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Covariation of the Indonesian Throughflow and South China Sea Throughflow Associated with the 1976/77 Regime Shift

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ABSTRACT

Changes in the Indonesian Throughflow (ITF) and the South China Sea throughflow—measured by the Luzon Strait Transport (LST)—associated with the 1976/77 regime shift are analyzed using the Island Rule theory and the Simple Ocean Data Assimilation dataset. Results show that LST increased but ITF transport decreased after 1975. Such changes were induced by variations in wind stress associated with the regime shift. The strengthening of the easterly wind anomaly east of the Luzon Strait played an important role in the increase of LST after 1975, while the westerly wind anomaly in the equatorial Pacific contributed significantly to the decrease in ITF transport after 1975, accounting for 53% of the change.

After 1975, the Kuroshio Current strengthened and the Mindanao Current weakened in response to a decrease in the total transport of the North Equatorial Current. Both the North Equatorial Countercurrent and the South Equatorial Current weakened after 1975, and an anomalous cyclonic circulation in the western equatorial Pacific prevented the tropical Pacific water from entering the Indian Ocean directly.

Key words: Indonesian throughflow, Luzon Strait Transport, regime shift, wind anomaly

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1. Introduction

The region around the Indonesian seas is a unique maritime continent, and the water exchange between marginal seas there is very active (Fig. 1). The Indonesian Throughflow (ITF) is the key element connecting the Pacific and Indian Oceans in the tropics, and therefore a critically important part of the "global conveyor belt" (Gordon, 1986). The Luzon Strait Transport (LST) carries the ENSO signals from the Pacific Ocean into the South China Sea (SCS), and acts as the oceanic bridge that plays an important role in regulating the circulation and heat/freshwater budgets in the SCS (Qu et al., 2004). The Kuroshio path across the Luzon Strait is determined by the transports at three secondary straits, namely, the Taiwan, Kalimantan, and Mindoro Straits, as well as by the strength of the Kuroshio south of the Luzon Strait (Yu et al., 2007). Water masses from the Pacific Ocean enter the Indian Ocean not only through the Indonesia seas, but also through the SCS (Metzger and Hurlburt, 1996; Lebedev and Yaremchu, 2000; Fang et al., 2005; Qu et al., 2005). The latter pathway is in fact a branch of the ITF and hence is named the SCS throughflow

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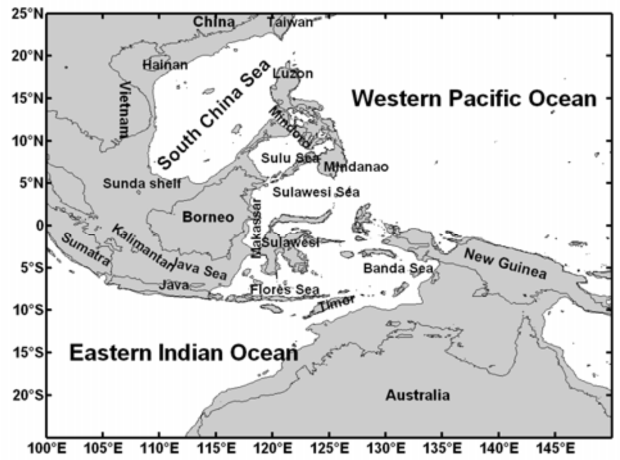

Fig. 1. Maps of the South China Sea and Indonesian seas. Region with water depth shallower than 100 m is stippled.

(Wang et al., 2006; Yu et al., 2007). Tozuka et al. (2007, 2009) pointed out that the SCS throughflow plays an important role in climate variability of the Indo-Pacific Ocean by changing the upper ocean thermal structure in the Makassar Strait.

ITF transport can be estimated using the Island Rule. Accordingly, winds in the South Pacific play an important role (Godfrey, 1989). However, there are many dynamical factors which can affect ITF transport. Wajsowicz (1993) suggested that friction induced by the Australian coast may reduce ITF transport. ITF transport decreases during El Niño events (e.g. Fieus and Molcard, 1996; Gordon and Fine, 1996; Meyers, 1996; Ffield et al., 2000), which is associated with the decreasing sea surface pressure difference between the Pacific and Indian Oceans (Wyrtki, 1961; Meyers, 1996). Li et al. (2004) pointed out that the Indian Ocean dipole can also influence the ITF. Therefore, the interannual variability of ITF transport is mainly associated with the tropical circulation adjustment (Li et al., 2005), while on the seasonal time scale, it is the response to the monsoon (Wang et al., 2002). The interdecadal variability of ITF transport is, on the other hand, controlled by the zonal wind stress off the southern tip of the Australian and in the equatorial Pacific (Meng et al., 2004).

Wind stress change in the equatorial Pacific during El Niño events can induce the intensification of the North Equatorial Current (NEC) (Wyrtki, 1974; Qiu and Lukas, 1996), and a northward shift of the NEC bifurcation point (Kim et al., 2004). As a result, the partition of the volume transport between the Kuroshio Current (KC) and the Mindanao Current (MC) varies. During El Niño events, the MC increases and the KC decreases (Masumoto and Yamagata, 1991; Tozuka et al., 2002); such changes are unfavorable for Pacific water to enter the Indian Ocean, but favorable for it to enter the SCS through the Luzon Strait (Yaremchuk and Qu, 2004; Qu et al., 2004). This behavior seems to be a "teapot-like" effect occurring near a gap of the western boundary (Sheremet, 2001). Wind stress in the equatorial Pacific is the main element responsible for the out-of-phase relationship between ITF transport and LST on the interannual time scale (Liu et al., 2006).

Recently, Wainwright et al. (2008) pointed out that the net westward volume transport between Australia and Indonesia showed a decrease of about 2.5 Sv after 1975, indicating that the regime shift of 1976/77 had an impact on the transport of the ITF. This is consistent with the result of Liu et al. (2007), that weakening of the easterly trade winds across the Pacific plays an important role in the decrease of ITF transport. The main goal in this paper is to explore the covariation of ITF transport and LST associated with the regime shift of 1976/77 using results from oceanic data assimilation products and the Island Rule theory.

2. Methodology

The authors used the latest Simple Ocean Data Assimilation (SODA) dataset, SODA_1.4.2, an assimilation product provided by Carton and Giese (2008), which spans the 44-year period from 1958 to 2001, forced by the European Center for Medium Range Weather Forecasts' atmospheric reanalysis (ERA-40). The model's computational domain extends to the North and South Poles, with a horizontal resolution of $0.4° \times 0.25°$ (lat×lon). Vertical resolution varies from 10 m in the upper levels to 500 m near the bottom, with a total of 40 vertical levels and a maximum depth of 5624 m. Model output variables are remapped onto a uniform $0.5° \times 0.5°$ grid in terms of monthly mean. The analysis here is mainly based on ocean circulation estimated by the SODA_1.4.2 dataset and wind stress from ERA-40.

Based on the steady and frictionless Sverdrup theory, ITF transport T can be obtained from the integration of wind stress projection along a closed path ABCD (Godfrey, 1989). That is,

$$T = \oint_{\mathrm{ABCD}} \tau^{(l)} dl / [\rho_0 (f_{\mathrm{D}} - f_{\mathrm{A}})] \tag{1}$$

where $\tau^{(l)}$ is wind stress projection along the path ABCD (Fig. 2); the segments AB and CD are at 42.25°S and 0.75°S respectively; and f_{A} and f_{D} are the corresponding Coriolis parameters at segments AB and CD respectively (Fig. 2). The mean density of sea

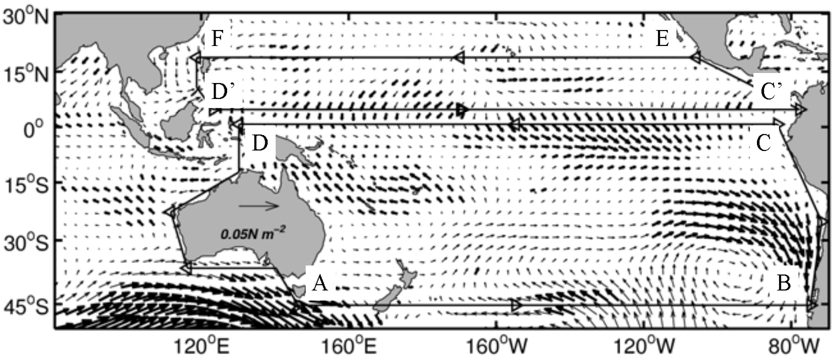

Fig. 2. Wind difference (1976–2001 minus 1958–1975) and the two integral paths for the Island Rule calculations. ABCD denotes the closed integral path along Australia to obtain ITF transport, and D'C'EF denotes the closed integral path along the Philippines to obtain LST. Latitudes of AB, CD, D'C' and EF are 45.25°S, 0.75°N, 4.75°N and 18.75°N, respectively. Units: N m^{-2}. The bold vector indicates a significant difference with a confidence level of 95%.

water is $\rho_0 = 1035\,\mathrm{kg\,m^{-3}}$.

However, Wajsowicz (1993) noted that the throughflow may experience friction against the Australian coast east of Timor, causing a difference in depth-integrated steric height (DISH) along the Australian coast from north to south of the Timor Passage. It seems reasonable to assume that this friction is linear, i.e. the DISH difference is proportional to the throughflow magnitude T. When this term in KT is added to the integral of long-path DISH gradient around ABCD (of which the sum must be zero), then Eq. (1) is altered to Eq. (2):

$$T = \oint_{\mathrm{ABCD}} \tau^{(l)} dl / [\rho_0 (f_{\mathrm{D}} - f_{\mathrm{A}} + K)] \tag{2}$$

Wajsowicz had discussed the frictional effect within the Indonesian seas, and it can reduce the mean throughflow by the order of 2 Sv, which can be accommodated by K being small compared to $(f_{\mathrm{D}} - f_{\mathrm{A}})$.

A similar approach can be applied to the Luzon Strait throughflow using an integral path along the D'C'EF; the segments D'C' and EF are at 4.75°N and 18.75°N respectively. Numerical studies have shown that the annual mean LST is controlled by the along-path wind stress integral and to a lesser degree by friction due to some narrow passages associated with the model geometry (Metzger and Hurlburt, 1996). In the case of LST, the difference in DISH from north to south along the west coast of the Philippines depends not only on the wind integral along it, but also on the friction related to the shallow and narrows passages. The work of Qu et al. (2000) shows that in this case the constant K must be about three to five times the value of $(f_{\mathrm{F}} - f_{\mathrm{D}})$. f_{F} is the coriolis parameter at segment EF.

The t-test is used to calculate confidence levels of the mean value difference between the pre- and post-regime shift:

$$t = \frac{\overline{x^c} - \overline{x^a}}{s\left(\frac{1}{n} + \frac{1}{m}\right)^{\frac{1}{2}}}$$

where $\overline{x^c}$ and $\overline{x^a}$ are the mean values in normal and abnormal years; n and m are the sample numbers; and s^2 is the unbiased estimator of the variance for difference values (Huang, 2000).

3. Analyses

3.1 *Variability of volume transports*

Figure 3 shows the 13-point-running means of LST and ITF transport (integrated from surface to bottom) estimated from SODA and the modified Island Rule theory, respectively. The zero-lag correlation coefficient between LST estimated by SODA $(17.25° - 21.75°\mathrm{N}, 120.25°\mathrm{E})$ and the Island Rule theory after the 13-point-running mean is 0.23 ($>$ 90% confidence level). The variability of ITF transport estimated from SODA $(8.25° - 25.25°\mathrm{S}, 113.25°\mathrm{E})$ is also consistent with that from the Island Rule theory; the zero-lag correlation coefficient is 0.50 ($>$ 95% confidence level). The differences between the SODA and Island Rule theory results are perhaps due to the ocean circulation adjustment and bottom friction.

The out-of-phase relationship between LST and ITF transport is also evident, and the zero-lag correlation coefficient between the two methods of transport inferred from SODA and the modified Island Rule theory is −0.31 and −0.39, respectively. The out-of-phase relationship is evident on the interannual time scale, and this relationship reflects the wind anomaly forcing

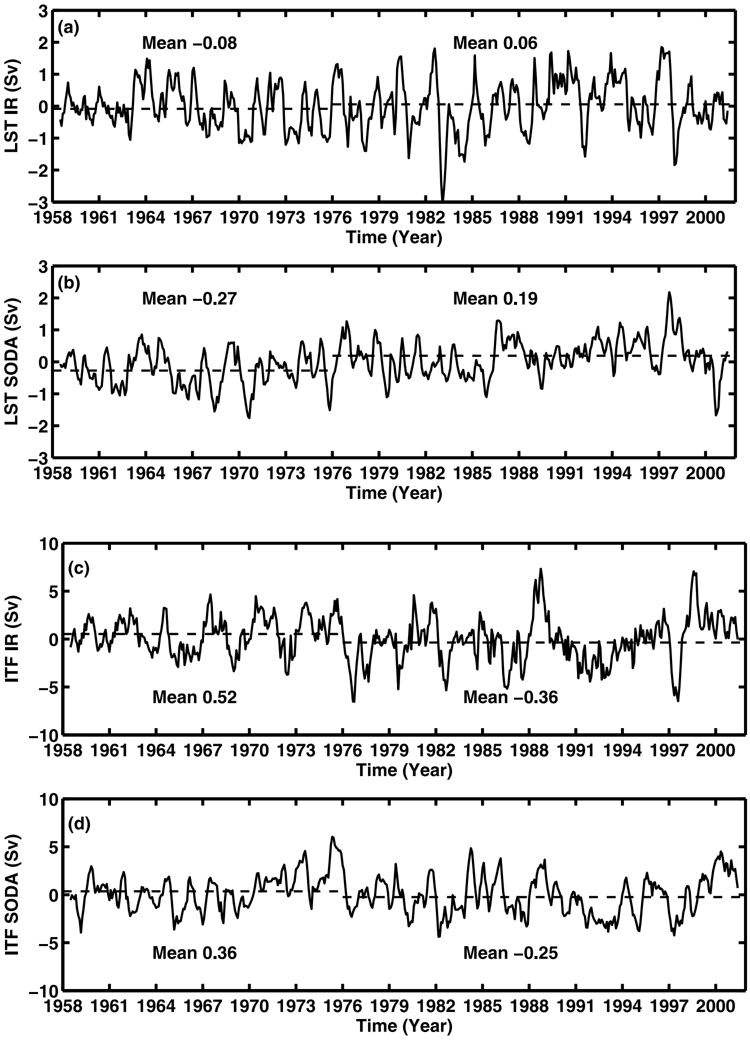

Fig. 3. The 13-point-running mean (solid) and the mean (dashed line) of the LST (a, b) and ITF transport (c, d) anomalies estimated by the Island Rule theory (a, c) and SODA dataset (b, d). The zero-lag correlation coefficients are 0.23 (a and b) and 0.50 (c and d), respectively. Mean seasonal cycles are removed.

in the equatorial Pacific (Liu et al., 2006). The undershooting/overshooting phenomena occurring at the Luzon Strait and the Sulawesi-Mindanao passage provides an interesting tool to study the relationship between LST and ITF transport from an ocean dynamics perspective.

3.2 *Changes associated with the regime shift of* 1976/77

The averaged LST and ITF transport anomalies before and after December 1975 are also shown in Fig. 3 (seasonal cycles are removed). The averaged LST anomaly estimated from the modified Island Rule theory is −0.08 Sv in the pre-1975 period and 0.06 Sv in the post-1975 period (Fig. 3a), while if estimated using SODA it is −0.27 Sv in the pre-1975 period and 0.19 Sv in the post-1975 period (Fig. 3b). For ITF, averaged transport in the pre-1975 period are 0.52 Sv and 0.36 Sv, shifting to −0.36 Sv and −0.25 Sv after 1975 based on the Island Rule theory and SODA dataset, respectively (Figs. 3c and 3d). This implies that the LST anomaly is strengthened after the 1976/77 regime shift, but the ITF transport anomaly is weakened. The LST anomaly increased by about 0.14–0.46 Sv after the regime shift, while the ITF transport anomaly decreased by about 0.61–0.88 Sv, as shown in Fig. 3.

Figures 4a–d show the probability distribution functions (PDFs) of the LST and ITF transport anomalies as estimated by the Island Rule theory and SODA. Distributions of LST show the mean after 1975

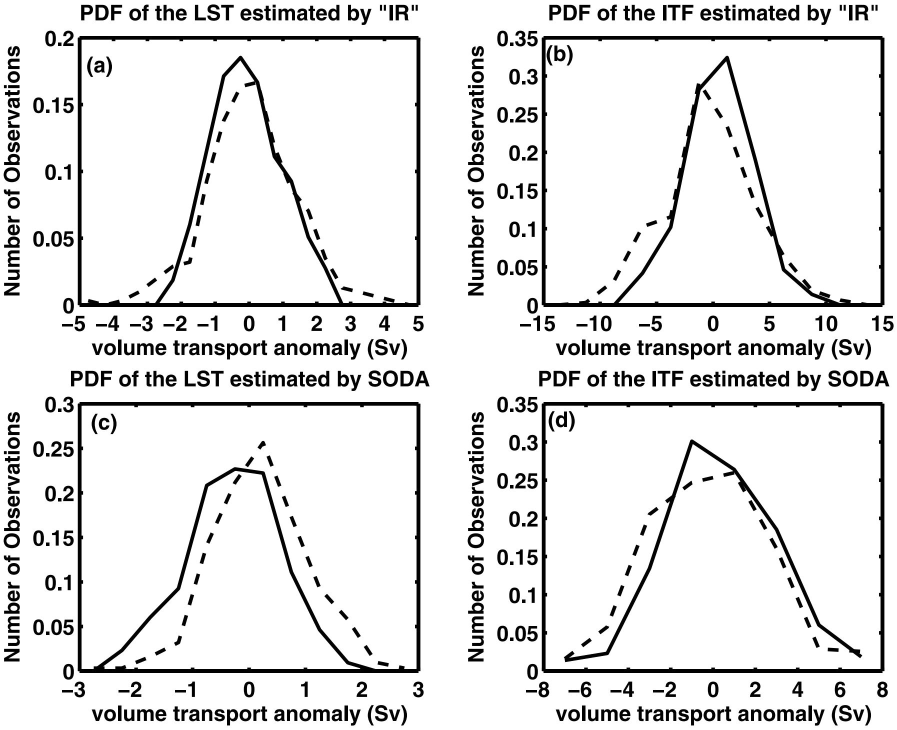

Fig. 4. Probability Distribution Functions of the LST (right) and ITF transport (left) anomalies estimated by the Island Rule theory (top) and SODA (bottom), respectively. Solid lines are for those before 1975, and the dashed lines after 1975. Seasonal cycles are removed.

has shifted to the right, indicating an increase in net westward transport through the Luzon Strait (Figs. 4a and 4c). Distributions of ITF transport show that the mean after 1975 shifted to the left, indicating a decrease in net westward transport between Australia and Indonesia (Figs. 4b and 4d). This decrease in ITF transport is consistent with weakened equatorial easterly winds (Vecchi et al., 2006; Alory et al., 2007).

3.3 *Different roles played by wind stress*

In general, LST had a tendency to increase from 1958–2001, while ITF transport had a tendency to decrease in the same period. The increase of LST and decrease of ITF transport after 1975 can perhaps be associated with the weakening of trade winds in the equatorial Pacific. In this section, different roles played by wind stress associated with the regime shift of 1976/77 are discussed according to the results of the modified Island Rule theory.

Averaged transport anomalies before and after December 1975 and the differences (post–1975 minus pre–1975) given by the wind stress integral along each segment of the paths D'C'EF and ABCD (D'C'EF consists of segments D'C', C'E, EF and FD'; and ABCD of AB, BC, CD and DA) are shown in Tables 1 and 2, respectively. The t-test is used to compare the difference between the averaged anomalies to ascertain their statistical significance.

The integrals along segments C'E, FD' and EF have increased by 0.03 Sv, 0.04 Sv, and 0.81 Sv, respectively, and the integral along segment D'C' decreased by 0.17 Sv after the climate shift. Total integrals increased by 0.71 Sv post-1975 (Table 1). The results show that the wind stress anomaly along segment EF plays an important role in the increase of LST after

Table 1. Averaged transport anomalies before and after December 1975 and their differences (1976–2001 minus 1958–1975) given by the wind stress integral along path D'C'EF respectively using the Island Rule. Units: Sv. The brackets denote confidence levels, and the seasonal cycles are both removed.

	1958–1975	1976–2001	Latter minus former
C'E(east)	−0.02	0.01	0.03 (80%)
FD'(west)	−0.02	0.02	0.04
D'C'(south)	0.10	−0.07	−0.17
EF(north)	−0.48	0.33	0.81 (90%)
D'C'EF(total)	−0.42	0.29	0.71 (80%)

Table 2. As in Table 1, but for path ABCD.

	1958–1975	1976–2001	Latter minus former
BC(east)	0.05	−0.03	−0.08 (99%)
DA(west)	−0.21	0.14	0.35 (99%)
AB(south)	0.30	−0.21	−0.51 (95%)
CD(north)	0.39	−0.27	−0.66 (99%)
ABCD(total)	0.52	−0.36	−0.88 (99%)

1975, which can contribute up to 92% of the total increase, while the easterly wind anomaly in the equatorial Pacific along segment D'C' obstructed the increase of LST after 1975. The contributions along the two cross-Pacific segments dominated (Godfrey, 1989), and the westward Rossby propagation in the western Pacific is very important to LST variability (Hu et al., 2001).

As for the integrals along ABCD, these decreased by 0.08 Sv, 0.51 Sv and 0.66 Sv after December 1975 along the segments BC, AB and CD, respectively, while it increased by 0.35 Sv along the segment DA after December 1975. In other words, the easterly wind anomaly in the southern subtropical Pacific, the northerly wind anomaly off the east coast of the Pacific Ocean, and the westerly wind anomaly in the equatorial Pacific were all favorable for the reduction of ITF transport after 1975; their contributions could reach 41%, 6% and 53%, respectively. In contrast, the wind anomaly along segment DA would enhance ITF. In general, the westerly wind anomaly in the equatorial Pacific is the main cause for the decrease in ITF transport after 1975.

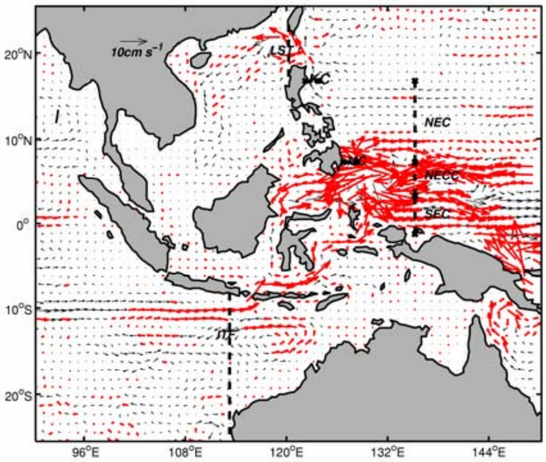

Fig. 5. Ocean circulation difference (1976–2001 minus 1958–1975) averaged in the upper 465 m. Units: cm s^{-1}. The red vector indicates significant difference with a confidence level of 95%. Regions with water depth shallower than 100 m are stippled.

3.4 *Changes of the western boundary currents*

Since changes in wind stress affect ocean circulation via baroclinic Rossby adjustment, the authors analyze ocean circulation associated with the regime shift of 1976/77 next. The mean ocean circulation difference before and after December 1975 in the upper 465 m is shown in Fig. 5, and the averaged volume transport anomalies estimated by the SODA dataset integrated from surface to bottom before and after December 1975 and their difference are given in Table 3.

Pacific water entered the SCS through the Luzon Strait, moving southward along the western boundary of the SCS after 1975; the water exited through the Kalimantan Strait and/or the Mindoro Strait and returned to the Pacific through the Makassar Strait. LST increased by 0.46 Sv, associated with easterly winds east of the Luzon Strait and northerly winds inside the SCS which strengthened after 1975. The eastward ocean current anomaly between Australia and Indonesia implied a decrease in ITF transport, which dropped by about 0.61 Sv after 1975. The results are consistent with that of the Island Rule theory.

Although the NEC (defined by the transport at 7.25°–16.75°N, 129.25°E) weakened by about 3.12 Sv due to the eastward ocean current anomaly south of 10°N, the ocean current around 15°N near the NEC bifurcation showed a westward anomaly after 1975. Corresponding to the decrease in total NEC, the KC at 16.75°N (from the coastline to 2° longitude offshore) showed above-normal levels of transport (0.61 Sv) and the MC at 7.25°N (from the coastline to 2° longitude offshore) showed below-normal levels (decreasing by 4.11 Sv) after 1975. The weakening of the MC was unfavorable for Pacific water to enter the Indian Ocean directly, according to Sheremet (2001). Both the NECC (3.25°–7.25°N, 129.25°E) and the SEC (1.25°S–3.25°N, 129.25°E have both weakened after 1975 by about 9.50 Sv and 5.89 Sv, respectively, and this induced a cyclonic circulation anomaly around this region, causing unfavorable conditions for Pacific water to enter the Indian Ocean (Fig. 5).

4. Discussion and conclusions

Results based on the Island Rule and SODA datasets both show that, after 1975, LST increased while ITF transport decreased. The 1976/77 regime shift affected these transports through changes in surface wind stress. The easterly wind anomaly east of the Luzon Strait played the key role in enhancing LST, and the westerly wind anomaly in the equatorial Pacific was the primary factor responsible for the de-

Table 3. As in Table 1, but using SODA. Positive value denotes eastward/northward transport.

	NEC	NECC	SEC	KC	MC	LST	ITF
1958–1975	−1.84	5.61	−3.48	−0.36	−2.43	0.27	−0.36
1976–2001	1.28	−3.89	2.41	0.25	1.68	−0.19	0.25
Latter minus former	3.12 (19%)	−9.50 (99%)	5.89 (99%)	0.61	4.11 (98%)	−0.46 (99%)	0.16 (98%)

crease in ITF transport after 1975. After 1975 the KC strengthened and the MC weakened, which corresponds to a decrease in total NEC despite a westward ocean current around 15°N near the NEC bifurcation point. Both the NECC and the SEC decreased after 1975, and an anomalous cyclonic circulation around this region was unfavorable for Pacific water to enter the Indian Ocean directly.

The covariation of ITF transport and LST associated with the 1976/77 regime shift was explored using results from SODA and the modified Island Rule theory, however LST estimated by the modified Island Rule theory is not satisfactory as reflected by the low confidence level in the difference between the averaged anomalies before and after December 1975 (Table 1). Previous studies have shown that monsoon forcing also plays an important role in controlling the variation of LST (Wyrtki, 1961; Liu et al., 2000). Monsoonal wind is an important mechanism inducing the seasonal variation of the intrusion by increasing the sea level along the south China coast in winter and decreasing it in summer (Metzger and Hurlburt, 1996; Chao et al., 1996). The sea surface height signals in the northwestern Pacific propagate westward, which can affect the SCS through the Luzon Strait (Hu et al., 2001; Jing et al., 2006). As shown in Fig. 2, the southward anomalies of wind stress before and after 1975 are quite obvious in the SCS. This local forcing could also induce an increase of LST after 1975, but was not reflected by the Island Rule results. Therefore, the estimation established in this study should be taken with caution and more work needs to be done to further understand the variation of LST associated with the 1976/77 climate shift.

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