

South China Sea throughflow impact on the Indonesian throughflow

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[1] In 2008–2009 the Makassar throughflow profile changed dramatically: the characteristic thermocline velocity maximum increased from 0.7 to 0.9 m/sec and shifted from 140 m to 70 m, amounting to a 47% increase in the transport of warmer water between 50 and 150 m during the boreal summer. HYCOM output indicates that ENSO induced change of the South China Sea (SCS) throughflow into the Indonesian seas is the likely cause. Increased SCS throughflow during El Niño with a commensurate increase in the southward flow of buoyant surface water through the Sulu Sea into the northern Makassar Strait, inhibits tropical Pacific surface water injection into Makassar Strait; during La Niña SCS throughflow is near zero allowing tropical Pacific inflow. The resulting warmer ITF reaches into the Indian Ocean, potentially affecting regional sea surface temperature and climate. **Citation:** Gordon, A. L., B. A. Huber, E. J. Metzger, R. D. Susanto, H. E. Hurlburt, and T. R. Adi (2012), South China Sea throughflow impact on the Indonesian throughflow, *Geophys. Res. Lett.*, 39, L11602, doi:10.1029/2012GL052021.

1. Introduction

[2] The archipelago between Asia and Australia, forming the only oceanic tropical interocean connection, offers a maze through which Pacific water spreads towards the Indian Ocean, in what is referred to as the Indonesian throughflow, ITF (Figure 1) [Gordon, 2005]. The ITF influences the large-scale ocean heat and freshwater inventories [Godfrey, 1996; Wajsowicz and Schneider, 2001; Murtugudde et al., 1998; Vranes et al., 2002] and sea surface temperature pattern linked to ENSO and the Asian monsoon [Webster et al., 1998; Wajsowicz, 2002]. About 80%, of the ITF ~ 15 Sv (Sv = 10^6 m³/sec) transport is carried by the western-most deep channel, Makassar Strait [Gordon et al., 2010].

[3] The Makassar Strait throughflow was measured at two sites at 2°52'S: 118°27'E and 118°37'E) within the 45 km wide Labani Channel, during the Arlindo program from late

1996 to mid-1998, when a strong El Niño suppressed the ITF [Gordon et al., 1999; Susanto and Gordon, 2005]. The two sites were again monitored during the INSTANT program from January 2004 through November 2006 [Gordon et al., 2008]. The western mooring was then maintained during the MITF (Makassar ITF) program from December 2006 through July 2011.

[4] The Makassar Strait throughflow time series (Figure 2) reveals that the maximum along-channel flow lies well below the sea surface, within the thermocline [Gordon et al., 2010]. While seasonal and interannual Makassar throughflow fluctuations are common, a particularly dramatic shift was recorded in 2008 and 2009, as the thermocline maximum throughflow strengthen and shoaled (Figure 2). We describe the 2008/09 profile and propose, with the support of HYCOM [Chassignet et al., 2003], a likely cause.

2. Makassar Throughflow Time Series

2.1. Observational Data

[5] The INSTANT/MITF time series for the 40–300 m layer (Figure 2) is derived from the mooring deployed on the western side of the Labani Channel. The INSTANT mooring was deployed in January 2004, recovered/redeployed in July 2005 and recovered in late November 2006, was replaced by the MITF mooring. The INSTANT 75KHz ADCP at 300 m, recorded ensembles of 40 pings at 30-minute intervals in 16 m bins.

[6] At the conclusion of the INSTANT mooring in 2006, a new mooring was deployed at the site utilizing the 75KHz ADCP instrument deployed at 500 m, recording hourly in 20 m bins. Treatment of the ADCP data from the INSTANT and MITF moorings is the same. Individual ensembles were interpolated to a uniform pressure grid based on the instrument's pressure data, then interpolated to a uniform hourly time base. As with all ADCP data, near surface data returns are contaminated by side lobe reflections from the surface. We have excluded the uppermost 40 m of data to avoid surface contamination effects. We estimate the error to be ± 0.02 m/s.

2.2. HYCOM Output

[7] The numerical output used in this study is from a global version of HYCOM, a community ocean model (<http://www.hycom.org>) that utilizes generalized vertical coordinates. The vertical coordinates are isopycnals, best used in the stratified deep ocean; levels of equal pressure (nearly fixed depths), more appropriate for mixed layer and unstratified ocean; or σ -levels (terrain-following), often the best choice in shallow water. HYCOM combines all three approaches by choosing the optimal distribution at every time step.

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Figure 1. Schematic of the South China Sea throughflow (dashed red arrows) and the Indonesian throughflow (solid red arrows) circulations. Topographic sill depths are given in black italics. The X indicates Makassar Strait mooring site.

[8] The global version of HYCOM has horizontal equatorial resolution of $1/12.5^\circ \cos(\text{lat}) \times 1/12.5^\circ$ (latitude \times longitude) or slightly finer than 9 km within the South China and Indonesian seas. It employs 32 hybrid vertical coordinate surfaces with potential density referenced to 2000 m and includes the effects of thermobaricity [Chassignet *et al.*, 2003]. The layer structure is chosen to have sufficient resolution in the mixed layer with increasingly thicker isopycnal layers with depth. Within the region of Sulu Sea flow into the Sulawesi Sea and continuing into Makassar Strait, the depth range of the top four layers ranges from 85 to 100 m (Figure 3). HYCOM for this version uses the K-Profile Parameterization for the mixed layer.

[9] The representation of the coastlines and bottom topography is critical in this region. The Naval Research Laboratory 2' Digital Bathymetric Data Base 2 was interpolated to the model grid and one pass of a 9-pt smoother was applied. Significant hand editing was performed with special emphasis on the sill depths of the key passages within the Indonesian Seas.

[10] The model was initialized using temperature and salinity from the Generalized Digital Environmental Model Version 3.0 climatology and was spun-up for ten model

years using a monthly climatology based on the 1978–2002 1.125° European Centre for Medium-Range Weather Forecasts 40-year reanalysis (ERA40). After spin-up, the model used the Fleet Numerical Meteorology and Oceanography Center 3-hourly 0.5° Navy Operational Global Atmospheric Prediction System (NOGAPS) forcing spanning the time frame January 2003–December 2010. For the wind forcing, the long-term (annual) mean from NOGAPS was replaced by the ERA40 mean for consistency on the large scale. Wind speed (but not direction) was corrected using the QuikSCAT scatterometer data.

[11] No oceanic data are assimilated into this version of HYCOM, except sea surface salinity (SSS) is relaxed to the Polar Science Center Hydrographic Climatology, as required to prevent long-term SSS drift due to inadequate precipitation minus evaporation forcing. In addition, monthly varying discharge from nearly 1000 rivers is included as an effective surface precipitation flux.

3. Makassar Throughflow Profile

[12] The Makassar Strait depth profile exhibits thermocline intensification, indicating limited participation of tropical

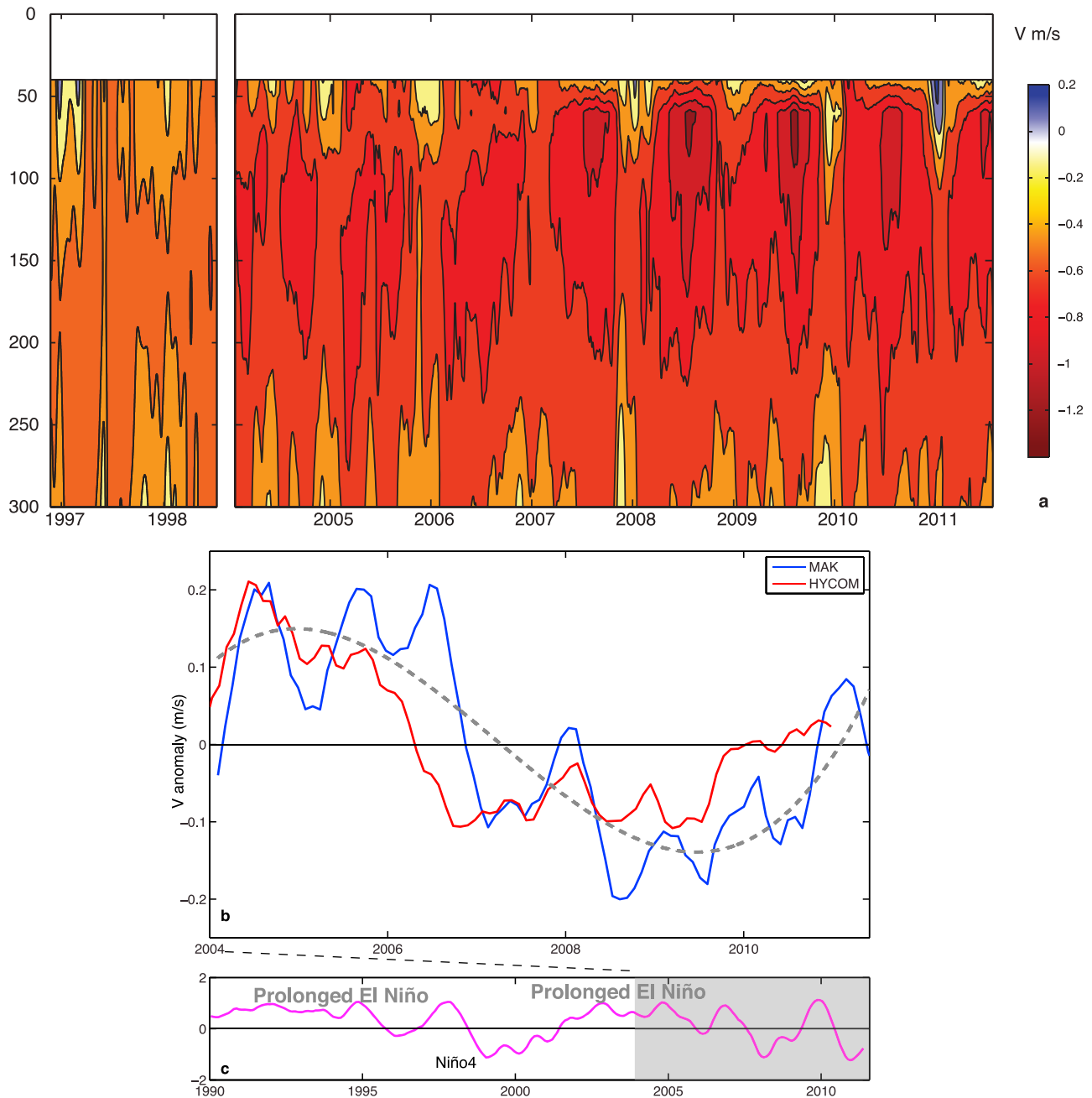


Figure 2. (a) Time series of along-channel flow (m/sec) within Labani Channel of Makassar Strait derived from observations from Arlindo (1996–98); INSTANT (2004–07); and Makassar ITF (2007–2011) programs at the mooring location (Figure 1). Negative values denote southward flow. The throughflow is weakest in boreal winter, strongest in boreal summer. During 2007 the velocity maximum shoaled, with increasing maximum speed, reaching a peak in maximum speed in 2008/2009. (b) The monthly mean anomaly of along-channel velocity at 60 m from the 2004–2011 mean. Blue: Makassar ADCP moored time series; red: HYCOM output. The seasonal signal has been removed, and the data smoothed with a 7-month running mean. The dashed curve is a 3rd order polynomial fit to the Makassar time series. (c) The apparent regime change in 2007, roughly coincides with a shift from prolonged El Niño to a period of more frequent El Niño/La Niña transitions.

Pacific surface water, resulting in cooler transport-weighted temperature than would a surface intensified profile. The restriction of the surface water component of the ITF is likely a consequence of the injection of low salinity, buoyant surface water from the SCS into the Makassar Strait, which blocks entry of Mindanao Current surface water

into Makassar Strait, diverting it into the North Equatorial Counter Current [Gordon *et al.*, 2003; Gordon, 2005].

[13] The Makassar southward thermocline velocity maximum (Figure 2) tends towards greater speeds as the velocity maximum layer shallows. A distinct seasonal cycle is evident, reaching a maximum during the southeast monsoon

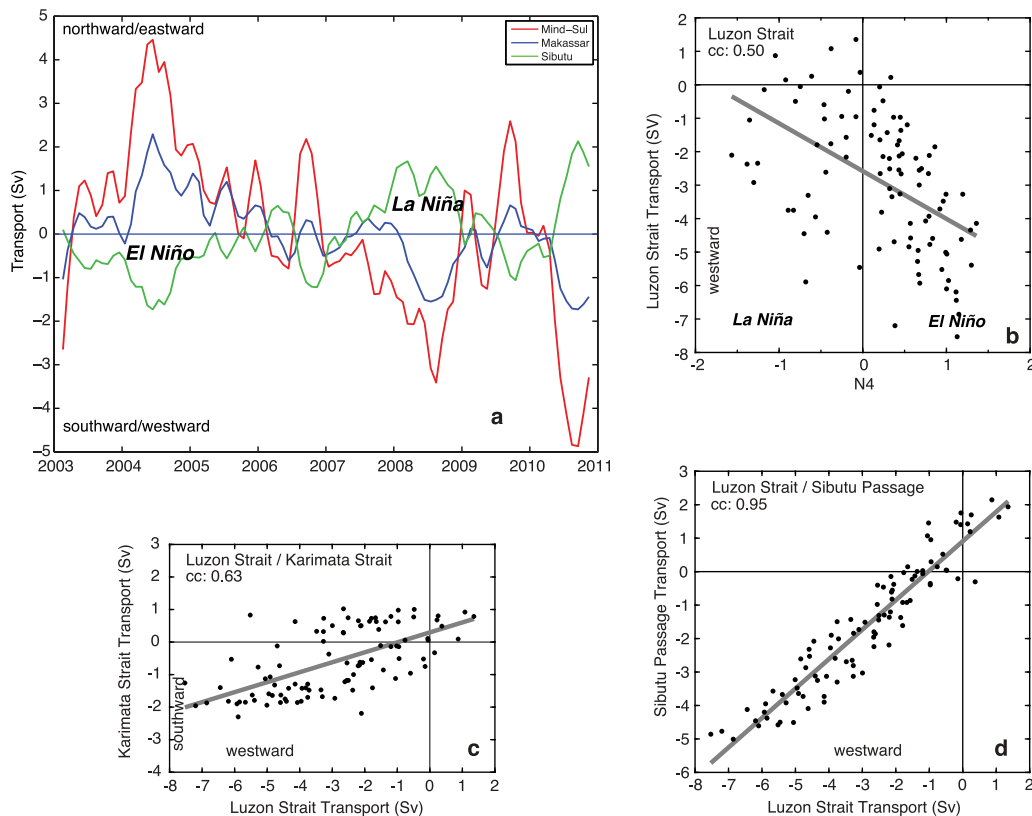


Figure 3. (a) HYCOM monthly transport anomaly relative to 2003–2010 for layers 1–4, upper ~85–100 m of Makassar Strait, Sibutu Passage, and the Mindanao–Sulawesi Sea (see Figure 1 for section positions). The seasonal cycle was removed and smoothed with a 1-2-1 filter. During El Niño southward transport of South China Sea surface water within the Sibutu Passage increases; decreasing during La Niña. The Makassar Strait southward surface layer transport is reduced during El Niño, as is the westward surface layer transport between Mindanao and Sulawesi; increasing during La Niña. (b) HYCOM full depth Luzon Strait transport scales to nino4 (N4). The westward throughflow within Luzon Strait feeding the South China Sea throughflow into the Indonesian seas, responds to ENSO: larger westward throughflow during El Niño. (c) HYCOM full depth Karimata Strait southward transport does not display a relationship to nino4. (d) HYCOM full depth Sibutu Passage southward transport is significantly correlated to the Luzon Strait throughflow.

(boreal summer), with minimum speeds in the northwest monsoon (boreal winter). Beginning in 2006, reaching a peak in 2008 and 2009, the southward speed increases and shoals significantly, from mid-thermocline depths of ~120–150 m to upper thermocline depths of 70–100 m. The average southward speed in 2008–09 in the depth interval from 50 to 150 m was 0.10 m/sec greater than in the INSTANT 2004–2006 period, an increase of 19%; the increase in the boreal summer was more dramatic: 0.25 m/sec, 47% increase relative to the 2004–2006 boreal summers.

[14] The Makassar Strait average temperature profile of the 1958–2007 Simple Ocean Data Assimilation (SODA) re-analysis period [Carton and Giese, 2008; Tillinger and Gordon, 2010] identifies the thermocline layer in the 50–200 m interval with a mean vertical temperature gradient of $0.31^{\circ}\text{C}/10\text{ m}$. The mean temperature at 140 m is 20°C with a standard deviation of 1.5°C ; at 70 m the mean temperature is 27°C at one standard deviation of 2.5°C ; the 18°C isotherm depth within Makassar Strait varies with ENSO: 167 m in the 1997 El Niño; 205 m in the 1999 La Niña [Tillinger and Gordon, 2010]. The strengthening

and shoaling of the Makassar throughflow velocity maximum observed in 2008 and 2009 represents a significant increase of warmer water incorporation into the ITF.

[15] We hypothesize that the change in the Makassar throughflow profile is a consequence of the greater westward transport within Luzon Strait and associated SCS throughflow of buoyant surface water via Sibutu Passage (Figure 1) into the western Sulawesi Sea, during El Niño relative to La Niña.

[16] The HYCOM output indicates that the Luzon Strait throughflow varies with ENSO: stronger and cooler during El Niño [Qu *et al.* 2004; Wang *et al.*, 2006; Hurlburt *et al.*, 2011]. The impact of ENSO events on Luzon Strait transport depends not only on the strength of the events, but also on specific structural characteristics that vary from one event to another [Hurlburt *et al.*, 2011; Shinoda *et al.*, 2011, Figure 4]. The Luzon Strait throughflow estimates range from near zero to over 6 Sv, averaging 4.5 Sv [Fang *et al.*, 2009, Table 2] with the HYCOM value of 2.9 Sv (Table 1). The Luzon Strait input, feeds the SCS throughflow, warming and freshening within the SCS by an

Table 1. Transports (Sv) Through the South China Sea/Interior Philippine Seas Inflow/Outflow Straits Averaged Over the Period January 2003–December 2010 Strait Locations Are Shown in Figure 1

| Strait | Transport (Sv) | ENSO Sensitive |
|-----------------------|----------------|----------------|
| <i>Net Inflow</i> | | |
| Luzon Strait | 2.87 | Yes |
| Surigao Strait | 0.97 | No |
| San Bernardino Strait | 0.13 | No |
| Total | 3.97 | |
| <i>Net Outflow</i> | | |
| Taiwan Strait | −1.63 | No |
| Sibutu Passage | −1.62 | Yes |
| Karimata Strait | −0.58 | No |
| Malacca Strait | −0.14 | No |
| Total | −3.97 | |

estimated 23 to 49 W/m² and 0.11 Sv (from P–E and river discharge), respectively [Fang *et al.*, 2009; Qu *et al.*, 2009] making it an important freshwater ‘conveyor’ within the Pacific western marginal seas [Qu *et al.*, 2006]. The SCS water is exported in approximately equal magnitude through Taiwan Strait and into the Indonesian seas (Table 1). The latter mainly along two paths: through Mindoro Strait into the Sulu Sea, with an additional inflow of 1 Sv from the Pacific primarily through Surigao Strait into the Bohol Sea of the Philippines (the Surigao Strait inflow estimated from observations is 0.3 Sv [Gordon *et al.* 2011]), feeding southward flow in 235 m deep Sibutu Passage into the western Sulawesi Sea [Hurlburt *et al.*, 2011; Metzger *et al.*, 2010]; with the 2nd smaller export through the 45–50 m deep Karimata Strait [Hurlburt *et al.*, 2011; Fang *et al.*, 2010] into the Java Sea (Table 1).

[17] HYCOM (Figure 3 and Table 1) shows that the Sibutu Passage throughflow matches the ENSO dependence of the Luzon Strait throughflow, while the Karimata transport, displaying a weak relationship to ENSO (Figure 3), is mostly seasonal [Fang *et al.*, 2010]. The Mindanao Current surface layer inflow into the Sulawesi Sea (Figure 3), exhibits ENSO sensitivity, but it is out-of-phase with the Sibutu Passage throughflow. Makassar Strait surface layer throughflow exhibits an ENSO relationship similar to Mindanao Current inflow. The Mindanao and Makassar surface layer transport fluctuations exceed Sibutu fluctuations (Figure 3a), suggesting that the Sibutu transport has a blocking effect due to the buoyance of ‘pooled’ Sulu Sea surface water injected into the western Sulawesi Sea during El Niño (localized, ENSO enhanced, net precipitation is not sufficient to account for the freshwater anomaly). The pooling effect is revealed in the HYCOM output, with the surface layer salinity of the western Sulawesi Sea being lower in the 2004 El Niño period than in the 2008 La Niña period (consistent with the 2004 and 2008 circulation patterns in Figure 3 of Hurlburt *et al.* [2011]). We find that insertion of a Sulu Sea 0–100 m surface slab within the western Sulawesi Sea water column induces a strong eastward surface layer pressure gradient in the Sulawesi Sea.

[18] From late 2007 into 2009 the HYCOM throughflow in upper 140 m of Mindoro Strait, linking the Sulu Sea to the SCS, is northward, in agreement with an observational time series [Hurlburt *et al.*, 2011]. This provides confidence in

the validity of the HYCOM northward transport during the same period of the upper 100 m Sibutu Passage (Figure 3).

[19] The polynomial fit to the smoothed north-south monthly velocity anomaly in Labani Channel at 60 m (Figure 2) from the 2004–2011 Makassar ADCP moored time series and from HYCOM output shows that the regime change in 2007, roughly coincides with a shift from prolonged El Niño to a period of more frequent El Niño/La Niña transitions. The HYCOM output in Makassar Strait agrees remarkably well with the observations.

4. Conclusions

[20] We investigate the relationship of the SCS surface layer throughflow and the Makassar Strait throughflow with the 1/12° global HYCOM experiment 18.2 over the period 2003–2010, comparing the relationship to the observed Makassar Strait throughflow from January 2004 through July 2011. We conclude (Figure 4) that the SCS southward throughflow of low salinity surface layer waters during prolonged El Niño periods builds a pool of buoyant surface water in western Sulawesi Sea that inhibits the surface layer contribution from the western tropical Pacific water via the Mindanao Current, into Makassar Strait, the primary pathway for the ITF. The HYCOM results indicate that the Sibutu Passage transport does not fully compensate the reduced Mindanao input (Figure 3), leading to reduced surface layer contribution to the Makassar throughflow during El Niño. During La Niña, the Sibutu Passage throughflow is near zero or northward, reducing the buoyant pool in the western Sulawesi Sea, permitting greater contribution of warm tropical Pacific water into the upper thermocline and surface strata of the Makassar throughflow.

[21] In this manner the ENSO sensitive SCS throughflow, builds a ‘freshwater plug’ in the western Sulawesi Sea (Figure 4) during prolonged El Niño periods, results in a deeper, cooler velocity maximum within Makassar Strait; whereas during La Niña the ‘freshwater plug’ dissipates, leading to an increase and shallowing into the warmer, upper thermocline layer, of the Makassar Strait throughflow velocity maximum. As the Makassar throughflow amounts to 80% of the total ITF, the SCS effect is a major contributor to the overall variability of ITF vertical structure.

[22] Increased transport within the warmer upper layer of the ITF is expected to have an impact on the heat budget of the Indian Ocean [Potemra *et al.*, 2003; Vranes *et al.*, 2002], as well as on the residence time of the waters of the tropical Indian Ocean [Gordon, 2005] and thermocline and SST patterns [Song *et al.*, 2004; Song and Gordon, 2004]. The ITF plume in 2 to 4 years spreads into the eastern and central tropical Indian Ocean [Song *et al.*, 2004]. The vertical profile of the ITF transport is important in regulating the stratification and surface heat fluxes of the Indian Ocean [Song and Gordon, 2004]. A thermocline-intensified ITF, relative to a surface-intensified ITF, cools the surface layer of the Indian Ocean while warming the Indian Ocean below the thermocline. The observed shoaling of the ITF velocity maximum induced by the SCS throughflow effect as described here, during La Niña, would shift the ITF stream within the Indian Ocean closer to that of surface-intensified ITF condition, warming the eastern tropical Indian Ocean SST with potential influence on the southeast Asian monsoon. Proper

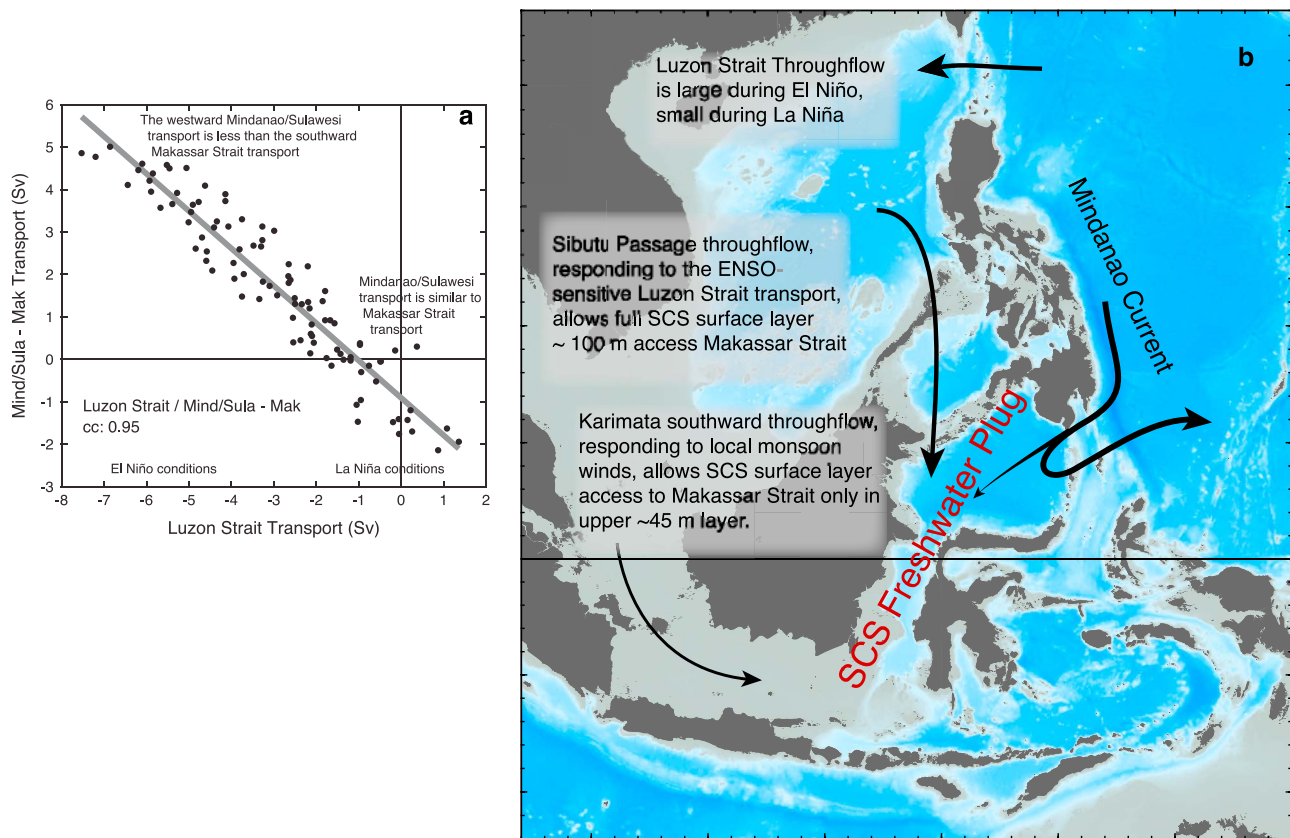


Figure 4. (a) Difference between transport through the Mindanao-Sulawesi section and that through Makassar Strait, plotted against Luzon Strait transport. Transports are from HYCOM results, are full depth, with westward and southward transports negative. Makassar Strait southward transport is larger than the Mindanao transport during El Niño when the westward Luzon Strait transport is large (upper left quadrant of plot). During La Niña, the Luzon Strait transport is small and the Mindanao transport is similar to the Makassar Strait transport (lower right quadrant). The Sibutu Passage throughflow responds to the Luzon Strait transport (Figure 3d), providing a direct connection to the Makassar Strait throughflow. (b) The transfer of SCS buoyant surface layer via Sibutu Passage into the western Sulawesi Sea inhibits Mindanao surface layer injection into the Makassar Strait during prolonged El Niño periods. The SCS surface water injected into the southern Makassar Strait through 45 m deep Karimata Strait is not sensitive to the ENSO phase.

model simulation of vertical profile of ITF is central to producing a valid representation of the climate system [Vranes *et al.*, 2002].

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