

**Transports estimate
in Sunda Shelf and
Strait of Malacca**

F. Daryabor et al.

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An estimate of the Sunda Shelf and the Strait of Malacca transports: a numerical study

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Abstract

Using the Regional Ocean Modeling System (ROMS), this study aims to provide an estimate of the volume, freshwater, heat, and salt transports through the Sunda Shelf and the Strait of Malacca in the southern region of the South China Sea (SSCS). The modeling system is configured with two one-way nested domains representing parent and child with resolutions of $1/2$ and $1/12^\circ$, respectively. The simulated currents, sea surface salinity, temperature and various transports (e.g., volume, heat, etc) agree well with the observed values as well as those estimated from the Simple Ocean Data Assimilation (SODA) re-analysis product. The ROMS estimated seasonal and mean annual transports are in accord with those calculated from SODA and those of limited observations. The ROMS estimates of mean annual volume, freshwater, heat and salt transports through the Sunda Shelf into the Java Sea are 0.32 Sv (1 Sv = 10^6 m³ s⁻¹), 0.023 Sv, 0.032 PW (1 PW = 10^{15} j s⁻¹), and 0.010×10^9 kg s⁻¹ respectively. The corresponding ROMS estimates for mean annual transports through the Strait of Malacca into Andaman Sea are 0.14 , 0.009 Sv, 0.014 PW, and 0.0043×10^9 kg s⁻¹ respectively. The relative percentages of mean annual transports computed individually from those of volume, heat, salinity, and freshwater between the Strait of Malacca and the Sunda Shelf range from 39 to 43.8%. This reflects that the Strait of Malacca plays an equally significant role in the annual transports from the SSCS into the Andaman Sea.

1 Introduction

The southern region of the South China Sea (SSCS) has complex bathymetry and water circulation near the equator in which the monsoon plays a dominant role (Daryabor et al., 2010, 2014, 2015). The SSCS connects to the Java Sea, which is a source of low-salinity water mass (Wyrтки, 1961) through the Sunda Shelf and Karimata Strait, as well as the Andaman Sea through the Strait of Malacca (Fig. 1). Therefore, the SSCS is important for water exchange through these Straits.

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The SSCS receives heat mostly from the sun and the atmosphere, as well as fresh-
water from precipitation, which can significantly affect the climate system of the region
(Gong and Wang, 1999; Zhang et al., 2003). The Asian–Australian monsoon system
largely influences the general current circulation in the South China Sea (SCS), partic-
ularly in the southern region (Wyrтки, 1961; Chu et al., 1999; Daryabor et al., 2015) and
hence regulates various transports across the Sunda Shelf/Karimata Strait and Strait
of Malacca. A better estimation of transports across the SSCS is important for under-
standing inter-ocean exchanges, particularly between the Indian and Pacific Oceans.
Numerous studies have estimated volume, freshwater, heat and salt transports in the
SCS from surface observations and numerical models. Wyrтки (1961), based on the
ship drift data, observed that outflow from the SCS into Java Sea through the Kari-
mata Strait is 4.5 Sv during winter and noted an inflow of 3 Sv into the SCS during
summer ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$). Cai et al. (2002), using the State Key Laboratory of Nu-
merical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics/Institute
of Atmospheric Physics Climate Ocean Model (LICOM) with horizontal resolution of
 $1/2^\circ$, estimated the mean annual volume transport through the Sunda Shelf into the
Java Sea is 0.93 Sv. In another study using the same model but with different config-
uration, Cai et al. (2005a) estimated 2.26 Sv from the Sunda Shelf to the Java Sea.
Song (2006), using sea surface height from satellites and ocean bottom pressure
data, estimated a mean transport of 7.5 Sv flowed out of the SSCS into the Java Sea
through the Karimata Strait for winter season. Furthermore, Fang et al. (2003), using
the Princeton/NOAA GFDL Modular Ocean Model (MOM2) with a resolution of $1/6^\circ$
for the SCS and adjacent seas and 3° for the global ocean, estimated the mean an-
nual volume (3.1 Sv), salt ($0.110 \times 10^9 \text{ kg s}^{-1}$), and heat (0.35 PW) transports through
Sunda Shelf into the Java Sea ($1 \text{ PW} = 10^{15} \text{ J s}^{-1}$). For the Strait of Malacca the cor-
responding estimates are 0.5 Sv , $0.017 \times 10^9 \text{ kg s}^{-1}$, and 0.06 PW respectively. Fang
et al. (2009), using the same model but with different configuration, estimated the an-
nual volume, heat and salt transports from the Sunda Shelf into the Java Sea to be
 1.16 Sv , 0.113 PW , $0.039 \times 10^9 \text{ kg s}^{-1}$ respectively, while those into the Strait of Malacca

are 0.16 Sv, 0.016 PW, $0.005 \times 10^9 \text{ kg s}^{-1}$. Recently, Fang et al. (2010), based on the Acoustic Doppler current profiler observations, estimated a mean volume transport of 3.6 Sv from the SSCS into the Java Sea for a period of 13 January to 12 February 2008.

The numerical estimates of various transports in the SSCS as mentioned above vary widely mainly due to the differences in model configuration and resolution. Also, observations of the SSCS transports remain limited compared with those in the northern region of the SCS. Owing to the complexity of bathymetry and flow patterns in the SSCS region, a high-resolution regional ocean model may be required for a better estimation of the transports. Hence, the motivation of this work is to use the Regional Ocean Modeling System (ROMS) with finer horizontal and vertical resolutions to compute the volume, freshwater, salt, and heat transports for the Sunda Shelf and Strait of Malacca. This study also estimates the transports in the Strait of Malacca, which have not been in previous studies (e.g., Cai et al., 2005a; Qingye et al., 2009). Section 2 discusses the model setup and data. Section 3 describes the analysis method. Section 4 discusses the modeled transports in the SSCS and Sect. 5 summarizes the findings.

2 Model description and data sources

The IRD (the Institut de Recherche pour le Développement (<http://www.romsagrif.org>)) version of the ROMS with two-nested domains is employed in this study. The coarse grid has horizontal spacing of resolution of $1/2^\circ$ and 30 vertical S-levels. The coarse model domain covers 20° S to 30° N and 90 to 140° E , encompassing the eastern Indian Ocean and western Pacific Ocean. The horizontal resolution of the fine grid is $1/12^\circ$, with 30 vertical S-levels also. The fine model domain is from 2.7° S to 15° N and 97.2 to 116.7° E (Fig. 1). Thus, the model comprises $99 \times 103 \times 30$ and $234 \times 210 \times 30$ fixed grid points for the parent and child domains, respectively. This model solves incompressible primitive equations in a split-explicit, free-surface, topography-following coordinate system with Boussinesq and hydrostatic approximations (Shchepetkin and

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McWilliams, 2003, 2005) which are described as follows:

$$\frac{\partial u}{\partial t} + \mathbf{U} \cdot \nabla u - f v = -\frac{1}{\rho_0} \frac{\partial p}{\partial x} - \frac{\partial}{\partial z} \left(-K_M \frac{\partial u}{\partial z} - \nu \frac{\partial u}{\partial z} \right) + F_u + D_u \quad (1)$$

$$\frac{\partial v}{\partial t} + \mathbf{U} \cdot \nabla v + f u = -\frac{1}{\rho_0} \frac{\partial p}{\partial y} - \frac{\partial}{\partial z} \left(-K_M \frac{\partial v}{\partial z} - \nu \frac{\partial v}{\partial z} \right) + F_v + D_v \quad (2)$$

where $\mathbf{U}(u, v, w)$ is the velocity vector; f is the Coriolis parameter calculated with the formula $2\omega \sin \varphi$, in which ω is the rotational angular velocity of the Earth and φ is latitude; ρ_0 a reference density of the sea water (approximately 1023 kg m^{-3}); p , the total pressure ($\cong -\rho_0 g z$); K_M , the vertical eddy viscosity; ν , the molecular viscosity; F_u and F_v , the frictional terms; D_u and D_v , the diffusive terms; and t , the time variable. The hydrostatic equation is given by:

$$\frac{\partial \rho}{\partial z} = -\rho g \quad (3)$$

Whereby ρ is the density and $g = 9.8 \text{ m s}^{-2}$ is acceleration due to gravity. The continuity equation for an incompressible fluid is expressed as follows:

$$\nabla \cdot \mathbf{U} = 0 \quad (4)$$

The primitive equations for temperature and salinity are advection diffusion equations given as follows:

$$\frac{\partial C}{\partial t} + \mathbf{U} \cdot \nabla C = -\frac{\partial}{\partial z} \left(-K_C \frac{\partial C}{\partial z} - \nu_\theta \frac{\partial C}{\partial z} \right) + F_C + D_C \quad (5)$$

The Symbol C is the tracer field (such as temperature and salinity); K_C is the vertical eddy diffusivity in $\text{m}^2 \text{ s}^{-1}$; ν_θ is the molecular diffusivity coefficient in $\text{m}^2 \text{ s}^{-1}$; F_C and D_C are friction and diffusive terms, respectively.

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Lateral tracer and momentum advection in the model is associated with the third-order upstream-biased scheme (Shchepetkin and McWilliams, 1998). The advection–diffusion split resolves spurious diapycnal mixing in S-coordinate models caused by the implementation of higher-order diffusive advection schemes (Marchesiello et al., 2009). The method used in this nested simulation maintains the low dispersion and diffusion capabilities of the original scheme. Moreover, vertical mixing is based on a non-local K-Profile Parameterization (KPP) scheme proposed by Large et al. (1994). The bottom boundary layer is generated by KPP bottom-boundary layer parameterization and a quadratic bottom drag (Veitch et al., 2010).

The nested model is implemented based on the parallel runs of the parent and child domains. This configuration is necessary to achieve interaction when more than one domain is used (Spall and Holland, 1991). The parent and child bathymetry is based on the ETOPO2 (<http://www.ngdc.noaa.gov>) of $1/30^\circ$ horizontal resolution. ETOPO2 is derived from depth soundings and satellite gravity observations (Smith and Sandwell, 1997). The topography is smoothed to reduce the pressure gradient error with a maximum relative topographic gradient ($r = \frac{\nabla h}{h}$) no larger than 0.2 (Daryabor et al., 2015). The vertical axis is resolved using 30 vertical fine-resolution layers from the bottom to the surface for both parent and child domains. The four lateral boundaries, A, B, C, and D, are specified at the Karimata Strait, the east of Luzon and Taiwan, the north of Taiwan, and east of the Andaman Sea at the northern tip of the Strait of Malacca, respectively (see Fig. 1). Open boundary conditions are prescribed in the lateral boundaries where an active, implicit, upstream-biased, radiation condition is implemented (Marchesiello et al., 2001). The boundary conditions are supplied by the climatological monthly mean salinity and temperature of the World Ocean Atlas 2005 (WOA 2005) (refer to <http://www.nodc.noaa.gov/OC5/WOA05/pubwoa05.html>) recommended by Antonov et al. (2006) and Locarnini et al. (2006), respectively. Moreover, hydrostatic and geostrophic equations (Eqs. 3 and 6) prescribed by Marchesiello

with that from the Group for High Resolution Sea Surface Temperature (GHRSSST) with a horizontal resolution of 0.05° for the period 2000 to 2006 (refer to http://podaac.jpl.nasa.gov/dataset/NCDC-L4LRblend-GLOB-AVHRR_OI). This product uses optimal interpolation (OI) using data from the 4 km Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Version 5 (Reynolds et al., 2007), and in situ ship and buoy observations. Hydrographic climatological data “HydroBase” version 2 with 1° horizontal resolution from <http://www.whoi.edu/science/PO/hydrobase/php/index.php> for the period 2000 to 2006 is also used to validate the model simulated climatological Sea Surface Salinity (SSS).

3 Methods of analysis

This section presents the calculations on the inter-ocean transport between the Sunda Shelf in the SCS and the Strait of Malacca. The present study uses prognostic-mode momentum components and tracer field to calculate and analyze the transport. The cross-sections of the Sunda Shelf (transect T1) and Strait of Malacca (transect T2) are specified by heavy red solid lines from the southern end of the Peninsular Malaysia to western Borneo (1.5° N from 104 to 109° E) and from the east coast of Sumatra to the southern end of Peninsular Malaysia (103.7° E from 0.2 to 1.5° N), respectively (Fig. 1). The SCS is a marginal sea with a depth of about 4000–5000 m in the central region and becoming shallower towards the southern region with depths of 50–70 m in the Sunda Shelf. The Strait of Malacca is located between the east coast of Sumatra and the west coast of Peninsular Malaysia, connecting the SCS and the Andaman Sea. The minimum depth of the Strait of Malacca (≤ 20 m) is in the southern part of the Strait connected to the Sunda Shelf whereas the maximum depth is in the northern part (Fig. 1). The transports in these sections are calculated from the surface to the

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bottom in the z coordinate. For the volume transport the following equation is used:

$$F_V = \int_A \mathbf{v} \cdot \hat{\mathbf{n}} dA \quad (7)$$

Where A represents the transect from the surface to the desired depth, dA denotes the area element, \mathbf{v} is the velocity component, and $\hat{\mathbf{n}}$ indicates the normal vector perpendicular to the transect. Thus, the direction of the normal velocity component relative to the normal vector is considered as the direction of transports. Hereafter, positive and negative values are referred to as “outflow” form and “inflow” to the SSCS, respectively. The heat transport F_H is calculated using:

$$F_H = \rho c_p \int_A (T - T_0) \mathbf{v} \cdot \hat{\mathbf{n}} dA \quad (8)$$

The symbol ρ is the water density with a mean temperature of 28 °C and a mean salinity of 33 psu, taken as 1023 kg m⁻³. The specific heat c_p for the above temperature and salinity is determined based on the calculation by Millero et al. (1973). T denotes the water temperature, and T_0 represents the reference temperature of 3.72 °C (Schiller et al., 1998; Fang et al., 2009, 2010). The salinity and freshwater transports are evaluated according to Eqs. (9) and (10), respectively, where S is the salinity (unit of psu), and S_0 is the reference salinity set to 34.544 (Fang et al., 2009, 2010).

$$F_S = \rho \int_A S \mathbf{v} \cdot \hat{\mathbf{n}} dA \quad (9)$$

$$F_W = \int_A \left(\frac{S_0 - S}{S_0} \right) \mathbf{v} \cdot \hat{\mathbf{n}} dA \quad (10)$$

4 Results and discussion

Generally, the modeled SST, SSS and circulation pattern in the SSCS are in good agreement with observations and previous studies (e.g., Chu et al., 1999; Xie et al., 2003; Daryabor et al., 2014, 2015). During winter (December-January-February) and summer (June-July-August), the model simulated the circulation patterns and major features including the western boundary currents along the Peninsular Malaysia's eastern continental shelf (PMECS) reasonably.

4.1 Sea surface temperature and salinity

The patterns of model simulated SST (Fig. 2) and SSS (Fig. 3) compare well with the observations of GHR SST and those of HydroBase climatological data, respectively. The seasonal variations in the modeled SST show that the SSTs are relatively lower during winter with an average of 26.5 °C north of 1.5° N. Because of the advection of cold waters from the north to the SSCS and relatively warmer through the Sunda Shelf from the south of 1.5° N towards the Java Sea with an average temperature of approximately 29 °C these well agree with the GHR SST (Fig. 2) and previous studies (Hu et al., 2000; Morimoto et al., 2000; Cai et al., 2005b, 2007; Daryabor et al., 2014, 2015). The modeled SSTs in the basin are relatively warmer with the average temperature 30 °C during summer because of increased solar radiation and the advection of warm waters from the southern region, especially from the Java Sea (Yanagi et al., 2001; Cai et al., 2005b; Daryabor et al., 2014, 2015). The major feature during summer is the “cold tongue” along the PMECS with the temperature range of 28.5 °C due to the existence of upwelling filament (Daryabor et al., 2014, 2015), which is also simulated by the model. Model output can be different from the observation due to several possible sources, particularly during summer monsoon because of the interaction of strong monsoon wind flow direction with bathymetry and topography at different entry points. In addition, characteristic turbulent diffusion times due to vertical turbulent diffusion and the vertical advection/convection in the upper layer during the strong southwest-

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erly winds explain why temperature is somewhat underestimated (Lonin et al., 2010). Another reason could arise from the changes in the vertical resolution at different locations due to the vertical configuration of the model (Lonin et al., 2010).

Changes in surface salinity reflect changes in freshwater flux (evaporation minus precipitation). Hence sea surface salinity pattern resembles that of surface freshwater flux (Fig. 3). Figure 3 shows the SSS is generally 32 to 34 psu in the region of study. However, the minimum occurs at the northern and southern coast of the PMECS ranging from 31.5 to 32 psu. In comparison, relatively low values of SSS averaging approximately 30.5 and 31 psu are observed and simulated in the Strait of Malacca during the winter and summer respectively. This is due to the net freshwater input in the corresponding regions where net precipitation is high (Fig. 3c and f). In addition, mixing between waters of different salinities may be the other reason that causes the original salinity to change gradually, particularly in the summer season along the southern coast of the PMECS. However, a deeper understanding of the issue will be studied in future.

Figure 4 shows the comparison of the seasonal cycle of modeled SST and SSS with those of GHRSSST and hydrographic climatological data (HydroBase2) averaged in the study area (101–109.5° E, 2° S–8° N).

The modeled seasonal cycle of sea surface temperature and salinity appears to be similar to GHRSSST and hydrographic climatological SSS, respectively. Figure 4a shows that during the monsoons (winter and summer), SST attains a maximum and minimum value of 27 and 30 °C respectively in January and June. The maximum seasonal cycle peak of SSS occurs prior to April with the value of approximately 33 psu. This peak gradually decreases to the lowest value of 32.5 from the months of June to September (Fig. 4b). Figure 4 shows that during both the winter and summer seasons the minimum and maximum SST is in consonance with the maximum and minimum SSS. This is attributed to the dominant monsoonal influence on the SST and SSS variations in the SSCS.

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4.2 Model current circulation

Figure 5 represents the surface currents, derived from model, satellite altimeter and scatterometer (OSCAR), and the SODA in the winter and summer seasons respectively. The simulated surface circulation patterns generally resemble those of OSCAR, SODA and the earlier studies (Chu et al., 1999; Morimoto et al., 2000; Cai et al., 2007; Tangang et al., 2011; Daryabor et al., 2014, 2015).

The model simulated the main features of the SSCS at the sea surface and depth of 30 m reasonably as compared with those shown in the OSCAR and SODA during winter and summer, including the strong boundary currents along the PMECS (Figs. 5–7). One notable feature is the cyclonic eddies (E_{1w} and E_{2w}) for the ROMS, but at slightly different locations for OSCAR and SODA during winter. These simulated features are located north of Natuna and north of Anambas Islands (for the island locations, see Fig. 1), with their center situated at about 6 and 4° N respectively. Similarly, during summer monsoon but with an anticyclonic rotation, the eddies (E_{1s} and E_{2s}) around the north of Natuna Islands and the north of Anambas Islands is simulated also. During summer, the western boundary current leaves the PMECS and bifurcates approximately at the latitude 8° N (Figs. 5 and 6). Recent study by Daryabor et al. (2015) pointed out that it may due to the formation of an adverse pressure gradient force and an adverse vorticity downstream in the near-shore waters around the coastal region. The currents at depths of 30 and 50 m exhibit patterns similar to those near the surface (Figs. 5–7). The cyclone and anticyclone eddies in the winter and summer seasons north of Natuna Islands and north of the Anambas Islands still persist. This may be related to the dominant effect of monsoons (December-January-February and June-July-August) that leads to the development of baroclinic instability in the region of study (Li et al., 2011; Chen et al., 2012; Daryabor et al., 2014, 2015).

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4.3 Seasonal and mean annual transports

This section discusses the seasonal and annual exchange of transports of volume, freshwater, heat, and salt between the SSCS and the Java Sea as well as their effects on distribution of temperature and salinity in the region of study. The same is also dealt with for the Strait of Malacca. Further transports and the effects of these exchanges through the main passages in the SSCS, their roles in the mechanism and the formation of thermohaline circulation in the upper SSCS as well as the changes of the ocean's ventilation rates and pathways are elaborated.

4.3.1 Seasonal transports

(a) Sunda Shelf

The seasonal cycles of various transports calculated from the sea surface to the bottom in the pathway of the Sunda Shelf indicated by transect T1 are depicted in Fig. 8. The ROMS estimated seasonal cycle of volume transport agrees well with those of SODA. In addition, both estimates are in good agreement with the observed values of Wyrcki (1961). In early January, the SODA and ROMS volume transports from the SSCS into the Java Sea are 4.9 and 5.7 Sv, respectively (Fig. 8a). These estimates of outflows into the Java Sea are consistent with the mostly southward flow in the Sunda Shelf during winter (Figs. 5–7). Meanwhile, the volume transport estimate of Fang et al. (2003) during January appears to be higher as compared to the ROMS estimated values by about 2 Sv. This higher estimate may be due to the coarse resolution of the Fang's model which is configured with the horizontal resolution of the coarse grid 3° and the fine grid of approximately $1/6^\circ$ with 15 vertical levels.

The ROMS estimated outflow in February is 4.5 Sv, which is comparable with the observed value of Wyrcki (1961). The volume transport gradually reduces to zero around April–May and becomes negative (inflow into the SSCS) starting from June to October when the flow becomes dominantly northwards. By early June, transport switches to

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(b) Strait of Malacca

Figure 9 compares the seasonal cycle of various transports estimated based on ROMS, SODA for the pathway of the Strait of Malacca indicated by transect T2 and those of Fang et al. (2003). As in the Sunda Shelf, ROMS and SODA estimates of transports in the Strait of Malacca are in good agreement with each other. However, in contrast to Sunda Shelf, Fang et al.'s estimates of transports during winter are lower than the ROMS estimates. The ROMS estimated volume transport through the Strait of Malacca in early January is approximately 1.8 Sv towards the Andaman Sea, which is slightly higher than the 1.4 Sv from SODA. As in the Sunda Shelf, the volume transport decreases and becomes zero in April. The volume transport switches to an inflow in late May and continues throughout the summer up to October with maximum values in August of approximately 0.9 and 0.6 Sv for ROMS and SODA respectively.

The inflow decreases further in autumn and switches back to outflow in November with a maximum rate of approximately 1.6 and 1.2 Sv for ROMS and SODA in December respectively (Fig. 9). In general, the volume transport estimates of the ROMS and SODA are in good agreement throughout the years. In contrast, Fang's study underestimated the volume transports in summer (Fig. 9a).

The seasonal cycle of freshwater transport (Fig. 9b) generally follows that of the volume transport. During the peak of the winter monsoon in January, freshwater transport enters the Strait of Malacca at a maximum rate of 0.073 and 0.065 Sv for the ROMS and SODA respectively. However, during summer, the inflow of the freshwater transports into the Strait of Malacca is estimated to be approximately 0.28 and 0.23 Sv for ROMS and SODA respectively. This inflow reverses its direction at the end of autumn. The seasonal cycle of heat (Fig. 9c) is also very similar to the seasonal cycle of volume transport. Estimates from ROMS and SODA are in accordance with each other. On the other hand, Fang's study underestimated the heat transport during the summer. During January the heat is transported into the Andaman Sea through the Strait of Malacca with an estimate of 0.18 PW for ROMS and 0.16 PW for SODA. In the summer season,

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the heat is transported into the corresponding area with an estimate of 0.096 PW for ROMS and 0.079 PW for SODA. For salt transport (Fig. 9d), ROMS and SODA estimate are also in good agreement. During winter, salt is transported into the Strait of Malacca with estimates of 0.068×10^9 and $0.067 \times 10^9 \text{ kg s}^{-1}$ for ROMS and SODA respectively. During summer the salt transport is into the Strait of Malacca with estimates of 0.034×10^9 and $0.041 \times 10^9 \text{ kg s}^{-1}$ for ROMS and SODA respectively. In contrast, Fang's study underestimated the salt transport during both summer and winter.

4.3.2 Mean annual transports

(a) Sunda Shelf

The ROMS mean of various annual transports through the Sunda Shelf and those of SODA are listed in Table 3. The model estimated mean annual volume transport shows the water flows out of the SSCS by 0.32 Sv through the Sunda Shelf and into the Java Sea. This is comparable with the corresponding value of 0.42 Sv of SODA.

Table 3 also presents the mean annual heat, salt, and freshwater transports through the Sunda Shelf. The ROMS and SODA estimates of heat transport from SSCS into the Java Sea through the Sunda Shelf are comparable with values of 0.032 and 0.042 PW respectively. Meanwhile, the modeled annual salt and freshwater transports flows into the Java Sea are $0.010 \times 10^9 \text{ kg s}^{-1}$ and 0.023 Sv, respectively. These estimates are comparable to those of SODA (i.e., $0.016 \times 10^9 \text{ kg s}^{-1}$ and 0.026 Sv). However, estimates of heat and salt transports from several numerical studies vary considerably due to different model configurations and resolutions. Cai et al. (2005a), using LICOM global model of horizontal of $1/2^\circ$ and uniform 12 levels in the upper 300 m estimated 0.17 PW and $0.066 \times 10^9 \text{ kg s}^{-1}$ of heat and salt transports through the Sunda shelf respectively. Fang et al. (2003), based on the MOM global ocean model with a horizontal resolution of $1/6^\circ$ and 15 uniform vertical levels, estimated the heat and salt transport of 0.35 PW and $0.11 \times 10^9 \text{ kg s}^{-1}$, respectively.

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Figure 10 shows that estimate of the annual volume transport (F_V) from the different model studies vary considerably and decrease exponentially. The previous estimates of mean volume annual transport differ between a maximum value of 3.15 Sv of Fang et al. (2003) and minimum of 0.5 Sv of Qingye et al. (2009). Table 4 shows the ocean model configurations and specifications used in the previous modeling studies.

These previous studies are mostly based on a global ocean model of various resolutions. As in Fig. 1 the length of the Sunda Shelf is noted to be approximately 500 km and maximum water depth of about 50 m across the passage. Hence the above differences in the estimate of F_V from different models may be due to the coarse horizontal and vertical resolutions of the models. Such a coarse model could produce relative differences in transport estimates through the Sunda Shelf. Fang et al. (2005) pointed that large transport values are due to the coarse horizontal and vertical resolutions, particularly in the shallow water region and the entrance of the Straits where are connected to the different regions.

(b) Strait of Malacca

Table 5 presents a comparison of the mean annual transports through the Strait of Malacca from ROMS, SODA, and those from the study by Fang et al. (2003). In consistent with the seasonal cycle of transport in Fig. 9, the ROMS and SODA estimate of various estimates are very much in good agreement with each other. All estimates of mean annual transports are positive indicating outflow into the Strait of Malacca. For volume transports, ROMS and SODA estimates are 0.14 and 0.13 Sv respectively. However, Fang et al. (2003) overestimated the mean volume annual transport of 0.5 Sv, about four times higher than that of ROMS estimates. ROMS and SODA estimates of mean heat annual transports are 0.014 and 0.013 PW respectively. For mean annual salt transport, ROMS and SODA estimates are 0.0043×10^9 and $0.0041 \times 10^9 \text{ kg s}^{-1}$. Similarly, Fang's study also overestimated the mean annual heat and salt transports. These discrepancies may be due to the relatively coarse horizontal resolution of the global ocean model used in Fang's study. The width of the cross-section in Strait of

Malacca (see Fig. 1) is about 140 km with depths of ≤ 20 m. With such a narrow and shallow Strait, using a global ocean model for transports estimation may be inaccurate.

The cross-section in the Strait of Malacca is narrower than the Sunda Shelf passage and hence lesser transports flow through it. The maximum outflow volume transport through the Sunda Shelf during January is 5.7 Sv, which is much higher than the corresponding outflow volume transport of 1.8 Sv for the Strait of Malacca. Owing to this shallow depth, the Strait of Malacca is often not captured in the simulation using a coarse global ocean model (Fang et al., 2005; Cai et al., 2005a; Qingye et al., 2009). However, in spite of the high value of outflow and inflow transports throughout the year, the outflow mean annual transports through the Sunda Shelf are relatively small. Interestingly, the outflow mean annual transports through the Strait of Malacca are equally significant compared to those of the Sunda Shelf. For mean volume and heat annual transports, the estimate for Strait of Malacca is about 43.8 % of the Sunda Shelf. For salt and freshwater, the percentages are about 43 and 39 %, respectively. This reflects that the Strait of Malacca plays equally important role in the annual transports from the Strait of Malacca into the Andaman Sea.

5 Summary and conclusion

Based on the results of ROMS simulation, transports of volume, freshwater, heat, and salt, through the inter-ocean passages are estimated in the SSCS for the Sunda Shelf and the Strait of Malacca. The simulated patterns of SST and current circulation are in good agreement with observations, re-analysis product of SODA, near-real time global ocean surface currents derived from satellite altimeter and scatterometer data (OSCAR). The estimated ROMS and SODA seasonal transports across both the Sunda Shelf and the Strait of Malacca are almost comparable to each other (Figs. 8 and 9). The ROMS estimated transports are also consistent with the observed values of Fang et al. (2010) for one-month duration of 13 January and 12 February 2008. However, estimates of transports from coarser global ocean model (Fang et al., 2003) are often

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higher during winter and lower during summer. This could be due to the inability of the coarser global ocean model in resolving the complexity in the SSCS region due to rapid changes by interaction with bathymetry and topography. This study shows that the mean annual transports in the Sunda Shelf are outflow transports into the Java Sea. Similarly, the mean annual transports in the Strait of Malacca are outflow transports from the Straits of Malacca towards the Andaman Sea. Owing to the relatively large area of the cross-section in the Sunda Shelf as compared to that in the Strait of Malacca, the seasonal transports in the Sunda Shelf are higher and vary considerably. However, in terms of mean annual transports, ROMS estimated transports indicate the importance of both passages in the Sunda Shelf and the Strait of Malacca. The percentages of estimated mean annual transports through the Strait of Malacca to those of the Sunda Shelf range from 39 to 43.8%. These percentages reiterate the equally importance of the Strait of Malacca as an inter-ocean transport passage from the SSCS into the Andaman Sea. Overall, this study provides estimates of various transports through inter-ocean passages in the SSCS. Nevertheless, a better estimate of transport is necessary to understand the changes in the ocean circulation as well as to enhance our knowledge on the role of transport distribution such as heat and freshwater which in turn affect the changes of the ocean's ventilation rates and pathways. This provides a better picture to assess the changes in the net uptake of gases such as O₂, CO₂ which influence the distribution of the nutrient balance in regulation changes in the marine ecosystem.

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Table 2. Estimates of mean volume (F_V), heat (F_H), salt (F_S), and freshwater (F_W) transports during winter (January and February) from observation (Fang et al., 2010), the SODA and ROMS.

Reference	F_V (1 Sv = 10^6 m ³ s ⁻¹)	F_H (1 PW10 ¹⁵ J s ⁻¹)	F_S (= 10^9 kg s ⁻¹)	F_W (1 Sv = 10^6 m ³ s ⁻¹)
Fang et al. (2010)	3.6 ± 0.8	0.36 ± 0.08	0.12 ± 0.03	0.14 ± 0.04
SODA	3.9	0.39	0.13	0.15
ROMS	4.8	0.48	0.16	0.18

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Table 3. Mean annual volume (F_V), heat (F_H), salinity (F_S), and freshwater (F_W) transports through the Sunda Shelf. Positive values indicate outflow transports.

Reference	F_V ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$)	F_H ($= 10^{15} \text{ J s}^{-1}$)	F_S ($= 10^9 \text{ kg s}^{-1}$)	F_W ($= 10^6 \text{ m}^3 \text{ s}^{-1}$)
SODA	0.42	0.042	0.016	0.026
ROMS	0.32	0.032	0.010	0.023

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Table 5. Mean annual volume (F_V), heat (F_H), salt (F_S), and freshwater (F_W) transports through the Strait of Malacca.

Reference	$F_V (= 10^6 \text{ m}^3 \text{ s}^{-1})$	$F_H (= 10^{15} \text{ J s}^{-1})$	$F_S (= 10^9 \text{ kg s}^{-1})$	$F_W (= 10^6 \text{ m}^3 \text{ s}^{-1})$
Fang et al. (2003)	0.50	0.060	0.0173	NA
SODA	0.13	0.013	0.0041	0.009
ROMS	0.14	0.014	0.0043	0.009

NA: Not available.

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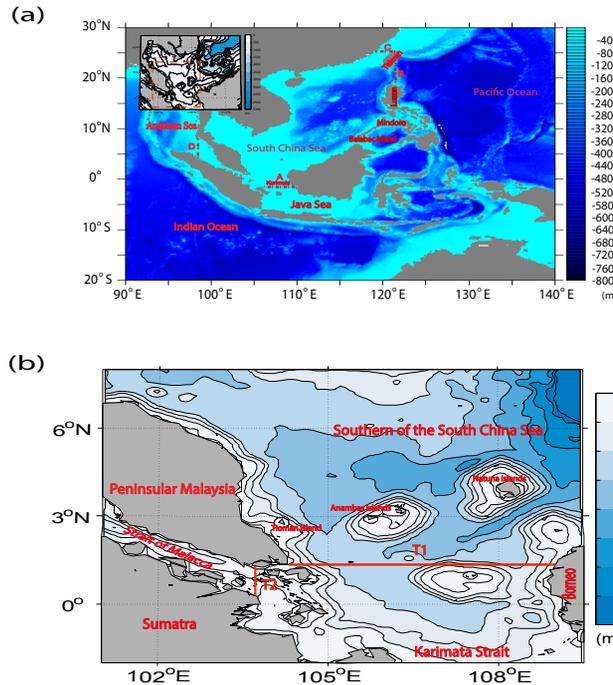


Figure 1. (a) Bathymetry (in meters) is in the coarse resolution domain and the top left corner of the map is for the fine resolution model domain. The red dot-dashed line marked with the letters A to D in (a) indicates the four lateral boundaries applied to simulation. The red dashed line in the top corner map indicates the region of study. Lower panel (b) shows bathymetry (in meters) for the southern part of the South China Sea with major passages of water mass transport through the Sunda Shelf and the Strait of Malacca, marked with the red solid-line cross sections (i.e., transect T1 and T2 respectively) used for the transport budget analysis.

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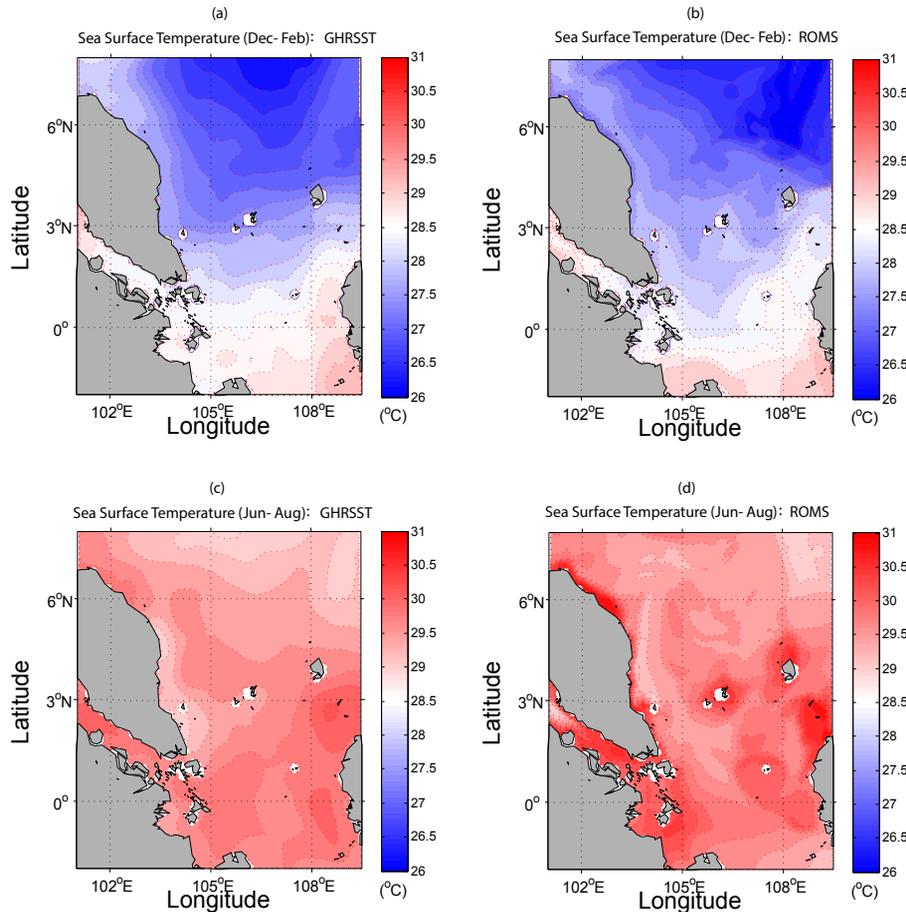


Figure 2. Seasonal variations in sea surface temperatures in °C for **(a–b)** winter monsoon (December-January-February) and **(c–d)** summer monsoon (June-July-August).

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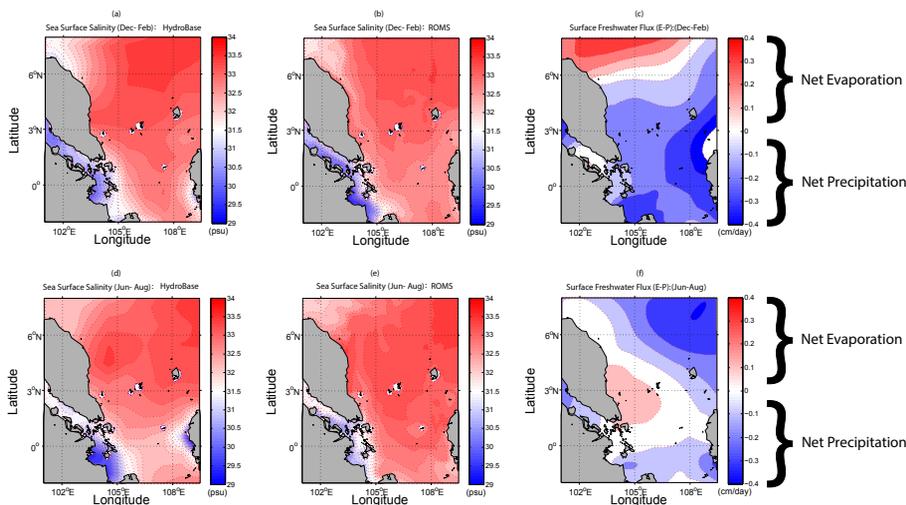


Figure 3. Seasonal variations in sea surface salinity in psu for **(a–b)** winter monsoon (December–January–February) and **(d–e)** summer monsoon (June–July–August). **(c–f)** demonstrates distribution of surface freshwater flux (cm day^{-1}) for the winter and summer seasons computed based on amounts of evaporation (E) and precipitation (P) from monthly climatological data (Da Silva et al., 1994).

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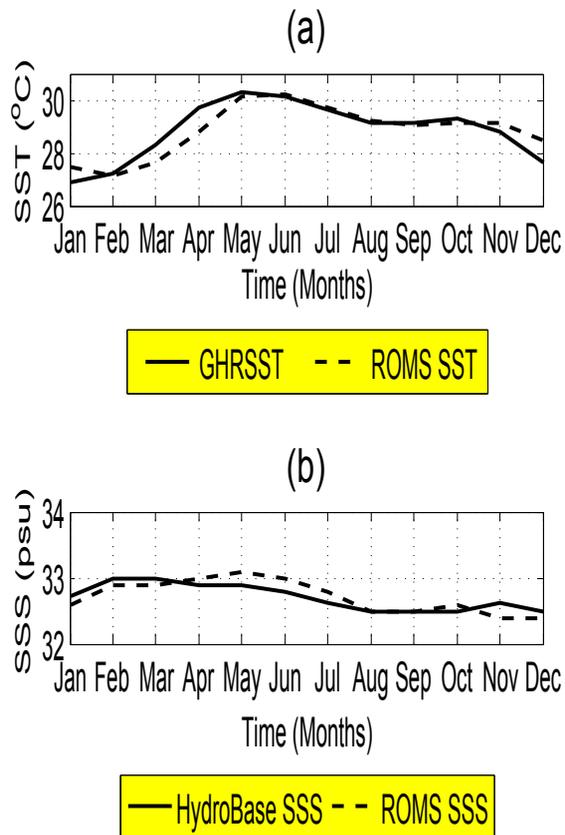


Figure 4. The seasonal cycle of SST ($^{\circ}\text{C}$) and SSS (psu) represented for the GHR SST and HydroBase SSS (the solid line) and with the dashed-lines for the model.

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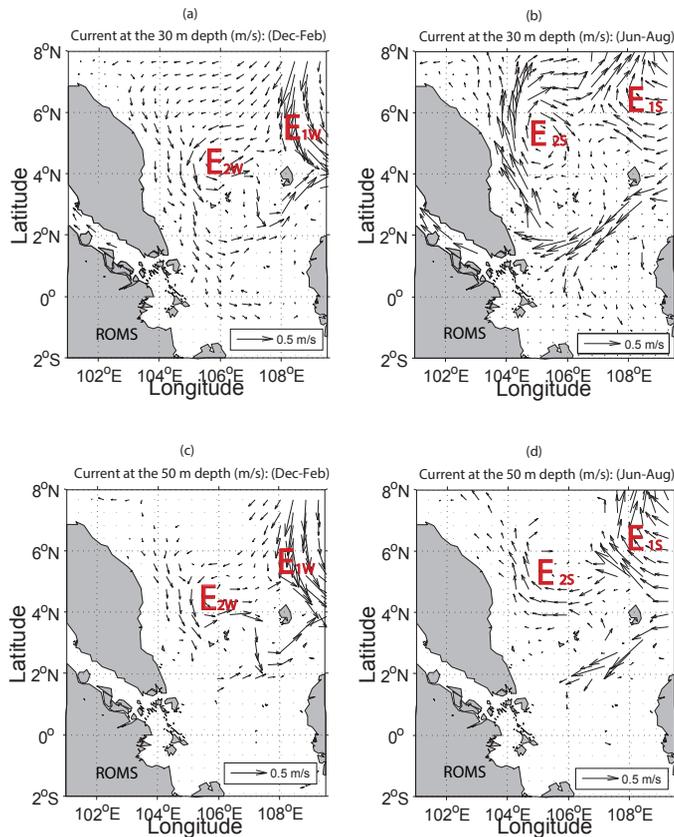


Figure 6. Seasonal patterns of the modeled sea currents (m s^{-1}): at the depth of 30 m (a, b), and in 50 m (c, d).

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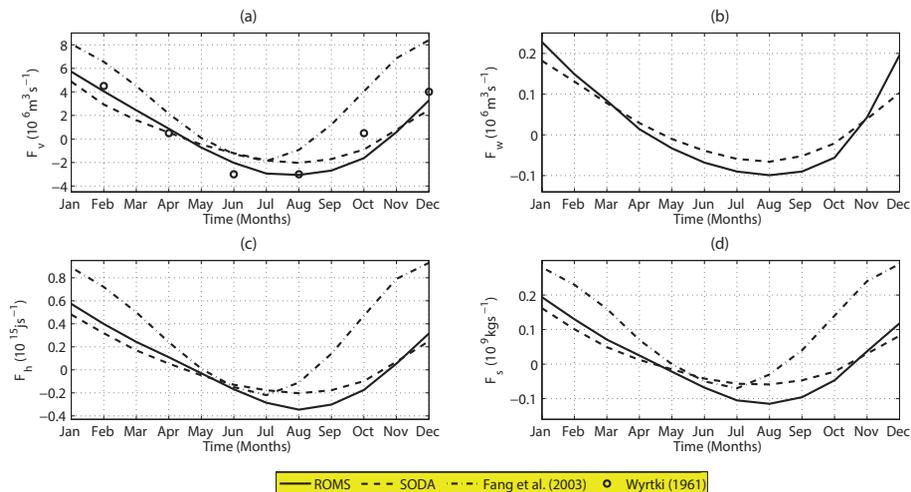


Figure 8. Seasonal variations in (a) volume, (b) freshwater, (c) heat, and (d) salt transport through the Sunda Shelf based ROMS (solid line), SODA (dashed line), and the dash-dot line estimated by Fang et al. (2003). Positive and negative values indicate outflow and inflow, respectively. The circles in (a) indicate observed volume transport by Wyrтки (1961).

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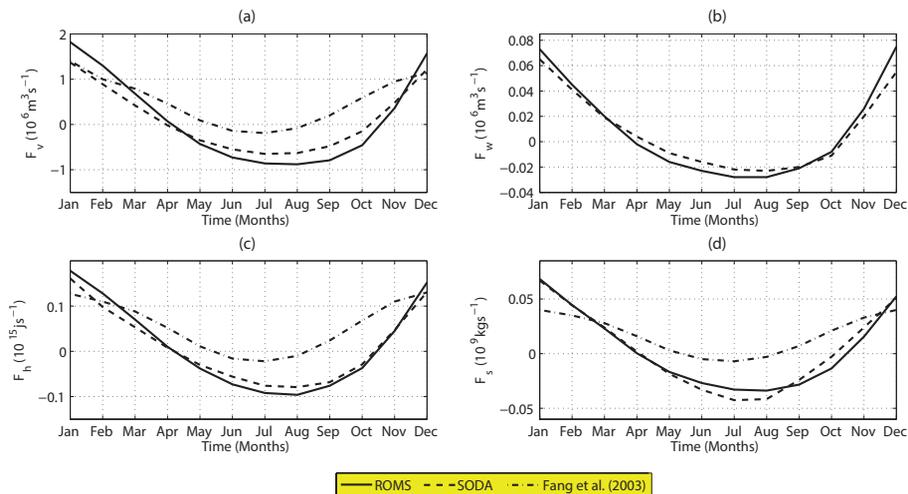


Figure 9. Seasonal variations in **(a)** volume, **(b)** freshwater, **(c)** heat, and **(d)** salinity transports in the Strait of Malacca based on ROMS (solid line), the SODA (dashed line) and Fang et al. (2003) (the dash-dot line). Positive (negative) means flow into (out) of the Strait of Malacca.

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