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Observations of the Karimata Strait througflow from December 2007 to November 2008

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Abstract
In order to quantitatively estimate the volume and property transports between the South China Sea and Indonesian Seas via the Karimata Strait, two trawl-resistant bottom mounts, with ADCPs embedded, were deployed in the strait to measure the velocity profile as part of the South China Sea-Indonesian Seas transport/exchange (SITE) program. A pair of surface and bottom acoustic modems was employed to transfer the measured velocity without recovering the mooring. The advantage and problems of the instruments in this field work are reported and discussed. The field observations confirm the existence of the South China Sea branch of Indonesian throughflow via the Karimata Strait with a stronger southward flow in boreal winter and weaker southward bottom flow in boreal summer, beneath the upper layer northward (reversal) flow. The estimate of the averaged volume, heat and freshwater transports from December 2007 to March 2008 (winter) is $(-2.7\pm1.1)\times10^6$ m^3/s, (-0.30 ± 0.11) PW, $(-0.18\pm0.07)\times10^6$ m^3/s and from May to September 2008 (summer) is $(1.2\pm0.6)\times10^6$ m^3/s, (0.14 ± 0.03) PW, $(0.12\pm0.04)\times10^6$ m^3/s and for the entire record from December 2007 to October 2008 is $(-0.5\pm1.9)\times10^6$ m^3/s, (-0.05 ± 0.22) PW, $(-0.01\pm0.15)\times10^6$ m^3/s (negative/positive represents southward/northward transport), respectively. The existence of southward bottom flow in boreal summer implies that the downward sea surface slope from north to south as found by Fang et al. (2010) for winter is a year-round phenomenon.

Key words: Karimata Strait transport, Indonesian throughflow, ADCP measurement, acoustic modem

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1 Introduction

In order to quantitatively estimate the volume and property transports between the South China Sea and Indonesian Seas via the Karimata Strait, two trawl-resistant bottom mount (TRBM) ADCPs were deployed in the strait (Fig. 1) to measure the velocity profile as part of the South China Sea-Indonesian Seas transport/exchange (SITE) program (Fang et al., 2010; Susanto et al., 2010). The SITE flow is one of the branches of the Indonesian throughflow (ITF), the seepage of warm tropical waters from the western Pacific Ocean into the Indian Ocean. The ITF has long been recognized as a key component of global ocean circulation, and the heat, freshwater, and nutrients carried by the ITF impact the basin budgets of both the Pacific and Indian Oceans (e.g., Bryden and Imawaki, 2001; Hirst and Godfrey, 1993; Potemra et al., 1997; Schneider, 1998; Susanto and Marra, 2006). Hence, scientists' ability to accurately estimate ITF variability is essential to understanding global ocean circulation and climate.

Although the studies of the ITF have been conducted for more than two decades, the SITE flow (Fig. 1) has been ignored in the past surveys because of its shallow water depths, which caused many to assume that it had no effect on the main ITF. However, scientists now know that the Karimata Strait plays an important role in the seasonal magnitude and variability of the main ITF (Fang et al., 2005; Fang et al., 2010; Gordon et al., 2003; Gordon et al., 2012; Qu et al., 2005; Qu et al., 2006; Wang et al., 2006; Tozuka et al., 2007; Tozuka et al., 2009; Susanto et al., 2010). Nevertheless, the numerical estimates of the Karimata Strait transport still contain great uncertainty (e.g., Lebedev and Yaremchuk, 2000; Fang et al., 2009; Yaremchuk, 2009; Tozuka et al., 2009). In addition, there have been no observation-based estimates of South China Sea throughflow, until recently when the SITE program was launched (Fang et al., 2010; Susanto et al., 2010). Based on one month's data from trawl-resistant bottom mount (TRBM) at the A1 (Fig. 1) in January-February 2008, Fang et al. (2010) concluded that the SITE volume, heat and freshwater transport could reach $(3.6\pm0.8)\times10^6$ m^3/s, (0.36 ± 0.08) PW, and $(0.14\pm0.04)\times10^6$ m^3/s, respectively. In this paper, we will give a detailed description of the field work, and present an analysis of nearly one year's worth of observation data on the SITE flow in the Karimata Strait, from December 2007 to November 2008.

Measuring velocity profiles using the ADCP in shallow water tropical regions, such as the Indonesian seas, presents many

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daunting challenges and risks, especially for long-term deployments, including high biofouling rates, high corrosion rates, large amounts of underwater cable and pipe routes, busy shipping lanes and high fishing activity/damage by trawlers, as well as spontaneous release and relocation. Soft bottom conditions may add an increased risk for the TRBM to become submerged in the mud. One possibility to overcome these challenges is to use a pair of omni-directional surface-bottom modems. The bottom modem is installed inside the TRBM ADCP housing while the surface modem on the ship is used to communicate to the bottom modem, which enables researchers to upload data.

In this paper, we discuss observation of the SITE flow in the Karimata Strait using the TRBM ADCP with a LinkQuest onmi-directional modem. The ADCP data were retrieved using a pair of the LinkQuest suface-bottom modems. First, we present the TRBM configuration and field measurements, and then we discuss the results of the velocity profile and estimate Karimata Strait volume transport from December 2007 to November 2008. We conclude with a summary of the main findings.

2 TRBM configuration and field measurements

2.1 *TRBM configuration*

Ideally, oceanographers would like to have a high resolution velocity profile of a water column from the ocean bottom to the surface at real/near-real time. Unfortunately, oceanographers must wait the entire duration of the deployment period (which can be weeks, months and even two years) before they are able to obtain and analyze the ADCP data. Advances in the ADCP and acoustic modem technology have created a new research opportunity for oceanography. Especially in the shallow water, where the ADCP can be mounted on the bottom using the TRBM, ADCPs can provide time series of current measurements with high vertical resolution from near surface to near bottom in water depths that include most of the world's continental shelves (e.g., Perkins et al., 2000; Book et al., 2005). In the first phase of the SITE program, two TRBMs were deployed in the Karimata Strait (Fig. 1) on 4 December 2007 using R/V *Baruna Jaya* IV, operated by the Agency for Assessment and Application of Technology (BPPT), Indonesia. The TRBM at Sta. A2 (Fig.1) was equipped with a LinkQuest 600 kHz ADCP, Seabird microcat 37SMP conductivity-temperature-pressure recorder, two ORE-CART acoustic releases, a pair of LinkQuest UWM2000 omni-directional modems, and a Xeostech GPS marine beacon. The TRBM at Sta. A1 carries the exact same equipment as the one at A2, except that the Seabird microcat was replaced by a RBR temperature-pressure logger.

The bottom modem is used to communicate with the ship-deck surface modem to set ADCP measurement parameters and/or retrieve data, for example, using a small ship without recovering the TRBM and/or in case TRBM cannot be recovered (Fig.2). The bottom modem is connected to the ADCP via an RS232 cable while the surface modem is connected to a PC on the ship or land via an RS232 cable. The surface modem should be powered by a DC power supply (12–24 V), while the bottom modem uses the FlowQuest ADCP internal battery or an external underwater DC power supply.

One advantage of using the FlowQuest ADCP in comparison with other brands is the option of saving the ADCP data into a smaller size file of 500 kb/dataset, which is essential to downloading data via modem with a limited communication/baud rate. Depending on environmental conditions, e.g., currents and turbidity, the baud rate is automatically adjusted up to a maximum of 9 600 bits per second with the operating frequency of 26.775–44.625 kHz.

The challenge during data retrieval is maintaining the ship in a stable position relative to the mooring. In order to keep a continuous connection between the surface and bottom modems, the ship must be within a radius of 4–5 (theoretically 7–8, the closer the better) times the water depth. It is recom-

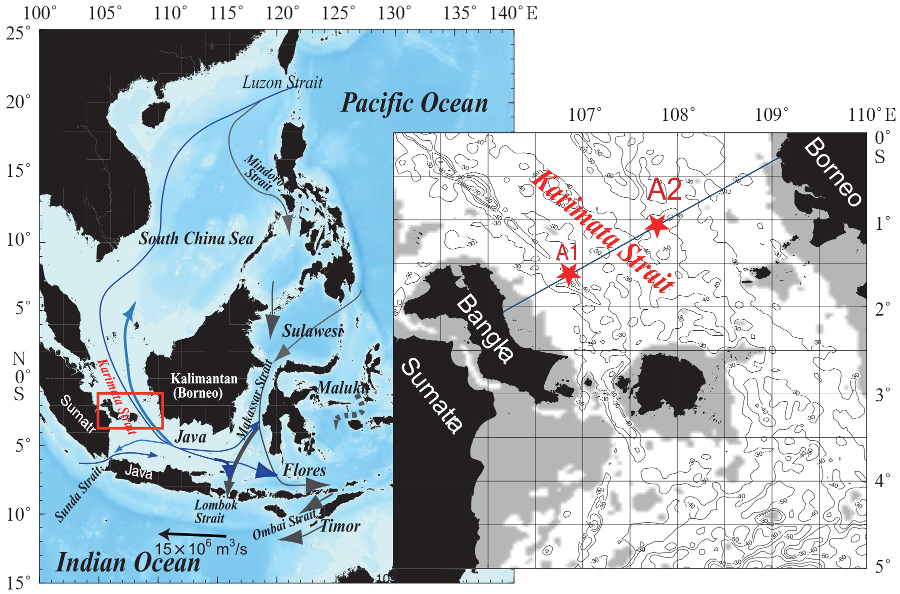

Fig.1. South China Sea-Indonesian Seas throughflow pathway through the Karimata Strait (red-box). Trawl resistant bottom mounted ADCP locations (A1 and A2 inset) in the Karimata Strait.

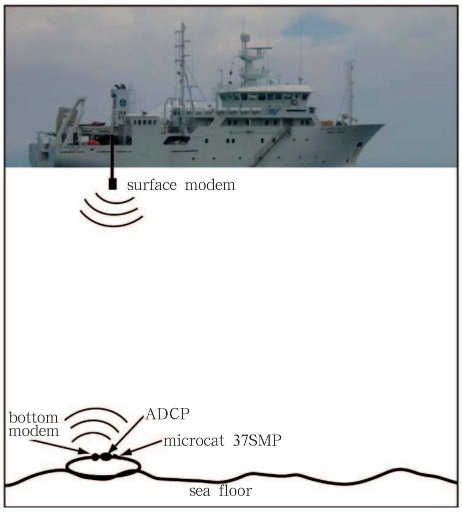

Fig.2. Schematic of surface and bottom modem configuration during data retrieval from R/V *Baruna Jaya* VIII. The TRBM is equipped with the ADCP, bottom modem, Microcat 37SMP, GPS beacon, and acoustic releases.

mended that the surface modem should be attached to a fixed platform on the ship. After the surface modem on the deck of the ship has been powered up and started, synchronization commands are sent to the bottom modem. With stable communication between the surface and bottom modems, we are able to run the FlowQuest ADCP software, which enable us to extract data as if we were connected to the ADCP via cable in a laboratory setting, i.e., configure deployment parameter settings, upload data, or stop deployment, etc.

2.2 *Field measurements*

The TRBMs at A2 and A1 were deployed in the Karimata Strait on 4 December 2007 and 12 January 2008, respectively (Fig. 1). The ADCP parameters were set to record the velocity of the water column with bin size of 1 m for A1 and 2 m for A2. The sampling intervals were 20 min for A1, and 10, 20 and 40 min for A2 for the periods from 4 December 2007 to 12 January 2008, 15 February to 10 May 2008, and 11 May to 1 November 2008, respectively. All the changes to the ADCP parameters were made via modem.

The A1 TRBM was recovered on 9 May 2008 and the A2 TRBM was recovered on 1 November 2008. The A2 ADCP data have about one month gap from 12 January to 15 February 2008, due to failure in setting the ADCP measurement parameters. In February 2008, we were able to retrieve the ADCP data from both the A1 and A2 TRBMs via modem. In May 2008, we planned to recover both A1 and A2, however, only A1 was able to be recovered. The A2 TRBM was submerged in the soft bottom. Again, using the modem we were able to retrieve the ADCP data from Sta. A2 and changed the sampling interval to 40 min, in order to conserve the battery. The main problem in transferring the ADCP data using an acoustic modem is the low communication rate, especially in a strait with strong current and turbid water. It took us more than 6 h to retrieve the A2 ADCP data because occasionally we lost the connection between the surface and bottom modems and the ship needed to be repositioned. Finally, on 1 November 2008, Sta. A2 was able to be recovered by professional divers and a remotely operated vehicle (ROV).

3 Results and discussion

3.1 *Velocity and volume transport*

The detailed data analysis and method to estimate the Karimata Strait transport have been described in Fang et al. (2010). Here, a brief description of the data and a data analysis are presented. The ADCP data obtained from the TRBM at A2 cover the period from 4 December 2007 to 1 November 2008, with about a one month gap from 12 January to 15 February 2008, due to the failure in setting ADCP measurement parameters during the January 2008 cruise. The ADCP data set obtained from Sta. A1 is only about one month long, from 12 January to 13 February 2008. A data quality control was applied to the ADCP data, with special attention to the near surface bins of the top 10% of the ADCP measurement range, which may have been contaminated by sea surface reflection. The quality of each ping at each of the four beams was checked for the percent “good”, the threshold value, the velocity shear between bins and consecutive time, the echo intensity, and the correlation magnitude. The ADCP data in the upper 10% water column were replaced with values linearly extrapolated from the layer below it, according to a constant shear assumption (e.g., Sprintall et al., 2009; Susanto et al., 2012).

After applying quality control to each individual instrument time series for both TRBMs at Stas A1 and A2, we decomposed the current vectors into along-strait and cross-strait components by rotating the velocity data parallel and perpendicular to the Karimata Strait. The downstream direction along the Karimata Strait axis is 334° (referenced to true north). The along-channel velocity is parallel to the Karimata Strait axis. Within this study, “velocity” refers to the along-strait velocity, with negative values indicating flow towards 154° (toward the Java Sea). The velocity time series of each mooring was compiled into a single velocity-depth time series by filtering and interpolating data to a common base time of 2 h.

Since there are no simultaneous observed current data from Stas A1 and A2, we will use A2 ADCP data alone to estimate the Karimata Strait transport. Following Fang et al. (2010), the gridded (2 m in depth and 2 h time interval) velocity data are transformed into ten equally spaced layers from the surface to the bottom and filtered with a two-day Lanczos low pass filter to remove tidal currents (Duchon, 1979).

Figure 3a shows the velocity time series from the TRBM at Sta. A2, spanning from 4 December 2007 to 1 November 2008. The one month gap between12 January and 15 February 2008 were filled with the estimated value based on A1 time series (Fang et al., 2010). A stronger southward velocity of up to 1.2 m/s was observed during the boreal winter of 2007/2008. During the boreal summer of 2008 the upper layer (from the sea surface to about 30 m depth) flow was reversed toward the South China Sea, while beneath this layer the flow was still southward with a much weaker velocity. These observed results indeed confirm the existence of a South China Sea branch of the Indonesian throughflow via the Karimata Strait. Fang et al. (2010) found that a downward sea surface slope from north to south in boreal winter existed in this area. The existence of southward bottom flow in boreal summer regardless of prevailing southerly monsoon winds implies that the southward sea surface slope is a year-round phenomenon.

Although it is not adequate to accurately determine the

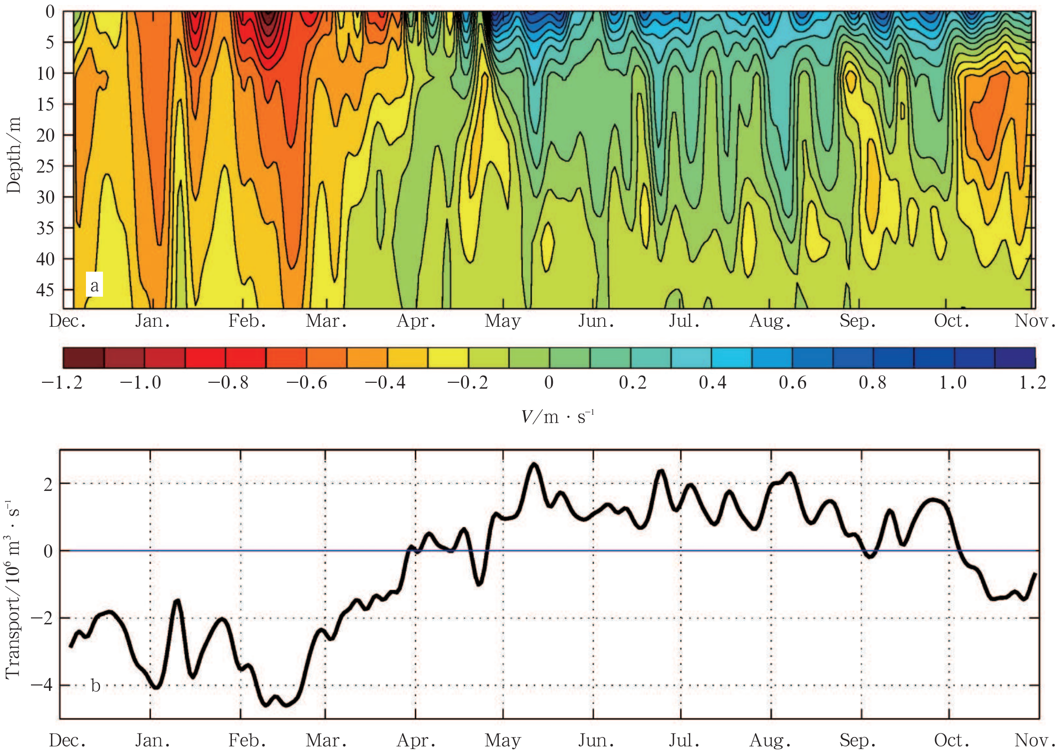

Fig.3. a. The along-strait velocity time series for the Karimata Strait derived from the ADCP at the A2 mooring, for the period from 4 December 2007 to 1 November 2008. The contour interval is 0.1 m/s. Negative values denote southeastward flow along strait velocity, which is parallel to the axis of the Karimata Strait (154° referenced to true north). b. Estimated Karimata Strait volume transport for the same period. Negative values indicate water transfer from the South China Sea to the Indonesian seas.

Karimata Strait transport based on a single mooring time series, we can estimate it by assuming that the velocity structure across the strait is inversely proportional to the local water depth, relative to the ADCP velocity and the depth of the A2 mooring. With velocity values in each grid, the Karimata Strait volume transport can be estimated using the same formula as Fang et al. (2010), as shown in Fig. 3b. It can be seen from Fig. 3b that the southeastward transport begins in early October and terminates in late March, while the reversed (northwestward) transport begins in early April and terminates in late September. The average transport from December 2007 to March 2008 is $-2.7\times10^{6}\ \mathrm{m^3/s}$ with a standard deviation of $1.1\times10^{6}\ \mathrm{m^3/s}$, while average transport for May to September 2008 is $1.2\times10^{6}\ \mathrm{m^3/s}$ with a standard deviation of $0.6\times10^{6}\ \mathrm{m^3/s}$. The entire record from December 2007 to October 2008 is $(-0.5\pm1.9)\times10^{6}\ \mathrm{m^3/s}$. The comparison with previous numerical model estimates of Karimata transport (e.g., Fang et al., 2005; Fang et al., 2009; Tozuka et al., 2009; Yaremchuk et al., 2009), Metzger et al. (2010), using 1/12° global version of HYbrid Coordinate Ocean Model (HYCOM), provide the closest estimate $-0.6\times10^{6}\ \mathrm{m^3/s}$ of inflow through Karimata Strait into the Java Sea. Using simultaneous measurements of ITF from the Makassar Strait, the primary inflow passage of the ITF, we can compare Karimata Strait transport to Makassar Strait transport. The average Makassar Strait transport from December 2007 to March 2008 is $-15.1\times10^{6}\ \mathrm{m^3/s}$, and $-11.9\times10^{6}\ \mathrm{m^3/s}$ from May to September 2008 (Susanto et al., 2012). In addition, the average volume transport in the Lombok Strait, as determined under the INSTANT program from 2004–2006, is $(-2.6\pm1.0)\times10^{6}\ \mathrm{m^3/s}$ (Sprintall et al., 2009).

During the boreal winter, the Karimata Strait volume transport is comparable with the annual average of the Lombok Strait transport and it is a relatively small compared with the Makassar Strait transport. However, because during winter the Karimata Strait transport carries low salinity and relatively warm water from the South China Sea, the Karimata Strait transport plays an important role in changing the upper layer of volume transport and heat and freshwater transports of the Makassar Strait. The Karimata Strait transport during the boreal winter can reach up to $-4.7\times10^{6}\ \mathrm{m^3/s}$, while during the boreal summer it can reach maximum of $2.6\times10^{6}\ \mathrm{m^3/s}$. For comparison, the annual mean of the Makassar Strait transport from 2004 to 2009 was $(-13.3\pm3.6)\times10^{6}\ \mathrm{m^3/s}$, with a maximum southward transport of $21.0\times10^{6}\ \mathrm{m^3/s}$ and a northward maximum of $0.6\times10^{6}\ \mathrm{m^3/s}$ (Susanto et al., 2012). Hence, Karimata Strait transport can contribute to the seasonal variability of more than $7\times10^{6}\ \mathrm{m^3/s}$ for the total transport. Consequently, the seasonal Karimata Strait transport can modify the stratification and water characteristics of the ITF before exiting into the Indian Ocean.

3.2 *Heat and freshwater transports*

To estimate heat and freshwater transports, we use all CTD data taken during the SITE cruises along the A-line (Fig. 1), the bottom temperature and salinity time series from the CTD in the A2 mooring, the group for high-resolution sea surface temperature (GHRSST) obtained from http://www.nodc.noaa.gov/SatelliteData/ghrsst/, and the world ocean atlas (WOA) salinity data obtained from http://www.nodc.noaa.gov/OC5/SELECT/woaselect/woaselect.html. The temperature profile time series at Sta. A2 is generated by combining the daily GHRSST, the daily bottom temperature, and the CTD casts. If there were no CTD casts during that month, we use a linear interpolation between the SST and bottom temperature. The cross-section temperature profile time series is generated based on the GHRSST along the A-line, the GHRSST and bottom temperature time series at A2 mooring and with an assumption that the vertical gradient temperature ($\mathrm{d}T/\mathrm{d}z$) is constant along the A-line. Hence, $\mathrm{d}T/\mathrm{d}z$ at A2 mooring is used as a reference for the cross section temperature profile. Following Fang et al., (2010), the daily gridded temperature profile time series are transformed into ten equally spaced layers from the surface to the bottom and at every 5 km horizontal distance from Bangka to Kalimantan Island (Fig. 1). Then the heat transport F_h can be calculated from

$$F_\mathrm{h} = \rho c_p \int\limits_A (T - T_0) u \,\mathrm{d}A, \qquad (1)$$

where ρ is the water density, taken 1021 kg/m^3 for a mean temperature of 28 °C and a mean salinity of 33; c_p is the specific heat; T is the water temperature; and T_0=3.72 °C is a reference temperature. ρc_p can be regarded as the heat capacity per unit volume, and 4.1 MJ/(m^3·K) is taken for the above temperature and salinity. The monthly mean heat transport is given in Table 1.

Similarly, the daily gridded salinity profile time series is generated by combining WOA salinity data and bottom salinity time series from A2 mooring. Following Fang et al., (2010), we can calculate the freshwater transport using the following formula:

$$F_\mathrm{w} = \int\limits_A [(S_0 - S)/S_0]\, u \,\mathrm{d}A, \qquad (2)$$

where S_0=34.62, is a reference salinity. The monthly freshwater transport is given in Table 1.

Table 1. Monthly mean heat and freshwater transports

	2007	2008										Mean
	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	
Heat transport (PW)	–0.28	–0.32	–0.43	–0.16	0.02	0.16	0.15	0.15	0.15	0.09	–0.07	–0.05
Freshwater transport /10^6 m^3·s^{-1}	–0.22	–0.17	–0.24	–0.09	0.02	0.11	0.13	0.17	0.12	0.07	–0.04	–0.01

Similar to the Karimata volume transport, the seasonal variability is clearly seen in the heat and freshwater transports. During the boreal winter, the Karimata heat transport can reach up to –0.43 PW which is comparable with the annual mean of the Makassar heat transport during the strong El Nino in 1997 (–0.5 PW; Ffield et al., 2000). The annual mean of Makassar heat transport from 2004 to 2006 is –0.6 PW (Susanto et al., 2012). Meanwhile, during the boreal summer the Karimata heat transport can reach up to 0.16 PW. The freshwater transport during the boreal winter can reach up to –0.24×10^6 m^3/s, while during the boreal summer it can reach up to 0.17×10^6 m^3/s. Consequently, the seasonal Karimata Strait volume, heat and freshwater transports can strongly modify the stratification and water characteristics of the ITF before exiting into the Indian Ocean.

4 Summary

We have successfully retrieved the ADCP data via an omnidirectional acoustics modem from two TRBM moorings in the Karimata Strait, Indonesia. The tandem configuration of the ADCP and a modem is ideal for the deployment from fixed platforms, such as oil rigs or harbor, where we can get real-time ADCP data. The main constraint is the low communication rate between the surface-bottom modems, especially for the observation in the strait, where we may experience harsh environmental conditions (high winds, strong tidal currents, turbid water, high biofouling rates). Until a cost-effective, high baud rate modem is commercially available (LinkQuest Inc. offers a high baud rate modem but the price is higher than the price of ADCP, pers. communication), oceanographers may have to patiently wait for the entire duration of the mooring deployment before they can recover and subsequently redeploy the mooring in order to retrieve the ADCP data.

Our observations show the mean volume, heat and freshwater transports of the Karimata Strait are (–2.7± 1.1)×10^6 m^3/s, (–0.30 ± 0.11) PW , (–0.18± 0.07)×10^6 m^3/s during the boreal winter from December 2007 to March 2008 and (1.2± 0.6)×10^6 m^3/s, (0.14 ± 0.03) PW, (0.12 ± 0.04) ×10^6 m^3/s during the boreal summer from May to September 2008, respectively. This confirms the existence of the South China Sea branch of the (ITF). Even though the annual mean of Karimata Strait volume, heat and freshwater transports are small, the amplitudes of the seasonal variability (up to 7 ×10^6 m^3/s, 0.60 PW, 0.41×10^6 m^3/s) play an important role in changing the seasonal variability of the ITF volume, heat and freshwater transports, and modifying the ITF water stratification before exiting into the Indian Ocean. Hence, the Karimata Strait should be considered as an important inflow passage of the ITF. The existence of southward bottom flow in boreal summer implies that the downward sea surface slope from north to south as found by Fang et al. (2010) for boreal winter is a year-round phenomenon.

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