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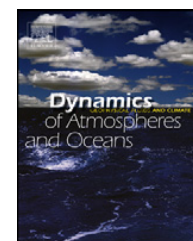
Interocean circulation and heat and freshwater budgets of the South China Sea based on a numerical model

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ABSTRACT

The South China Sea (SCS) interocean circulation and its associated heat and freshwater budgets are examined using the results of a variable-grid global ocean model. The ocean model has a 1/6° resolution in the SCS and its adjacent oceans. The model results from 1982 to 2003 show that the western Pacific waters enter the SCS through the Luzon Strait with an annual mean volume transport of 4.80 Sv, of which 1.71 Sv returns to the western Pacific through the Taiwan Strait and East China Sea and 3.09 Sv flows toward the Indian Ocean. The heat in the western Pacific is transported to the SCS with a rate of 0.373 PW (relative to a reference temperature 3.72 °C), while the total heat transport through the outflow straits is 0.432 PW. The net heat transport out of the SCS is thus 0.059 PW, which is balanced by a mean net downward heat flux of 17 W/m² across the SCS air–sea interface. Therefore, the interocean circulation acts as an "air conditioner", cooling the SCS and its overlaying atmosphere. The SCS contributes a heat transport of 0.279 PW to the Indian Ocean, of which 0.240 PW is from the Pacific Ocean through the Luzon Strait and 0.039 PW is from the SCS interior gained from the air–sea exchange. The Luzon Strait salt transport is greater than the total salt transport leaving the SCS by 3.97 Gg/s, implying a mean freshwater flux of 0.112 Sv (or 3.54×10^{12} m³/year) from the land discharge and P − E (precipitation minus evaporation). The total annual land discharge to the SCS is estimated to be 1.60×10^{12} m³/year, the total annual P − E over

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the SCS is thus 1.94×10^{12} m^3/year, equivalent to a mean P − E of 0.55 m/year. The SCS freshwater contribution to the Indian Ocean is 0.096 Sv. The pattern of the SCS interocean circulation in winter differs greatly from that in summer. The SCS branch of the Pacific-to-Indian Ocean throughflow exists in winter, but not in summer. In winter this branching flow starts at the Luzon Strait and extends to the Karimata Strait. In summer the interocean circulation is featured by a north-northeastward current starting at the Karimata Strait and extending to the Taiwan and Luzon Straits, and a subsurface inflow from the Luzon Strait that upwells into the surface layer in the SCS interior to supply the outward transports.

1. Introduction

The South China Sea (SCS) is one of the greatest marginal seas in the world. It connects the outer oceans through the Taiwan, Luzon, Mindoro, Balabac, Karimata and Malacca Straits (Fig. 1, these straits are hereafter called the interocean passages). Recent studies have revealed that the SCS is an important passage of the Pacific-to-Indian Ocean throughflow and exerts significant impact on the throughflow (Metzger and Hurlburt, 1996; Lebedev and Yaremchuk, 2000; Fang et al., 2002, 2005; Qu et al., 2005, 2006; Tozuka et al., 2007). It has been also shown that the SCS interocean circulation plays a critical role in the SCS water mass formation (Fang et al., 2005; Yu et al., 2008).

On the other hand, as a large marginal sea, the SCS receives great amounts of heat and freshwater from the sun and atmosphere, and thus plays an important role in the climate system of the Southeast Asia (Gong and Wang, 1999; Zhang et al., 2003). Great efforts have been devoted to the study of the SCS air–sea interactions. Wang et al. (1997), Yang et al. (1999), Liu (2002), Qu et al. (2004) and Qu et al. (2006) estimated the surface heat flux of the SCS using surface observations. Qu et al. (2006) calculated the heat and freshwater fluxes using NCEP atmospheric model results. These studies reveal that the SCS receives a net heat gain from the sun and the overlaying atmosphere and a net freshwater gain from the land discharge and the overlaying atmosphere. However, the observation-based estimate of the SCS surface freshwater flux is still not available due to the uncertainty in the estimation of evaporation. Obviously, in terms of long-term average, the heat and freshwater gains through the air–sea interface must be balanced by the net outgoing heat and freshwater transports induced by interocean circulation. Thus, the interocean circulation plays a critical role in the SCS heat and freshwater balance.

As shown in Fig. 1, the Luzon Strait connects the SCS to the western Pacific, through which the Pacific water is transported into the SCS. The Taiwan Strait connects the SCS to the East China Sea (ECS). In terms of annual mean the SCS water is transported toward the ECS through the Strait and eventually flows back to the Pacific. The Mindoro and Balabac Straits connect the SCS to the Sulu Sea. The Karimata Strait connects to the Java Sea, and the Malacca Strait to the Andaman Sea, respectively. Through these straits the SCS water is transported to the Sulu, Java and Andaman Seas, respectively, and then eventually merges into the Indian Ocean (Fang et al., 2005; Qu et al., 2006).

Up to date the observation-based estimates of volume, heat and freshwater transports through these passages are not available except a few volume transport estimates through the Taiwan and Luzon Straits. In fact, based on the conservation of volume, heat and salt, the surface fluxes can also be inversely inferred from an ocean model. Fang et al. (2002) first studied the heat and salt balances of the ECS and the SCS using a diagnostic global ocean model. Their study shows that the total annual mean outward heat transport through the Taiwan, Mindoro, Balabac, Karimata and Malacca Straits exceeds the inward heat transport through the Luzon Strait by 0.08 PW (1 PW = 1×10^{15} W), implying a net downward total heat flux of the same amount through the SCS surface. A drawback of their model is that the vertical grid near the sea surface was too coarse to resolve the above Straits sufficiently. Qu et al. (2004) used a numerical model to study the heat budget in the upper SCS and yielded a downward surface heat flux of 19 W m^{-2}. In their model, however, the Taiwan and Balabac Straits were closed. Therefore, more accurate estimates of the transports and their seasonal variations through the interocean passages are still needed using an improved model. In addition, as mentioned above, the
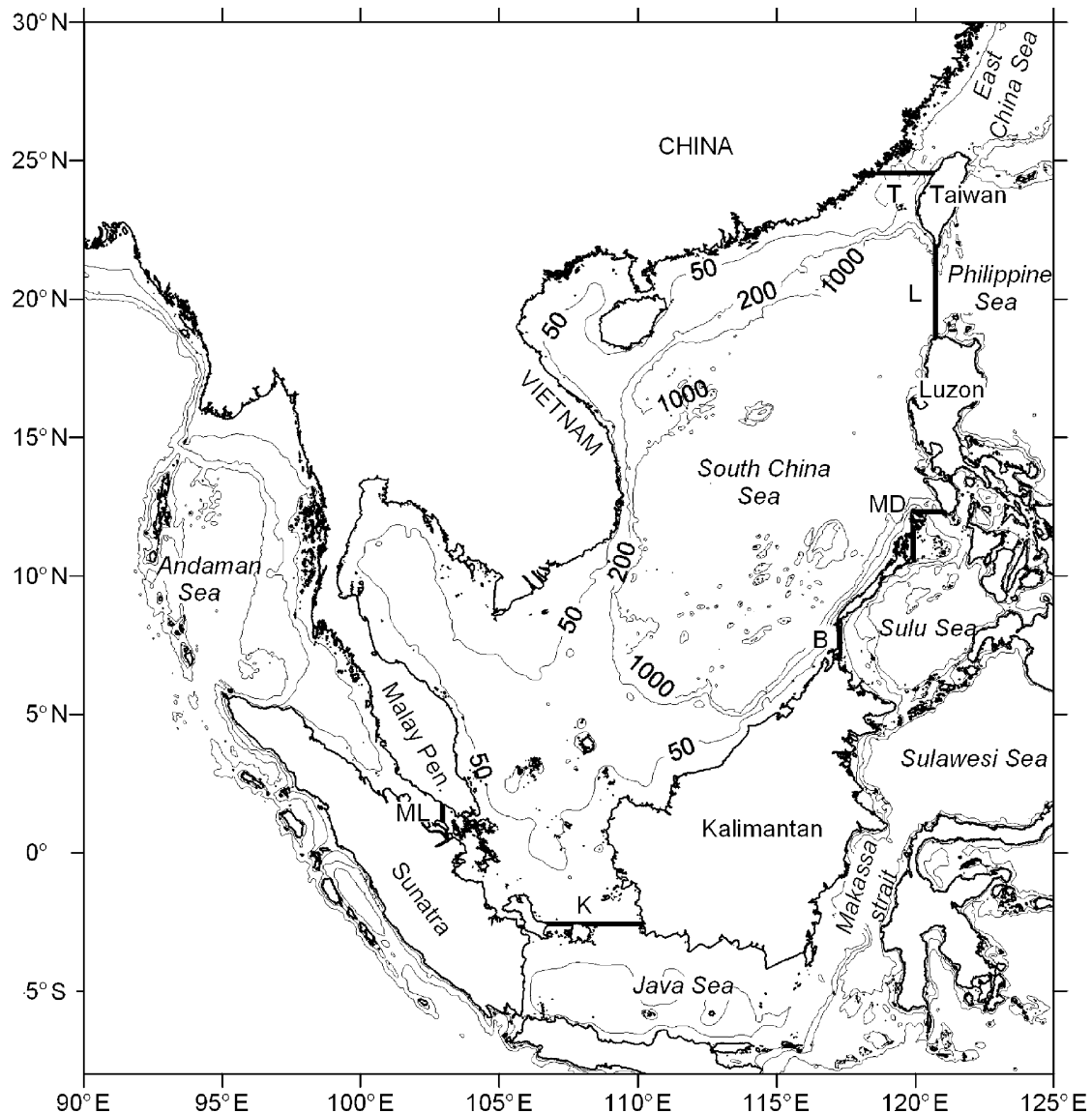
Fig. 1. South China Sea and its interocean passages. Solid lines indicate the transects for calculation of interocean transports, with L, T, MD, B, K, and ML representing those in the Luzon, Taiwan, Mindoro, Balabac, Karimata and Malacca Straits, respectively. Isobaths are in meters.

received heat and freshwater gains must be transported to the outer oceans to conserve the heat and freshwater contents in the SCS. To reveal the details of the SCS heat and freshwater budgets and the degree of influence of the SCS on its connecting straits and outer oceans, qualitative estimates of the heat and freshwater transports through individual interocean passages are needed.

The model of Fang et al. (2002) has recently been updated and has been run in a prognostic mode for 22 years (1982–2003). In this paper we will present an analysis of the interocean circulation and associated heat and freshwater budgets of the SCS based on the model results. Though the model has been run for more than 22 years, the freshwater forcing on the sea surface used is monthly means of the Levitus climatology. Thus the present analysis will concentrate on the annual mean and seasonal features.

2. Model description and methods for analysis

2.1. Model description

The numerical model used in this study is developed from the MOM2, which is a three-dimensional primitive equation numerical ocean model with Boussinesq, hydrostatic and rigid lid approximations

(Pacanowski, 1996). This model is a quasi-global model, with its northern boundary closed at 87°N and southern boundary along the Antarctic coast. To better resolve the circulation features in the East Asian marginal seas, a meridional spacing of 1/6° for the latitudes from 20°S to 60°N and a zonal spacing of the same size for the longitudes from 98° to 156°E are used. For the rest of the domain, the horizontal grid sizes are gradually turned down to 2°. The fine grid area covers the Japan/East Sea, the ECS (including the Bohai and Yellow Seas), the SCS, and the Indonesian Seas. Vertically, the model has 18 levels with grid sizes from the sea surface to bottom of 4, 6, 10, 15, 23, 32, 48, 69, 88, 132, 216, 332, 468, 611, 747, 862, 946 and 991 m. The ocean bottom topography is taken from the National Geophysical Data Center dataset (ETOPO5) with a 5′ × 5′ resolution. The model seabed is truncated at 5600 m. The initial temperature and salinity fields of the model are interpolated from the January climatology by Levitus and Boyer (1994). The model is first spun up for 7 years forced with annually cyclic sea surface boundary conditions to reach an equilibrium state. At this stage the NCEP reanalysis climatological monthly wind stresses from 1948 to 2000 are imposed on the model, and the surface temperature (SST) and salinity (SSS) are relaxed with a timescale of 50 days toward the monthly climatologies by Levitus and Boyer (1994). Then the model is further integrated from December 1981 to October 2004. At this stage the NCEP reanalysis monthly wind stresses are imposed, the SST is relaxed with a timescale of 50 days toward the monthly Reynolds SST (Reynolds and Smith, 1994). The SSS is relaxed with the same timescale toward the monthly climatologies by Levitus and Boyer (1994). To avoid rapid changes from a month to the subsequent month, all monthly fields are interpolated to produce corresponding fields at each time step. Monthly averages of the model results from January 1982 to December 2003 are discussed in the present study.

The verification of model results for the mean state and seasonal cycle has been reported in earlier publications (e.g., Fang et al., 2002; Wei et al., 2003; Wang et al., 2006), and will further be discussed in Section 3.

2.2. Methods of analysis

The sill depths of the Taiwan, Balabac, Karimata and Malacca Straits are all shallower than 50 m; and those of the Mindoro and Luzon Straits are about 400 and 2500 m, respectively. Thus the water column is divided into four layers: (1) the surface layer, containing the 1st to 5th model layers and ranging from the sea surface to 58 m; (2) the subsurface layer, containing the 6th to 10th model layers and ranging from 58 to 427 m; (3) the intermediate-to-deep layer, containing the 11th to 14th model layers and ranging from 427 to 2054 m; (4) the bottom layer, containing the 15th to 18th model layers and ranging from 2054 to 5600 m. The sill depths of the Luzon and Mindoro Straits in the model are 2801 and 427 m, respectively. According to the above division only the surface layer water can pass through all passages. The subsurface layer water can pass through the Luzon and Mindoro Straits, while the intermediate-to-deep layer and the bottom layer waters can only pass through the Luzon Strait. In addition, the surface layer roughly corresponds to the Ekman layer.

In order to calculate the transports through the interocean passages, transects are set for the passages as shown in Fig. 1. The volume transport F_V is calculated from

$$F_V = \int_A v_n \, dA \qquad (1)$$

where A represents the transect from the sea surface to bottom, dA denotes the area element; and v_n is the velocity component perpendicular to the transect.

The heat transport F_H is calculated from

$$F_H = \rho C_p \int_A (T - T_0) v_n \, dA \qquad (2)$$

where ρ is the water density, C_p the specific heat, T the water temperature, T_0 a reference temperature. The choice of the reference temperature is somewhat arbitrary (Schiller et al., 1998). Often T_0 is simply taken 0 °C. In this case F_H is also called temperature transport. To give the calculated value of F_H a specific physical sense, it is more desired to use the mean temperature of the corresponding return

flow as the reference temperature. However, it is hard to define which flow is the corresponding return flow. In the calculation of the heat transport of the Indonesian Throughflow (ITF), Schiller et al. (1998) used 3.72 °C, the mean temperature of the water from southern Tasmania to 50°S, as the reference temperature. This value was also adopted by Ffield et al. (2000). To facilitate a comparison of the SCS interocean heat transports to the ITF heat transports, the value of 3.72 °C is also used as the reference temperature in this study.

From Eqs. (1) and (2) a transport-weighted mean temperature is defined as

$$T_T = F_H (\rho C_p F_V)^{-1} + T_0 \tag{3}$$

The salt transport is calculated from

$$F_S = \rho \int_A S v_n \, dA \tag{4}$$

where S is the salinity. The freshwater transport is calculated from

$$F_W = \int_A \left[\frac{S_0 - S}{S_0} \right] v_n \, dA \tag{5}$$

where S_0 is a reference salinity. Since the freshwater transported into the SCS is eventually mixed with the SCS interior water, the SCS mean salinity, 34.544, is used as the reference salinity.

In this study, all the above quantities are first calculated using monthly results, then the mean values are calculated by averaging those monthly values.

3. Results and discussion

3.1. Interocean volume transports

The model-produced ensemble mean volume transports through the interocean passages, the Luzon, Taiwan, Mindoro, Balabac, Karimata and Malacca Straits, are listed in Table 1a. One can see that an annual mean volume transport of 4.80 Sv from the western Pacific flows into the SCS through the Luzon Strait, of which 1.71 Sv goes into the ECS through the Taiwan Strait and returns to the western Pacific, 1.77 Sv flows to the Sulu Sea through the Mindoro and Balabac Straits, 1.16 Sv flows to the Java Sea through the Karimata Strait, and the left 0.16 Sv flows to the Andaman Sea through the Malacca Strait. The latter three, amounting to 3.09 Sv, will eventually flow toward the Indian Ocean. It is worth noting that the Mindoro and Balabac Straits transport will join the ITF at the Makassar Strait, one of the inflow passages of the ITF, after passing through the Sulu and Sulawesi Seas; the Karimata Strait transport will join the ITF at ITF's outflow passages after passing through the Java Sea; while the Malacca Strait transport enters the Indian Ocean directly.

The model-produced ensemble mean zonal velocities at the cross-section in the Luzon Strait (transect L in Fig. 1) are shown in Fig. 2. Note that the sill depth of the Luzon Strait is about 2500 m, but the model maximum depth at this section is 2801 m. From this figure we can observe that the Luzon Strait inflows mainly occur in the surface and subsurface layers. A small amount of inflow occurs in the bottom layer. Outflows occur in the intermediate-to-deep layer. The volume transports passing through the surface (0–58 m), subsurface (58–427 m), intermediate-to-deep (427–2054 m) and bottom (>2054 m) layers are shown in Fig. 3. It can be seen that a pair of overturning circulation exists in the subsurface to deep layers of the SCS. The total surface layer outward transport through the Taiwan, Mindoro, Balabac, Karimata and Malacca Straits, 4.07 Sv, is much larger than the surface layer inward transport through the Luzon Strait, 1.49 Sv, implying that the subsurface water from the western Pacific upwells into the SCS surface layer with a mean rate of 2.58 Sv as illustrated in Fig. 3.

So far there have been a number of estimates of the Luzon Strait transport. The existing estimates based on observations and numerical simulations are listed in Table 2. One can find that the result of this study, 4.8 Sv, is quite close to the mean value of the existing estimates, 4.5 Sv. The model-produced vertical structure of the Luzon Strait transport also agrees with previous studies based on observations. Yuan et al. (2008) analyzed the current measurements of spring 2002 in the Luzon Strait and found
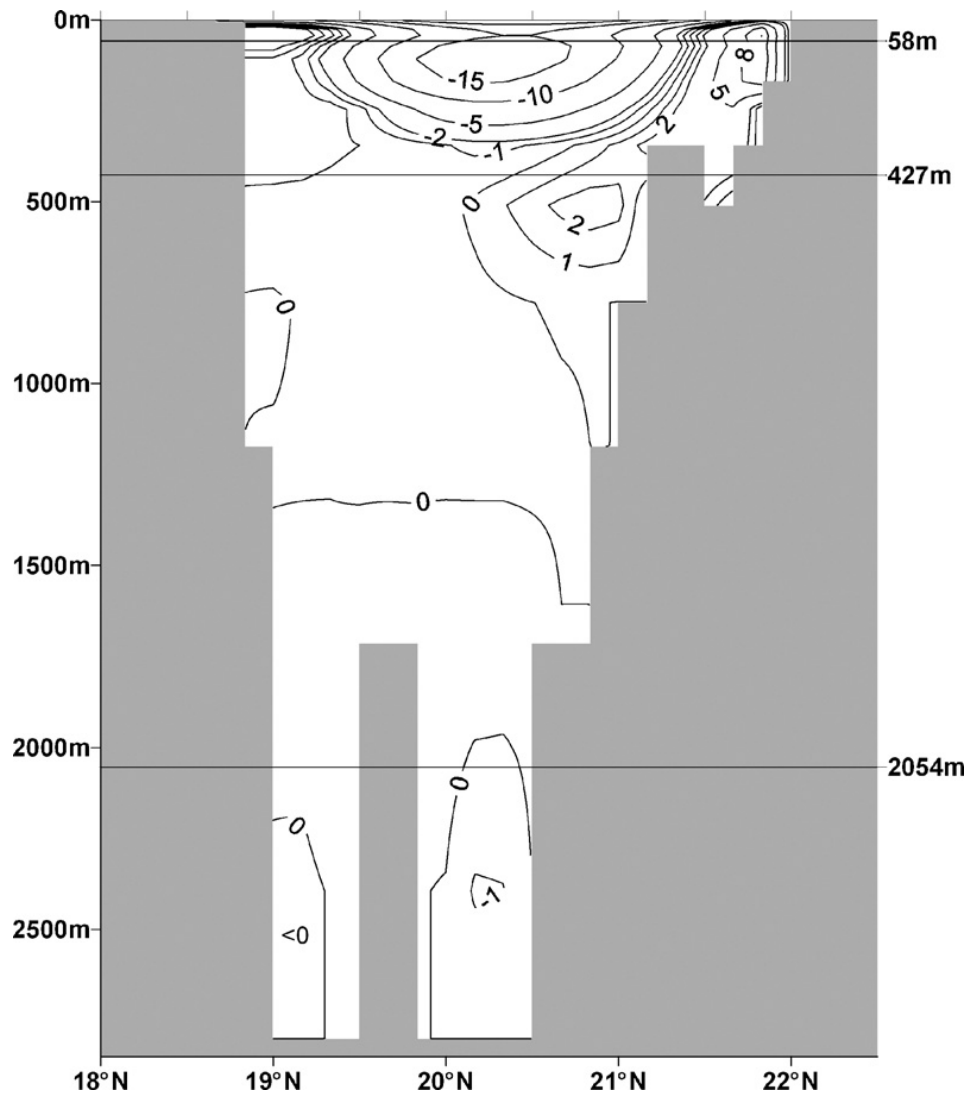
Fig. 2. Model-produced mean zonal velocities at the cross-section in the Luzon Strait. The location of the section is labeled L in Fig. 1.
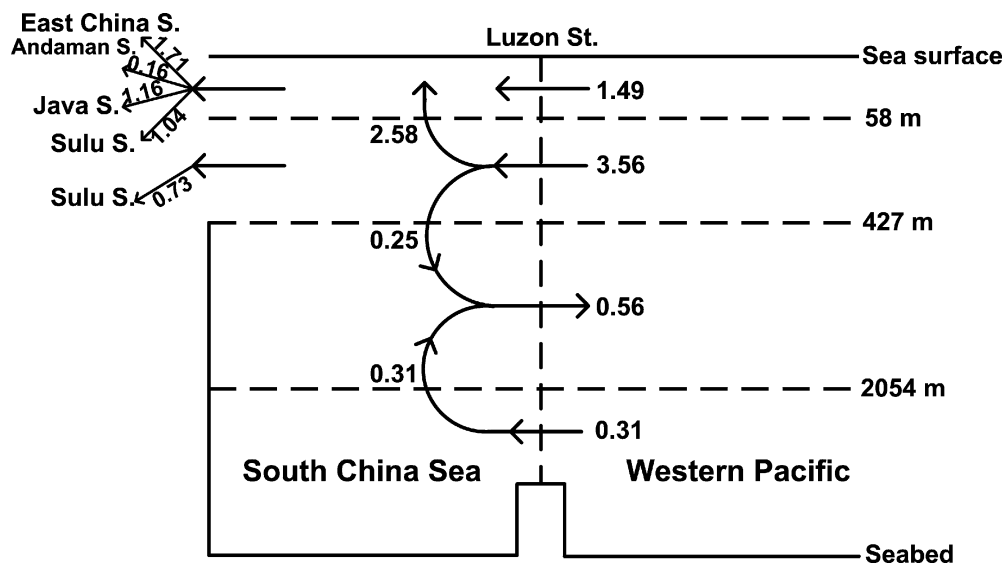

Fig. 3. A schematic diagram of the annual mean interocean circulation of the South China Sea. The numbers labeled to the arrows indicate the transport magnitudes (in Sv = 10^6 m^3/s) produced from the numerical model.

Table 1
Mean volume, heat, salt and freshwater transports through the interocean passages of the South China Sea.

Layer	Luzon	Taiwan	Mindoro	Balabac	Karimata	Malacca	Total
a. Volume transports, Sv (=10^6 m³/s)							
0–58 m	−1.49	1.71	0.62	0.41	1.16	0.16	2.58
58–427 m	−3.56		0.73				−2.83
427–2054 m	0.56						0.56
2054–2801 m	−0.31						−0.31
Total	−4.80	1.71	1.35	0.41	1.16	0.16	0.00
b. Heat transports, PW (=10^{15} W)							
0–58 m	−0.136	0.153	0.059	0.039	0.113	0.016	0.244
58–427 m	−0.245		0.052				−0.193
427–2054 m	0.006						0.006
2054–2801 m	0.002						0.002
Total	−0.373	0.153	0.111	0.039	0.113	0.016	0.059
c. Salt transports, Gg/s (=10^6 kg/s)							
0–58 m	−52.63	60.16	21.54	14.10	39.27	5.30	87.74
58–427 m	−126.01		25.57				−100.44
427–2054 m	19.86						19.86
2054–2801 m	−11.13						−11.13
Total	−169.91	60.16	47.11	14.10	39.27	5.30	−3.97
d. Freshwater transports, 10^3 m³/s							
0–58 m	1.2	13.6	16.4	12.7	52.2	9.0	105.1
58–427 m	0.5		5.8				6.3
427–2054 m	−0.2						−0.2
2054–2801 m	0.8						0.8
Total	2.3	13.6	22.2	12.7	52.2	9.0	112.0

Luzon, Taiwan, . . . refer to the Luzon Strait, Taiwan Strait, . . ., respectively. Positive/negative value indicates outward/inward transport.

that the zonal components of the mean currents at 200 and 500 m depths are westward, while that at 800 m depth is eastward. Liu and Liu (1988) observed that the mean current at an abyssal level in the Luzon Strait is toward the SCS, and estimated that the transport within 2000–2700 m is 1.2 Sv. Our model-produced transport in the upper 427 m layer is basically consistent with the observation-based estimates (Qu et al., 2000; Liang et al., 2002). The direction of the transport in the intermediate-to-deep layer derived from the model agrees with the observation by Yuan et al. (2008). The model-produced transport at the bottom layer is westward with a magnitude of 0.31 Sv. Its direction is consistent with the observation by Liu and Liu (1988), although its magnitude seems to be too small, likely due to the coarse vertical resolution and insufficient mixing in lower layers of the model. The model-produced

Table 2
Existing estimates of zonal volume transports through the Luzon Strait (in Sv = 10^6 m³/s).

Source	Spring	Summer	Fall	Winter	Annual mean	Method
Wyrtki (1961)	0.0	2.8	−0.5	−2.8	−0.1	Dynamic calculation (0–175 m)
Huang (1983)	−11.0	4.0	6.0	−31.0	−8.0	Dynamic calculation (0–1200 m)
Metzger and Hurlburt (1996)					−4.4	Numerical model
Liu et al. (2000)	−3.8	−2.7	−6.9	−7.4	−5.2	Numerical model (POCM, 0–200 m)
Qu et al. (2000)		−0.2		−5.3	−3.1	Dynamic calculation (0–400 m)
Chu and Li (2000)		−1.4		−13.7	−6.5	P-vector method
Lebedev and Yaremchuk (2000)		−4.5		−6.3	−5.4	Numerical model
Fang et al. (2002)	−4.1	−1.2	−7.7	−13.3	−6.4	Numerical model
Liang et al. (2002)					−3.3	ADCP measurement (0–300 m)
Qu et al. (2006)					−3.8	Numerical model (OFES)
Tozuka et al. (2007)					−3.6	Numerical model
Mean	−4.7	−0.5	−2.3	−11.4	−4.5	

Positive/negative value indicates eastward/westward transport.

Table 3
Existing estimates of annual mean net heat flux over the South China Sea.

Source	Annual mean net heat flux (W/m^2)	Net heat gain of the SCS (PW)	Remark
Wang et al. (1997)	25	0.088	From COADS, 1958–1987
Yang et al. (1999)	25	0.088	From COADS, 1950–1995
Fang et al. (2002)	23	0.080	From ocean model
Qu et al. (2004)	19	0.067	From ocean model
Qu et al. (2006)	18	0.063	From NCEP reanalysis
Mean	22	0.077	

Positive value indicates downward flux.

eastward transport in the intermediate-to-deep layer is likely to have a low bias, due to insufficient mixing in the model.

As of this date, the observation-based transport estimates for the SCS outflow passages are still lack except the Taiwan Strait. Using a limited number of current observations, Fang et al. (1991) estimated that the Taiwan Strait transports are 1.0 and 3.1 Sv in cold and warm half year, respectively, and the annual mean is 2 Sv. Using shipboard ADCP observations, Wang et al. (2003) obtained an annual mean transport of 1.8 Sv, ranging from 0.9 Sv in winter to 2.7 Sv in summer. Based on their shipboard ADCP measurements, Jan et al. (2006) reported that the Taiwan Strait transport ranges from 1.16 to 2.34 Sv between March and August. The present model result, 1.7 Sv, is within the range of above observation-based estimates. Bimonthly transports for February, April, June, August, October and December through the Java Sea estimated by Wyrtki (1961) are 4.5, 0.5, −3.0, −3.0, 0.5 and 4.0 Sv, respectively, with an annual mean of 0.6 Sv eastward. The eastward transport through the Java Sea should be basically equal to the southward transport through the Karimata Strait (Fig. 1). In our model the latter is 1.16 Sv southward (Table 1a), the same in direction as the Wyrtki's estimate but greater in magnitude (the recently recovered current measurement data from a collaborative program by the First Institute of Oceanography, China, the Agency for Marine and Fishery Research, Indonesia, and the Lamont-Doherty Earth Observatory, Columbia University, USA, show that our model-produced winter Karimata Strait transport is close to the observation. The observed results will be reported later on).

3.2. Interocean heat transports and heat budgets

The model-produced heat transports through the SCS interocean passages are listed in Table 1b. One can see that the heat in the western Pacific is transported to the SCS with a rate of 0.373 PW, while the total outward heat transport through the Taiwan, Mindoro, Balabac, Karimata and Malacca Straits is 0.432 PW. This implies that a net heat gain of 0.059 PW through the surface of the SCS is required. Since the area of the SCS bounded be the cross-strait transects shown in Fig. 1 is 3.52×10^6 km^2, the mean net heat flux per unit area should be 17 W/m^2. Therefore, the interocean circulation acts as an "air conditioner", cooling the SCS and its overlaying atmosphere.

The values of mean net heat flux obtained in previous studies are listed in Table 3. The value obtained from our model is slightly smaller than the observation-based estimates (Wang et al., 1997; Yang et al., 1999), but close to the results derived from other ocean models (Fang et al., 2002; Qu et al., 2004) and the NCEP atmosphere model (Qu et al., 2006).

A schematic diagram for the SCS heat budget is shown in Fig. 4. This figure illustrates that the SCS obtains 0.373 PW from the Pacific Ocean and 0.059 PW from the air–sea heat exchange. The gained heat is transported to the East China, Sulu, Java and Andaman Seas with rates of 0.153, 0.150, 0.113 and 0.016 PW, respectively. The latter three, amounting to a total of 0.279 PW, flows eventually toward the Indian Ocean. This is a significant contribution as compared to the heat transport of the ITF, 1.15 PW, estimated by Schiller et al. (1998) using model result, and the heat transport through the Makassar Strait, 0.39–0.63 PW estimated by Ffield et al. (2000) using observational results.

It is interesting to examine how the 0.059 PW heat gain is distributed to the outflows. Using Eq. (3) we obtain that the transport-weighted temperature of the inflow water at the Luzon Strait is 23.2 °C, while those of outflows at the Taiwan, Mindoro, Balabac, Karimata and Malacca Straits are 26.1, 24.3,
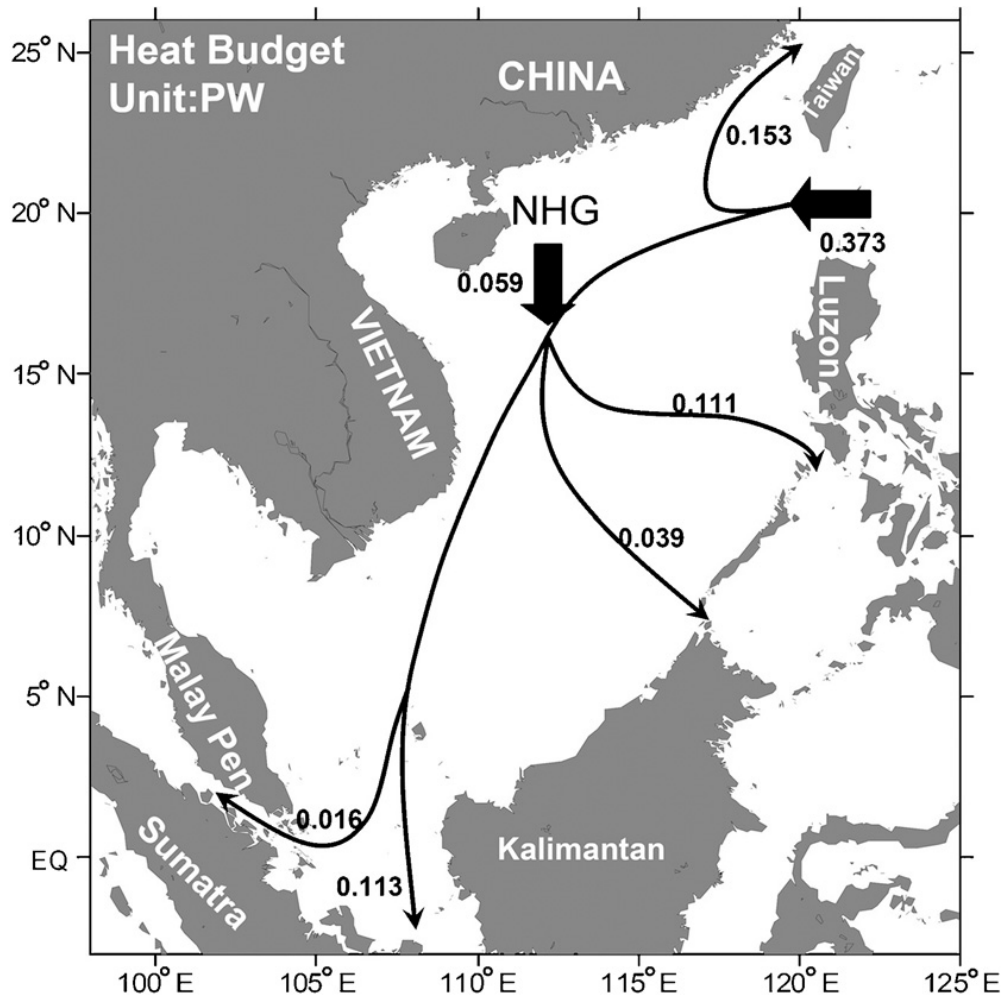
Fig. 4. A schematic diagram of the South China Sea heat budget. NHG represents the net heat gain (in WP = 10^{15} W).

27.4, 28.1 and 28.5 °C, which are higher than that at the Luzon Strait by 2.9, 1.1, 4.2, 4.9 and 5.3 °C, respectively. Therefore, the principal thermal process can be described as follows: in addition to the surface layer inflow, the major part of the Luzon Strait inflow water in the subsurface layer upwells into the surface layer and is heated, and then transported to the outer oceans. The total 0.059 PW heat flux gained in the SCS interior is distributed to the outflows of the above straits with amounts of 0.020, 0.006, 0.007, 0.023 and 0.003 WP, respectively. Fig. 5 illustrates the partition of the heat transports through the interocean passages. Fig. 5a shows that, without surface heating, the heat transport of 0.373 PW from the Pacific Ocean flows out through the Taiwan, Mindoro, Balabac, Karimata and Malacca Straits with rates of 0.133, 0.105, 0.032, 0.090 and 0.013 PW, respectively. Fig. 5b shows that the heat gain of 0.059 PW from the air–sea exchange is transported by the interocean circulation toward the outer oceans through the Taiwan, Mindoro, Balabac, Karimata and Malacca Straits with rates of 0.020, 0.006, 0.007, 0.023 and 0.003 PW, respectively. The heat transport through the Taiwan Strait goes back to the Pacific Ocean. Thus the SCS contributes a heat transport of 0.279 PW to the Indian Ocean, of which 0.240 PW is from the Pacific Ocean through the Luzon Strait and 0.039 PW is from the SCS interior gained from the air–sea exchange.

3.3. Interocean freshwater transports and freshwater budgets

The interocean salt transports are listed in Table 1c. The inward salt transport from the western Pacific through the Luzon Strait is 169.91 Gg/s, while the total outward salt transport is 165.94 Gg/s. This implies that there is a virtual salt flux of 3.97 Gg/s over the SCS surface. The mean salinity of the SCS is $S_0 = 34.544$, so that the corresponding freshwater input is equal to 0.112 Sv (or 3.54×10^{12} m^3/year).
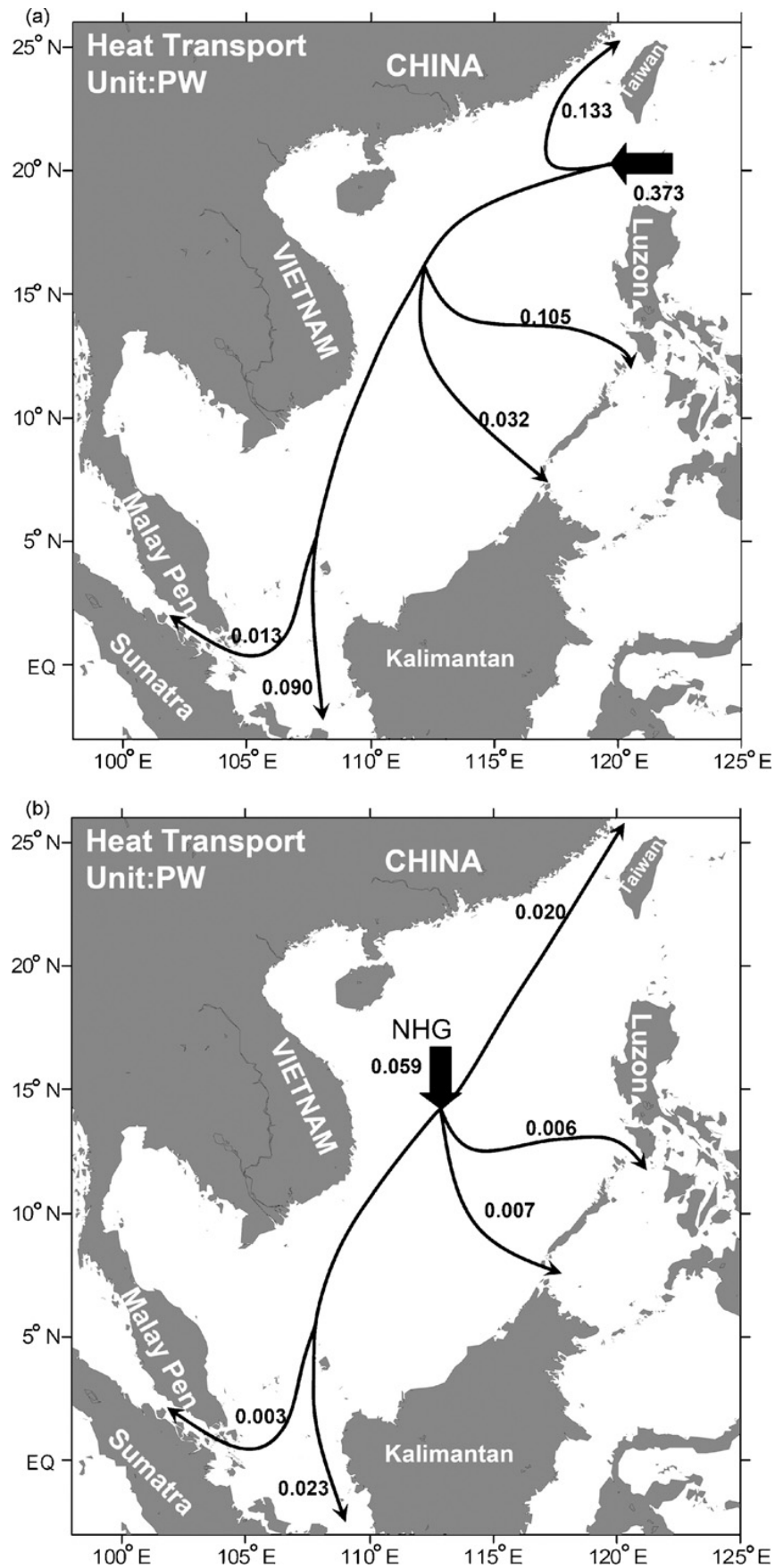
Fig. 5. Partition of the exit heat transports. (a) Exit heat atmosports originating from the Luzon Strait. (b) Exit heat transports originating from the air–sea heat exchange over the SCS.

Table 4
Land discharges into the South China Sea.

River name	Mean annual discharge, 10^9 m³/year	Mean rate, 10^3 m³/s
Mekong	475	15.1
Pearl	326	10.3
Red	123	3.9
Rajang	70	2.2
Han	25	0.8
Pahang	18	0.6
Total major river discharge	1037	32.9
Total land discharge	1595	50.6

Total land discharge includes the discharges from major rivers, small rivers and the lands directly, and is obtained from the total major river discharge divided by 0.65.

This freshwater input consists of two parts: one is the discharges from the surrounding lands, including rivers; the other is the precipitation minus evaporation (P − E) over the SCS surface. The rivers that discharge freshwater into the SCS with a mean rate greater than 250 m³/s include the Mekong, Pearl, Red, Rajang, Han and Pahang Rivers. The estuaries of the Mekong and Red Rivers are located in Vietnam; those of the Pearl and Han Rivers are in China, and those of Rajang and Pahang Rivers are in Malaysia. The mean annual discharges and their corresponding rates can be found in Sun (2006) and Dai and Trenberth (2002), and are given in Table 4. The total annual discharge from these six rivers
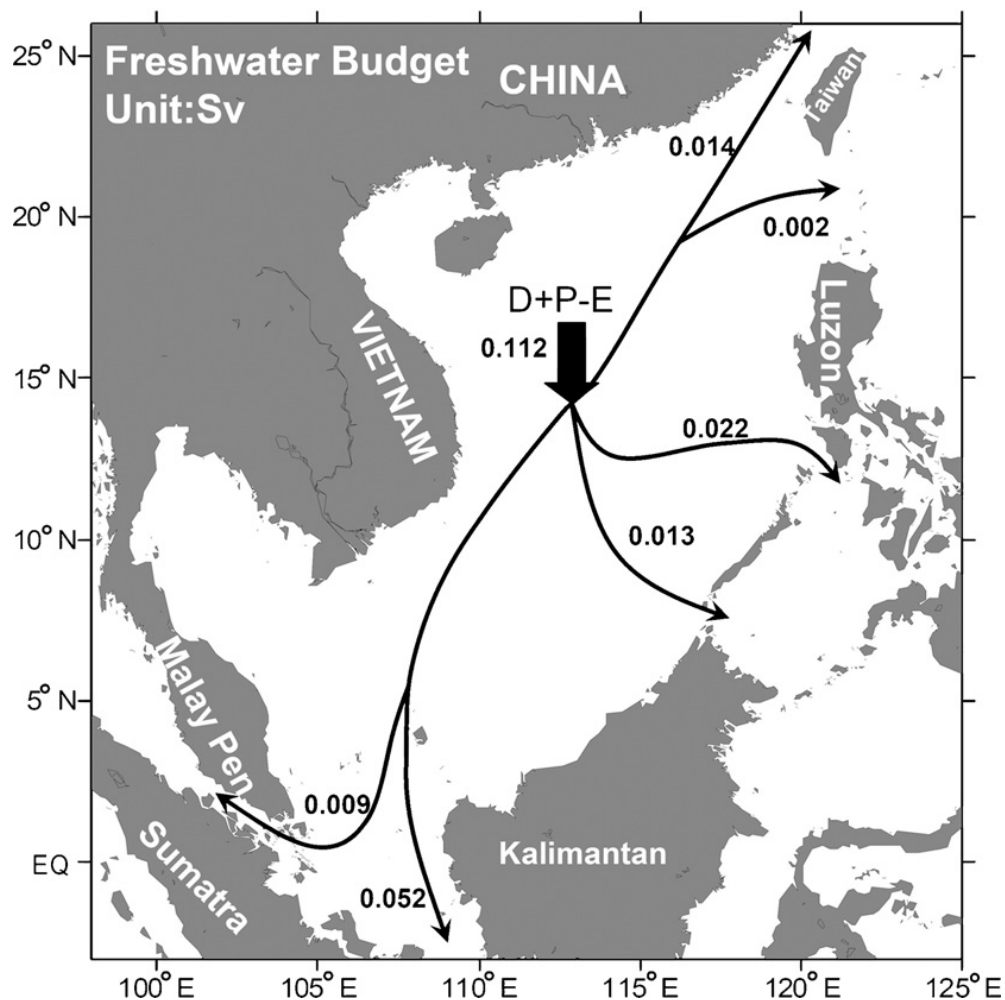

Fig. 6. A schematic diagram of the South China Sea freshwater budget. D + P − E represents the net freshwater gain, that is, the discharge from the land plus precipitation minus evaporation (in Sv).
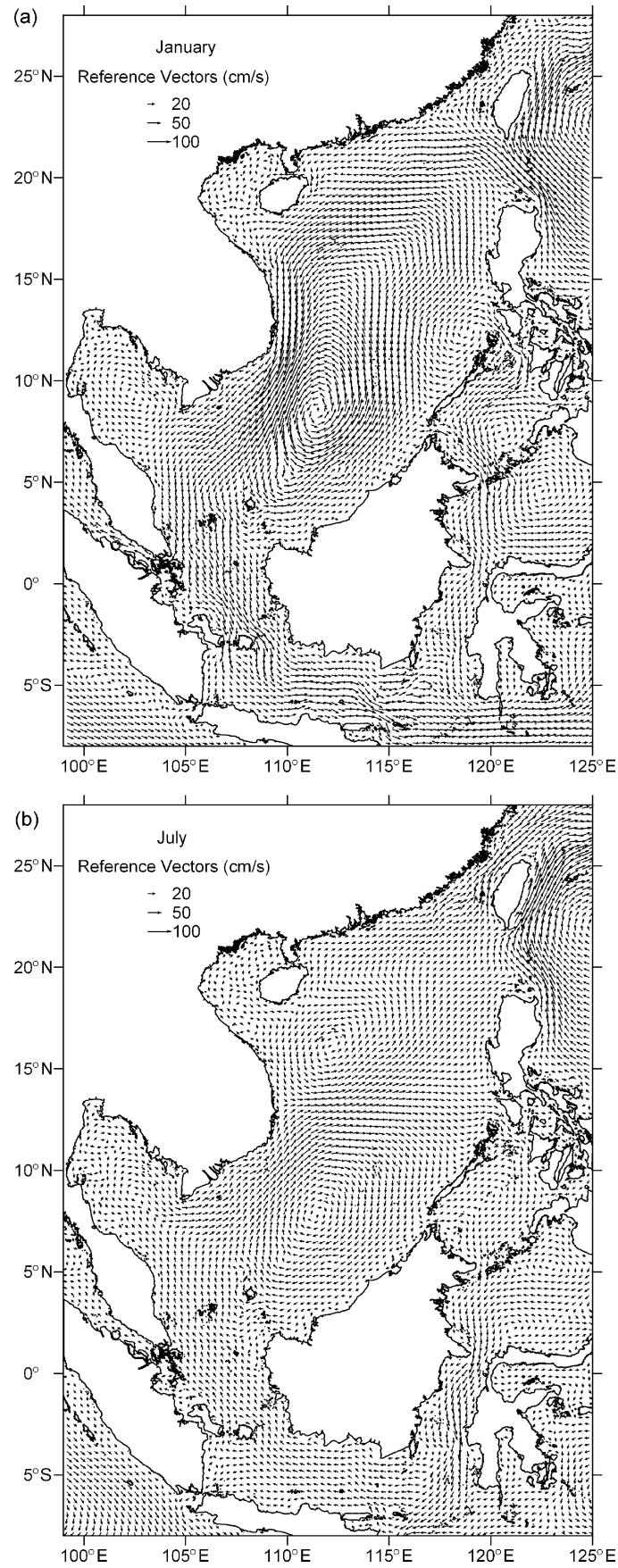
Fig. 7. Model-produced surface layer (0–58 m) currents (in cm/s) in January (a) and July (b).

is 1.037×10^{12} m^3/year, and the corresponding discharge rate is 32.9×10^3 m^3/s. It is hard to estimate the discharges from small rivers and from the lands directly. Perry et al. (1996) analyzed the global land discharges and found that the discharge from the major rivers (>250 m^3/s) accounts for about 65% of the total land discharge, the remainder consists of from small rivers, 33%, and entering the ocean underground, 2%. Assuming that this relation is applicable to the SCS, then the total annual land discharge into the SCS is 1.60×10^{12} m^3/year and the corresponding rate is 0.051 Sv. As a result, the P − E over the SCS is equal to 0.061 Sv, or 1.94×10^{12} m^3/year. The latter divided by the SCS area yields a mean P − E of 0.55 m/year.

The interocean freshwater transports are given in Table 1d. As above mentioned, the SCS receives freshwater from the land discharge and P − E with a rate of 0.112 Sv. The calculation using Eq. (5) shows that this gained freshwater from the atmosphere and surrounding lands is distributed to the outward flows through the Luzon, Taiwan, Mindoro, Balabac, Karimata and Malacca Straits with rates of 0.002, 0.014, 0.022, 0.013, 0.052, 0.009 Sv, respectively. The horizontal freshwater transports through the Taiwan and Luzon Straits, amounting to 0.016 Sv, flow toward the Pacific Ocean. The total freshwater contribution of the SCS to the Indian Ocean is 0.096 Sv. The greatest outward freshwater transport occurs at the Karimata Strait, amounting to 47% of the total net freshwater gain over the SCS. The Karimata Strait freshwater transport mainly occurs in winter (see next subsection), and blocks the surface warm water in the Makassar Strait from flowing southward and thus greatly reduces the ITF heat transport (Gordon et al., 2003; Fang et al., 2005; Tozuka et al., 2007). A schematic diagram for the freshwater budget is shown in Fig. 6.

3.4. Seasonal variation of the SCS interocean circulation

The alternating monsoon winds not only change the SCS interior circulation (e.g. Fang et al., 1998) but also greatly influences the SCS interocean transports. Fig. 7 illustrates the model-produced mean surface layer currents in January and July. The circulation patterns agree well with the earlier model results (e.g. Shaw and Chao, 1994; Xue et al., 2004) and empirical diagrams (Fang et al., 1998). Compared to the previous models, the present model is able to reasonably reproduce the currents in the interocean passages, and the simulated winter cyclonic gyre and summer anticyclonic gyre located southeast of Vietnam, the two most important features of the SCS seasonal circulation, are more realistic.

The model-produced seasonal cycles of volume transports through the interocean passages are shown in Fig. 8. In this figure the transports through the Mindoro and Balabac Straits are combined because both enter the Sulu Sea. Following the alternating monsoon winds, the Luzon Strait surface transport goes from the western Pacific to the SCS during October to the next May, but reverses its
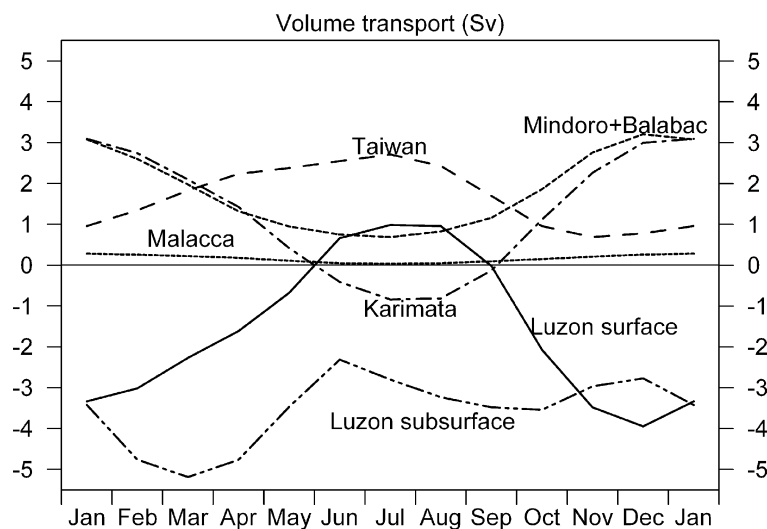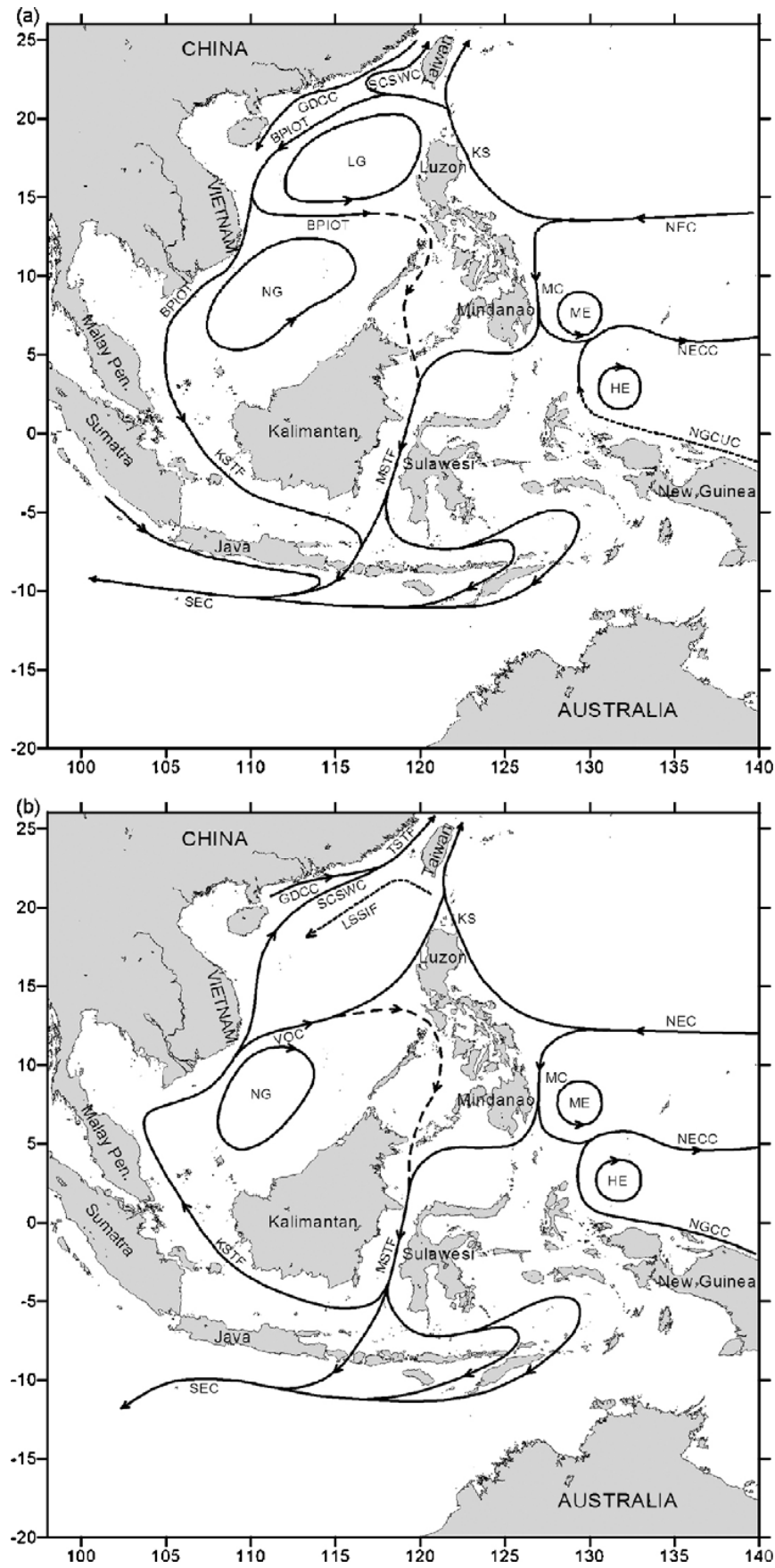

Fig. 8. Seasonal variation of the volume transports (in Sv) through the Luzon Strait surface layer, Luzon Strait subsurface layer, Taiwan Strait, Mindoro and Balabac Straits, Karimata Strait and Malacca Strait. Positive/negative value indicates outward/inward transport.

direction during June to September. Unlike the surface flows, the subsurface transport in the Luzon Strait is always westward. The Taiwan Strait transport is outward throughout the year, but the flow is much stronger in summer than in winter. This is consistent with the observations (Fang et al., 1991; Wang et al., 2003). The Karimata Strait transport is southward from October to the next May, but northward from June to September. This is consistent with the current features shown in Wyrtki (1961), but our model-produced transports are slightly smaller both in winter and summer (our annual mean is greater, see Section 3.1).

Based on our model results and previous understanding, schematic diagrams of winter and summer circulation in the SCS and its surrounding oceans are given in Fig. 9. One can see that the western Pacific water intrudes into the SCS through the Luzon Strait, forming a Branch of the Pacific-to-Indian Ocean throughflow in winter. This flow runs westward along the South China shelf break, and turns south as it approaches the SCS west shore, then runs along the SCS western boundary, and finally exits the SCS through the Karimata Strait. The Karimata Strait throughflow, combined with the Makassar Strait throughflow, flows out toward the Indian Ocean through the ITF outflow passages. According to the model results, part of the Branch of the Pacific-to-Indian Ocean throughflow enters the Sulu Sea mainly through the Mindoro Strait.

In summer, the Karimata Strait throughflow is reversed, and the Branch of the Pacific-to-Indian Ocean throughflow no longer exists. Along the SCS western boundary, the northward current, which is driven by southerly monsoon winds, splits into two branches as it approaches the southeast coast of Vietnam. Its west branch goes further northward and finally enters the ECS through the Taiwan Strait. Its east branch forms the Vietnam Offshore Current (Fang et al., 1998). The major part of this offshore current flows toward the Luzon Strait and enters the western Pacific, and its minor part may flow toward the Mindoro Strait and enters the Sulu Sea. It is worth noting that a small amount of the Makassar Strait throughflow turns westward and flows toward the SCS through the Karimata Strait. The model-produced inflow from the Karimata Strait in July is only 0.84 Sv, while the total surface layer outflows through the Taiwan, Luzon, Mindoro, Balabac Straits is 4.42 Sv. Therefore, a water supply from subsurface layers with a rate of 3.58 Sv is required to conserve water mass, and most of this water supply is carried by a subsurface flow from the Luzon Strait, known as the Luzon Strait Subsurface Inflow (Fig. 9). The evidence of the inflow can be found in the study of Qiu et al. (1984). In their Fig. 10, one can see a westward subsurface current, which was proposed by them as the SCS Branch of Kuroshio. The present study indicates that the summer SCS Branch of Kuroshio is present as a subsurface current rather than a surface current. This inflow can also be seen in the model-produced 100 m flow fields of Qu et al. (2004) and Wang et al. (2006).

4. Summary

A three-dimensional primitive equation numerical global ocean model with variable grid is employed to investigate the SCS interocean circulation and associated heat and freshwater budgets. The model is integrated in a prognostic mode from December 1981 to October 2004, with the NCEP reanalysis monthly wind stresses imposed at the surface, and with the SST and SSS relaxed toward the monthly Reynolds SST and Levitus monthly climatologies, respectively. The results suggest that:

(1) Annual mean volume transport from the western Pacific to the SCS through the Luzon Strait is 4.80 Sv, of which 1.71 Sv return to the Pacific and 3.09 Sv flow toward the Indian Ocean. The

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Fig. 9. Circulation patterns of the South China Sea and Indonesian Seas, with emphasis on the interocean circulation. (a) Winter. (b) Summer. The short-dashed lines represent subsurface currents. The long-dashed lines indicate that the currents are drawn only on the basis of model results. The abbreviations stand for the following: GDCC, Guangdong Coastal Current; HE, Halmahera Eddy; KS, Kuroshio; KSTF, Karimata Strait Throughflow; LG, Luzon Gyre; LSSIF, Luzon Strait Subsurface Inflow; MC, Mindanao Current; ME, Mindanao Eddy; MSTF, Makassar Strait Throughflow; NEC, North Equatorial Current; NECC, North Equatorial Countercurrent; NG, Nansha Gyre; NGCC, New Guinea Coastal Current; NGCUC, New Guinea Coastal Undercurrent; SEC, South Equatorial Current; SCSWC, South China Sea Warm Current; TSTF, Taiwan Strait Throughflow; VOC, Vietnam Offshore Current. The winter circulation pattern is adapted from Zheng et al. (2006).

transport to the Indian Ocean is distributed as follows: 1.77 Sv pass through the Makassar Strait (one of the ITF inflow passages), 1.16 Sv pass through the ITF outflow passage, and 0.16 Sv enters the Indian Ocean directly.

(2) A considerable amount of the subsurface layer water intrudes into the SCS from the western Pacific, and upwells into the SCS surface layer before flowing out through the SCS interocean passages. In the subsurface to deep layers a pair of overturning circulation exists.

(3) An annual mean heat transport of 0.373 PW (relative to the reference temperature of 3.72 °C) from the western Pacific flows into the SCS through the Luzon Strait. The heat transport through the Taiwan Strait is 0.153 PW, which finally returns to the Pacific through the ECS. The total heat transport toward the Indian Ocean is 0.279 PW, of which 0.150, 0.113 and 0.016 pass through the Sulu, Java and Andaman Seas, respectively. Therefore, the total outward heat transport exceeds the inward one by 0.059 PW, indicating a mean net downward heat flux of 17 W/m^2 across the surface of the SCS. This 0.059 PW net heat gain through air–sea exchange over the SCS is distributed to the outflows through the Taiwan, Mindoro, Balabac, Karimata and Malacca Straits with rates of 0.020, 0.006, 0.007, 0.023 and 0.003 PW, respectively. The SCS heat contribution to the Indian Ocean, 0.279 PW, originates from two sources: one is from the Pacific Ocean through the Luzon Strait, 0.240 PW, and the other, 0.039 PW, is from the SCS interior gained from the air–sea exchange.

(4) Annual mean salt transport from the western Pacific into the SCS through the Luzon Strait is 169.91 Gg/s, which exceeds the total exit salt transport of 165.94 Gg/s by 3.97 Gg/s. Thus the net freshwater gain from the land discharge and P − E can be inversely estimated to be 0.112 Sv. Since the total freshwater discharge from the lands into the SCS is 0.051 Sv, the total freshwater gain from P − E over the SCS should be 0.061 Sv, which is equivalent to a P − E of 0.55 m/year. The net freshwater gain of 0.112 Sv from the land discharge and air–sea exchange over the SCS is distributed to the outflows through the Luzon, Taiwan, Mindoro, Balabac, Karimata and Malacca Straits with rates of 0.002, 0.014, 0.022, 0.013, 0.052 and 0.009 Sv, respectively. The total freshwater contribution of the SCS to the Indian Ocean is 0.096 Sv, of which 0.035, 0.052 and 0.009 Sv pass through the Sulu, Java and Andaman Seas, respectively.

(5) The patterns of the SCS shallow interocean circulation in winter are quite different from that in summer mainly due to the alternating monsoon forcing. The Karimata Strait transport is southward in winter and northward in summer. As a result, the SCS branch of the Pacific-to-Indian Ocean throughflow exits in winter, but not in summer. The winter interocean circulation is featured by a west-southwest-southward current, the SCS branch of the Pacific-to-Indian Ocean throughflow, which starts from the Luzon Strait and extends to the Karimata Strait. The summer interocean circulation is featured by a north-northeastward current, starting from the Karimata Strait and extending to the Taiwan and Luzon Straits, and a subsurface inflow from the Luzon Strait that upwells into the surface layer in the SCS interior to supply the outward transports. The generation and seasonality of the SCS shallow interocean circulation can be explained by the "island rule" theory of Godfrey (1989).

(6) The SCS deep interocean circulation can occur only through the Luzon Strait. It is characterized by a pair of overturning circulations, with westward flows prevailing in the upper and bottom layers and eastward flows prevailing in the intermediate-to-deep layer.

Acknowledgments

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