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An overview of 10-year observation of the South China Sea branch of the Pacific to Indian Ocean throughflow at the Karimata Strait

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Abstract

Besides the Indonesian throughflow (ITF), the South China Sea throughflow (SCSTF) also contributes to the water transport from the Pacific to the Indian Ocean. However, this South China Sea (SCS) branch at the Karimata Strait is poorly observed until 2007, even though its importance has been suggested by numerical studies for decades. In this paper, we review the nearly 10-year field measurement in the Karimata Strait by the execution of the projects of "SCS-Indonesian Seas Transport/Exchange (SITE) and Impacts on Seasonal Fish Migration" and "The Transport, Internal Waves and Mixing in the Indonesian Throughflow regions (TIMIT) and Impacts on Marine Ecosystem", which extend the observations from the western Indonesian seas to the east to include the main channels of the ITF, is introduced. Some major achievements from these projects are summarized.

Key words: South China Sea, Indonesian seas, Indonesian throughflow (ITF), Karimata Strait, South China Sea throughflow

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1 Introduction

Ocean circulation plays critical roles in the heat balance around the globe. At its most basic level, the warm water from the tropical Pacific Ocean flows into the Indian Ocean through the Indonesian seas, which in turn joins the Agulhas Current to loop around the Africa and travels northward in terms of the Gulf Stream in the Atlantic Ocean. Upon reaching the North Atlantic, these waters sink and creep southward along the ocean floor. While exiting the Atlantic, it joins the eastward flow in the Southern Ocean, with part of the waters move northward to intrude into the Indian Ocean, whereas most of them enter and cross the Antarctic Circumpolar Current (ACC) to become a source of the Antarctic Bottom Water (AABW). The deep and bottom waters move northward to enter the Pacific Ocean where they upwell, only to seep back into the Indian Ocean through the South China Sea (SCS) and the Indonesian seas at low latitudes. This throughflow from the Pacific to the Indian Ocean joins the Agulhas Current subsequently, making the so called "great ocean conveyor belt" closed (Broecker, 1991; Gordon, 2005; Talley, 2013).

The seepage of warm waters from the equatorial West Pacific Ocean to the Indian Ocean via the Indonesian seas is called the Indonesian throughflow (ITF), which has been long time recognized as a key component of global ocean circulation (Wyrtki, 1961; Gordon et al., 2003; Gordon and Fine, 1996). The driving force of the ITF is the pressure gradient between the West Pacific and the eastern Indian Ocean across the Indonesian seas (Wyrtki, 1961, 1987; Gordon, 1986). The water transport of the Indonesian throughflow is estimated at a low value of 1.5 Sv (1 Sv=10^6 m^3/s) by Wyrtki (1961) and much higher values from 5.1 up to 18 Sv summarized by Gordon (1986) before direct measurements of current are available. Since 1983, expendable bathythermograph (XBT) have been repeatedly used along a section between Fremantle, Australia and Sunda Strait, Indonesian (IX1 section) to measure the upper ocean temperature and monitor the ITF vari-

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*Corresponding author, E-mail: weizx@fio.org.cn ability. With the temperature data from XBT along the IX1 section, Meyers et al. (1995) calculated the mean geostrophic throughflow-transport to be 5 Sv relative to 400 m water depth. This has been followed by more studies and the transport across the IX1 section has been shown to have large uncertainty (Liu et al., 2005, 2015; Wijffels et al., 2008). Satellite altimeter provides a proxy for the ITF transport by empirical formula, which can be used to produce a longer time series for the interannual variability of ITF (Potemra, 2005; Sprintall and Révelard, 2014; Susanto and Song, 2015).

Direct measurements of the ITF come from the International Nusantara Stratification and Transport (INSTANT) program from 2004 to 2006 (Sprintall et al., 2004, 2009; Gordon et al., 2010) and earlier Arlindo program from 1996 to 1998 (Gordon and Susanto, 1999; Susanto and Gordon, 2005). When the INSTANT program ended in 2006, a single mooring in the Makassar Strait was carried through (Susanto et al., 2012). Meanwhile, a mooring array in the Timor Passage was operated to monitor the ITF as part of the Australian Integrated Marine Observing System (IMOS) since 2007 (Moltmann et al., 2010; Moltmann, 2011). The efforts of direct velocity measurements of the ITF provide better estimation of the ITF, improving our knowledge about the ITF and its relationship with the Indian and Pacific climate (Sprintall and Révelard, 2014; Van Sebille et al., 2014; Yuan et al., 2011, 2013).

The other passage for the throughflow from the Pacific to the Indian Ocean is through the SCS, with inflow of clod and salty water via the Luzon Strait and outflow of warm and fresh water via the Karimata Strait (Fang et al., 2003, 2005, 2009; Qu et al., 2005, 2009; Du and Qu, 2010). The outflow waters then travel eastward and southward to join the main route of the ITF and flow into the Indian Ocean through the Sunda Strait, respectively (Fang et al., 2010; Susanto et al., 2013). This passage is referred as the SCS branch of the Pacific to Indian Ocean throughflow or the SCS throughflow (Fig. 1a) (Fang et al., 2003, 2005; Qu et al., 2005; Wang et al., 2006). The SCS branch or SCS Throughflow is an important conveyor for bring the signals from the Pacific to the SCS, which can influence the SCS circulation or even to reach at the eastern Indonesian seas and the Indian Ocean (Qu et al., 2004, 2006; Liu et al., 2011).

The water transport across the Karimata Strait derived from numerical simulations are between 1.3 and 4.4 Sv from the SCS to the Java Sea (JS) in boreal winter, and between 0.3 and 2.1 Sv from the JS to the SCS in boreal summer, respectively (Lebedev and Yaremchuk, 2000; Cai et al., 2005; Fang et al., 2005; Yaremchuk et al., 2009; Xu and Malanotte-Rizzoli, 2013; He et al., 2015). Although the volume transport of the SCS branch is relatively smaller than the ITF, the heat and freshwater transports by it could be up to 0.2 PW and 0.1 Sv (Qu et al., 2006; Fang et al., 2009), comparable to the heat transport of 0.41 PW for the ITF (Vranes et al., 2002). The significant heat and freshwater transports make the SCS branch play an important role in the modulation of ITF variability (Tozuka et al., 2007, 2009; Gordon et al., 2012). For example, the freshwater transported by the SCS branch can affect the ITF vairiability in two aspects: it contributes to the total ITF, and at the same time it reduces the ITF by inhibiting the main ITF through the Makassar Strait (Fang et al., 2010; Gordon et al., 2012). Numerical experiment shows that blocking the SCSTF would warm the SCS, and change the period of the El Niño-South Oscillation (ENSO) (Tozuka et al., 2015). Meanwhile, numerical experiment of blocking SCSTF results in significant changes of the Pacific low-latitude western boundary current system including the Kuroshio and Mindanao Currents as well as the North Equatorial Current bifurcation (Wang et al., 2011a). In addition, the phytoplankton community and environmental parameters in the Sunda shelf are found influenced by the SCS branch transport (Ke et al., 2014), which in turn influence the local fishery (Hendiarti et al., 2004, 2005).

So far, most of the investigations about the SCS branch of the throughflow at the Karimata Strait rely on the numerical simulation. The only *in situ* observation was done more than 50 years ago by Wyrtki (1961) until the “SCS-Indonesian Seas Transport/Exchange (SITE) and Impact on Seasonal Fish Migration” project was initiated jointly by researchers from China, Indonesia, and the United State in October 2006 (Fang et al., 2010; Susanto et al., 2010). Based on the observation of the first stage of the SITE cruise, the volume, heat and freshwater transport from the SCS to the Indonesian seas are estimated at 3.6 Sv, 0.36 PW, and 0.14 Sv during 13 January to 12 February 2008, respectively (Fang et al., 2010; Susanto et al., 2013). Up to 2016, a total of 19 cruises have been accomplished, providing nearly 10 years of time series for the current velocities at the Karimata Strait. A detailed description of the SITE project is introduced in Section 2. Section 3 introduces the project entitled “The Transport, Internal Waves and Mixing in the Indonesian Throughflow Regions (TIMIT) and Impacts on Marine Ecosystem”, which extend the observation from western Indonesian seas to the east to include the main channels of ITF such as the Lombok and Makassar Straits. Achievements from the SITE and TIMIT projects are reviewed in Section 4. Section 5 is a summary.

2 The SITE project

In view of a lack of any direct observations of the SCS branch in the Karimata Strait, researchers from the First Institute of Oceanography (FIO), Ministry of Natural Resources of China, the Agency for Marine & Fisheries Research (AMFR), Ministry of Marine Affairs and Fisheries of Indonesia, and the Columbia University and University of Maryland from the United States, conducted a collaborative observing project, the South China Sea-Indonesian Seas Transport/Exchange (SITE), to explore the heat and freshwater fluxes between the SCS and the Indonesian seas through the Karimata Strait. The Karimata Strait is located between the southern SCS and the Java Sea with a mean water depth shallower than 50 m (Fig. 1a). The Gaspar Strait is located between the Bangka Island and Belitung Island. The Karimata Strait is located between Bilitung Island and Kalimantan Island (Fig. 1b).

The first two cruises were carried out between December 2007 and January 2008, during which there were two Trawl Resistant Bottom Mounts (TRBMs) deployed at A1 and A2 in the Karimata Strait (Fig. 1b). The TRBM at A1 was carried a LinkQuest Inc. 600 kHz acoustic Doppler Current Profile (ADCP), and a RBR Ltd. Temperature-pressure logger. The configuration of the TRBM at A2 was same as that at A2 except that a Sea-Bird conductivity-temperature-pressure recorder was used instead of the RBR logger. The averaged depths at A1 and A2 are 36.6 and 48.0 m, respectively, as measured from the pressure sensors. Both TRMBs were equipped with an acoustic modem to communicate with the ship-deck to retrieve data from the ADCP in case of TRBM cannot be recovered in the next cruise. The third cruise only retrieved the data from the ADCP in both Stas A1 and A2, with the TRBMs remain under service. The TRBMs were recovered in the fourth and fifth cruises in May 2008 for A1 and November 2008 for A2, respectively.

Since November 2008, the SITE project was extended to in-

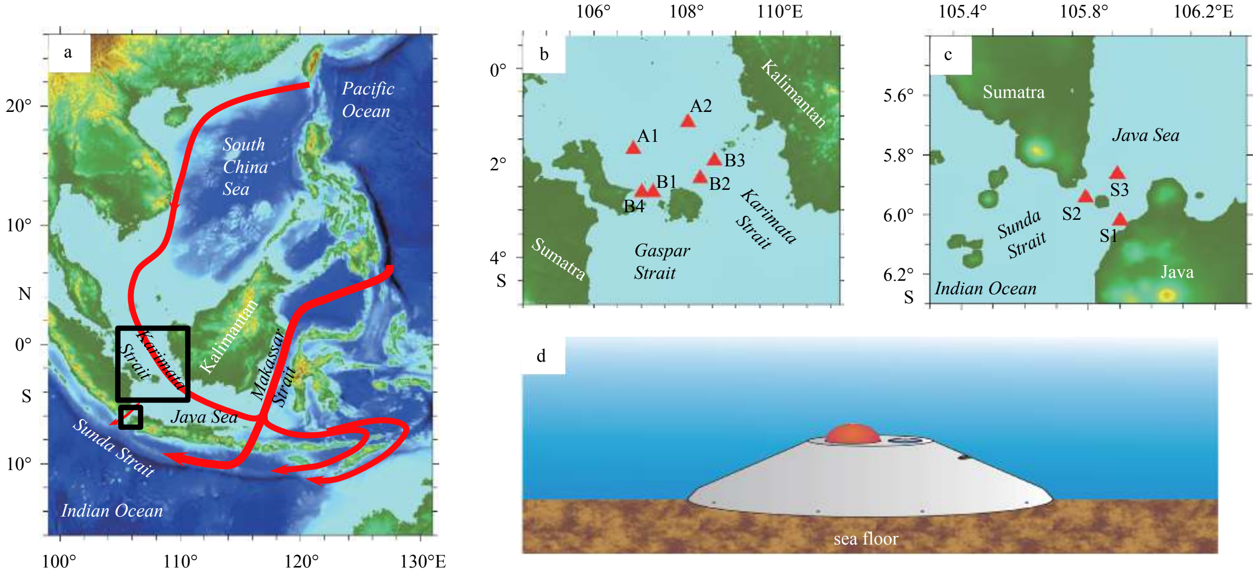


Fig. 1. Schematic map of the Indonesian throughflow (solid) and the South China Sea branch (dashed) of the Pacific to Indian Ocean throughflow (a), TRBM stations in the Karimata Strait (b), TRBM stations in the Sunda Strait (c), and TRBM deployed on the sea floor (d).

clude the Sunda Strait with the consideration of their impacts on seasonal fish migration. Moreover, in order to depict detailed feature of the Karimata throughflow, the stations were changed to B1 in the Gaspar Strait between the Bangka Island and Belitung Island, and B2 and B3 in the Karimata Strait between the Belitung Island and Kalimantan Island in the subsequent observations (Fig. 1b). During the 12th cruise in June 2012, we deployed an additional TRBM at B4 in the Gaspar Strait, hence the maintenance of TRBMs at B1–B4 and B2–B3 were continued until May 2016. In the Sunda Strait, a total of three TRBMs stations were selected (Fig. 1c). All the TRBMs along Section B and in the Sunda Strait were equipped with an upward-looking ADCP (Fig. 1d). There were different types of ADCP including Flowquest 300 kHz, RDI Inc. 300 or 600 kHz ADCP being opted for each of the TRBMs. These TRBMs were repeatedly recovered and redeployed from 2008 through 2016 at the same positions in the Karimata Strait and Sunda Strait. So far, a total of 19 cruises have been accomplished (Table 1).

Throughout the SITE period, over 250 CTD casts were taken within the Karimata, Sunda and Lombok Straits (Fig. 2a). After the 13th cruise, the interaction between the SCS branch and the ITF has been considered. Whereafter, we carried out the 14th cruise to deploy a subsurface mooring equipped with two Flowquest 150 kHz ADCP and a SBE 37 CTD in the Lombok Strait. The CTD casts (Fig. 2a), mixing measurement using TurboMAP (Fig. 2b) and five section of towed vehicle (Fig. 2c) were done during the cruise. The towed vehicle carried multi-sensors including temperature, conductivity, pressure, chlorophyll *a*, turbidity, dissolved oxygen, pH and nutrients (Cui et al., 2010; Wang et al., 2011b). The towed vehicle was operated to draw undulating profiles at a range of 20–200 m along the section.

3 TIMIT project

The INSTANT program deployed 11 subsurface mooring in the main inflow and outflow passages, i.e., the Makassar, Lombok, Ombai Straits and the Lifamatola and Timor Passages. However, it overlooked the Karimata Strait, and the mooring in the Lifamatola Passage only covers the water depth greater than 1 250 m. The lack of observations in these places leads to the nonconservation around 2.3–3 Sv for the inflow and outflow transport of the ITF. Therefore, synchronized observations covering the entire water column in the inflow passages (Karimata, Makassar and Lifamatola) and outflow passages (Sunda, Lombok, Ombai, Savu and Timor) are required. Meanwhile, the Indonesia is concerned about how the ITF dynamics impacts on the marine ecosystem of the surrounding seas. Hence, as an integral part of the arrangement between China and Indonesia for the Indonesia-China Center for Ocean and Climate (ICCOC), the plan of operation for “The Transport, Internal Waves and Mixing in the Indonesian Throughflow regions (TIMIT) and Impacts on Marine Ecosystem” was signed by scientist from FIO and AMFR in December 2013. The TIMIT project is proposed under these circumstances to observe long-term current velocity profile time series in the Makassar, Lombok and Ombai Straits, and the Lifamatola Passage. Combined with the observations of SITE in the Karimata and Sunda Straits and that in the Timor Passage by the IMOS, it will be possible to quantify the total inflow and outflow of the Pacific to Indian Ocean throughflow and related processes within the Indonesian seas. The first cruise of the TIMIT project was carried out in October 2015, during which three subsurface moorings were deployed in the Makassar and Lombok Straits (Fig. 3). The CTD casts, TurboMAP mixing, and towed vehicle sections were also done (Fig. 3). The subsurface mooring in the Lombok and Makassar Straits were recovered in September 2016. The TIMIT project was then suspended due to some reason and no more cruises were carried out. Nevertheless, an independent cooperation between the Institute of Oceanology, Chinese Academy of Sciences (IOCAS) and the Indonesian Institute of Sciences (LIPI) has been established to observe the source of the ITF, and the observation was subsequently extended to the internal Indonesian seas.

4 Achievements based on SITE and TIMIT observations

Based on the early observation of the SITE project at Stas A1

Table 1. Schedule of the SITE cruises

Sequence	Period	Vessel name	Objective
1	1–5 Dec. 2007	R/V *Baruna Jaya IV*	Deploy 1 TRBMs in Karimata, CTD casts
2	10–13 Jan. 2008	R/V *Baruna Jaya I*	Deploy 1 TRBMs in Karimata, CTD casts
3	11–17 Feb. 2008	R/V *Baruna Jaya III*	Retrieve ADCP data from 2 TRBMs via modem in Karimata, CTD casts
4	5–13 May 2008	R/V *Baruna Jaya VIII*	Recover 1 TRBMs in Karimata, CTD casts
5	23 Oct.–10 Nov. 2008	R/V *Baruna Jaya VIII*	Recover 2 TRBMs in Karimata, deploy 3 TRBMs in Karimata and 2 in Sunda, CTD casts
6	7–21 Aug. 2009	R/V *Geomarin III*	Recover 3 TRBMs in Karimata and 2 in Sunda, CTD casts
7	11–26 Oct. 2009	R/V *Geomarin III*	Recover 3 TRBMs in Karimata and 2 in Sunda, CTD casts
8	17 Feb.–3 Mar. 2010	R/V *Geomarin III*	deploy 2 TRBMs in Sunda, CTD casts
9	5–19 Nov. 2010	R/V *Madidihang*	Recover 3 TRBMs in Karimata and 3 in Sunda, deploy 1 TRBMs in Karimata and 1 in Sunda, CTD casts
10	13 Sep.–8 Oct. 2011	R/V *Baruna Jaya VIII*	Recover 2 TRBMs in Karimata and 3 in Sunda, deploy 1 TRBMs in Karimata and 1 in Sunda, CTD casts
11	7–29 Jun. 2012	R/V *Baruna Jaya III*	Recover 1 TRBMs in Karimata and 3 in Sunda, deploy 4 TRBMs in Karimata, CTD casts
12	20–29 Nov. 2012	R/V *Baruna Jaya VIII*	Recover 4 TRBMs in Karimata, deploy 4 TRBMs in Karimata, CTD casts
13	28 Jun.–7 Jul. 2013	R/V *Baruna Jaya VIII*	Recover 4 TRBMs in Karimata and 1 in Sunda, deploy 4 TRBMs in Karimata, CTD casts
14	15–24 Nov. 2013	R/V *Baruna Jaya VIII*	deploy 1 subsurface mooring in Lombok, CTD casts
15	18 Apr.–4 May 2014	R/V *Baruna Jaya IV*	Recover 4 TRBMs in Karimata, deploy 4 TRBMs in Karimata, CTD casts
16	10–21 Sep. 2014	R/V *Baruna Jaya VIII*	Recover 1 subsurface mooring in Lombok, CTD casts, Towed CTD, TurboMAP turbulence
17	18–25 Dec. 2014	R/V *Baruna Jaya VIII*	Recover 4 TRBMs in Karimata, deploy 4 TRBMs in Karimata, CTD casts
18	2–20 Jun. 2015	R/V *Baruna Jaya VIII*	Recover 4 TRBMs in Karimata, deploy 4 TRBMs in Karimata and 2 in Sunda, CTD casts
19	17–28 May 2016	R/V *Baruna Jaya VIII*	Recover 4 TRBMs in Karimata and 2 in Sunda, CTD casts

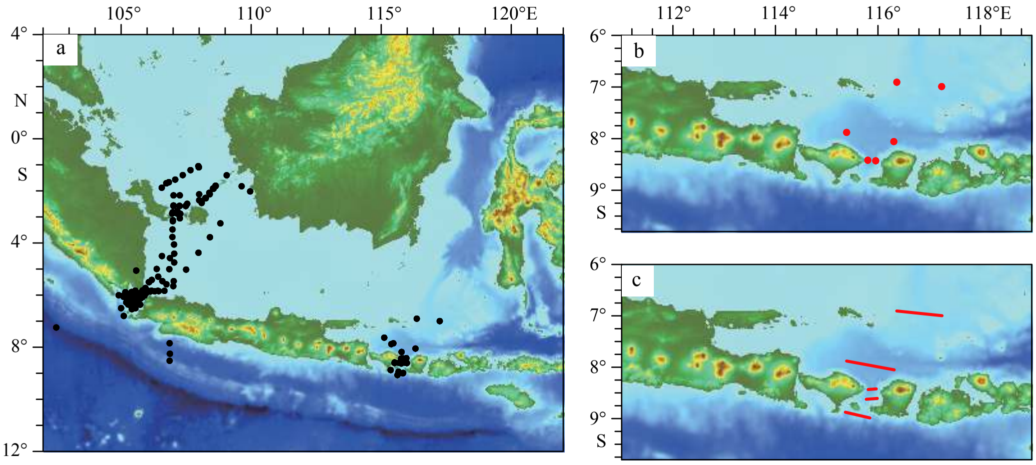


Fig. 2. CTD stations (a), TurboMAP stations (b) and towed vehicle sections (c).

and A2, the volume, heat and freshwater transport from the SCS to the Indonesian seas are estimated to be 3.6 Sv, 0.36 PW, and 0.14 Sv during 13 January to 12 February 2008, respectively (Fang et al., 2010). The mean along-channel velocity, temperature, and salinity during 13 January to 12 February 2008 are shown in Fig. 4. The mean volume, heat and freshwater transport is (–2.7±1.1) Sv, (–0.30±0.11) PW, and (–0.18±0.07) Sv during boreal winter (December 2007 to March 2008), and (1.2±0.6) Sv, (0.14±0.03) PW, and (0.12±0.04) Sv during boreal summer (May to September 2008), respectively (Susanto et al., 2013). The along-strait velocity time series for the Karimata Strait during 4 December 2007 to 1 November 2008 are shown in Fig. 5. Throughout the SITE period, the annual mean volume transport through the Karimata Strait is around 0.75 Sv, with significant seasonal and interannual variability (Fig. 6).

The oceanpgraphy in the Sunda Strait is also investigated based on SITE observation (Susanto et al., 2016; Xu et al., 2018; Li et al., 2018). Zonal wind is found to be the dominate force for the water transport across the Sunda Strait. During boreal winter, there is around 0.24 Sv low-salinity water entering the Java Sea through the Sunda Strait to reduce the main ITF in the Makassar Strait. During boreal summer, there are 0.83 Sv lower-salinity water entering the Indian Ocean from the Java Sea (Susanto et al., 2016). The seasonal variability of wind stress and along strait ve-

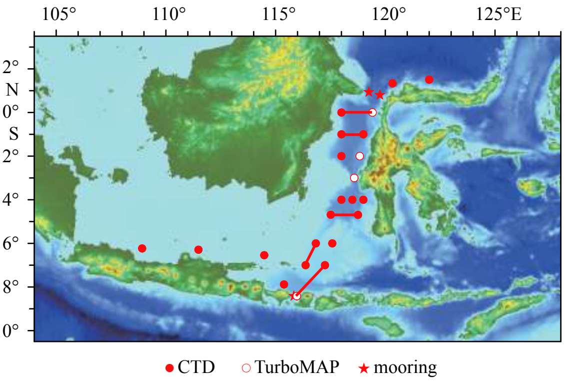


Fig. 3. CTD (solid dot), TurboMAP (dashed dot), subsurface mooring (solid star) stations and towed vehicle sections (solid line) of the first TIMIT cruise.

locity in Sunda Strait are shown in Fig. 7.

In addition, strong intraseasonal variability (ISV) of the current is found in the Sunda Strait (Fig. 8). The ISV accounts for up to 59% of the total subtidal current variance in the Sunda Strait. During the period of observations, the annual mean of intraseasonal exchange rate in the Sunda Strait was (0.26±0.17) Sv. This value is comparable to the seasonal exchange rate of (0.34±0.15) Sv, suggesting that the ISV makes an important contribution to the water exchange between the Java Sea and Indian Ocean (Li et al., 2018).

The ISV of the Sunda Strait throughflow is found to influence the distribution of chlorophyll *a* concentrations in the Sunda Strait (Xu et al., 2018). The chlorophyll *a* concentrations in the south of the Sunda Strait are lower/higher during the inflow/outflow period of the ISV events in March through May (Fig. 9). The mechanism attributes to both the nutrient-rich water transpor-

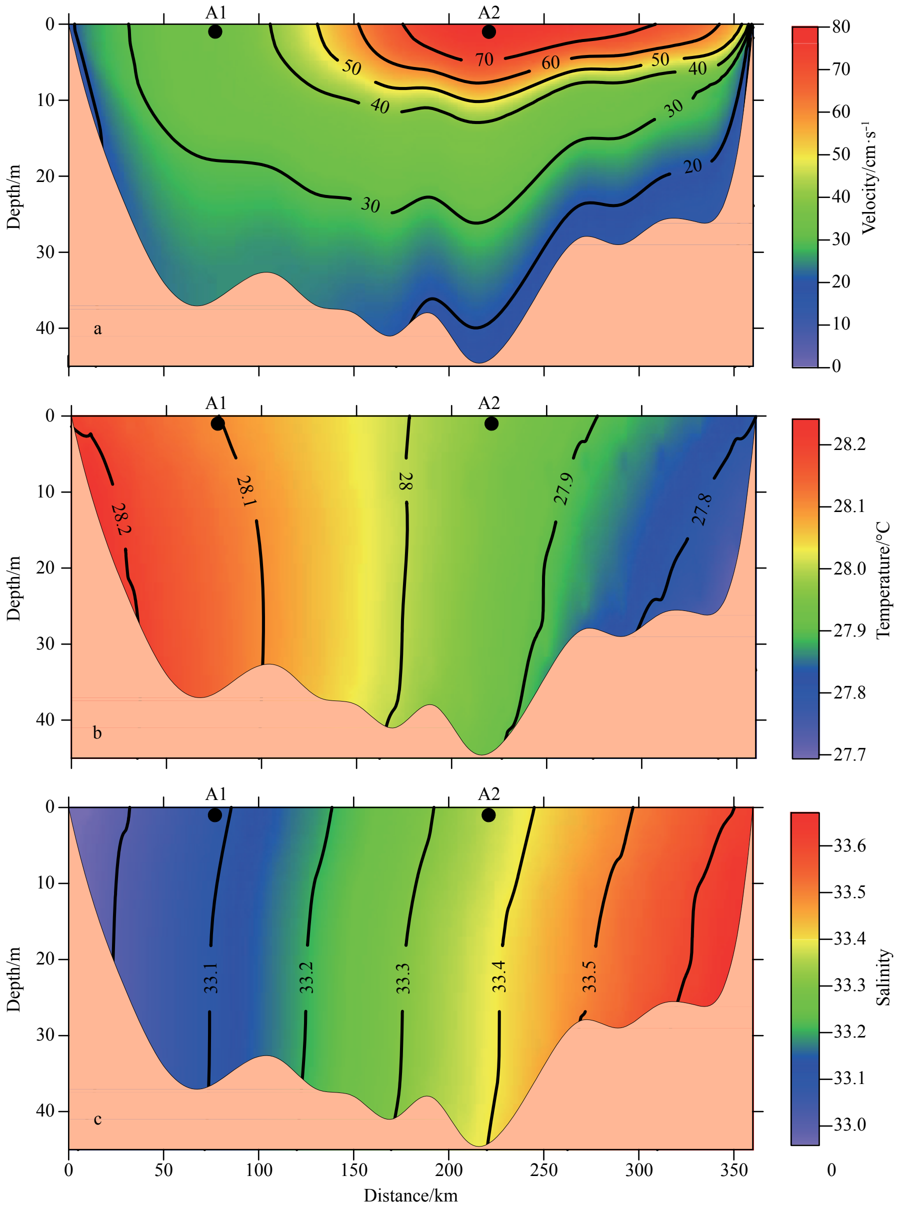


Fig. 4. Distributions of mean along-channel velocity (a), temperature (b), and salinity (c) on Section A for the month from 13 January to 12 February 2008. Bathymetry along the section is based on the nautical chart published by the Indonesian Hydro-Oceanographic Service, with minor adjustment near A1 and A2 based on bottom pressure observations at these two stations (Fang et al., 2010).

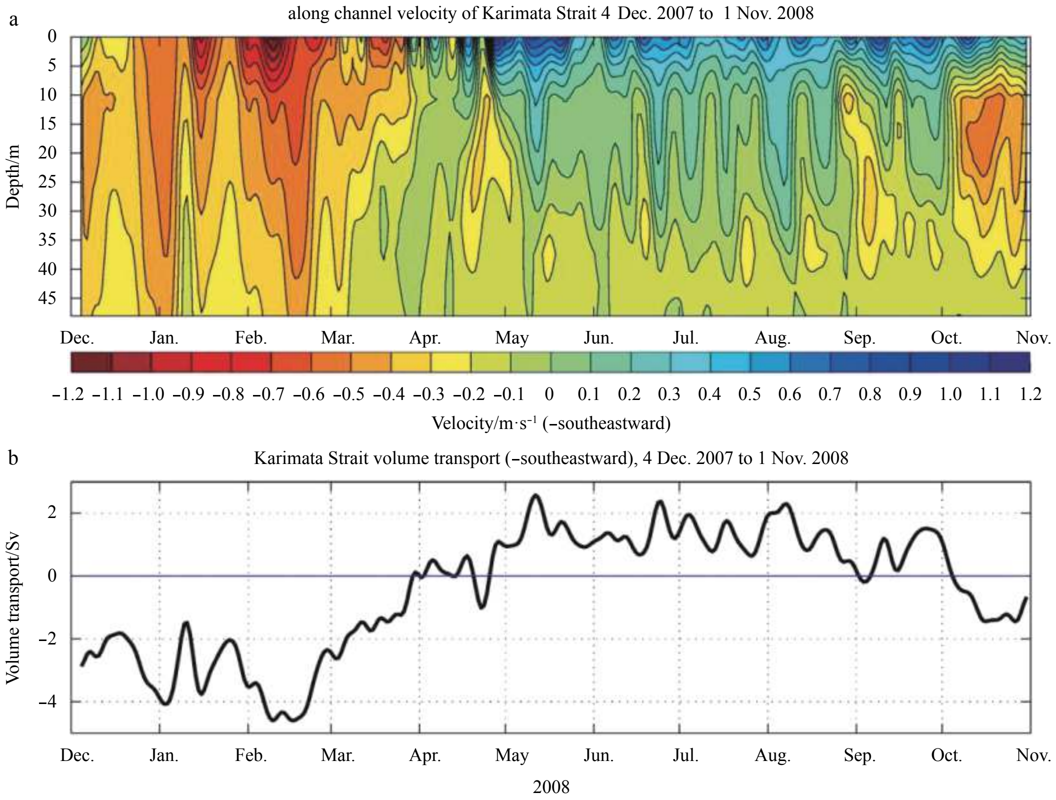


Fig. 5. The along-strait velocity time series for the Karimata Strait derived from the ADCP at the A2 mooring for the period from 4 December 2007 to 1 November 2008 (a), and estimated Karimata Strait volume transport for the same period (b). a. The contour interval is 0.1 m/s, and negative values denote southeastward flow along strait velocity, which is parallel to the axis of the Karimata Strait (154° referenced to true north). b. Negative values indicate water transfer from the South China Sea to the Indonesian seas (Susanto et al., 2013).

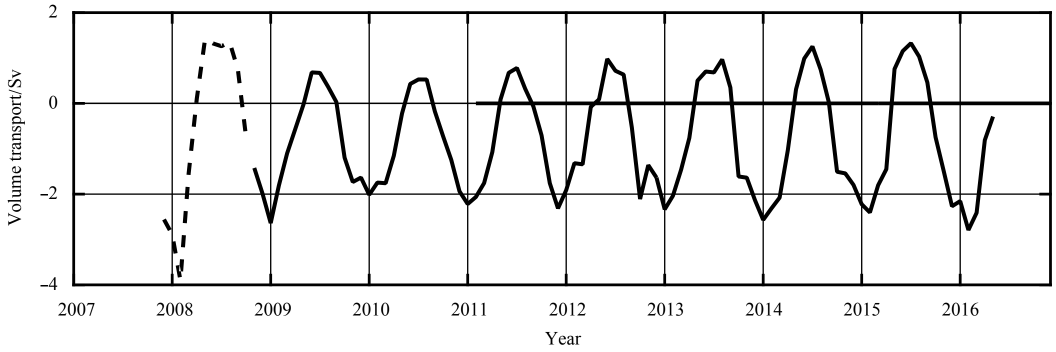


Fig. 6. Volume transport through the Karimata Strait. Dashed and solid lines indicate the transport along Sections A (December 2007 to November 2008) and B (December 2008 to May 2016), respectively.

ted by the intraseasonal flow in the Sunda Strait and by the upwelling and Ekman transport driven by the local sea surface wind anomalies.

The tidal elevation, current and energy flux in the Karimata Strait is investigated using the sea level record and current profile observation (Wei et al., 2016). The results show that the diurnal tides are the dominant constituents in the Karimata Strait, with the largest amplitude greater than 50 cm for the constituent K_1, whereas smaller than 5 cm for the constituent M_2. The tidal currents are rectilinear type in the strait. The diurnal tidal energy flows from the SCS to the JS. The semi-diurnal tidal energy flows from the SCS to the JS through the Karimata Strait and flows from the JS to the SCS through the Gaspar Strait (Fig. 10). These characteristics imply that the Karimata Strait locate in the anti-nodal band of the diurnal tidal waves and in the nodal band of the semidiurnal tidal waves.

5 Summary

The pathway of the throughflow from the Pacific to the Indian Ocean is the only oceanic channel for the heat and salt transport between the two oceans. Moreover, the throughflow region locates on the “21st-Century Maritime Silk Road”, which is the

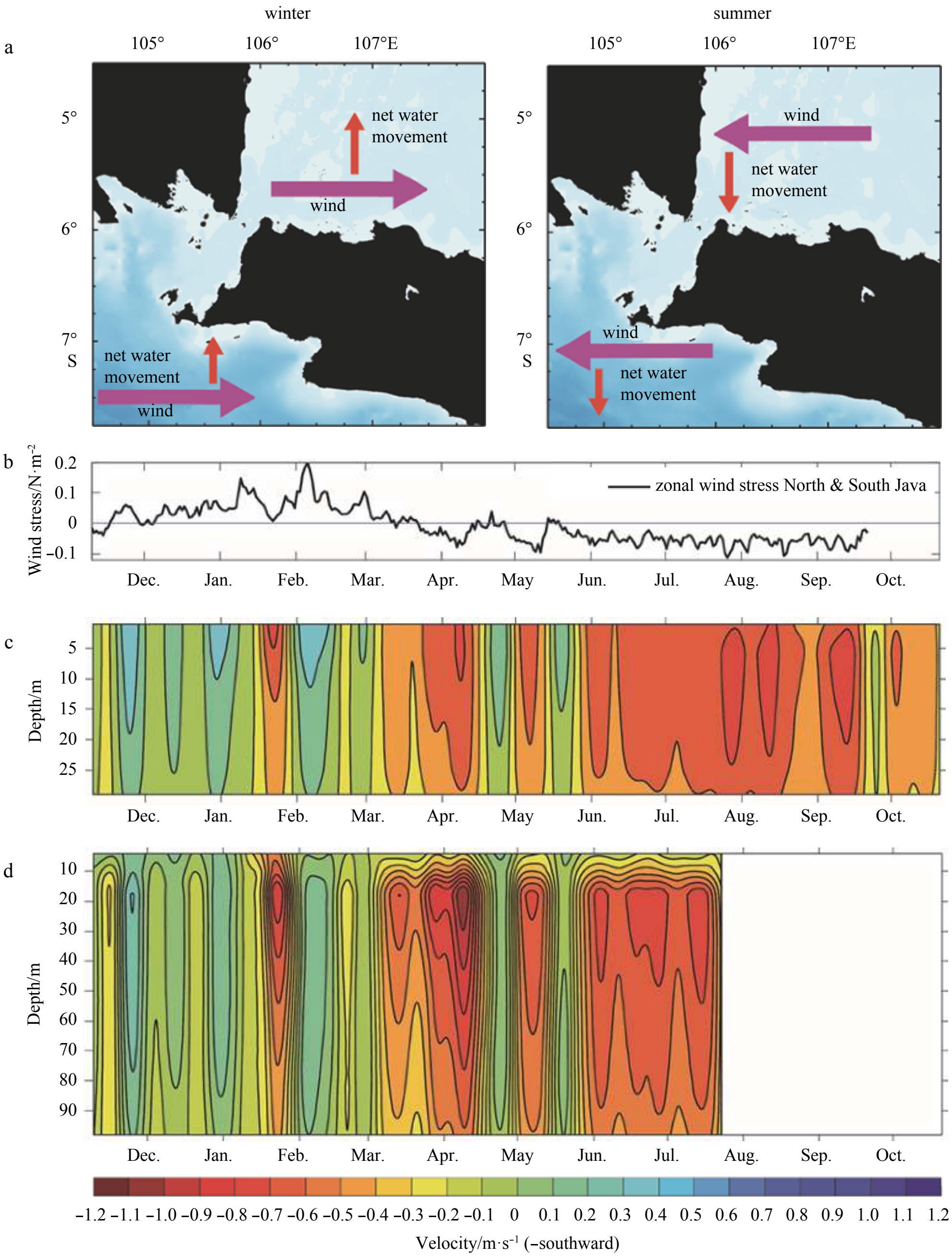


Fig. 7. The variability of wind stress and along-strait current in the Sunda Strait. a. Schematic of Ekman transport in the Southern Hemisphere during boreal winter and summer monsoons. Wind directions are indicated by the purple arrows and their net water transport/displacements, which are 90° to the left of wind directions, by the red arrows. b. Averaged zonal wind stress to the north and south of the Java Island from 12°S to 3°S and 100°E to 115°E. c. Along-strait velocity profile time series in the Sunda Strait based on trawl-resistant, bottom-mounted acoustic Doppler current profiler (ADCP) data collected at Sunda East from November 2008 to October 2009. d. Similar data as in c, based on the Sunda West ADCP from November 2008 to July 2009. For clarity in the velocity plots, a two-week low-pass filter has been applied (Susanto et al., 2016).

key route for the international trade between China and Southeast Asia and Africa countries—over 95% of the cargoes rely on the maritime freightage, most of which are through the Karimata, Makassar, Lombok, Sunda and Maluca Straits. The throughflow regions are strongly influenced by climate or oceanic variability from intraseasonal to interannual timescale (e.g., Madden-Julian Oscillation, Kelvin waves, monsoon, Indian Ocean Dipole, ENSO). Meanwhile, complicated topography and geometry in the throughflow regions resulting in complicate tidal system and wave system, which influence the navigation directly. Although there have been some observations in the Indonesian seas, it is still insufficient. As the importance of the Indonesian seas in marine environment and climate, a new round of monitor the joining area of the Indo-Pacific Ocean is still urgently required and expected to be conducted in the near future.

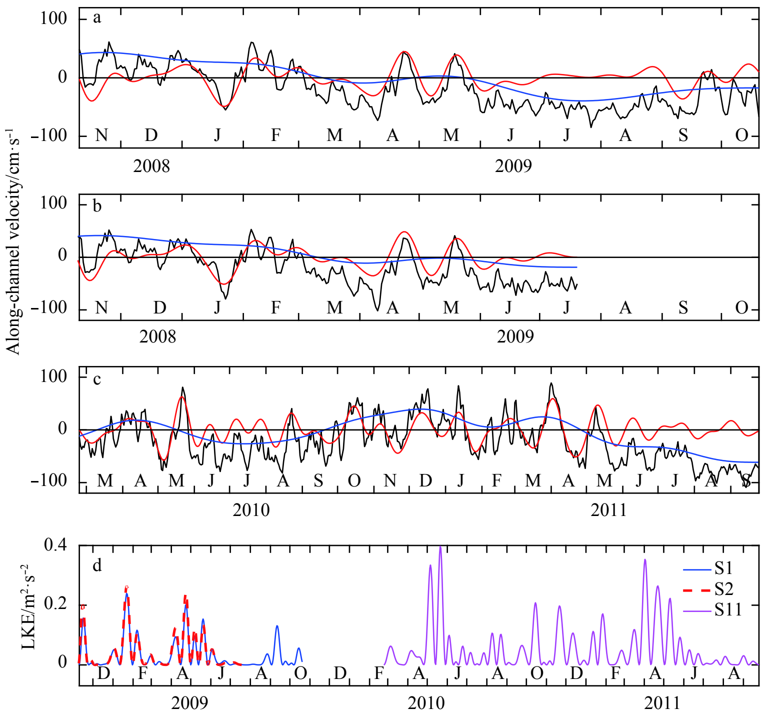
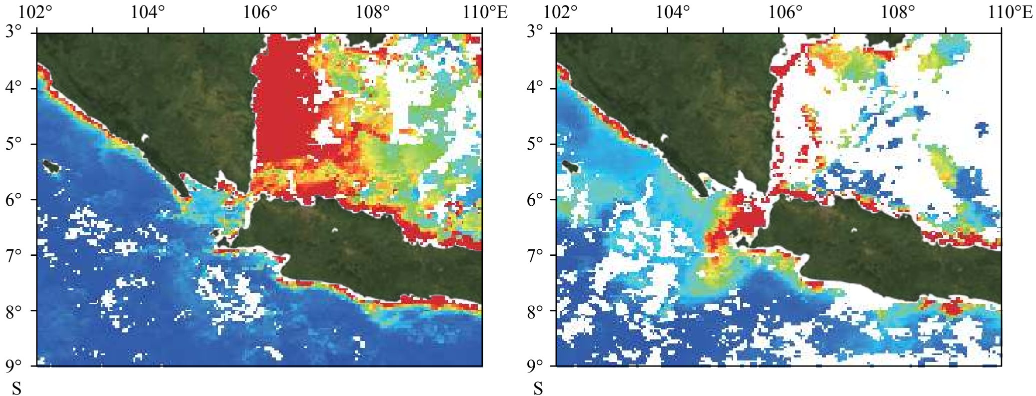


Fig. 8. Time series of vertically averaged along-channel velocities at S1 (a), S2 (b), and S3 (c); and time series of the low-frequency kinetic energy (LKE) at these stations in the Sunda Strait (d). In a, b and c, the black lines indicate the daily mean values; the red lines the intraseasonal variation after 20-90-day bandpass filtering; and the blue lines the seasonal variation after 90-day low-pass filtering. The annual means (–17, –25 and –18 cm/s at S1, S2 and S11, respectively) are removed before plotting. Positive/negative values represent inflow/outflow into/from the Java Sea along the channel (Li et al., 2018).

a. March of +v' events

d. March of –v' events



b. April of +v' events

e. April of –v' events

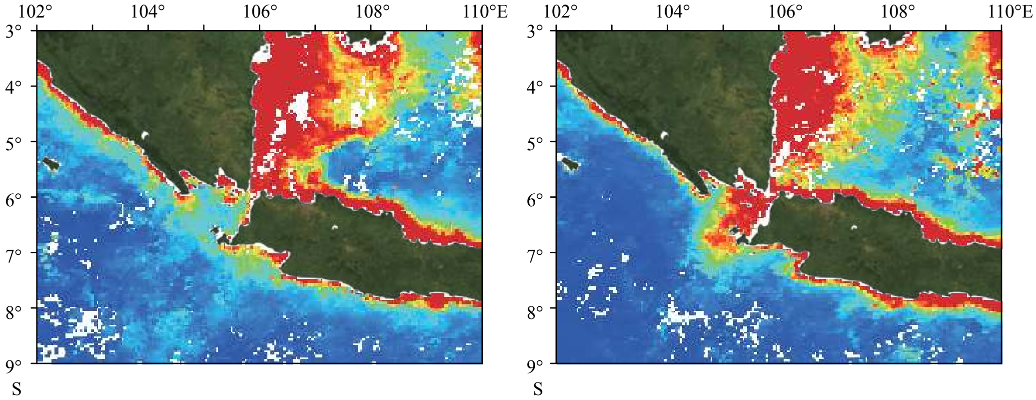


Fig. 9.

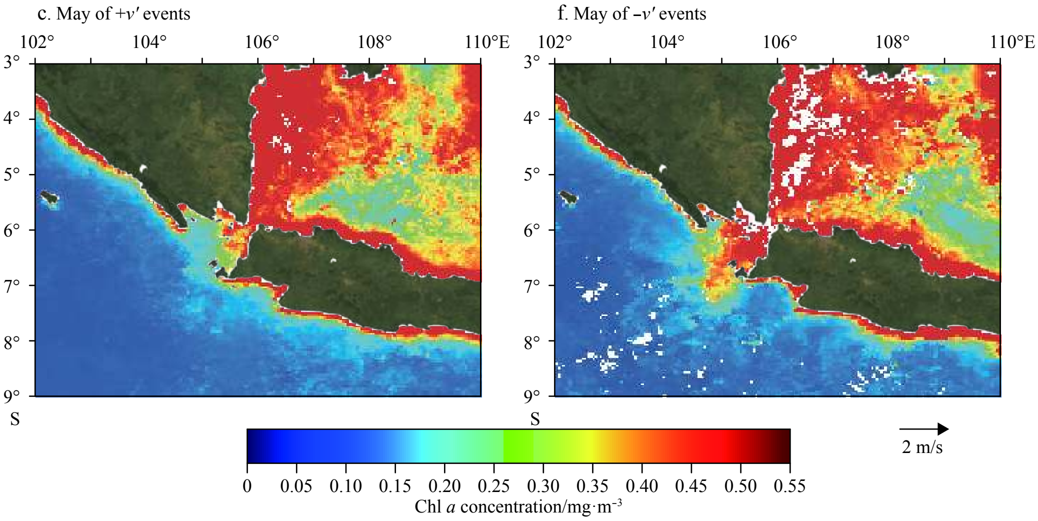


Fig. 9. Composite chlorophyll *a* concentrations (mg/m^3) and sea surface winds (m/s) for positive (a–c) and negative ISV (d–f) events from March through May. The positive and negative ISV events refer to the net inflow (form Indian Ocean to Java Sea) and net outflow (from Java Sea to Indian Ocean) through the Sunda Strait, respectively (Xu et al., 2018). $+v'$ means positive ISV, and $-v'$ negative ISV.

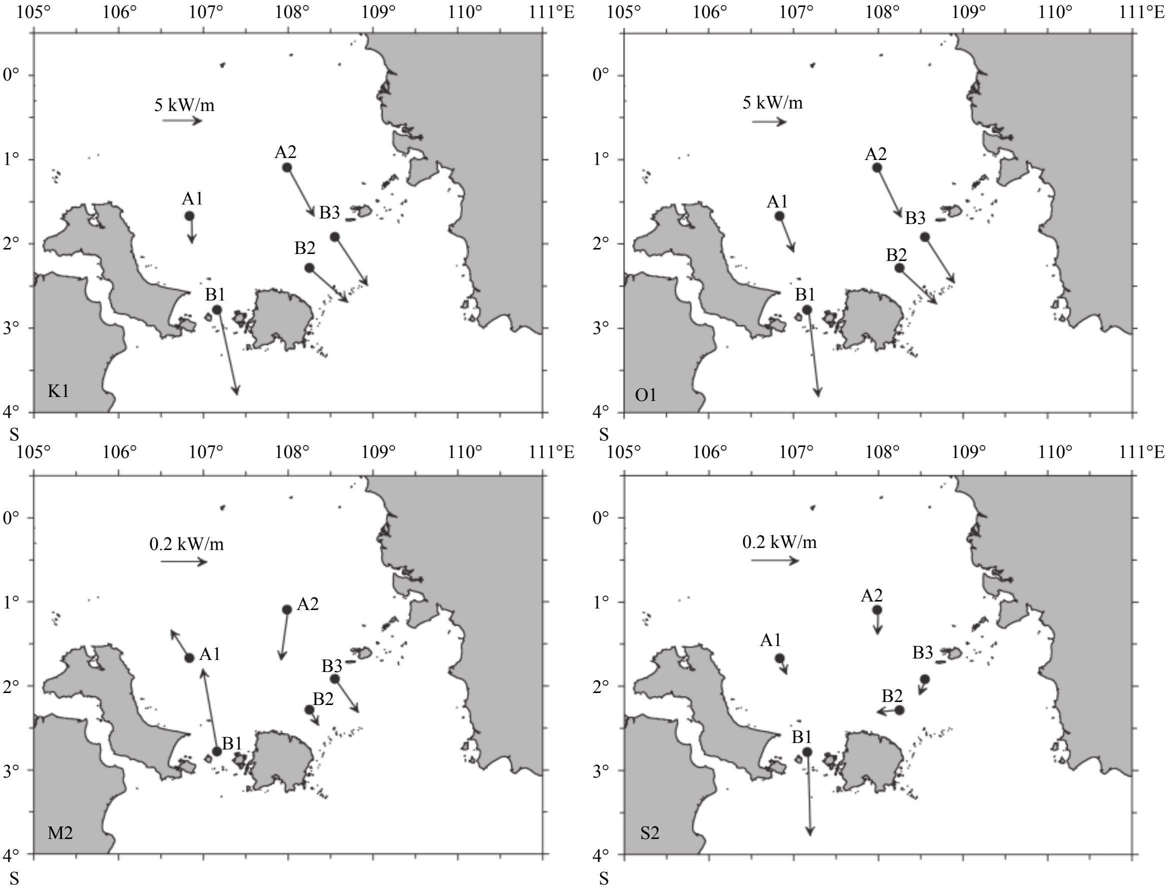


Fig. 10. Horizontal tidal energy flux density across the Karimata Strait derived from sea level record and current profile observations of the SITE project (Wei et al., 2016).

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