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RESEARCH ARTICLE

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Special Section:

Recent Progresses in Oceanography and Air-Sea Interactions in Southeast Asian Archipelago

Key Points:

- A high-resolution regional ocean model is used to investigate impact of strait transport variability on SCS circulation and ITF
- Sibutu Strait is essential for the SCS circulation and the subsurface Makassar throughflow
- Impact of the Karimata Strait is limited on the Sunda Shelf and the ITF surface flow

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Exploring the Importance of the Mindoro-Sibutu Pathway to the Upper-Layer Circulation of the South China Sea and the Indonesian Throughflow

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Abstract Using a high-resolution ($0.1^\circ \times 0.1^\circ$) regional ocean model, this study investigates the impact of strait transport variability on the South China Sea (SCS) circulation and Indonesian throughflow, with a focus on the Mindoro-Sibutu pathway via the Sulu Sea, upon closing various straits within the Maritime Continent. Closing the Sibutu Strait reduces the Luzon Strait throughflow into the SCS by 75%, and the Mindoro-Sibutu deep exchange is reversed, thus flowing into the SCS. No significant change occurs over the shallow Sunda Shelf of the southern SCS, which is primarily driven by local monsoon winds. The impact of closing the Karimata Strait is limited to the Sunda Shelf and the Java Sea. The Sibutu Strait throughflow is fundamental in governing the SCS's low salinity, buoyancy, and upper layer injection into the Makassar Strait, which is the primary component of the Indonesian throughflow, thus inhibiting the transport within the upper 200 m of the throughflow. Closing both the Sibutu and Karimata Straits increases the southward Makassar Strait throughflow transport by ~ 3 Sv, which is derived entirely from the Mindanao Current.

1. Introduction

The Maritime Continent (MC), consisting of an array of islands and peninsulas separated by passages and seas of varied dimensions, offers circuitous pathways for the Indonesian throughflow (ITF), thereby transferring approximately 15 Sv of Pacific Ocean water into the Indian Ocean (Gordon, 1986; Gordon et al., 2010; Sprintall et al., 2013, 2014; Yuan et al., 2011, 2013). The Makassar Strait throughflow is the primary pathway of the ITF, with a transport of approximately -12 Sv (Feng et al., 2018; Gordon et al., 2008; Gordon et al., 2010, 2019; Li et al., 2018; Lukas et al., 1996; McCreary et al., 2007).

The South China Sea (SCS) is within the western margin of the MC, with several straits connecting it to the Pacific Ocean and Indonesian seas (Chu et al., 1999). The SCS throughflow (SCSTF; Metzger & Hurlburt, 1996; Qu et al., 2005; Wang et al., 2006; Wang et al., 2006; Gordon et al., 2012) involves an inflow of western tropical Pacific water through the Luzon Strait (Qu et al., 2004; Xu & Oey, 2014), with an outflow into the Java Sea and the Sulawesi Sea through the Karimata Strait (sill depth of 45 m) and the Mindoro-Sibutu passages (sill depth of ~ 300 m), respectively. Based on a high-resolution ocean model (Advanced Taiwan Ocean Prediction), Xu and Oey (2014) found the three-layer transport structure within the SCS: the upper layer (surface to 570-m deep) exhibits cyclonic circulation; the middle layer (570 to 2,000 m) is characterized by an anticyclonic circulation; and the deep layer (2,000 m to the sea floor) is cyclonic in the northern and anticyclonic in the southern SCS. Wei et al. (2016) investigated the circulation patterns of the surface, subsurface, intermediate, and deep layers using an ocean general circulation model, revealing that the intermediate and deep circulations are directly affected by the monsoon forcing and the Luzon Strait throughflow. Within the SCSTF, cooler and saltier Pacific water is transformed into a warmer, fresher, more buoyant outflow into the Indonesian Sea, which impacts ITF (Qu et al., 2000, 2005, 2006; Liu et al., 2006; Tozuka et al., 2009; Qu et al., 2009; Fang et al., 2009; Liu et al., 2012; Gordon et al., 2012). The SCS-Indonesian Seas Transport/Exchange project and the Transport, Internal Waves and Mixing in the Indonesian throughflow (TIMIT) regions

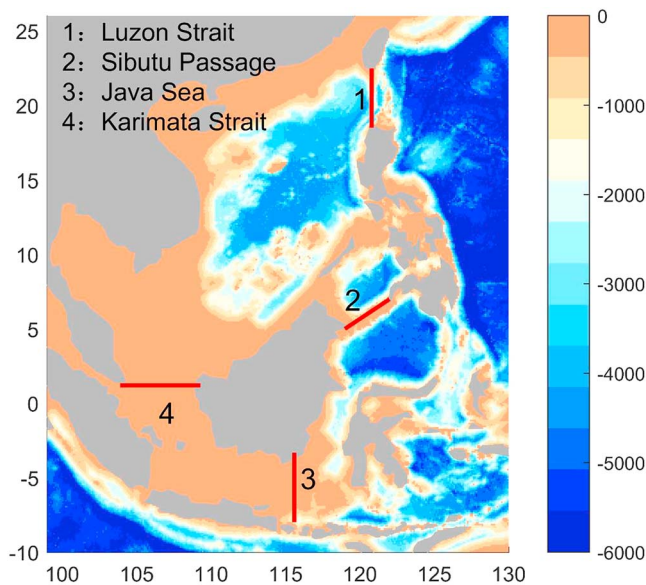


Figure 1. The subdomain of ATOP model topography. Four sections mark the key straits: (1) the Luzon Strait, (2) the Sibutu Passage, (3) the Java Sea, and (4) the Karimata Strait. Closed-strait experiments: (1) closure of the Luzon Strait—section 1; (2) closure of the Sibutu Strait—section 2; (3) Closure of the Luzon and Sibutu straits—sections 1 and 2; (4) Closure of the Karimata Strait at Makassar—section 3; (5) Closure of the Karimata Strait at Makassar and the Sibutu Strait—sections 2 and 3; and (6) Closure of the Karimata Strait at Singapore and the Sibutu Strait—sections 2 and 4.

project measured the currents and transport within the Karimata Strait from 2008 to 2013 (Fang et al., 2010; Susanto et al., 2010, 2013; Wei et al., 2016; Wei et al., 2019). The annual mean volume transport of the Karimata Strait was -0.75 Sv, with -3.6 Sv during the boreal winter months from January to February 2008 (Fang et al., 2010) and about 1.2 Sv during boreal summer (Susanto et al., 2013; Wei et al., 2019).

The SCSTF interacts with the ITF through two pathways: (1) along the Vietnam coast onto the shallow Sunda Shelf to enter the Java Sea through the Karimata Strait (Susanto et al., 2013) and the southern entrance to the Makassar Strait (Gordon et al., 2012; Qu et al., 2009; Tozuka et al., 2007, 2009) and (2) through the Mindoro passage into the Sulu Sea, through the Sibutu Strait into the Sulawesi Sea, to converge with the ITF at the northern entrance of the Makassar Strait (Gordon et al., 2012; Han et al., 2009; Sprintall et al., 2012; Wang, Wang, et al., 2006; Wei, Fang, et al., 2016). By closing the Luzon-Karimata pathway in a relatively coarse-resolution global ocean model (MOM3.0), Tozuka et al. (2007) showed that the maximum velocity of the Makassar flow occurred at the surface, rather than at a depth of 120 m as observed, with an increase of 0.2 m/s. Gordon et al. (2012), using observations and reanalysis data, suggested that the SCSTF could modulate the ITF by injecting low salinity upper-layer water into the western Sulawesi Sea through the Mindoro-Sibutu passages.

While the MOM3.0 resolution, varying from 0.4° in the tropical region to 2° outside the tropics, may be high enough to simulate the Karimata Strait, the 40 -km wide Mindoro-Sibutu pathway is not easily resolved. In this paper, we use results from a high-resolution ($0.1^\circ \times 0.1^\circ$) regional

ocean model to investigate the impacts of the key straits on the SCS circulation and ITF variability. Following the procedures of Tozuka et al. (2007), we conducted a series of sensitivity experiments by sequentially closing the Luzon, Karimata, and Sibutu straits.

The paper is organized as follows. Section 2 gives a brief introduction to the regional ocean model and the configurations of the sensitivity experiments. Section 3 describes the results by comparing the control and sensitivity experiments. A summary and discussion are provided in section 4.

2. Model and Methods

The ocean model used in this study is a parallel version of the Princeton Ocean Model (Advanced Taiwan Ocean Prediction; Oey et al., 2013, 2014). The model includes the North Pacific and the MC, with a constant resolution of $0.1^\circ \times 0.1^\circ$. The World Ocean Atlas monthly climatological temperature and salinity are specified along the southern open boundary (Oey & Chen, 1992a, 1992b). Depth-averaged transports are specified from the estimates of Ganachaud and Wunsch (2000) using the Flather radiation scheme (Oey & Chen, 1992a, 1992b). There are 41 sigma levels, with a finer resolution near the surface and the ocean bottom and with a fourth-order scheme used to minimize the sigma-level pressure-gradient errors (Berntsen & Oey, 2010). The Mellor and Yamada level 2.5 turbulent closure scheme is used for vertical eddy viscosity and diffusivity (Mellor & Yamada, 1982), and the Smagorinsky turbulence closure is used for horizontal diffusivity (Smagorinsky, 1963).

In a previous study (Wei, Fang, et al., 2016), the model simulation of the North Equatorial Current, Mindanao Current, Kuroshio, and the SCSTF/ITF throughflows were validated by comparing model simulations with observational data, SODA and OFES reanalysis data, as well as the results from a $1/12^\circ$ high-resolution model for the Indonesian seas (INDO12). Using the control experiment of Wei, Fang, et al. (2016), we conducted a set of sensitivity experiments by closing the Luzon, Karimata and Mindoro-Sibutu straits in sequence to assess the impacts of these straits between the control and sensitivity experiments.

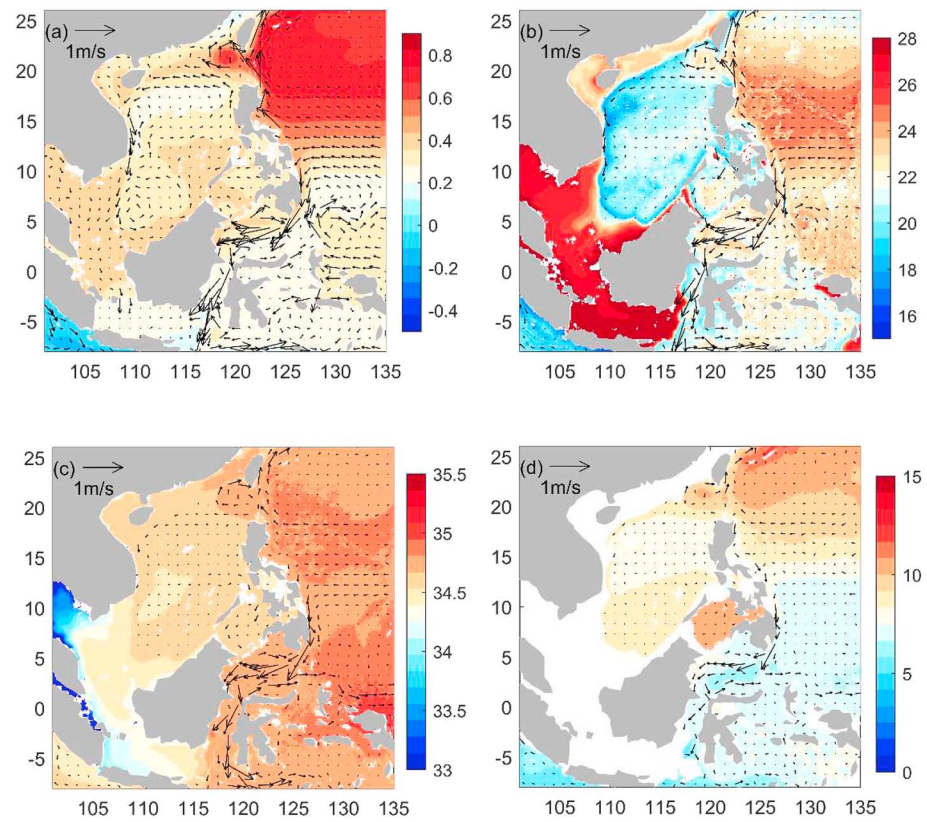


Figure 2. Control experiment (2008–2012): (a) 4-year averaged sea surface height and surface velocity pattern, (b) upper 300-m mean temperature and 150-m velocity, (c) upper 300-m mean salinity and 300-m velocity, and (d) 500-m mean temperature and velocity.

The model domain spans the Pacific, from 99 °E to 70 °W and from 15 °S to 72 °N, with the subdomain of our region of interest, within 100–140 °E and 15 °S–25 °N, which includes the key passages: the Luzon, Sibutu, and Karimata straits (Figure 1). We conducted six sensitivity experiments: (1) closing the Luzon Strait (CLS)—section 1; (2) closing the Sibutu Strait (CSS)—section 2; (3) closing the Luzon and Sibutu straits (CLSSs)—sections 1 and 2; (4) closing the Karimata Strait (CKM) within the Java Sea—section 3; (5) closing the Karimata Strait within the Java Sea and Sibutu Strait—sections 2 and 3 (CKMS); and (6) closing the Karimata Strait on the Sunda Shelf (CKSS), near Singapore and Sibutu Strait—sections 2 and 4. The sensitivity experiments were conducted from January 2004 to December 2011, and the last 4-years' (2008–2011) simulation results were used for analysis. In the following sections, we define two branches of the SCSTF: SCSTF-Karimata refers to the throughflow across the Karimata Strait, and SCSTF-Mindoro-Sibutu refers to the throughflow along the Mindoro–Sibutu pathway.

3. Results

3.1. Control Experiment

In the control experiment with all pathways open, the model produces a total ITF transport (positive direction is northward and eastward) of -12.3 Sv within the Makassar Strait, in which the Mindanao Current-Sulawesi Sea inflow is the primary contributor. The SCSTF is injected into the ITF via two pathways: the Mindoro–Sibutu passages (-2.2 Sv) and the Karimata Strait (-0.8 Sv). The Kuroshio intrusion into the SCS through the Luzon Strait is -4.6 Sv, with outflows from the SCS via the Taiwan Strait (1.1 Sv), Karimata Strait (-0.6 Sv), and Mindoro Strait (-4.2 Sv). The ITF export into the Indian Ocean occurs through three straits, the Lombok Strait (-3.6 Sv), Ombai Strait (-3.5 Sv), and Timor Strait (-4.6 Sv), totaling -11.7 Sv. The transports of all key straits are in accordance with INSTANT values reported in Gordon et al. (2010, 2012). Validations and comparisons with observations and previous studies for the total

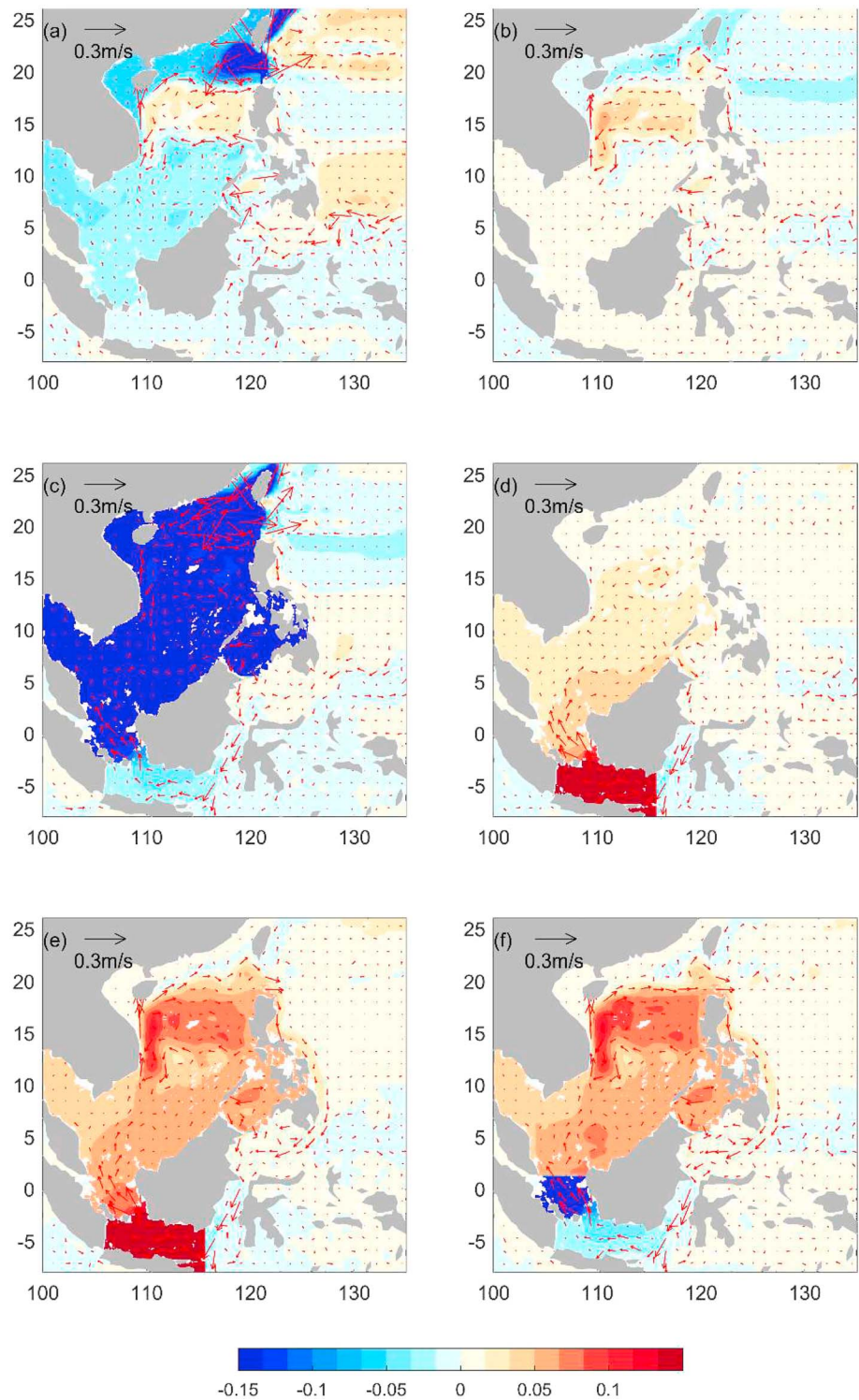


Figure 3. Differences of mean sea surface height and surface velocity pattern between control experiment and sensitivity experiments: (a) CLS, (b) CSS, (c) CLSS, (d) CKM, (e) CKMS, and (f) CKSS.

transport of the NMK/SCSTF/ITF currents and their variability are discussed by Wei, Fang, et al. (2016). In this study, we emphasize the SCS circulation and ITF variability within the upper 300 m (the velocity at 500 m is significantly lower than the surface flow) when closing the four key straits in the sensitivity experiments.

Table 1
Mean Transport (Unit: Sv) of Key Straits

Experiment	Luzon	Karimata	Mindoro	Sibutu	MC-Sulawesi	Makassar
Ctrl	−4.6	−0.8	−4.2	−2.2	−17.4	−12.3
CLS	0	−0.7	1.3	2.9	−23.3	−13.0
CSS	−1.0	−0.8	−0.2	0	−20.7	−14.8
CLSS	0	−0.1	0	0	−20.7	−14.3
CKM	−5	0	−4.3	−2.7	−17.4	−15.8
CKMS	−0.4	0	−0.1	0	−22	−15.7
CKSS	−0.4	0	−0.1	0	−22.3	−16.0

Note. Bold items mean the straits are closed and have no transport. The Luzon Strait (121 °E, 18–24 °N); Mindoro Strait (121–122 °E; 12 °N); Sibutu Passage (119–120 °E, 5.2 °N); Makassar Strait (117–120 °E; 2.9 °S); and MC-Sulawesi (125 °E; 1–6 °N) section.

The sea surface height and surface velocity pattern for the upper ocean in the control experiment from 2008 to 2012 clearly demonstrate the NEC bifurcation and its northward flowing branch, the Kuroshio Current, and the southward flowing branch, the Mindanao Current (Figure 2). The Kuroshio intrudes into the SCS, forcing the SCSTF along the northwest coast of the SCS basin into the Sunda Shelf and the Karimata Strait. The Mindanao Current branches into the Sulawesi Sea and the Makassar Strait, with a much higher velocity than that of the SCSTF (Figure 2a). The velocity at the depth of 150 m is comparable to the surface field for both the ITF and SCSTF. At this depth, the SCSTF is inhibited at the 40-m Sunda Shelf southern boundary, and therefore, the deeper Mindoro–Sibutu pathway is a more significant exit for the SCSTF (Figure 2b). The depth-averaged temperature of the upper 300 m shows that the SCS is cooler than the western Pacific by ~4 °C, and the Sunda Shelf is cooler than the western Pacific by ~7 °C. On the other hand, the upper 300-m depth-averaged salinity decreases from the western Pacific to the SCS and the Sunda Shelf (Figure 2c).

3.2. Impacts of the Key Straits on the SCS Circulation

To examine the impacts of the key straits on the SCS and ITF, the differences between the sensitivity and control experiments (sensitivity minus control) are shown in Figure 3. By CLS, the differences in the surface velocity field between the two experiments show a reversal of the SCSTF–Mindoro–Sibutu throughflow (backward throughflow) from the Mindoro Strait to the Luzon Strait (Figure 3a), as the SCSTF almost vanishes (within both the SCSTF–Karimata and SCSTF–Mindoro–Sibutu branches) in the CLS experiment (not shown). In the experiment with the CSS, the “backward SCSTF–Mindoro–Sibutu throughflow” still exists, but it is weaker than in the CLS experiment (Figure 3b). The SCSTF does not vanish in the CSS run but becomes much weaker than the control run, further confirming the Mindoro–Sibutu passage as the more significant exit path. If the Luzon and Sibutu straits (CLSS) are closed, the dynamic ocean passage from the western Pacific to the SCS completely shuts down.

The southern exit of the SCSTF at the shallow Karimata Strait and its variability is primarily determined by the local monsoon winds (Wei, Fang, et al., 2016). To further examine the monsoon effect, we closed the Karimata Strait in two sections: a meridional section in the Java Sea close to the southern Makassar Strait (CKM; Figure 3d) and a zonal section near Singapore (CKSS; Figure 3f). Based on the velocity differences between the control and CKM runs (Figure 3d), closing Karimata near the Makassar Strait causes an inverse “flow” over the Sunda Shelf, but the SCS interior circulation does not change significantly. The ITF southward surface velocity increases by approximately 0.2 m/s. This result is in accordance with Wei, Fang, et al. (2016), who showed that local monsoon effects were basically limited over the Sunda Shelf and the Makassar ITF. If both the Karimata Strait in the Java Sea and Sibutu Strait (CKMS) are closed, the SCS interior circulation changes dramatically (Figure 3e) as in the CSS run (Figure 3b). The SCS interior circulation with a closed Karimata Strait near Singapore (CKSS) is very similar to the CKMS run, which confirms the monsoon effect over the Java Sea as a localized feature.

Closing either the Luzon Strait or Sibutu passage does not change the transport via the Karimata Strait (0.7–0.8 Sv; Table 1). The transport along the Mindoro–Sibutu pathway is governed by the Luzon Strait inflow and is insensitive to the Karimata Strait transport. Notably, all sensitivity experiments enhance the Makassar ITF transport, although closing both the Karimata and Sibutu straits (CKSS) has the greatest effect on the ITF

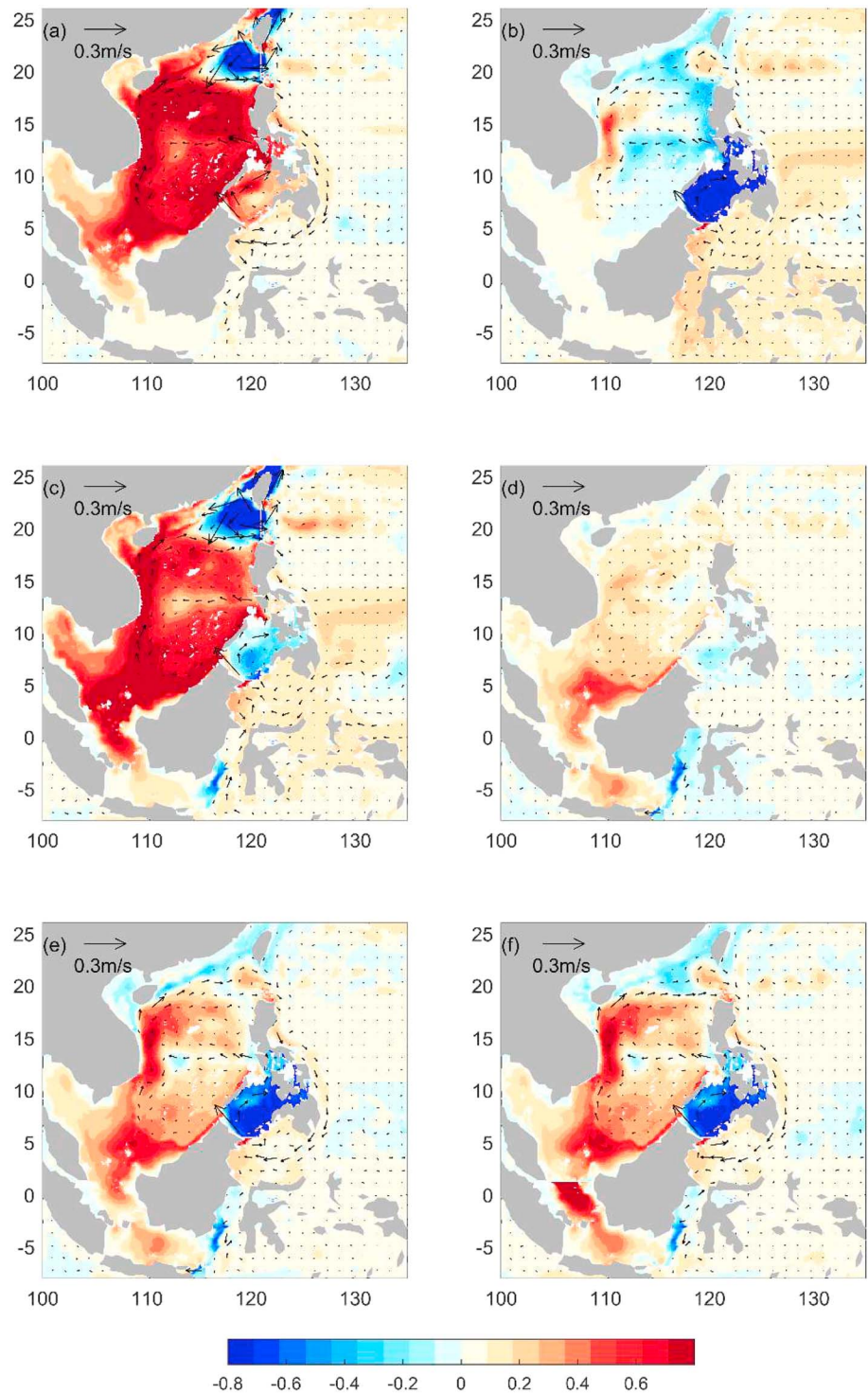


Figure 4. Differences of upper 300-m mean temperature and 150-m velocity between control experiment and sensitivity experiments: (a) CLS, (b) CSS, (c) CLSS, (d) CKM, (e) CKMS, and (f) CKSS.

transport (~ 3 Sv), since it shuts down the upstream inflow through the Mindoro-Sibutu pathway and the downstream inflow from the Karimata Strait.

Closing the Luzon Strait (CLS) causes a 0.6 °C increase in the upper 300-m temperature in the SCS (Figure 4a). CSS causes a significant temperature decrease in the Sulu Sea of up to -0.8 °C, which is

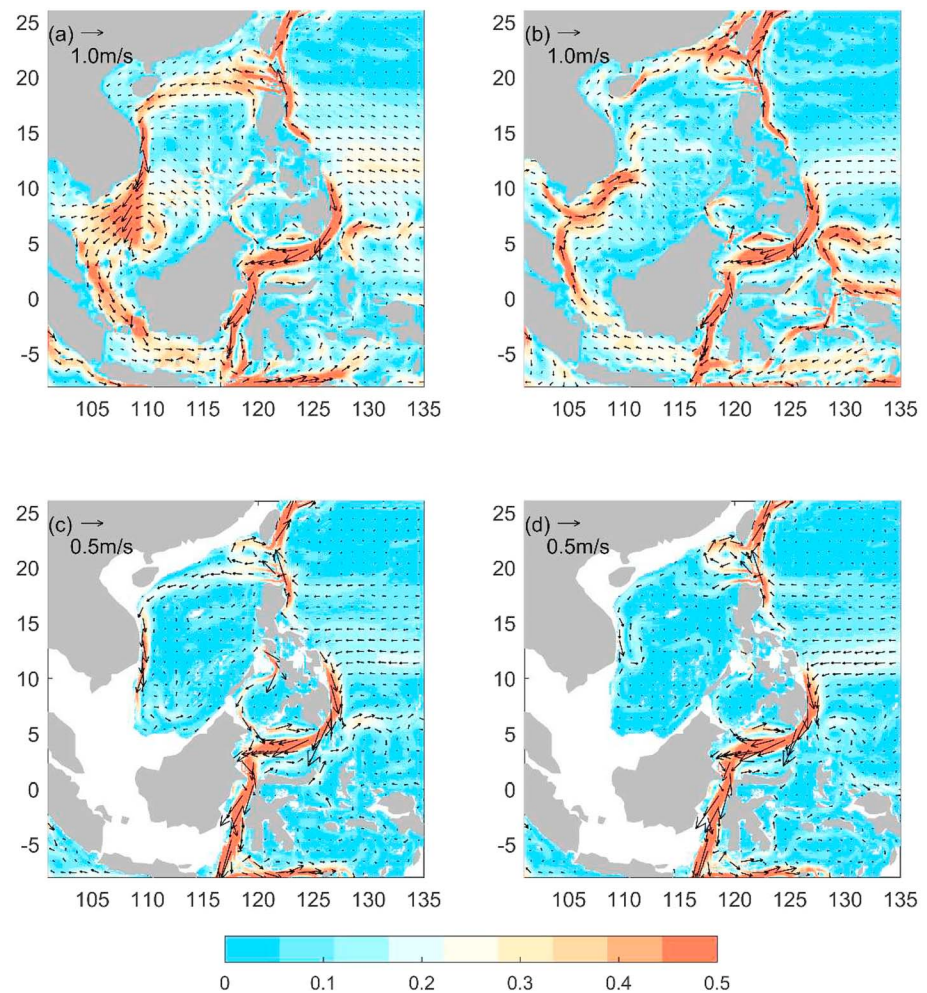


Figure 5. Time-averaged velocity fields in (a) winter (January–March) and (b) summer (July–September) at surface and (c) winter and (d) summer at 150-m depth. Color shading indicates the current speed, $(u^2 + v^2)^{1/2}$.

further advected to the northern SCS by the “backward throughflow” (Figure 4b). The potential temperature is above 9 °C from the sea surface to the sea floor. The temperature of the Sulu Sea is higher than that within the SCS and Sulawesi Sea by 7–8 °C at the deep depths (Chen et al., 2006). Strong mixing exists in the Sulu Sea, and the salinity is quite different from adjacent seas, as the North Pacific water types are much more attenuated (Qu & Song, 2009). The dramatic temperature decrease in the Sulu Sea is likely due to the vorticity change, shifting from a weak cyclonic flow in the control run (Figure 2b) to a strong anticyclonic flow (Figure 4b). Similar to the impact of the Karimata Strait on the SCS, closing the Karimata Strait affects temperature only over the Sunda Shelf. The most significant thermal structure change in the SCS interior is primarily caused by closing the Sibutu Strait.

The SCS circulation is a highly seasonal consequence of monsoon winds (Figure 5). During winter, there is southward flow from the Luzon Strait along the Vietnam coast toward the Karimata Strait, which then merges with the Makassar Strait throughflow and exits to the Indian Ocean. During the summer, when southwest monsoon winds prevail, the surface currents are reversed. The Makassar Strait throughflow moves southward in both seasons, although it is weaker in the winter. The SCSTF through the Mindoro-Sibutu passage is obvious at a depth of 150 m, as its southern SCS export is blocked by the 40-m Sunda Shelf (Figure 5c).

The velocity differences between the sensitivity and control runs (sensitivity minus control) in winter are shown in Figure 6. Closing the Luzon and Sibutu Straits exerts a significant impact on the SCS circulation

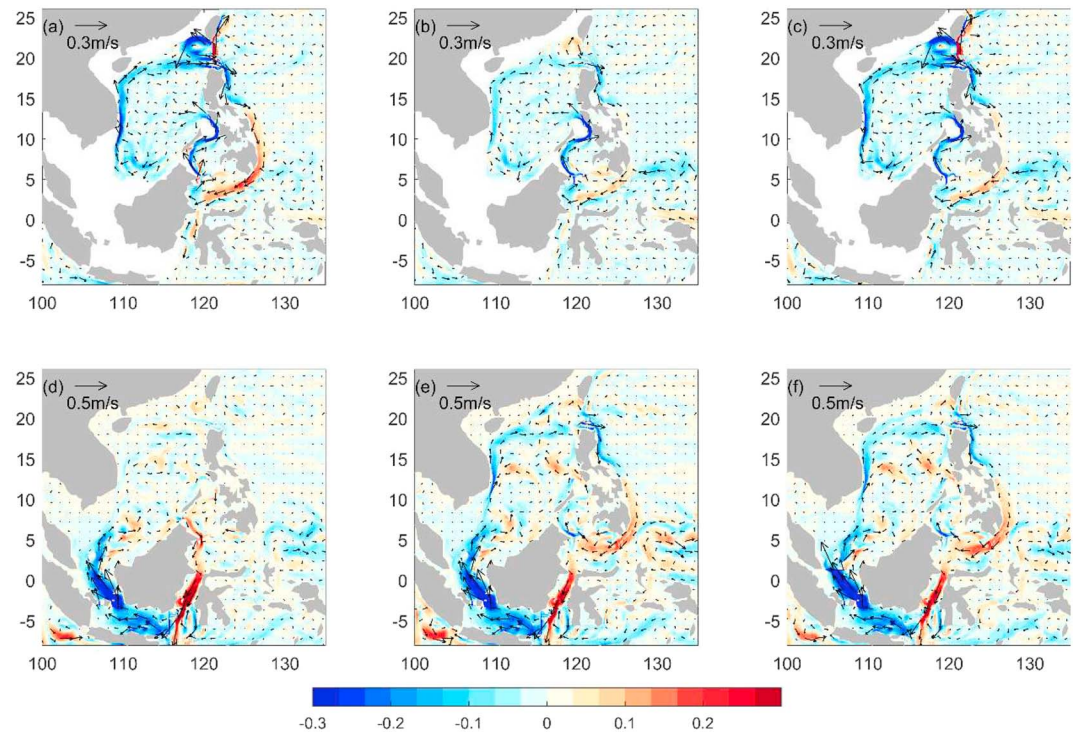


Figure 6. Differences of 150-m velocity between sensitivity experiments and the control experiment in winter (JFM) for (a) CLS, (b) CSS, and (c) CLSS; and surface velocity for (d) CKM, (e) CKMS, and (f) CKSS. Color shading indicates the current speed, $(u^2 + v^2)^{1/2}$.

at the depth of 150 m, but there is no significant change to the Makassar Strait throughflow (Figures 6a–6c). In contrast, closing the Karimata Strait does not change the SCS interior flow but dramatically increases the Makassar Strait throughflow velocity by up to 0.3 m/s (Figure 6d). Notably, the coastal current along the Vietnam coast is sensitive to the closing of the Sibutu Strait. The SCS circulations in the summer season (not shown) are not as sensitive to the Sibutu Strait being open or closed as in the winter season.

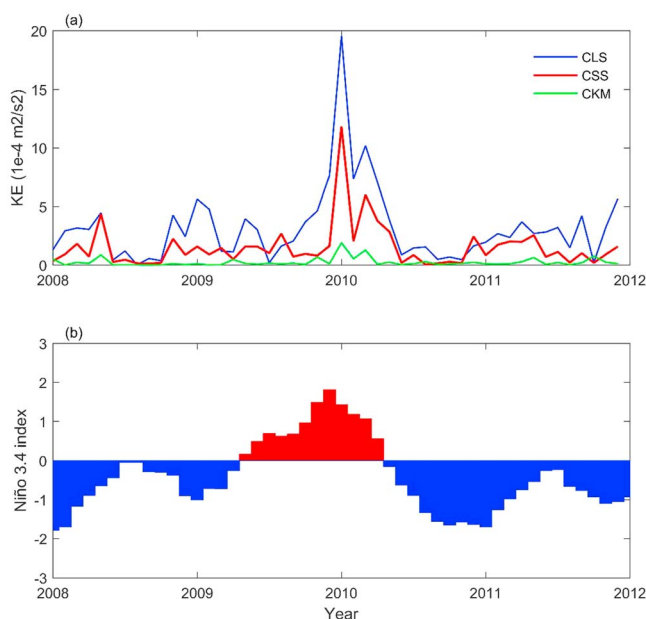


Figure 7. Kinetic energy $(u^2 + v^2)/2$ of the 150-m velocity anomaly (sensitive minus control) averaged over the SCS (a) and Niño 3.4 index (b).

Figure 7 shows the kinetic energy of the 150-m velocity anomaly (sensitive minus control) averaged over the SCS. Closing the Luzon Strait clearly has the largest impact on the SCS, as the SCSTF is completely shut down. For the Sibutu and Karimata Straits, the impact of the former accounts for more than 50% and the latter for less than 20%. Compared with the Niño3.4 index, the impact of the key straits on the SCS was prominent during the El Niño event of 2010, when the Luzon Strait intrusion was enhanced (Gordon et al., 2012). Table 1 shows that closing the Sibutu Strait leads to a decreased Luzon inflow, with the total transport decreasing from -4.6 to -1 Sv, mainly in the upper 500 m. Compared with the control experiment, the upper-layer velocity decreases by approximately 75%. In addition, closing the Sibutu Passage can also affect the middle layer (570–2,000 m) outflow, but there is no significant change in the deep layer (Figure 8).

3.3. Impact of the Key Straits on ITF Variability

The Makassar Strait throughflow has a total transport of -12 Sv, with approximately 80% of the volume derived from the Mindanao-Sulawesi inflow and 20% from the Sibutu and Karimata straits. To further demonstrate the impact of the key straits on the Makassar Strait throughflow

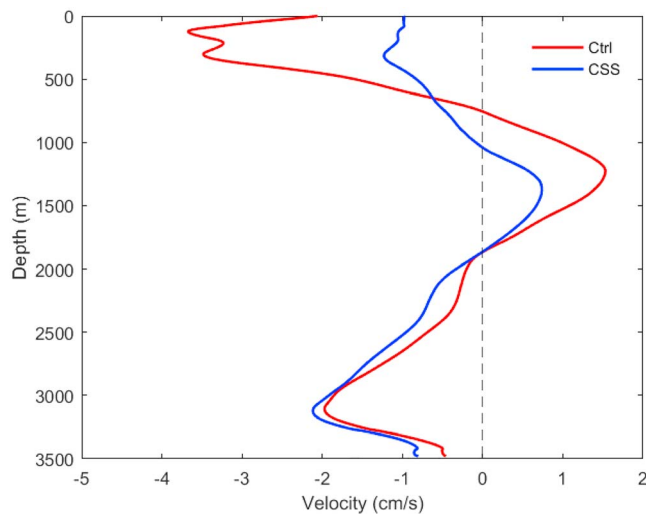


Figure 8. The three-layer velocity structure of Luzon Strait. 4-year (2008–2012) width-averaged zonal current in Luzon Strait.

As shown in Table 1, closing both the Karimata and Sibutu Straits has the greatest impacts on the Makassar Strait throughflow transport. Figure 11 compares the vertical velocity profiles in the Makassar Strait between the sensitivity and control runs. The enhanced southward velocity occurs mainly in the upper 300 m, although different straits affect different depths. The impact of closing the Karimata Strait is large at the surface and small in the subsurface. For example, in January, the surface velocity increases by approximately 0.3 m/s with a closed Karimata Strait (blue line), when the Karimata inflow over the 40-m deep Sunda Shelf is against the Makassar Strait throughflow. In contrast, closing the Sibutu Strait shows an impact on the subsurface but a very weak impact on the surface. In July, the maximum velocity increase of approximately 0.4 m/s occurs at a depth of approximately 100 m, as the Sibutu deep flow with freshwater intrusions plays more important roles in the Makassar Strait subsurface velocity profile in summer (Gordon et al., 2012).

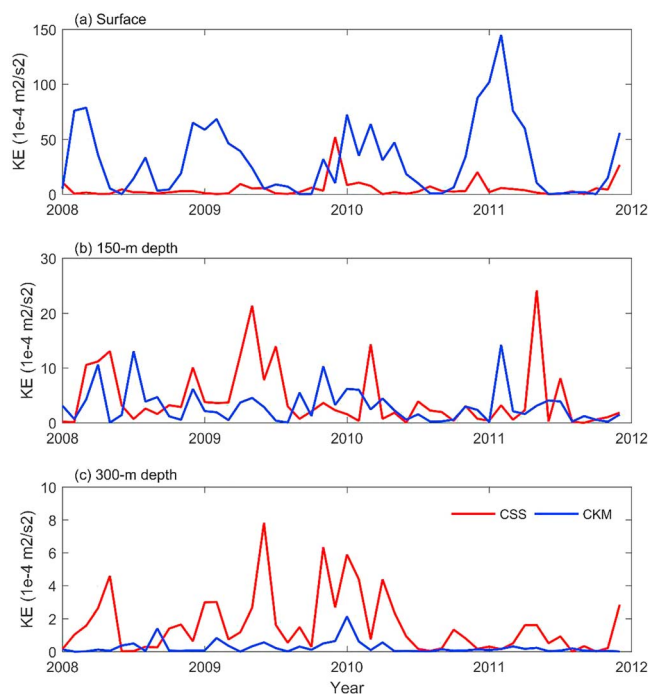


Figure 9. Kinetic energy $(u^2 + v^2)/2$ of the velocity anomaly (sensitive minus control) averaged within the Makassar Strait box (marked in Figure 5d) at (a) surface, (b) 150-m depth, and (c) 300-m depth. Red line: CSS minus control; Blue line: CKM minus control.

variability, Figure 9 shows the kinetic energy of the velocity anomaly (sensitive minus control) averaged within the Makassar Strait box (marked in Figure 5d). At the surface, the Karimata Strait's impact is dominant, while at 150 and 300 m, the Sibutu Strait's impact becomes more significant, since the Karimata Strait sill depth is ~50 m.

Figure 10 shows the transport time series correlation coefficients between the Mindanao-Sulawesi inflow and the Makassar Strait throughflow. In the control experiment, the correlation coefficients are approximately 0.75, indicating that the Mindanao-Sulawesi inflow determines the downstream Makassar Strait throughflow variability. With the Sibutu Strait closed, the correlation coefficients increase to 0.98–0.99 for the CSS, CLSS, CKMS, and CKSS runs (Figures 7b, 7c, 7e, and 7f). In contrast, with only the Luzon Strait or Karimata Strait closed, the correlation coefficients are 0.9 and 0.84, respectively. This result indicates that the Sibutu Strait is the most important inflow modulating the Makassar Strait throughflow variability, while the Karimata inflow plays a secondary role. Without these two inflows, the Makassar ITF variability will be completely dominated by the Mindanao-Sulawesi input directly from the western tropical Pacific Ocean.

On the other hand, we observed that the ITF subsurface velocity maximum still exists even with both the Sibutu and Karimata straits closed. This result is the opposite of the result reported by Tozuka et al. (2009) with a relatively coarse resolution of $0.1^\circ \times 0.1^\circ$, who showed that the subsurface velocity maximum vanished when closing the Luzon-Karimata-Mindoro Strait in a global ocean model. Our model results suggest that the ITF subsurface maximum is insensitive to the inflows of the Karimata and Sibutu straits and, thus, could originate from the Mindanao-Sulawesi inflow. A notable subsurface velocity core also exists in the Mindanao-Sulawesi inflow at 125° longitude (Figure 12), which likely governs the vertical profile of the Makassar ITF. A recent in situ ADCP measurement of the Mindanao undercurrents by Zhang et al. (2014) also confirmed that the Mindanao Current has a subsurface maximum at a depth of approximately 100 m at (8°N , 127°E ; see their Figure 2a).

4. Summary and Discussion

In this study, we investigate the impacts of closing the Luzon, Sibutu, and Karimata straits on the upper 300 m within the SCS and the ITF using a high-resolution ($0.1^\circ \times 0.1^\circ$) regional ocean model. Closing the Sibutu Strait induces significant changes in the SCS temperature and circulation; the Luzon Strait intrusion is reduced by 75%, and the Mindoro-Sibutu

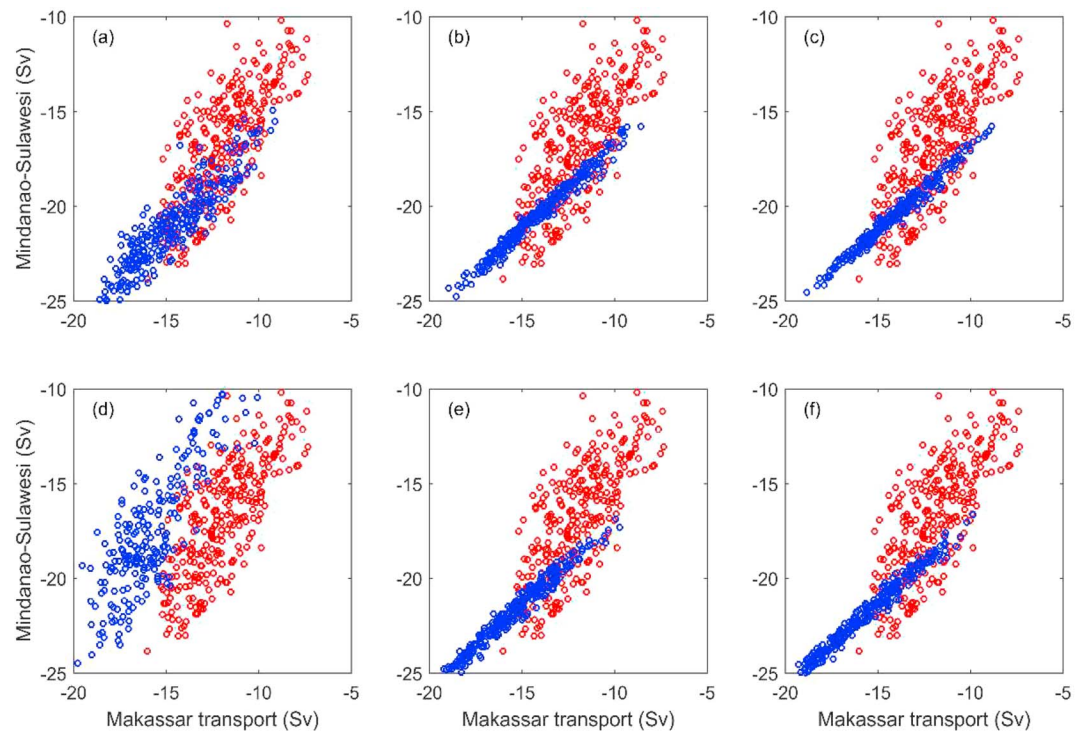


Figure 10. Correlation coefficients (CCs) between the Makassar ITF and the Mindanao-Sulawesi inflow in sensitivity experiments: (a) CLS experiment, CC = 0.90; (b) CSS experiment, CC = 0.99; (c) CLSS experiment, CC = 0.99; (d) CKM experiment, CC = 0.84; (e) CKMS experiment, CC = 0.99; and (f) CKSS experiment, CC = 0.98. The CC of the control experiment is 0.75. The x axis is the transport value of the Makassar Strait; the y axis is the transport value of the Mindanao-Sulawesi section. The red dots are the 5-day mean transport of control experiment, while the blue dots are the results from the sensitivity experiments. The correlation coefficients are calculated from Makassar transport time series and the Mindanao-Sulawesi time series.

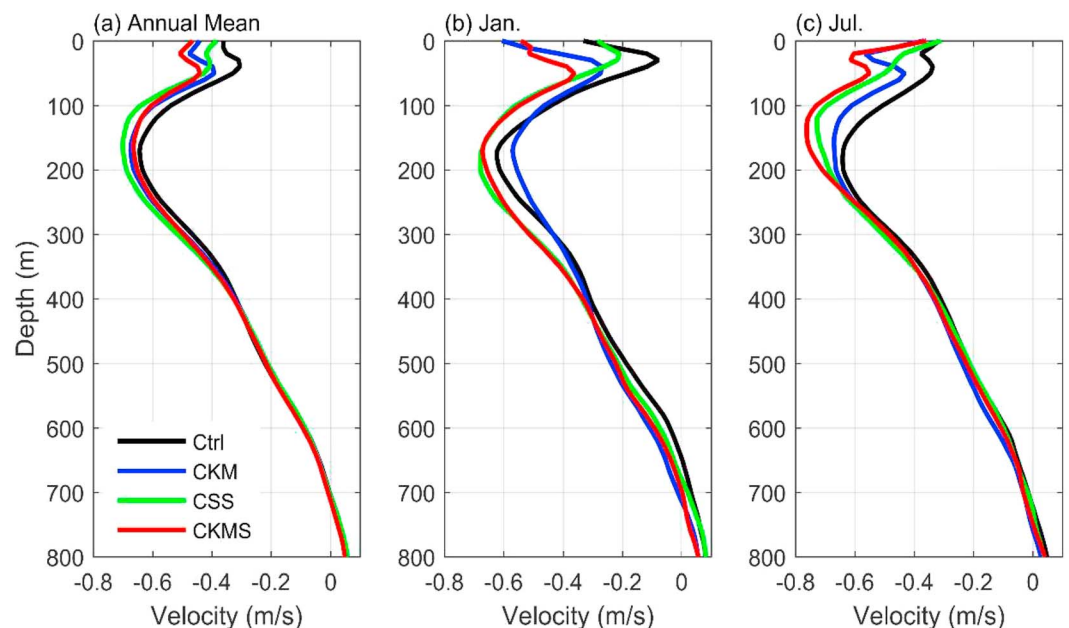


Figure 11. Makassar Strait velocity vertical profile of the control experiment (black line) and sensitivity experiments: (a) annual mean; (b) January mean; and (c) July mean.

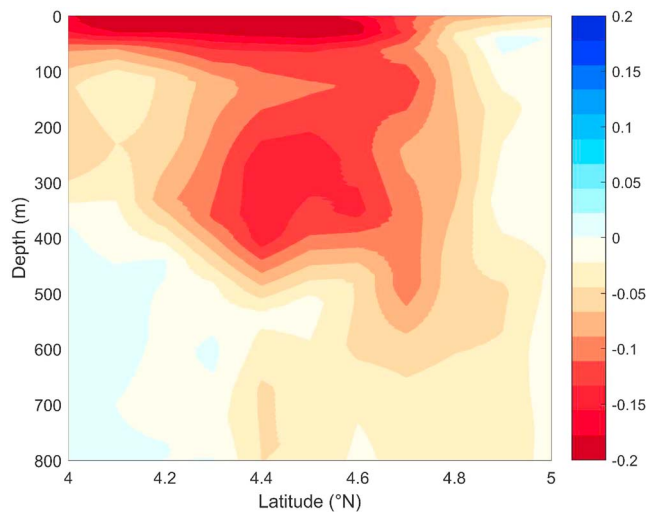


Figure 12. Vertical section difference in U component at 125°E between the CKMS sensitivity experiment and control experiment (CKMS minus control)

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throughflow is reversed, thereby flowing into the SCS. In contrast, the impact of closing the Karimata Strait is limited to the Sunda Shelf of the southern SCS and the Java Sea. This result confirms that the Mindoro-Sibutu deep passage is the major exit point for the SCS freshwater outflowing to the Sulawesi Sea—the so-called “freshwater plug” mechanism proposed by Gordon et al. (2012). Meanwhile, closing the Sibutu Strait produces insignificant changes in the shallow Sunda Shelf, which is primarily driven by local monsoonal winds. Both the Sibutu and Karimata straits are shown to significantly affect the Makassar flow transport and variability. The Sibutu Strait controls the SCS freshwater injection into the ITF within the upper 200 m, while the Karimata Strait injects low-salinity water into the Java Sea within a more confined surface layer (<50 m).

Within the MC, there are many oceanic passages and straits with varying dimensions and depths that connect the SCS with the NMK currents, Indonesian seas, and ITF. Among these passages and straits, some straits/passages are crucial for modulating the inter-ocean exchange, for example, the Luzon Strait (~ 150 -km wide and 2,000-m deep), the Karimata Strait (~ 200 -km wide and 45-m deep), and the Sibutu Strait (~ 40 -km wide and 300-m deep). While ocean general circulation model

reanalysis products have been commonly used in previous studies to interpret the mechanisms determining SCS/ITF variability, their relatively coarse resolutions of 1° – 2° are insufficiently fine to resolve key straits, such as the Mindoro-Sibutu Strait. Therefore, difficulties exist in fully understanding the impacts of these key straits on the surrounding seas and flows.

Due to the insufficient resolution of global ocean models for the MC, very few sensitivity experiments have been conducted with open/closed straits along the SCS and the Indonesian throughflows. Tozuka et al. (2007) is perhaps the only study in which a “NOSCST” experiment was designed by closing the Luzon, Taiwan, Mindoro, and Karimata straits. However, the model resolution at the Mindoro Strait was 0.4° – 2° , which was obviously unable to resolve the Mindoro-Sibutu passage (~ 40 -km wide). Our model results are in accordance with those of Tozuka et al. (2007) in that the Makassar ITF transport is enhanced significantly when blocking the SCSTF, but differences are also apparent. On the one hand, our sensitivity experiments indicate that the Mindoro-Sibutu passage, rather than the Karimata Strait, is the major exit for the SCSTF outflow. On the other hand, the vertical profile of the Makassar flow, with a velocity maximum at the depth of 150 m, is insensitive to closing either the Karimata Strait or the Sibutu Strait, or even both. Our results imply that such a vertical profile might originate from its inflow, the Mindanao Current, which was observed by Zhang et al. (2014) with a similar vertical velocity profile.

The freshwater plug mechanism was first proposed by Gordon et al. (2012), who interpreted the inhibition effect of the SCSTF on the southward ITF by delivering and accumulating SCS freshwater in the Sulawesi Sea surface layer and, thus, building a low-salinity pressure head toward the western Pacific. This speculation is confirmed and validated in our sensitivity experiments by adopting a 0.1° resolution to explicitly resolve the Mindoro and Sibutu straits. As shown in this study, the Sibutu Strait affects not only ITF variability but also the SCS interior circulation pattern. The Luzon Strait inflow is reduced by $\sim 75\%$ if the Sibutu Strait is closed. Although the impact of the Karimata Strait cannot extend to the SCS basin, it does affect the Makassar flow variability in the upper 50 m. When closing the two major SCSTF pathways of the Karimata and Sibutu Straits, the Makassar ITF will be completely controlled by the Mindanao Current inflow.

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