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Contribution of the Karimata Strait transport to the Indonesian Throughflow as seen from a data assimilation model

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ABSTRACT

A particle-tracking experiment based on Bluelink ReANalysis (BRAN) is designed to explore the contribution of a branch of the South China Sea Throughflow, the Karimata Strait (KS) transport, to the Indonesian Throughflow (ITF) from the Pacific to the Indian Ocean. Results of the particle-tracking experiment show that most of the KS transport enters the Indian Ocean during the first half of a calendar year, with a maximum transport of more than 3 Sv in March–April. The annual average contribution of the KS transport to the ITF is 1.6 Sv, 13% of the annual mean ITF transport, while in February–April, the contribution is above 20%. Interannual variations of the KS transport into the Indian Ocean are modulated by the El Niño-Southern Oscillation (ENSO). More SCS waters through KS can enter the Indian Ocean during El Niño phase, and less SCS waters through KS can enter the Indian Ocean during La Niña phase. SCS waters through KS can also enter the Pacific, especially during La Niña and negative Indian Ocean Dipole phase.

1. Introduction

The Karimata Strait (KS) is a 40-m deep and 360-km wide channel between the Belitung Island and the southern part of the west coast of the Kalimantan Island, which links the South China Sea (SCS) with the Indonesian Seas, including the Java Sea, Flores Sea, Banda Sea, and the Makassar Strait (Fig. 1). The buoyant, fresh water from SCS intrudes into the southern Makassar Strait through the KS and the Java Sea (JS) in boreal winter and inhibits the warm surface water from the Pacific from flowing southward (Gordon et al., 2003). Qu et al. (2005) speculated that the SCS water can also enter the Pacific through the Makassar Strait.

The KS transport is important for the SCS itself because the net heat and freshwater the SCS gains from the air–sea interface can only be balanced by horizontal advection, namely the South China Sea Throughflow (SCSTF). The SCSTF has an inflow of cold and salty water through the Luzon Strait and outflows of warm and fresh water through the Mindoro Strait, the Taiwan Strait, and the KS (Qu et al., 2006). So far only two observation-based estimates of transport through the KS are available: one was by Wyrtki (1961) using ship drift data, with transport estimates of 4.5 Sv southward in boreal winter and 3 Sv northward in boreal summer; the other was by Fang et al. (2010), with the transport estimate of 3.6 Sv southward in the boreal winter of 2007–2008. Annual-mean volume transports through the KS range from 0.3 to 1.6 Sv ($1\ \text{Sv} = 10^6\ \text{m}^3\ \text{s}^{-1}$) in various numerical models (Fang et al., 2005, 2009; Tozuka et al., 2007, 2009; Yaremchuk et al., 2009).

The Makassar Strait is considered as the primary pathway of the Indonesian Throughflow (ITF) transport (Lukas et al., 1996). Since the volume transport through the KS is estimated to be about one order of magnitude smaller than the ITF volume transport, the transport through the KS has often been overlooked in the ITF literatures. After the importance of the SCSTF was revealed (Qu et al., 2005), a number of studies focused on how (Tozuka et al., 2007) and why (Gordon et al., 2003; Wang et al., 2006) the SCSTF transport during the boreal winter inhibits the Pacific-to-Indian Ocean heat transport.

Whereas the annual-mean volume transport of the SCSTF is much smaller than that of the ITF, the KS transport is northward in boreal summer and southward in boreal winter, while the Makassar Strait has its minimum transport during October to December and reaches its maximum values towards the end of the northwest and southeast monsoons (Gordon et al., 2008). Thus, seasonally the KS transport may make non-negligible contribution to the ITF, which has not been quantified up to now. In this study, we use velocity fields from the Bluelink ReANalysis (BRAN) to investigate the variability of the KS volume transport and its contribution to Pacific-to-Indian Ocean volume transport.

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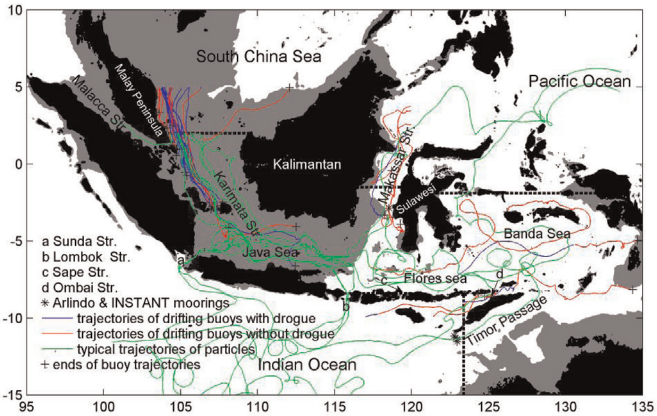

Fig. 1. Geography of the study region, with names of the straits and seas given in the text. The gray shaded region is shallower than 100 m in depth. Particles are deployed along the 2°N transect (dashed line). Particles go across the transects indicated by dashed lines and straits into the SCS, Pacific Ocean and Indian Ocean.

This paper is organized as follows. Section 2 introduces BRAN and compares the model with observations. Section 3 shows the seasonal cycle of volume transports through the KS. A particle-tracking experiment is designed, and results are analyzed in Section 4 to estimate its contribution to the ITF. Finally, discussions are presented in Section 5.

2. Data and model validation

2.1. Data

BRAN is a data-assimilating model product based on a 10 km horizontal resolution and 10 m vertical resolution (in the upper 300 m) hydrodynamic model. BRAN assimilated along-track sea-level anomalies (SLA) from satellite altimeters and tidal gauges, satellite sea surface temperature, in situ temperature and salinity profiles (from Argo, XBT, TAO) (Oke et al., 2008). BRAN 2.1, which is used in this study, realistically captures the details of the seasonal circulation in the Asian–Australian region including the circulation in the Indonesian Seas, in comparison with existing observations (Schiller et al., 2008).

Fig. 2 shows surface current maps from BRAN in January and July. In boreal winter (January), the model captures the energetic western boundary current of the Western Pacific, the Mindanao Current, and its associated recirculation. The western boundary current in the South China Sea feeds into the southward-flowing KS transport, driven by the winter monsoonal winds in the South China Sea. The surface current in the Makassar Strait is northward during this time of the year. The surface transport from the KS flows strongly eastward into the Banda Sea, with visible leakage through the Lombok Strait. In boreal summer (July), surface currents in both the KS and Makassar Strait reverse, with the Makassar Strait transport feeding the ITF through the Nusa Tenggara, an east–west series of islands from Lombok to Timor. In general, BRAN captures the energetics of the narrow boundary currents, their seasonal variations, and their interactions with various topographic features in the Indonesian Seas.

2.2. Comparisons with velocity measurements in the Makassar Strait

As part of the Indonesian-US Arlindo program, two moorings were deployed near 3°S in the Makassar Strait for more than one year from December 1996 (Fig. 1). Two moorings were deployed at the same sites in the International Nusantara Stratification and Transport (INSTANT) program, and a 3-year (2004–2006) time series of velocity measurements were obtained. These data are not assimilated into the BRAN model.

BRAN has captured the seasonal variations of the vertical velocity profiles in the Makassar Strait, however, there are discrepancies. Compared with mooring observations over the same time period in the Makassar Strait (Fig. 7 of Susanto and Gordon (2005) and Fig. 2 of Gordon et al. (2008)), BRAN has underestimated near-surface southward flow, overestimated thermocline maximum and underestimated southward flow below 300 m. Compared with the seasonal cycle of velocity profiles observed by the INSTANT moorings (Fig. 2 of Gordon et al. (2008)), the profiles of BRAN have some different seasonal characteristics (Fig. 3a): greater thermocline maximum during January/February/March (JFM; the Northwest Monsoon) than during July/August/September (JAS; the Southeast Monsoon). The JAS velocities above the thermocline in BRAN were as strong as the subsurface maximum and much stronger than those from the moorings. The southward velocities during October/November/December (OND) were the weakest, except for those near the surface, in contrast to the observed profiles that nearly overlapped with its annual mean. Below the depth of 300 m, the southward velocities decreased rapidly in all four seasons and nearly disappeared at the depth of 500 m, which is also not consistent with the mooring profiles. Nevertheless, the discrepancies in the deep layers may not affect the particle tracking calculations based on near surface velocity in this study.

2.3. Comparisons with drifting buoys

Data from surface drifting buoys serves as another set of independent observations to compare with the model. We compare the near-surface currents from BRAN with those from all available interpolated drifter data in the Indonesian Seas (Fig. 1) provided by the Marine Environmental Data Service (Table 1). The velocities derived from drifting buoys with drogues are compared with the reanalysis field from the second model level at 15-m depth. Due to the limited drifters with drogues in the Makassar Strait, Flores Sea and Banda Sea, comparisons between the velocities from drifters without drogue and the BRAN velocities at 5-m depth are also available as references. We calculate the complex cross-correlation of velocities following the method of Kundu (1976) and the root-mean-squared error (RMSE) and deviations of the speed.

The comparison between drifter and BRAN surface currents in the KS and Java Sea achieves great skills, with the complex correlation coefficient of 0.88 and the phase angle (i.e., the error in the direction of the current) of 0.5°. The positive deviation of speed means the simulated current field is slightly stronger than the observed. The skills in the Makassar Strait, Flores Sea and Banda Sea are lower, but the drifter velocity is still significantly correlated with BRAN (Table 1). The trajectories of drifters without drogues are affected strongly by wind and do not follow currents strictly.

Statistical analyses show that the correlation of current fields in the Indonesian Seas is higher or as good as that of the northwest quadrant of the Australian region (Table 2 of Oke et al. (2008)); in our comparison, the RMSE of current speed, however, is larger in the Makassar Strait, Flores Sea and Banda Sea along with a significant negative deviation of speed. This means that in these channels, the directions and variations of surface currents are well simulated in BRAN, while the mean speeds from BRAN are lower than those from observations. This result is consistent with comparisons of the velocity observations in the Makassar Strait, namely, the near-surface southward flow is underestimated in BRAN. It is still worthy of noting that all the observations of drifting buoys were obtained in November to May, so the statistics are only reliable for this period.