Equatorial Current (SEC) between 8^0S to 14^0S and tend to intensify it. While some of the ITF waters feed the monsoon currents off the Somali coast, much of it enters the Agulhas Current system (Warren, 1981; You, 1998). Along the Agulhas Current system, some of it enters the Atlantic Ocean via Agulhas eddies (also known as Agulhas Leakage; Gordon, 1986) which have been identified to contain relatively fresh Indonesian thermocline water (Gordon, 1986; Song et al., 2004) while rest turns back along the Agulhas Retroflection (Read and Pollard, 1993). A branch of freshwater also diverges from the Throughflow in the Timor Passage near the western coast of Australia and makes its way southwards, known as the Leeuwin Current. The numerical models of Hughes et al (1992), Hirst and Godfrey (1993, 1995), Lee et al (2002) etc. are strengthened by this evidence that the ITF plays an important role in the global thermohaline circulation.

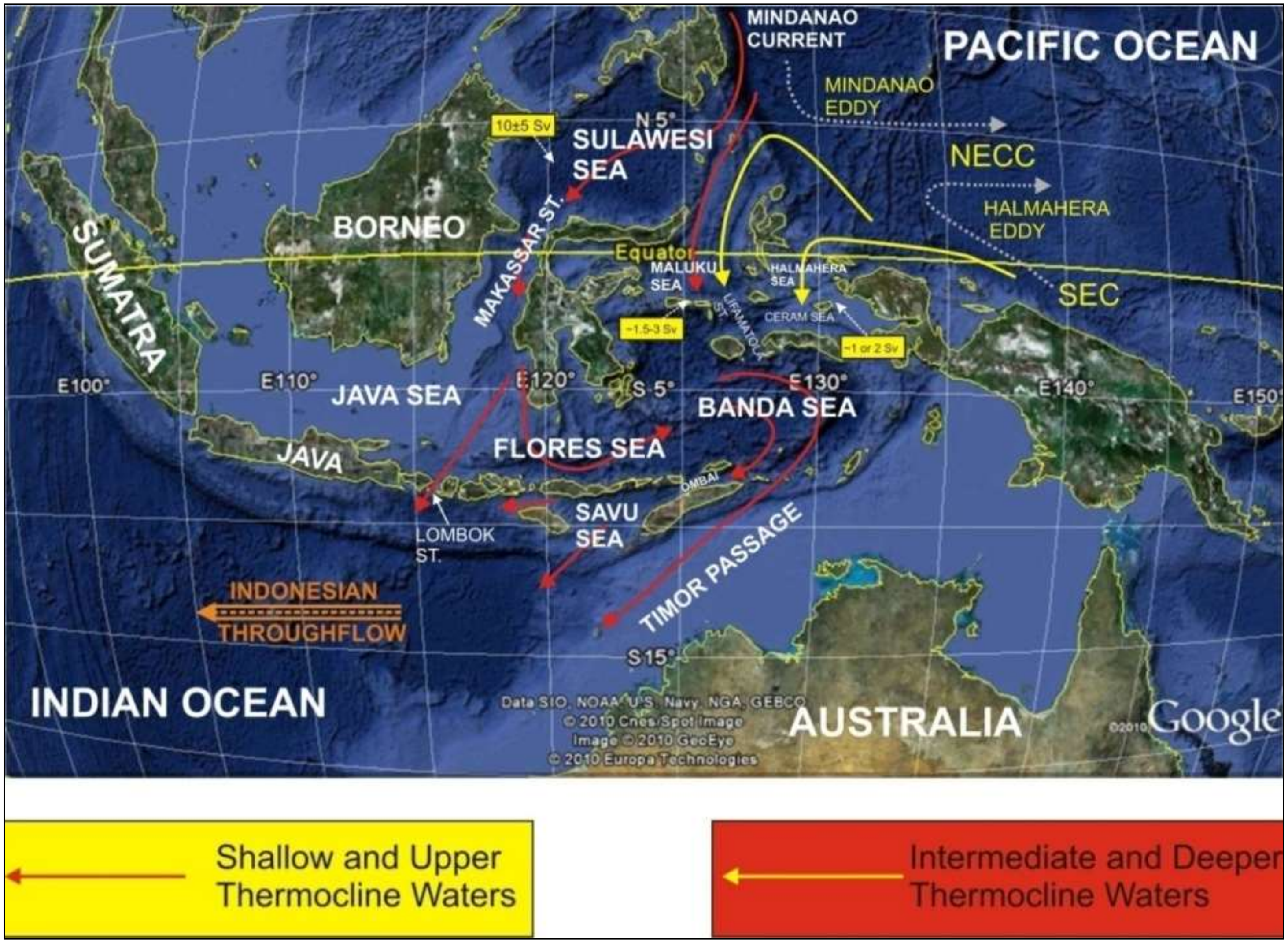

Figure1. The Indonesian Throughflow and routes taken by the water to enter the Indian Ocean from the Pacific Ocean. Values in the boxes are the estimates of the volume of the Throughflow (modified from Sprintall,)

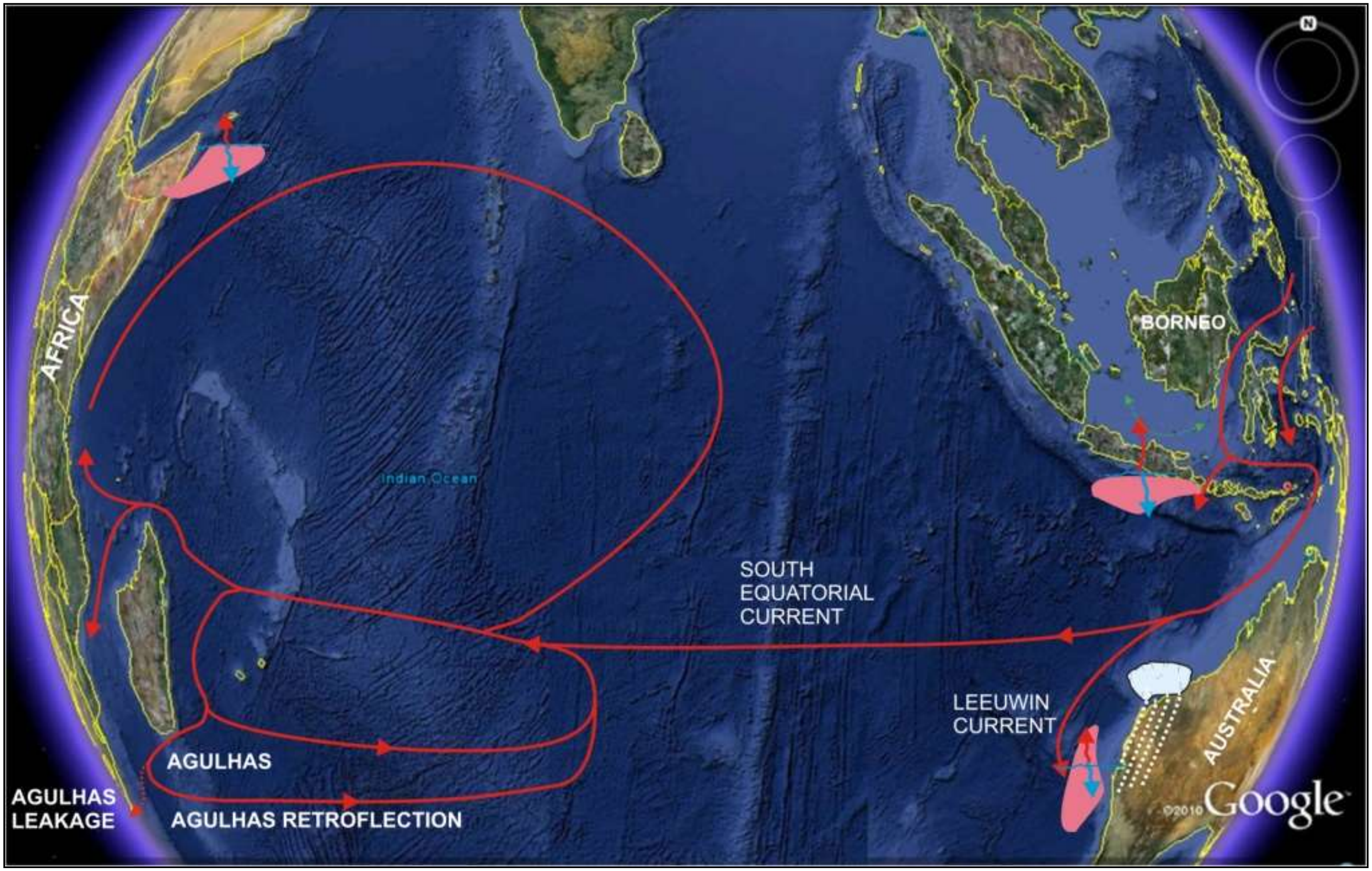

Figure 2. Exit of ITF waters from the Indian Ocean through Agulhas Leakage (modified from from Oppo and Rosenthal, 2010)

Transformation of the Pacific thermocline waters

The Indonesian seas are not just passive channel for the interocean exchange. The waters derived from the North and South Pacific undergo intense mixing in the Banda Sea and the stratification of the inflowing Pacific water is modified before its export into the Indian Ocean (Gordon et al) by tidal and wind-induced mixing and by sea-air fluxes (Ffield and Gordon, 1992, 1996). In the Banda Sea, where the two routes of thermocline waters converge, the transformation of the incoming Pacific water leads to a unique water mass that has a constant salinity below 20^0C (Koch-Larrouy et al., 2007). The intense mixing required for the transformation of the Pacific waters is a result of activities of the internal tides in the ITF region (Schiller, 2004; Hatayama, 2004; Robertson and Ffield, 2005; Ffield and Gordon, 1996; Ray et al., 2005). The archived data and advection-diffusion model infer a relatively large vertical diffusivity coefficient for the Indonesian thermocline (1-2 cm^2s^{-1}: Ffield and Gordon, 1992, Hautala et al., 1996) and thus the predicted high rates of tidal dissipation suggest that the tidal action is a source of enhanced mixing (Ffield and Gordon, 1996). However a few other sets of measurements and numerical experiment have suggested that mixing is highly variable in the Indonesian seas, which is enhanced at sills and continental shelves (up to 60 cm^2s^{-1}) (Hatayama, 2004), while lowered down in the sub-basin interiors ($0.09cm^2s^{-1}$) (Alford et al., 1999; Ffield and Robertson, 2005; Robertson and Ffield, 2005). The amount of energy transferred from barotropic tides to baroclinic tides over the Indonesian semi-enclosed seas is 0.11 TW as given by the Carre`re and Lyard (2003) model, which represents 10% of the energy transfer in the global ocean (1.1 TW) for a surface of 0.5% of the entire ocean (Koch-Larrouy et al., 2007).

Dissipation of tidal energy occurs as tidal currents flow over the shelves, induced turbulent mixing and as tidal waves reflect from sloping topography, perturbing isopycnal surfaces and generating internal waves (internal tides) with large amplitudes and shear that can eventually break and mix (Sandstrom and Oakey, 1995) thereby increasing the potential energy of interior of the seas (Ffield and Gordon, 1996).

Estimates of the ITF Mass and Heat transport

The complex topography and variable currents in the Indonesian archipelago region make it difficult to estimate the water mass exchange between the Pacific and Indian Oceans through the ITF (Chong et al., 2000). Model studies have shown the throughflow not only affects the global thermohaline circulation and heat budget (Gordon, 1986) but also the current system and precipitation around Australasia and global weather patterns and SST (Godfrey, 1996). The extent of these changes depends on the magnitude and variability of the throughflow. The ITF actually consists of several filaments of flow that occupy different depth levels and weave their way through the complex island geometry comprised of broad shallow shelves and deep basins (Sprintall et al., 2009).

In recent years a number of monitoring programs have measured aspects of the ITF from its Pacific source, through the internal seas, to the exit passages. The programs range from individual yearlong mooring deployments, a three-year shallow pressure gauge array (SPGA) in the exit passages, to decade long XBT transects within the Indonesian region. These programs suffer from the lack of temporal coherence, i.e. the data cover different time periods and depths in the different passages of the complex pathways toward the Indian Ocean, leading to ambiguity of the mean and variable nature of the ITF, and the transformation of the thermohaline and transport profiles within the interior seas. For this reason an international co-operative effort was planned to deploy multi-year moorings for direct Throughflow velocity, salinity and temperature measurements simultaneously in Makassar Strait, Lifamatola Passage, Lombok Strait, Ombai Strait and Timor Passage. The program called INSTANT (International Nusantara Stratification And Transport) involved 5 nations: Australia, France, Indonesia, Netherlands and USA.

The INSTANT program was established to directly measure the depth dependent ITF from the intake of Pacific water at Makassar Strait and Lifamatola Strait, to the Nusa Tenggara exit channels into the Indian Ocean (Sprintall et al., 2004; Gordon et al., 2008; Sprintall et al., 2009; Van Aken et al., 2009).

The past estimates of the mean ITF mass transport, based on direct and indirect measurement methods, are wide ranging values from near zero to 30 Sv (Sprintall et al., 2009; Godfrey, 1996). Various workers have given the estimates based on their observations viz. *Wyrtki (1961) 1.7 Sv, Godfrey and Golding (1981) 10 Sv, Piola and Gordon (1984) 14 Sv, Fine (1985) 5.1 Sv, Fu (1986) 6.6 Sv*, etc. The magnitude and variability of the ITF are still sources of major uncertainty in measurements by modeling and observation (Sprintall et al., 2004) and are dominant sources of error in the basin wide heat and freshwater budgets for the Pacific and Indian Oceans (Wiffels et al., 2001).

To date the best estimate of the total ITF transport has been calculated to be around 10-14 Sv but this value cannot be treated as very precise because of the different sampling years of the different direct measurement programs (Sprintall et al., 2009). To determine the accurate values of the heat and freshwater transports of the ITF, multiyear simultaneous measurements of the full depth velocity structure in all the major passages are essential.

To obtain a complete ITF transport estimate, an array of 11 moorings was deployed as part of the INSTANT program (Sprintall et al., 2004) simultaneously over a period of ~3 years in the Makassar and Lifamatola passages where the major inflow occurs and in the three major outflow passages of Lombok, Ombai and Timor.

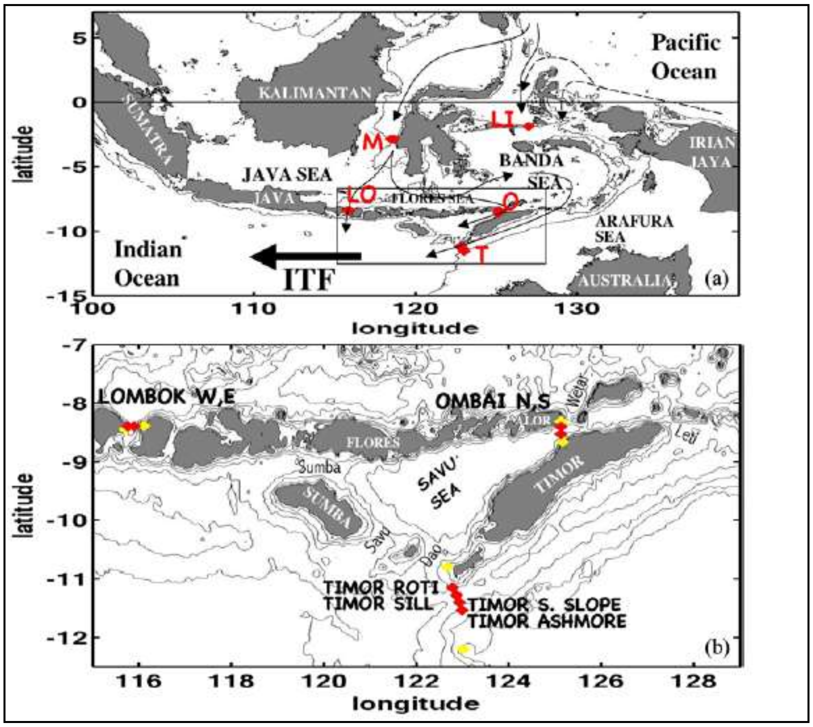

Figure-2 (a) The location of INSTANT moorings deployed in Makassar Strait (M), Lifamatola Strait (LI), Lombok Strait (LO), Ombai Strait (O), and Timor Passage (T) are shown as red diamonds. (b) The boxed inset shows the location of the INSTANT moorings (red diamonds) and shallow pressure gauges (yellow diamonds) deployed in the exit passages along Nusa Tenggara, showing the 200, 500, 1000 (also in Figure 2 a), 2000, and 4000 m isobaths. (Sprintall et al., 2009)

The existing transport estimate of the strength of the warm Makassar Strait branch based on the INSTANT Moorings measurements is calculated to be 11.6 Sv, which is 27% more than (Gordon et al., 2008) Arlindo Experiment measurements (Gordon et al., 1999) of 9.3 Sv. The main transport in the Lifamatola Passage, responsible for the cold part of the ITF and the ventilation of the Banda Sea, amounts to 2.4 to 2.5 Sv, almost 60% higher (van Aken et al., 2009) than the previous estimation of 1.5 Sv (van Aken et al., 1988). The ITF volume from the three outflow passages has been estimated to be: 7.5 Sv through the Timor Passage, 4.9 Sv through the Ombai Strait and 1.8 Sv through the Lombok Strait (Sprintall et al., 2009).

The ITF has a significant control over the Pacific and Indian Oceans heat budget. The temperature and ocean current time series obtained for the ITF region for any duration can be utilized to calculate the heat transport by the Throughflow and consequently influences the Southern Indian Ocean heat flux (Pandey and Pandey, 2006). The ITF heat derived from the Pacific Ocean is ultimately lost to the atmosphere in the Southern Indian Ocean (Vranes, 2002; Gordon and Ffield, 2002). The ITF modifies the heat and freshwater budgets and air-sea fluxes of the Pacific and Indian oceans and thus it may find a significant role in controlling the El Nino Southern Oscillation (ENSO) and Asian monsoon (Webster et al., 1998; Lee et al., 2002; Hirst and Godfrey, 1993; Godfrey, 1996; Gordon et al., 2003). The heat flux of ITF is lower during El Nino while it is higher during La Nina (Meyers, 1996).

The Makassar Strait contribution to the heat flux of the ITF has been estimated to be 0.66-1.15 PW (Petawatts, 1 PW= 10^{15} W) from the previous modeling studies (Schneider and Barnett, 1997; Schiller et al., 1998; Gordon and McClean, 1999). Vranes et al. (2002) determined a mean heat transport of 0.43 PW from the Makassar Strait. The high SST in the tropical Pacific (Kraus and Levitus, 1986) and Indonesian region (Sprintall and Liu, 2005), the Ekman pumping is believed to play a substantial role in the ITF heat transport. This fact is strengthened by the estimates made by Fieux et al. (1994) of Ekman transports of 1.4 Sv towards the Indian Ocean between Australia and Bali, and 5.3 Sv between Bali and Timor, and 1.8 Sv towards the Indian Ocean along a transect between Java and Australia by Potemra et al. (1997). The Ekman heat transport is ~0.5 PW (Vranes at al., 2002), however in response to the stronger but sporadic winds of the NW monsoon, an enhanced Ekman heat transport of ~1 PW occurs associated with the increased northward transport of ~10-15 Sv (Sprintall and Liu, 2005).

During the NW monsoon (November to March), the Ekman flow caused due to the southeastward winds causes the warm waters to accumulate in the Banda Sea, which reduces the ITF transport. The SE monsoon (July to September) has more intense northwestward winds and the resulting local Ekman transport enhances the ITF (Sprintall and Liu, 2005).

ITF transport profile

As part of the US–Indonesian Arlindo program, a number of moorings were placed in the Indonesian seas to measure the features of the ITF (e.g. velocity, temperature, amount etc.). The Arlindo Makassar Strait mooring measurements suggest a complex vertical profile of transport, with implications for interocean thermohaline fluxes and mass budget of the western Pacific warm pool water: the most persistent and strongest ITF occurs within the thermocline and not within the warm surface layer (Gordon and Susanto, 1999; Gordon *et al*., 1999a).

Most of the numerical models used to study the effects of ITF on the Indian Ocean (e.g. Hughes et al., 1992; Hirst and Godfrey, 1993; Godfrey, 1996; Murtugudde et al., 1998; Wajsowicz, 2001; Lee et al., 2002) focus on the effects of the opening and closing of the Indonesian seaways, and overlook the effects of secondary characteristics of the ITF as the vertical profiles of the ITF temperature, salinity and transport, on the Indian Ocean (Song and Gordon, 2004). Wajsowicz (2001) model, using two wind stress climatologies, obtained different profiles of the ITF transport, temperature and salinity and different total transport of ITF in upper 300 m, thus making the impact of variation of the vertical profile of the ITF transport to the Indian Ocean quite significant (Song and Gordon, 2004). The Makassar Strait mooring measurements suggest that the ITF transport is highest within the thermocline rather than at the sea surface (Gordon et al., 1999, 2003). Thus it is important for climate models to simulate correctly the vertical structure of the ITF in discussing its effects on the climate system (Gordon et al., 2003).

The Lamont Ocean Atmosphere-Mixed-Layer (AML) model by Song and Gordon (2004) shows that the ITF transport profile is important in regulating the Indian Ocean stratification and surface heat fluxes.

Effect of seasonal reversal of the winds on the ITF Mass and Heat Transport

The ITF is a low-frequency geostrophic flow combined with a surface wind-driven current (Meyers, 1996; Potemra et al., 1997; Sprintall and Liu, 2005). The easterly trade winds in the western Pacific and the reversing monsoonal winds over the southern Indonesian seas play an important role in the ITF’s variable annual cycle (Wyrtki, 1987). During the northwest monsoon (November to March), the winds directed towards southeast cause the Ekman flow to force the low salinity, buoyant warm waters from the Java Sea and South China Sea to enter and accumulate in the Makassar Strait and the Banda Sea (Gordon et al., 2003), thereby reducing the

ITF transport. During the monsoon transition months or southeast monsoon (July to September), the winds are to the northwest and more intense and they draw the more saline surface waters of the Banda and Flores seas into the Java Sea, thereby intensifying the ITF flow (Gordon et al., 2003). These strong winds result in a lower sea level along the south coast of Nusa Tenggara island chain causing the enhancement of ITF by this local Ekman response (Sprintall and Liu, 2005).

Effects of ITF on climate

The ITF plays an important role in El Niño Southern Oscillation (ENSO) and Asian monsoon climate phenomenon by modifying the heat and fresh water budgets and air-sea heat fluxes of the Pacific and Indian Ocean. ITF transfers fresh and warm water from Pacific to Indian Ocean, the temperature of which was thought to be 22^0C (Piola and Gordon, 1986) to 24^0C (Toole and Warren, 1993; Robbins and Toole, 1997). However the recent measurements from the Makassar Strait suggest that the temperature of the ITF transported waters is at least 9^0C lower than the earlier estimates (Vranes et al, 2002).

The variability of the ITF is largely controlled by the fluctuations in the intensity, geographic extent and position of WPWP. The El Niño-Southern Oscillation (ENSO) events cause a reduction in the Throughflow because of lowering of the western Pacific sea level (Kuhnt et al, 2004) and disruption of the WPWP. As a result extremely cold SSTs and a shallow thermocline are observed along the Indian Ocean coasts of Java, Timor and Sumatra (Meyers, 1996). The La Niña events cause intensification in the Throughflow, as the trade winds resume their original path, but with an increased intensity. The coupled ocean models of Schneider (1998), Wajsowicz and Schneider (2001) indicate that during the periods of intensified throughflow, the centre of WPWP moves westward. Thus, changes in IT intensity would not only drive changes in global atmospheric circulation and affect mid-latitude wind systems, but would also influence interannual climate anomalies, such as the ENSO and southeast Asian monsoon systems (Nichols, 1984; Webster, 1998; Kuhnt et al., 2004). Throughflow related SST anomalies in the tropical Indian Ocean are additionally related to wind and precipitation anomalies that may have implications on the longterm variability of the Indian and Australasian monsoons and lead to severe floods in eastern Africa and droughts in Indonesia (Wajsowicz, 2002; Sprintall et al., 2003; Kuhnt et al., 2004).

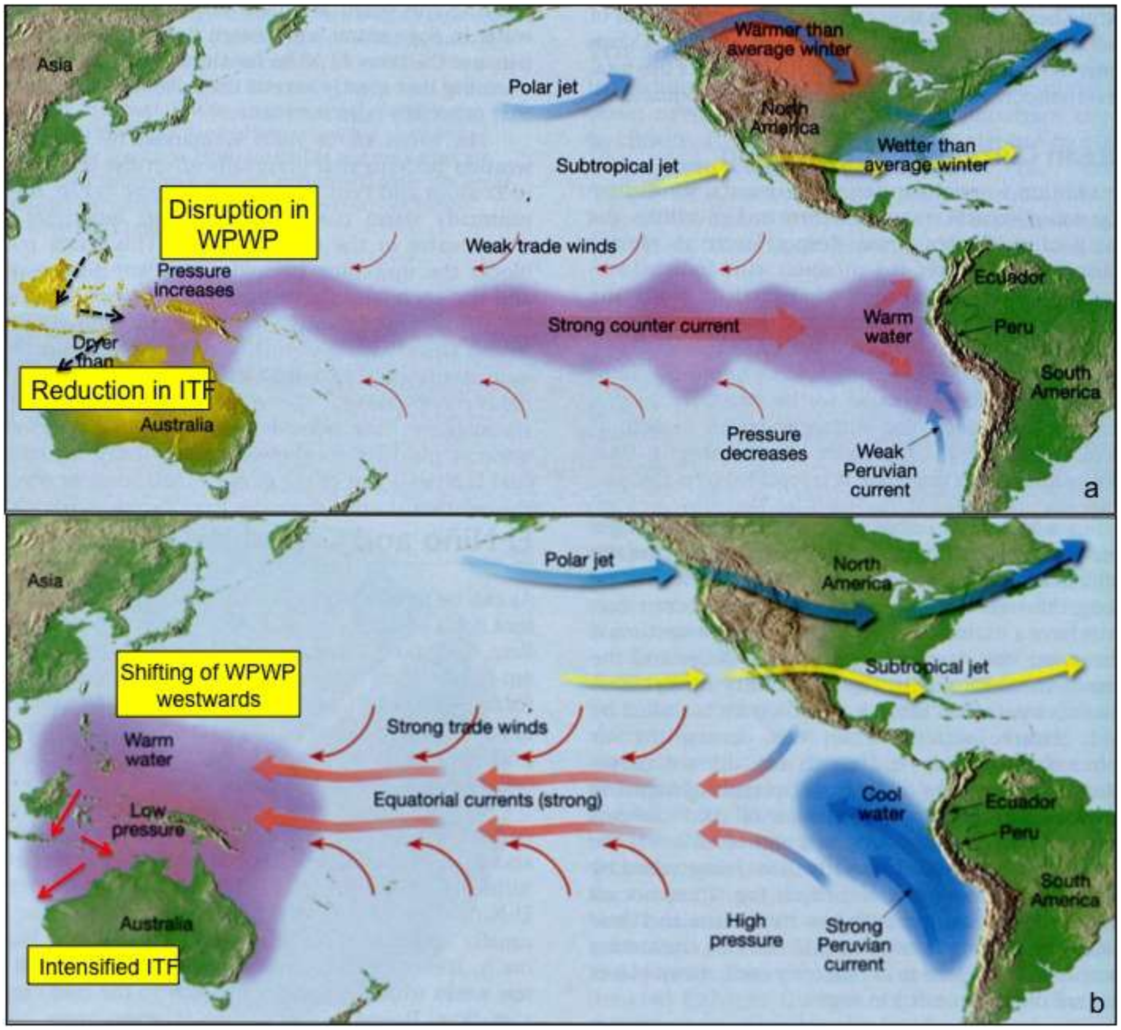

Figure 3- (a) Reduction in the intensity of ITF during El Niño event. The reversal of trade winds causes lowering of sea level in the western Pacific and disruption in WPWP, thereby reducing the throughflow. (b) The La Niña event resumes the normal direction of flow of trade winds with an increased intensity, causing the WPWP to shift westwards. As a result, the ITF also gets intensified.

Neogene evolution of Indonesian Throughflow

The opening and closing of the ocean gateways have always been associated with changes in the global thermohaline circulation (Kennett et al., 1985; Bice et al., 2000); the Indonesian gateway being one of the three critical zonal tropical passages, which strongly influenced global ocean circulation in the late Mesozoic, Paleogene and Neogene (Kuhnt et al., 2004). The other two passages, Panama and Tethys Gateways, are now closed but the Indonesian Gateway is still open for surface and intermediate water circulation, which makes the tectonic and oceanographic history of the Indonesian Archipelago and SE Asia-Australia collision zone of considerable importance for understanding of Neogene regional and global climate change (Kuhnt et al., 2004). The study of major tectonic changes in this region is important for understanding the effect of opening and closing of the Indonesian Gateway in Cenozoic climate evolution, WPWP variability and El Nino.

Various workers have assigned different ages for the restriction of the Indonesian seaway, which could be divided into four major time windows constituting the Neogene *viz.* Miocene (Nishimura, 1992; Ali et al., 1994; Hall, 1996, 2002- Early Miocene; Kennett et al., 1985- Middle Miocene), Pliocene (Srinivasan and Sinha, 1998; Cane and Molnar, 2001- Early Pliocene), Pleistocene and Holocene.