ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 22, NO. 6, 2005, 946–954

A Note on the South China Sea Shallow Interocean Circulation

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(Received 24 February 2005; revised 4 July 2005)

ABSTRACT

The existing estimates of the volume transport from the Pacific Ocean to the South China Sea are summarized, showing an annual mean westward transport, with the Taiwan Strait outflow subtracted, of 3.5±2.0 Sv (1 Sv=10^6 m^3 s^{-1}). Results of a global ocean circulation model show an annual mean transport of 3.9 Sv from the Pacific to the Indian Ocean through the South China Sea. The boreal winter transport is larger and exhibits a South China Sea branch of the Pacific-to-Indian Ocean throughflow, which originates from the western Philippine Sea toward the Indonesian Seas through the South China Sea, as well as through the Karimata and Mindoro Straits. The southwestward current near the continental slope of the northern South China Sea is shown to be a combination of this branch and the interior circulation gyre. This winter branch can be confirmed by trajectories of satellite-tracked drifters, which clearly show a flow from the Luzón Strait to the Karimata Strait in winter. In summer, the flow in the Karimata Strait is reversed. Numerical model results indicate that the Pacific water can enter the South China Sea and exit toward the Sulu Sea, but no observational evidence is available. The roles of the throughflow branch in the circulation, water properties and air-sea exchange of the South China Sea, and in enhancing and regulating the volume transport and reducing the heat transport of the Indonesian Throughflow, are discussed.

Key words: South China Sea, interocean circulation, branch of the Pacific-to-Indian Ocean throughflow, Karimata Strait

1. Introduction

The South China Sea (SCS) has many channels connecting with the outer oceans/seas (Fig. 1). The widest and deepest channel is the Luzón Strait, which is the main entrance to the SCS from the Western Pacific Ocean, having a sill depth of about 2500 m. On the north, the Taiwan Strait connects with the East China Sea, with a sill depth of about 70 m. In the vicinity of Mindoro Island, there are a number of channels connecting the SCS with the Sulu Sea. The main channel is the Mindoro Strait, which has a sill depth of about 400 m. Another connection between the SCS and Sulu Sea is the straits south of Palawan with the Balabac Strait as a main passage. These straits are shallow and contain numerous coral reefs. On the south, the Karimata, Gaspar and Banka Straits (for short, we will hereafter use the Karimata Strait to represent these three straits) connect the SCS with the Java Sea. These straits have a total width of about 250 km and a sill depth of 40 m. On the southwest, the Starit of Malacca links the SCS with the Indian Ocean via the Andaman Sea. Though through the Starit of Malacca, the SCS water can flow into the Indian Ocean directly without passing through the Indonesian Seas, whereas the eastern Starit of Malacca is narrow and shallow, not allowing for significant transport to pass through. Therefore, the most important connecting channels are the Luzón, Taiwan, Mindoro and Karimata Straits. Since the latter three channels are shallow, the deep interocean circulation can only penetrate the Luzón Strait, while the shallow interocean circulation of the SCS can occur through all the channels.

The importance of the Pacific-to-Indian Ocean Throughflow (PIOT) for the world ocean thermoha-

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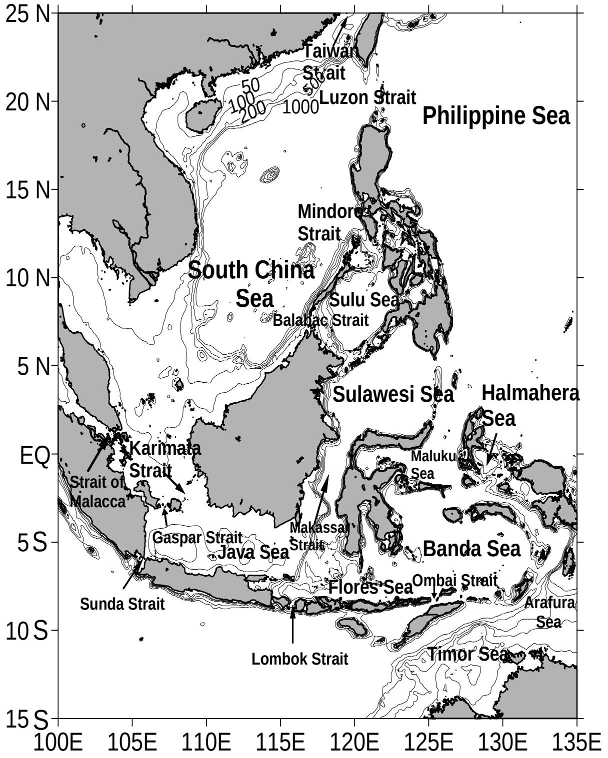

Fig. 1. Map of the South China Sea and Indonesian Seas. The depths of the isobaths are given in meters.

line circulation is now well recognized. However, the contribution of the SCS to the Indonesia Throughflow (ITF) has not been sufficiently investigated. At the times of Dale (1956) and Wyrtki (1961), the currents in the Karimata Strait were well recognized to have a monsoon-following nature, that is, southward in winter and northward in summer (the seasons in this paper refer to the Northern Hemisphere unless otherwise specified). The currents in the other straits were also believed to follow the monsoon winds. Their estimation was mainly based on ship drift records and the knowledge of monsoon winds. Since then, a few current measurements have been carried out in the Luzón and Taiwan Straits, but none in the Mindoro and Karimata Straits. Lebedev and Yalemchuk (2000) first noted the importance of the SCS in the ITF from their model results. Qu et al. (2000) proposed that the Pacific water could flow into the SCS through the Luzón Strait and exit through the Mindoro Strait. Fang et al. (2001) also independently produced similar model results to Lebedev and Yaremchuk (2000). Gordon et al. (2003) found that the less-saline water from the Java Sea, which can be traced back to the SCS, blocked the upper-layer outflow from the Makassar Strait. The observed transport-weighted temperature of the Makassar throughflow was 15°C, in contrast to the previous estimate of 24°C. In this short note we will present some evidence to show a possible branch of the PIOT passing through the SCS as well as its relation to the ITF by summarizing existing studies and our recent numerical model results.

2. The Luzón Strait transport

There has been a great deal of descriptive and quantitative studies focusing on the westward intrusion of the Western Pacific water into the SCS through the Luzón Strait. In the present paper, we will only summarize the quantitative results of the intruding transports. Some studies have provided estimates for

Table 1. Existing estimates of zonal volume transports through the Luzón Strait (in Sv).

Source	Spring	Summer	Fall	Winter	Annual mean	Taiwan Strait transport subtracted	Method
Wyrtki, 1961	0.0	2.75	−0.5	−2.75	−0.1	−0.1 (0.0)	Dynamic calculation (0–175 m)
Huang, 1983	−11.0	4.0	6.0	−31.0	−8.0	−6.5 (1.5)	Dynamic calculation (0–1200 m)
Metzger and Hurlburt, 1996					−4.4	−4.4 (0.0)	Numerical model
Liu et al., 2000	−3.8	−2.7	−6.9	−7.4	−5.2	−3.7 (1.5)	Based on POCM (0–200 m)
Qu, 2000		−0.2		−5.3	−3.1	−1.6 (1.5)	Dynamic calculation (0–400 m)
Chu and Li, 2000		−1.4		−13.7	−6.5	−5.0 (1.5)	P-vector method
Lebedev et al., 2000		−4.5		−6.3	−5.4	−5.4 (0.0)	Numerical model
Metzger et al., 2001					−1.8	−1.1 (0.7)	Numerical model
Fang et al., 2001	−4.1	−1.2	−7.7	−13.3	−6.4	−5.2 (1.2)	Numerical model
Liang et al., 2002					−3.3	−1.8 (1.5)	ADCP measurement (0–300 m)
Mean	−4.7	−0.5	−2.3	−7.5	−4.4	−3.5±2.0	

Note: Positive(negative) values indicate eastward(westward) transport. The values in the parentheses represent the outward transports through the Taiwan Strait used in the present estimation.

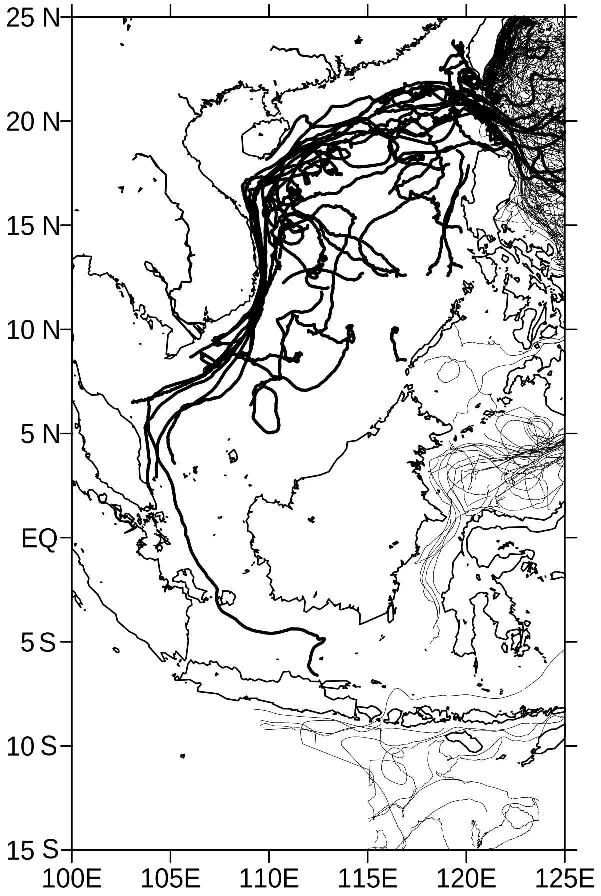

Fig. 2. Trajectories of satellite-tracked drift buoys (from the WOCE dataset). Thick lines show the trajectories of the drifters deployed in or entering the South China Sea; thin lines show those not entering the South China Sea. The trajectories clearly show that a current intrudes into the South China Sea through the Luzón Strait in winter, and forms a throughflow branch toward the Karimata Strait and the Indonesian Seas.

all four seasons, while others have only given estimates for two seasons, or only the annual values. The annual mean transport of existing investigations are calculated and shown in Table 1. From the table we can see that all investigations reveal that the Luzón Strait transport is toward the west, stronger in winter and weaker in summer. Since the deep interocean circulation can occur only through the Luzón Strait, its inflow transport should be balanced by its outflow transport, and thus the net transport given in Table 1 can be attributed to the shallow interocean circulation, though there is not a clear division between the deep and shallow interocean transports in the Luzón Strait.

Since the purpose of the present paper is to evaluate the water volume flux from the SCS toward the Indonesian Seas, which finally enters the Indian Ocean, the volume transport through the Taiwan Strait is subtracted from that through the Luzón Strait. Most previous numerical studies either calculated the Taiwan Strait transport or closed the Taiwan Strait. For these studies, we use the transport values calculated by themselves. All the previous studies based on field measurements of currents, or temperature and salinity, do not provide estimates for the Taiwan Strait transport. In these cases, we specify an outflow of 1.5 Sv for the Taiwan Strait. The values with the Taiwan Strait transport subtracted are also shown in Table 1. We can observe from the table that the transports with the Taiwan Strait transport subtracted are still westward. The mean value of all estimates is 3.5 Sv. The scatter of different investigations is pretty large, having a standard deviation of 2.0 Sv. That is to say, the existing estimates show that the intruding transport is in the range from 1.5 Sv to 5.5 Sv. Since the outflow through the Taiwan Strait has been subtracted, the above estimated imported water will flow out through the southern passages and will eventually enter the Indian Ocean.

3. Sea surface heat flux of the South China Sea

The sea surface heat flux of the SCS has been evaluated by Wang et al. (1997), Yang et al. (1999), and Liu (2002). Wang et al. (1997) used the Comprehensive Ocean and Atmosphere Data Set (COADS) from 1958 to 1987 to calculate the heat flux. The annual mean distribution chart showed that for most parts of the SCS, the net heat flux was toward the ocean, with a spatial average of about 30 W m^{-2}. Yang et al. (1999) used longer COADS data, from 1950 to 1995, and obtained monthly values of the net heat flux averaged for the entire SCS. It was shown that the monthly fluxes are toward the ocean from February through October, and toward the atmosphere merely in November, December and January. The annual mean was also about 30 W m^{-2} and downward. Liu (2002) used the Southampton Oceanographic Centre (SOC) air-sea flux climatology (Josey et al., 1999) and obtained the mean net heat flux of the SCS as 58 W m^{-2}, also toward the ocean. All these estimations show that the heat flux entering into the SCS through the air-sea interface exceeds that going out from the SCS. This heat gain must be balanced by a heat loss due to water exchanges occurring at the lateral open boundaries of the SCS. That is to say, there must be some cooler water imported into the SCS and warmer water exported from the SCS.

Fang et al. (2001, 2003) did calculate the heat transports through the openings of the SCS from their numerical model results. The annual mean total outward heat transport through the Taiwan, Mindoro, Balabac, Karimata and Malacca Straits was more than the inward heat transport through the Luzón Strait by

0.08 PW, which divided by the area of the SCS yielded a downward heat flux through the SCS sea surface of 23 W m^{-2}.

4. Winter branch evidenced by trajectories of satellite-tracked drifters

The SCS branch of the PIOT in winter can be confirmed by the trajectories of the satellite-tracked drifters shown in Fig. 2. The data are from the World Ocean Circulation Experiment Global Data Version 3.0 (WOCE Data Products Committee, 2002). Some drifters deployed in the Pacific Ocean did intrude into the SCS through the Luzón Strait in winter, as reported by Centurioni et al. (2004). Figure 2 has a larger coverage than the study area of Centurioni et al., showing that the drifters continued to move southwestward along the shelf break in the northern SCS and turned toward the south off the middle Vietnam coast. During the drifting, most of the drifters were lost. Only five reached near the east coast of the Malay Peninsula, and one finally entered the Java Sea through the Gaspar Strait. The trajectories clearly indicate a flow from the Philippine Sea east of the Luzón Strait toward the Karimata Strait passing through the SCS.

5. Currents from a refined variable-grid global ocean circulation model

The model reported in Fang et al. (2001, 2003) is based on the GFDL MOM2 model (Pacanowski, 1996). This model has been extended and refined recently. The previous model has two major shortcomings. First, the uppermost two layers have a thickness of 25 m. The MOM2 requires a minimum of two layers at all ocean interior grid points. Thus the shallowest water depth of the model is 50 m, which is significantly deeper than some parts of the straits connecting the different regions. This tends to produce transport values that are too large. The second shortcoming is that the fine-grid portion of the model only covers the sea area north of the equator. Thus the resolution is not enough for the Indonesian Seas, including the Karimata and Gaspar Straits. In the refined model, the grid sizes from the sea surface downwards are chosen to be 4, 6, 10, 15, 23, 32, 48, 69, 88, 132, 216, 332, 468, 611, 747, 862, 946 and 990 meters. So the shallowest model depth can be reduced to 10 m. The horizontal fine grid (1/6° resolution) now is extended to 20°S (Fig. 3) to cover the Indonesian Seas. The coefficients of the horizontal eddy viscosity and diffusivity are taken to be 5×10^3 and 1×10^2 m^2 s^{-1} respectively. Those of the vertical eddy viscosity and diffusivity are taken to be 1×10^{-4} and 2×10^{-5} m^2 s^{-1} respectively.

As a first experiment, we simulate the annually-cyclic circulation fields by means of the robust prognostic approach. The initial temperature and salinity fields are derived through interpolation from the Levitus and Boyer (1994) climatologies for January. The ocean surface boundary conditions for heat and freshwater transfers are specified by nudging the sea surface temperature and salinity toward the Levitus and Boyer

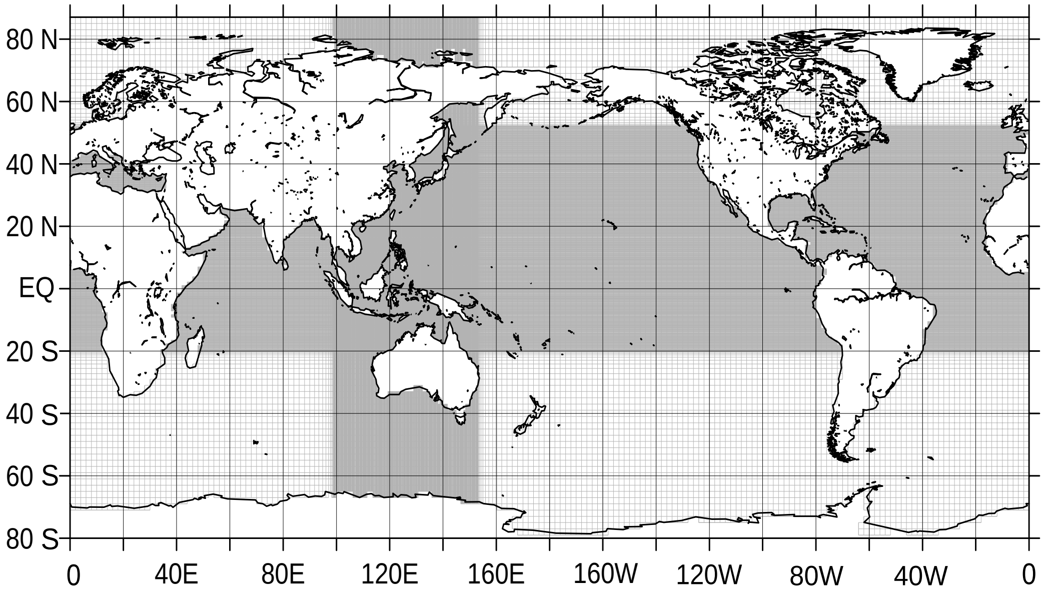

Fig. 3. Model grid. The meridional spacing is 1/6° for the band from 20°S to 50°N and 2° for the rest. The zonal spacing is 1/6° for the band from 99° to 150°E and 2° for the rest.

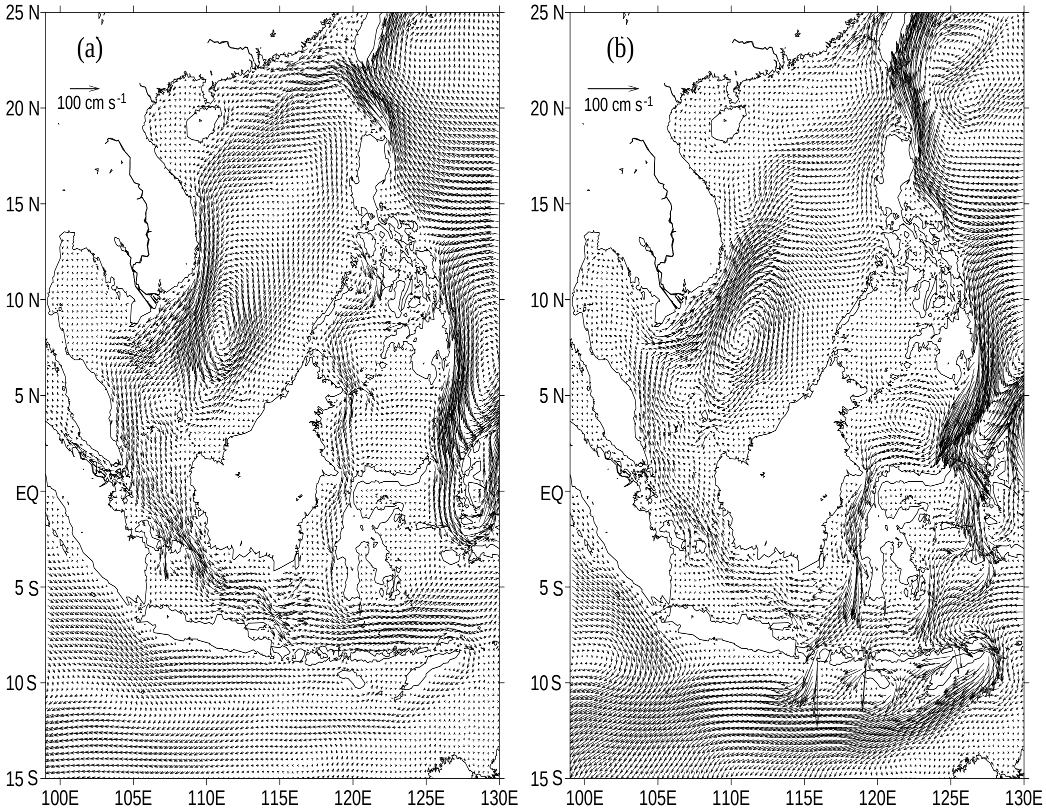

Fig. 4. Model-produced upper-layer (0–58 m) currents in the South China Sea and Indonesian Seas for (a) January and (b) July.

(1994) climatologies, which are interpolated from monthly fields to form fields for each time step. The wind stresses are interpolated from the reduced Hellerman and Rosenstein (1983) monthly fields. Since the drag coefficient adopted by Hellerman and Rosenstein (1983) is believed to have a high bias by about 25% (Stockdale et al., 1993), the original wind stress magnitudes are multiplied by 0.75 before being applied to the simulation.

The model was run for 10 years with annually-cyclic sea surface boundary conditions to reach stationary annually-cyclic circulation fields. The model results of the last year are used in the present analysis. The model-produced upper-layer (0–58 m) current fields for January and July are shown in Fig. 4. The winter current field clearly shows a flow pathway from the Western Pacific to the northern and western SCS and finally to the Karimata Strait and Java Sea (Fig. 4a). In summer, the flow in the Karimata Strait is reversed and weaker (Fig. 4b). This flow originates from the Indonesian Seas and exits through the Taiwan Strait and surface layer of the Luzón Strait. The wintertime southwestward current over the continental slope of the northern SCS was first reported and named the South China Sea Branch of the Kuroshio by Guo et al. (1985). From Figs. 2 and 4a we see that this current can continue to flow along the southeastern coast of Vietnam and eastern coast of Malaysia and can further enter the Indonesian Seas via the Karimata Strait. Figure 4a further shows that a part of the imported water can enter the Sulu Sea through the Mindoro and Balabac Straits. The outward flows through the Mindoro and Balabac Straits will also further enter the Makassar Strait through the Sulu and Sulawesi Seas. The above waters will eventually enter the Indian Ocean. In addition, Fig. 2 shows that some drifters entering the SCS originate directly from the Philippine Sea away from the Luzón Strait rather than from the Kuroshio main stream east of Luzón Island. Therefore, it is more appropriate to call this branch the South China Sea branch of the Pacific-to-Indian Ocean throughflow. Though the drifter trajectories provide evidence for the existence of the branch, measurements of the transports in the Karimata and Mindoro Straits are of essential importance in providing quantitative estimates.

Table 2. Volume and heat transports through the openings of the South China Sea.

Month	Karimata Strait	Malacca Strait	Balabac Strait	Mindoro Strait	Taiwan Strait	Luzon Strait
Volume transport (in Sv)						
Jan.	4.22	0.43	0.73	3.07	−0.66	−7.80
Feb.	3.76	0.41	0.60	2.63	−0.40	−7.00
Mar.	2.96	0.36	0.48	2.09	0.22	−6.12
Apr.	1.74	0.29	0.38	1.52	1.06	−4.99
May	0.40	0.17	0.37	0.97	1.33	−3.24
Jun.	−0.86	0.06	0.40	0.68	1.75	−2.03
Jul.	−1.54	−0.01	0.50	0.77	2.11	−1.83
Aug.	−1.51	0.01	0.56	0.89	1.79	−1.74
Sep.	−0.82	0.06	0.62	1.13	0.70	−1.68
Oct.	0.92	0.17	0.78	1.58	−0.59	−2.87
Nov.	2.59	0.29	0.98	2.65	− 0.98	−5.52
Dec.	3.92	0.40	0.91	3.24	−0.88	−7.60
Mean	1.32	0.22	0.61	1.77	0.45	−4.37
Total	3.92				0.45	−4.37
Heat transport (in PW)						
Jan.	0.473	0.050	0.076	0.282	−0.064	−0.723
Feb.	0.418	0.046	0.061	0.243	−0.038	−0.707
Mar.	0.332	0.041	0.049	0.194	0.021	−0.594
Apr.	0.198	0.033	0.039	0.142	0.107	−0.408
May	0.045	0.020	0.040	0.095	0.137	−0.191
Jun.	−0.101	0.007	0.046	0.074	0.183	0.024
Jul.	−0.183	−0.001	0.058	0.089	0.224	0.017
Aug.	−0.179	0.001	0.065	0.101	0.192	−0.046
Sep.	−0.097	0.007	0.072	0.121	0.075	−0.224
Oct.	0.105	0.020	0.089	0.158	−0.064	−0.623
Nov.	0.299	0.033	0.109	0.255	−0.106	−0.746
Dec.	0.450	0.046	0.098	0.301	−0.092	−0.713
Mean	0.147	0.025	0.067	0.171	0.048	−0.411
Total	0.410				0.048	−0.411

Note: Positive (negative) values indicate outward (inward) transports.

It is worthwhile to point out that the current over the continental slope of the northern SCS and along the eastern coast of Vietnam is not solely from the western Pacific. Rather, it is a combination of the above-mentioned branch and the SCS interior cyclonic gyral circulation driven by wind stress over the SCS, as indicated by the model-produced current field (Fig. 4a). Therefore, the southwestward current observed by Guo et al. (1985), which had a volume transport of 7.7–9.8 Sv, should be attributed to both the intruding current from the Philippine Sea and the current associated with the SCS interior gyre, the Northwest (NW) Luzón cyclonic gyre (Fang et al., 1998).

The monthly and annual mean volume and heat transports through the openings of the SCS are listed in Table 2. The model results show that the annual mean volume transport intruding into the SCS through the Luzón Strait is 4.37 Sv. The outward transports through the Taiwan, Mindoro, Balabac, Karimata and Malacca Straits are 0.45, 1.77, 0.61, 1.32 and 0.22 Sv, respectively. The latter four values sum up to a total of 3.92 Sv, which is quite close to the average value of the previous estimates (3.5±2.0) shown in Table 1. Though the model-produced annual mean transport through the Mindoro Strait is larger than that through the Karimata Strait, the maximum monthly mean transport through the Karimata Strait is larger than that through the Mindoro Strait. Thus the model results indicate that these two straits are of similar importance in exchanging SCS water with the outer oceans. The total outward heat transport is 0.458 PW, exceeding the inward heat transport by 0.047 PW. This implies that a net heat transfer of 0.047 PW across the SCS air-sea interface is required.

The net heat flux per unit area is 14 W m^{-2}, which is smaller than that given in Fang et al. (2003), as mentioned above.

6. Significance of the SCS shallow interocean circulation and the SCS branch of the Pacific-to-Indian Ocean throughflow

The existence of the SCS branch of the Pacific-to-Indian Ocean throughflow is of essential importance for the SCS oceanography. First, the transports associated with the interocean circulation are comparable with those associated with the interior circulation. The Sverdrup transports induced by wind stress curl over the SCS can reach a maximum of ~4 Sv in winter and a maximum of ~3 Sv in summer (Liu et al., 2001). The transports through the Karimata Strait should be comparable with the SCS Sverdrup transports (the maximum values estimated by Wyrtky (1961) and the present model are 4.5 and 4.2 Sv for winter, and 3.5 and 1.5 Sv for summer, respectively). Second, it has been noticed since the time of Wyrtki that the characteristics of the SCS water masses resemble those of the NW Pacific water. This similarity can only be maintained by the exchange between the SCS and outer oceans. For the upper layer, the exchange is caused by the shallow interocean circulation, in which the winter SCS branch of the PIOT plays a major role. The water masses of the upper ocean are modified by sea surface fluxes and mixing with the lower layer water. The averaged sea surface heat flux should be in balance with the total net heat transport through all openings of the SCS. In this regard, this interocean circulation plays a key role in governing the temperature of the upper layer water. The other water properties in the upper layer of the SCS are also affected by this circulation. In particular, the renewal timescale of the SCS upper-layer water is mainly determined by the intensity of this branch. This is also a key factor in evaluating and forecasting the pollution state of the SCS. It is worth noticing that a 3.5 Sv inflow can inject 0.11×10^6 km^3 of western Pacific water into the SCS within a year, which is equivalent to a volume with an area equal to the entire SCS and a thickness of 32 m. Third, the flow in the Karimata Strait is stronger and toward the south in winter, importing cooler water into the SCS through the Luzón Strait and exporting warmer water out from the SCS. The flow is weaker and toward the north in summer. The boreal summer corresponds to winter in the Java Sea. So during this period the northward Karimata Strait flow imports cooler water into the SCS through the strait and exports warmer water out from the SCS mainly through the Taiwan Strait and the surface layer of the Luzón Strait. Therefore, either in winter or summer, the flow cools the SCS. This in turn results in a net downward heat transfer across the sea surface of the SCS, agreeing with the previous computations of the heat flux as described in Section 3.

The SCS shallow interocean circulation also has significant influence on the ITF. First, the previous studies and the present model reveal that there is a net transport from the Western Pacific to the SCS and further toward the Indonesian Seas through the Karimata, Mindoro and other straits. This net transport will enhance the ITF. Second, it is well known that the ITF is stronger in boreal summer and weaker in boreal winter (e.g., Masumoto and Yamagata, 1996), while the flow in the Karimata Strait is northward in summer and southward in winter. Thus the Karimata Strait transport can regulate the ITF by making the transport through the ITF outflow passages between Sumatra and Australia more uniform than that through the ITF inflow passages between Kalimantan and New Guinea. Third, as found by Gordon et al. (2003), the water carried by the flow from the SCS to the Java Sea in winter has a low salinity feature. The flow thus makes the water less dense in the southern mouth area of the Makassar Strait. This lighter water blocks to a certain degree the outflow from the Makassar Strait. This further causes the vertical profile of the Makassar throughflow to have a feature that its maximum velocity is present in the subsurface layer (~200 m), where the water temperature is significantly lower than the surface temperature. Thus the flow from the Karimata Strait eventually considerably reduces the Pacific to Indian Ocean heat transport.

7. Concluding remarks

A branch of the Pacific-to-Indian Ocean throughflow can been clearly observed in boreal winter from numerical model results, which is consistent with the trajectories of satellite-tracked drifters. In the Karimata Strait, the flow is southward and stronger in boreal winter, and is northward and weaker in boreal summer. Numerical model results also indicate that considerable Pacific water can enter the South China Sea and exit toward the Sulu Sea through the Mindoro Strait, but no observational evidence is yet available. In terms of annual mean, there is a net transport from the Pacific Ocean to the SCS through the Luzón Strait. Beside the outflow through the Taiwan Strait, which enters the East China Sea, the majority of the imported Pacific water flows out through the Karimata, Mindoro and Balabac Straits and eventually joins the ITF. A small part flows out directly into the Indian Ocean through the Starit of Malacca . The net downward heat flux also implies that there must be some cooler water entering the SCS and warmer water exiting from the SCS. The flow is greatly significant in the SCS circulation, water properties and air-sea exchange. It is also of significant in enhancing and regulating the volume transport of the ITF, and reducing the heat transport of the ITF.

The SCS branch of the Pacific-to-Indian Ocean throughflow in winter has a similar meaning to the SCS Kuroshio branch, which was first proposed by Guo et al. (1985). In view of the fact that this branch originates not only from the Kuroshio but also directly from the western Philippine Sea east of the Kuroshio, and that this branch can continue flowing toward the Indonesian Seas, we call it the SCS branch of the Pacific-to-Indian Ocean throughflow. The southwestward current observed by Guo et al. (1985) should be a combination of this branch and the current associated with the SCS interior gyre driven by wind stress curl over the SCS.

Though the present study provides some estimates for the shallow interocean transport through the SCS on the basis of previous studies and model results, it is most likely that the estimates contain significant uncertainty. Therefore, it is of essential importance to measure the transports and their seasonal variation through the Karimata and Mindoro Straits.

Acknowledgments. The present work was supported by the National Science Foundation of China through Grants Nos. 40520140074, 40136010 (for G. Fang) and 40476016 (for Z. Wei), partly supported by The National Science Foundation (U. S. A) through Grant OCE-02-19782 and ONR Grants Nos. 014041-0698 and 014051-0272 (for R. D. Susanto), and partly supported by ONR through Grants 040611-8331 and 050303-7499 (for Q. Zheng). The authors would like to thank the anonymous reviewers for their valuable comments and suggestions on the manuscript.

REFERENCES

Centurioni, L. R., P. P. Niiler, and D. K. Lee, 2004: Observations of inflow of Philippine Sea surface water into the South China Sea through the Luzón Strait. *J. Phys. Oceanogr.*, **34**(1), 113–121.

Chu, P. C., and R. Li, 2000: South China Sea isopycnal-surface circulation. *J. Phys. Oceanogr.*, **30**, 2419–2438.

Dale, W. L., 1956: Wind and drift currents in the South China Sea. *The Malaysian Journal of Tropical Geography*, **8**, 1–31.

Fang Guohong, Fang Wendong, Fang Yue, and Wang Kai, 1998: A survey of studies on the South China Sea upper ocean circulation. *Acta Oceanographica Taiwanica*, **37**(1), 1–16.

Fang Guohong, Wei Zexun, B. H. Choi, Wang Kai, and Fang Yue, 2001: Interbasin transports of fresh water, heat and salt through the boundaries of Pacific-Asian marginal seas from an ocean circulation model. *Proc. 11^{th} PAMS/JECSS*, Local Organizing Committee of the 11th PAMS/JECSS, Cheju, Korea, 53–57.

Fang Guohong, Wei Zexun, B. –H. Choi, Wang Kai, Fang Yue, and Li Wei, 2003: Interbasin freshwater, heat and salt transport through the boundaries of the East and South China Seas from a variable-grid global ocean circulation model. *Science in China* (*D*), **46**(2), 149–161.

Gordon, A. L., R. D. Susanto, and K. Vranes, 2003: Cool Indonesian throughflow as a consequence of restricted surface layer flow. *Nature*, **425**(23), 824–828.

Guo Zongxin, Yang Tianhong, and Qiu Dezhong, 1985: The South China Sea Warm Current and the southwestward current on its right side in winter. *Tropic Oceanology*, **4**, 1–9 (in Chinese).

Huang Qizhou, 1983: Variations of velocity and transport of the Kuroshio in the Bashi Channel. *Tropic Oceanology*, **2**(1), 35–41. (in Chinese)

Hellerman, S., and M. Rosenstein, 1983: Normal monthly wind stress over the world ocean with error estimates. *J. Phys. Oceanogr.*, **13**, 1093–1104.

Josey, S. A., E. C. Kent, and P. K. Taylor, 1999: New insights into the ocean heat budget closure problem from analysis of the SOC air-sea flux climatology. *J. Climate*, **12**, 2856–2880.

Lebedev, K. V., and M. I. Yaremchuk, 2000: A diagnostic study of the Indonesian Throughflow. *J. Geophys. Res.*, **105**(C5), 11243–11258.

Levitus, S., and T. Boyer, 1994: *World Ocean Atlas*. NOAA, Washington D. C., 117pp.

Liu Hailong, 2002: The mean and seasonal characteristics of sea surface fluxes in the China adjacent seas. M. S. thesis, Institute of Oceanology, Chinese Academy of Sciences, 39pp. (in Chinese)

Liu Qinyu, Yang Haijun, Li Wei, and Liu Cho-Teng, 2000: Velocity and transport of the zonal current in the Luzón Strait. *Acta Oceanologica Sinica*, **22**(2), 1–8.

Liu Zhengyu, Yang Haijun, and Liu Qinyu, 2001: Regional dynamics of seasonal variability in the South China Sea. *J. Phys. Oceanogr.*, **31**, 271–284.

Liang, W.-D., T. Y. Tang, Y. J. Yang, M. T. Kuo, and W.-S. Chuang, 2002: Upper ocean current around Taiwan. *Deep-Sea Res.*, Part II, **50**, 1085–1150.

Masumoto, Y., and T. Yamagata, 1996: Seasonal variations of the Indonesian throughflow in a general ocean circulation model. *J. Geophys. Res.*, **101**(C5), 12287–12293.

Metzger, E. J., and H. E. Hurlburt, 1996: Coupled dynamics of the South China Sea, the Sulu Sea, and the Pacific Ocean. *J. Geophys. Res.*, **101**(C5), 12331–12353.

Metzger, E. J., and H. E. Hurlburt, 2001: The nondeterministic nature of Kuroshio penetration and eddy shedding in the South China Sea. *J. Phys. Oceanogr.*, **31**(7), 1712–1732.

Pacanowski, R. C., 1996: MOM2 Version2, Documentation, User's Guide and Reference Manual. Geophysical Fluid Dynamics Laboratory/NOAA, GFDL Ocean Tech. Rep. 32, Princeton, 329pp.

Qu, T., 2000: Upper-layer circulation in the South China Sea. *J. Phys. Oceanogr.*, **30**, 1450–1460.

Qu, T., H. Mitsudera, and T. Yamagata, 2000: Intrusion of the North Pacific waters into the South China Sea. *J. Geophys. Res.*, **105**, 6415–6424.

Stockdale, T., D. Anderson, M. Devey, P. Delecluse, K. Kattenberg, Y. Kitamura, M. Latif, and T. Yamagata, 1993: *Intercomparison of Tropical Pacific Ocean GCMs*. WCRP79, WMO/TD-545, World Meteorological Organization, Geneva, 90pp.

Wang Dongxiao, Zhou Faxiu, and Li Yongping, 1997: Annual cycle of sea surface temperature and sea surface heat budget. *Acta Oceanologica Sinica*, **19**, 35–44. (in Chinese)

WOCE Data Products Committee, 2002: WOCE Global Data, Version 3.0. WOCE International Project Office WOCE Report No. 180/02, Southampton, UK.

Wyrtki, K., 1961: *Physical Oceanography of the Southeast Asian Waters*. Scripps Institution of Oceanography, La Jolla, California, 195pp.

Yang Haijun, Liu Qinyu, and Jia Xujing, 1999: On the upper oceanic heat budget in the South China Sea: Annual cycle. *Adv. Atmos. Sci.*, **16**(4), 619–629.