Seasonal variation of the Sunda Shelf Throughflow

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Abstract. The Sunda Shelf Throughflow (SSTF) is defined as a seasonal reversal shallow current system flowing from the South China Sea to the Indonesian Throughflow (ITF) region via the Natuna and Java Seas. This current system plays an important role on transferring heat and freshwater fluxes into the ITF system and vice versa. This paper aims to investigate seasonal changes of transport volume in three sections within the Sunda Shelf region (namely Natuna, Karimata and Java section). We used the validated daily ocean circulation model outputs from INDESO configuration between 2008 and 2014. It is shown that mean transport volume of the SSTF is relatively small on the order of -0.5Sv toward the ITF region (1Sv=10⁶m³/s) due to a strong seasonal reversal flow of the SSTF forced by the monsoonal winds. However, on seasonal scale this transport volume strengthens drastically to about 2-3Sv (1-2 Sv) during the northwest (southeast) monsoon period, which is in good agreement with previous studies. Transport estimate in Java section is reduced to about -0.1Sv may be due to a leakage of the flow via Sunda Strait and also a strong recirculation of Makassar ITF into Java Sea.

1. Introduction
The Sunda Shelf (SS) situated geographically in the Southeast Asia region, is characterized with a shallow continental shelf with a depth averaging less than 100 m [1]. This region is surrounded by the Malaysia Peninsula, the Indochina Peninsula, Kalimantan (Borneo) Island, Sumatera Island and Java Island. Configuration of the seas and straits within the Sunda Shelf are Natuna Sea, Karimata Strait, Malacca Strait, and Java Sea. In the northern part of SS, there is South China Sea (SCS) which is referred to as the largest marginal sea in the Southeast Asia waters [2] and even in the world [3]. The SCS connects the outer seas through Luzon Strait, Taiwan Strait, Mindoro Strait, Balabac Strait, Karimata Strait and Malacca Strait. Based on previous studies, the SCS is revealed as an important passage of the Pacific-to-Indian Ocean Throughflow [3][4][5][6][7][8][9][10] and plays a crucial role in the SCS water mass formation [7][11].
Water mass with high salinity and low temperature of the Western Pacific entering the SCS via the Luzon Strait [12]. Furthermore, this water mass is transported to East China Sea through Taiwan Strait and flowing back to the Pacific. The water is also transported to the Sulu Sea through Balabac and Mindoro Strait and towards Andaman Sea through Malacca Strait. From the South China Sea, the water that comes from the Western Pacific entering to the Indonesian waters through Natuna Sea and Karimata Strait. This flow thus is called as “Sunda Shelf Throughflow (SSTF)”. It flows from SCS to Java Sea which is a source of low salinity water mass [13] and even merges to the ITF, exiting to the Indian Ocean [7, 9]. Water exchange through Sunda Shelf (Natuna Sea and Karimata Strait) is mainly driven by monsoon winds [14]. The southeasterly (or southwesterly) monsoon winds prevail during boreal summer (Apr-Sept), in contrast, the northwesterly (or northeasterly) monsoon winds develop during the boreal winter (Oct-Mar). Moreover, there is a north-south sea level slope between Natuna Sea and Java Sea in
the boreal winter, creating a horizontal pressure gradient that contributes significantly on driving the SSTF [14].

Previous studies have estimated transport volume of the SSTF from surface observation and numerical models. [13] observed that outflow from the SCS to Java Sea through Karimata Strait is -4.5 Sv during boreal winter and noted an inflow of 3 Sv into the SCS during boreal summer (negative/positive indicates southward/northward transport) [17] using sea surface height from satellites and ocean bottom pressure data, estimated a mean transport of -7.5 Sv through Karimata Strait during boreal winter. From ADCP observations between 13 January and 12 February 2008, [14] estimated a mean transport volume of the SSTF of -3.6 Sv. [15][16] using LICOM numerical model with horizontal resolution of ½°, estimated the mean transport volume into Java Sea is -0.93 Sv, but with different configuration he estimated the SSTF -2.26 Sv. Other modeling system from MOM2 with a resolution of 1/6° for the SCS and adjacent seas and 3° for the global ocean, [18, 19] estimated the mean volume transport of the SSTF -3.1 Sv, which much smaller (1.16 Sv) when using different model configuration. [20] use Regional Ocean Modeling System (ROMS), estimated mean transport volume of the SSTF of -0.32 Sv, and mean transport volume via Malacca strait is 0.14 Sv. Recently, [21] using OFES modeling system with a resolution of 1/10°, estimated mean transport volume through Karimata Strait of -0.7 Sv.

During the project of the Indonesian operational oceanography of INDESO (Ministry of Fisheries and Marine Affairs, 20012), a simulation of an eddy-resolved 3-dimensions ocean general circulation model of NEMO coupled with PISCES biogeochemical model using INDESO configuration has been successfully performed over the Southeast Asia seas (90°E-145°E, 20°S-25°N). Unlike other numerical ocean model, this INDESO simulation has been assimilated and validated with many observation data sets over the model domain [22]. These available daily model output data set of current, temperature, and salinity between 2008 and 2014 provide invaluable data sets for study the physics and dynamics of the ocean over the model domain. A lot of research that used INDESO model namely [23] using INDESO model to describe spatial and temporal variation in Makassar Strait, [24] used it to study upwelling dynamic based on Satellite and INDESO Data in the Flores Sea. Recently, [25] conducted a study about Variability of water mass Transport in Western Banda Sea using INDESO model. In particular, this paper aims to investigate seasonal variation of Sunda Shelf Throughflow (SSTF) that flows through Natuna Sea, Karimata Strait and Java Sea using daily averaged 3-dimension model output of ocean current components, temperature and salinity from INDESO model between 2008 and 2014.

2. Material and Methods

2.1. Study area

The area of study was conducted in Sunda Shelf regions, covering Natuna Sea, Karimata Strait, and Java Sea (Fig. 1). In study area map, there were 3 (three) red lines (A, B, C) represent transects for transport volume calculation.
Figure 1. Study area of Sunda Shelf region. Red lines denote for transect of transport volume estimates in A (Natuna Sea, 1.7°N), B (Karimata Strait, 2.75°S), and C (Java Sea, 114.5°E). Black rectangle denotes for sampling box for model and data validation of sea surface temperature and sea surface height.

2.2. Configuration of the INDESO model output
The INDESO is a project of development and utilization of oceanography data for maritime and fisheries needs. The resolution of 1/120° (9.25 km) is applied on 3-dimensional OGCM of NEMO [26] from INDESO configuration, performed by Mercator-Ocean [22]. The horizontal grid is an extraction of global ORCA (a global tripolar used in NEMO) grid at 1/120° (9 km) developed at Mercator Ocean. The vertical grid is spread over 50 levels. Whereas lateral boundary forcing from global OGCM of 1/4° and atmospheric forcing field is required by daily meteorological data from ECMWF. The bathymetry used in the INDESO configuration is based on ETOPO2V2g with grid area of 2' and GEBCO with grid area of 1' [22]. The other data used from input model is assimilated data from satellites and Argo data. The output datasets of this model are daily averaged 3-dimension model output between 2008 and 2014. The output of variables used in this study are seawater temperature, salinity, zonal and meridional current, and sea surface height.

2.3. Data analysis
The analysis of time-series data of zonal and meridional component in each section Natuna, Karimata and Java were conducted using Power Spectral Density (PSD) and Cross-Power Spectral Density (Cross-PSD) analysis [27] to examine transport volume time series of all sections and its periodicity (between Natuna Sea and Java Sea) according to [28].

Furthermore, to estimate transport volume of SSTF through Sunda Shelf (Natuna section (A), Karimata section (B) and Java section (C)) in Figure 1 and it can be calculated using the following formula based on [29]:

\[
Q_{vA} = \int_A^0 \int_0^b v dx dz
\]

(1)

\[
Q_{vB} = \int_B^0 \int_0^b v dx dz
\]

(2)

\[
Q_{vC} = \int_C^0 \int_0^b u dy dz
\]

(3)

where \(Q_{vA}, Q_{vB}\) and \(Q_{vC}\) are transport volume estimates at Natuna section (A), Karimata section (B) and Java section (C) by integral operation taking into account of a length of section (m), depth integration (0 - 60 m / depth of A section; 0 – 40 m /depth of B section; and 0 – 120 m /depth of C section), and zonal and meridional current component (u and v in m/s).
To analyze transport of Sunda Shelf Throughflow (SSTF) were visualized as monthly average on A, B, C section in Figure 1. Each monthly average represents monsoon period. The Northwest Monsoon (NWM) period occurs from October to March, while the Southeast Monsoon (SEM) period occurs from April to September with peaks of the monsoon period are December-February (DJF) and June-August (JJA), respectively. We made tabulation of mean and standard deviation of transport volume of Natuna section (A), Karimata section (B) and Java section (C) on each Monsoon period (DJF, MAM, JJA and SON) to described differences among transport volume on seasonal periods.

Power Spectral Density (PSD) analysis [28] was used to find out the significant energy peaks for respective periods within time-series data with 95% confidence interval. In this research, time series data length (N) is 2557 and segment length is 1024 used for PSD calculation. The PSD of transport

where $X_i = \text{Fourier component, } x_n \text{ is data values, } n = 0, 1, \ldots, N-1; i = 1, 2, \ldots, n_d; k = 1, 2, \ldots, N/2$

We also used Cross Power Spectral Density (Cross PSD) to find out shared periodicity from both of time series data. Their correlation degree is indicated by its normalized coherence value varied from minimum (0) to maximum (1). The result of cross-PSD analysis is co-spectrum energy that shows magnitude of energy fluctuations at specific frequency within both of time-series data; coherency and phase showed correlation and phase difference (lag and lead) at specific frequency within both of time-series data. Positive (negative) phase means one time series leads (lags) to another series. According to equation from [28, 30], co-spectrum estimate is calculated by following formula:

$$ G_{XY}(f_k) = \frac{2\Delta t}{T} \left[ X(f_k) \ast Y(f_k) \right] $$

where $G_{XY}(f_k)$ is density spectrum of cross energy in frequency to $-k$ ($f_k$); $f_k = \frac{k}{N\Delta t}$ is the discretized frequencies; $X(f_k)$ is Fourier component of x; $Y(f_k)$ is Fourier component of y; $\Delta t$ is time cross sampling data (1 day); $T$ is data period.

The value of coherence is estimated by following equation [29, 30]:

$$ \gamma^2_{XY}(f_k) = \frac{|S_{xy}(f_k)|^2}{S_x(f_k)S_y(f_k)} $$

where $\gamma^2_{XY}(f_k)$ is coherence value in frequency to $-k$ ($f_k$), $S_{xy}(f_k)$ is density spectrum of cross energy in frequency to $-k$, $S_x(f_k)$ and $S_y(f_k)$ are density spectrum energy $X(f_k)$ and $Y(f_k)$

Phase is estimated by following equation [29, 30]:

$$ \theta_{xy}(f_k) = \tan^{-1} \left( \frac{Q_{xy}(f_k)}{C_{xy}(f_k)} \right) $$

where $Q_{xy}(f_k)$ is imaginer value from $G_{XY}(f_k)$ and $C_{xy}(f_k)$ is real value from $G_{XY}(f_k)$.

In this research, the cross-PSD analysis was used to obtain coherency and phase between transport volume in Natuna sea ($Q_{oa}$) and in Java sea ($Q_{ac}$).

2.4. Model validation

To determine a performance and accuracy of the model output datasets, time-series data of zonal current velocity from the model outputs were compared with observed satellite data from http://marine.copernicus.eu. Boundary of data validation region (4°S - 6°S and 110°E - 112°E) is shown with black box in figure 1. Both of observed satellite data and model data were in the data along 2008 - 2014. To assess how model represents actual condition, correlation coefficient is calculated using equation from [28]:

$$ r = \frac{1}{N-1} \sum_{i=1}^{N} \left( \frac{(x_i - \bar{x})(y_i - \bar{y})}{s_x s_y} \right) $$

where $r = \text{correlation coefficient; } N = \text{total number of data; } \bar{x}$ and $\bar{y}$ is mean of INDESO model output and observed satellite data during 2008 - 2014; $x_i$ and $y_i$ is $i$th value of model and observed satellite data; and $S_x$ and $S_y$ is standard deviation of model (x) and observed satellite data (y).
The statistical correlation coefficient between INDESO model output and observed satellite time series are reasonably high of 0.91. It is shown clearly that fluctuation of zonal current velocity in the model and observed satellite data are in an excellent agreement and very strong correlated [31]. The zonal current velocity time series data reveal strong seasonal variation. During the NWM (October – March), the direction of current is dominated by eastward flow with the peak of NWM of zonal current velocity occur in December. While westward flow occurs during the SEM (April – September) with the peak of SEM of zonal current velocity happened in June.

![Figure 2](image-url)  
**Figure 2.** Time-series of INDESO model (red line) and observed satellite data (black line) in 2008 – 2014 (statistical correlation coefficient for zonal current velocity is 0.91).

3. Results and discussion

3.1. Characteristics of SSTF along Natuna, Karimata, and Java section

The mean vertical section of the meridional current component ($v$) of INDESO model from January 2008 to December 2014 at 1.7°N (Natuna section (a)) and at 2.75°S (Karimata section (b)) is depicted in Figure 3. The SSTF through Natuna section is indicated by a northward flow that is found from surface to depth of 20 m with a maximum speed exceeding 0.09 m/s. But in a deeper layer, the flow is southward with a speed magnitude exceeding 0.12 m/s. The average flow rate of SSTF in Karimata section (Figure 3b) is about 0.12 m/s at a depth of 20 m, with dominant flow towards to South. Furthermore, the circulation pattern of SSTF through Java section (Figure 4) is dominated by an eastward flow with a maximum speed exceeding 0.14 m/s.

![Figure 3](image-url)  
**Figure 3.** The cross-section of the averaged meridional current component ($v$) of SSTF through Natuna section at 1.7°N (a) and Karimata section at 2.75°S (b); the color in meridional currents show the speed scale (m/s). Positive (negative) indicates southward (northward).
Figure 4. The cross-section of the averaged zonal current component (u) of SSTF through Java section at 114.5°E; the color in meridional currents show the speed scale (m/s). Positive (negative) indicates eastward (westward).

3.2 Annual cycle of Sunda Shelf Throughflow
The annual cycle of SSTF in the Sunda Shelf (Natuna, Karimata and Java Sea) varied on seasonal pattern. In Northwest season (December to February), the current direction in Natuna Sea prevails to Southward with a current velocity of about 0.33 m/s at a surface (Figure 5). While in May, there is a reversal of current direction to north. In the Southeast period (June to August), the current is dominant to north with a maximum speed exceeding 0.5 m/s. Then the current changes direction in October. The current moves back to south.

Figure 5. Annual cycle of SSTF through Natuna section. Negative (positive) value indicates southward (northward). The color in meridional currents show the speed scale (m/s).

The annual cycle of the meridional current component of SSTF through Karimata section has similar pattern with in Natuna section. In the Northwest periods, the direction of current is dominated by southward flow with a maximum speed exceeding 0.41 m/s. Then the current changes direction in May.
The current flow in the Southeast season is dominated by a northward flow with a maximum speed of about 0.155\text{m/s}. The current changes direction again in October. The current moves back to southward. (Figure 6).

**Figure 6.** Annual cycle of SSTF through Karimata section. Negative (positive) value indicates southward (northward). The color in meridional currents show the speed scale (m/s).

**Figure 7.** Annual cycle of SSTF through Java section.
The annual cycle of the zonal current component of SSTF through Java section is depicted in Figure 7. In the Northwest periods, the direction of current is dominated by eastward flow with a maximum speed exceeding 0.60m/s. Then the current changes direction in May. The current flow in the Southeast season is dominated by a westward flow with a maximum speed of about 0.48m/s. The current changes direction again in October. The current moves back to eastward.

In general, water exchange through the Sunda Shelf (Natuna Sea and Karimata Strait) is mainly driven by monsoon winds [14]. The southeasterly (or southwesterly) monsoon winds prevail during boreal summer (Apr-Sept), in contrast, the northwesterly (or northeasterly) monsoon winds develop during the boreal winter (Oct-Mar). Moreover, there is north-south sea level slope between Natuna Sea and Java Sea in the boreal winter, creating a horizontal pressure gradient that contributes significantly on driving the SSTF [14] so that the ocean current of SSTF flows to the southward when it passed Natuna Sea and Karimata Strait and SSTF flows to eastward when it entering the Java Sea.

3.3 Time series of transport volume of the Sunda Shelf Throughflow

The transport volume of SSTF through Natuna section (NS) from January 2008 to December 2014 is presented in Figure 8a. The fluctuation range of transport is between -3.166Sv (to South) to +1.644Sv (to North), with an average value of -0.529Sv and a standard deviation of 0.964. The annual cycle of the transport of SSTF through NS showed the transport strengthened during Northwest Monsoon toward the south and obtained its maximum in January (-1.730Sv) in the final the season, whereas it become relaxed at 0.519Sv in July in the Southeast monsoon period toward to the North. (Figure 8b). Visually, the transport movement of SSTF through NS is dominated by an annual time scales (341-day), intra-seasonal time scales (90 – 20 day) and tide time scales (14.7 day).

![Figure 8](image_url)  
Figure 8. Time series of transport volume in Natuna section (a), and transport volume climatology (b).

The Karimata section (KS) has similar pattern with time series of NS, the transport volume of SSTF showed a range of fluctuations between -2.885Sv (to south) to +1.344Sv, with an average of about -0.495Sv and a standard deviation 0.919 Sv (Figure 9a). The annual cycle of SSTF through KS showed the transport also strengthened during Northwest Monsoon to the south with its maximum in January (-1.168Sv) in the final the season, whereas it become relaxed at 0.548Sv in the Southeast monsoon (July) toward to North (Figure 9b). Same with NS, the transport movement of SSTF through KS is dominated by an annual time scales (341day), intra-seasonal time scales (90 – 20 day) and tide time scales (14.7 day).
In the Java section (JS), the transport volume of SSTF shows the range of fluctuation between -0.263Sv (toward to West) to +3.638Sv (toward to East), with average of approximately 0.123Sv and a standard deviation of approximately 1.219Sv (Figure 10a). The annual cycle of JS transport became strong during Northwest Monsoon toward to East and reached its maximum in January (+1.804Sv), and subsequently it relaxed to -1.262Sv in August during Southeast season (Figure 10b). Visually, the JS transport fluctuation shows an annual, intra-seasonal and tide fundamental periods. It means annual and intra-seasonal variation becomes dominant in this region.

3.4 Seasonal transport volume of the Sunda Shelf Throughflow

Monsoon is traditionally defined as a seasonal reversing wind. It can be used to describe seasonal changes in atmospheric circulation. Indonesian is influenced by Asia-Australian Monsoon. The Asia-Australian monsoon consists of Northwest monsoon/ NWM (from October to March) with peak of NW monsoon is December to February and Southeast monsoon/ SWM (from April to September) with peak
of SE monsoon is June to August. The NWM is known as the boreal winter and the SEM is known as the boreal summer. The first transitional season (March to Mei /MAM) is between NWM and SEM. The second transitional season is between SEM and NWM from September to November (SON). Transport volume of the SSTF through the Sunda Shelf regions (Natuna Sea, Karimata Strait and Java Sea) on different seasonal periods is depicted in Table 1. For Natuna and Karimata section, positive (negative) value indicates southward (northward). While positive (negative) value indicates eastward (westward) for Java section. In the Natuna and Karimata section, the maximum southward transport occurs in peak of Northwest monsoon (NWM/ DJF) and the maximum northward transport occurs in peak of Southeast monsoon (SWM/ JJA). Whereas in Java Section, the maximum eastward also occurs in peak of NWM and the maximum westward transport also occurs in peak of SWM.

Table 1. Average and standard deviation of estimated transport volume of SSTF through Natuna, Karimata and Java section in different monsoon periods.

| Section | Transport Volume Estimate of the SSTF (in Sv) |
|---------|-----------------------------------------------|
|         | Dec-Jan-Feb (peak of NWM period) |
| Natuna  | -1.590 (±0.231) |
| Karimata| -1.546 (±0.224) |
| Java    | 1.536 (±0.389) |

Table 2 provides another comparison of transport volume of this study with various methods (modeling and observation). [20] using LICOM global model of 1/2° horizontal resolution and 12 uniform vertical levels, estimated 3.4Sv and 0.2Sv of transport volume during boreal winter and boreal summer, respectively. From this study, we known no reversal of the transport volume from winter to summer. [20] based on HYCOM global model of 1/2° horizontal resolution and 20 uniform levels, estimated transport volume of 2.1Sv and -1.0Sv during January and June respectively. The estimates from two model studies are not consistent with the [20] based on ROMS and SODA.

Table 2. The study of seasonal transport volume through the Sunda Shelf.

| No | Research by  | Transport volume (Sv) | Methods |
|----|--------------|------------------------|---------|
|    |              | Winter | Summer |         |
| 1  | Cai et al (2005a) [20] | 3.4 (Dec) | 0.2 (June) | Model |
| 2  | Qingye et al., (2009) [20] | 2.1 (Jan) | -1.0 (June) | Model |
| 3  | Fang et al (2010) [32] | 3.6±0.8 (Jan to Feb) | - | Observation |
| 4  | Susanto et al (2013) [33] | -2.7±1.1 | 1.2±0.6 | Observation |
| 5  | Daryabor et al (2015) [20] | 3.3 (Dec); 5.7 (Jan) | -2.0 (June) | Model |
| 6  | Wang et al (2019) [34] | -1.99 (Dec to Feb) | 0.69 (June to Aug) | Observation |

Table 2 also provides a comparison of transport from SCS into Java Sea using observation method. [32] based on the ADCP deployed for a period of 13 January to 12 February 2008 estimated 3.6±0.8 Sv. The other observed method was done by [33]. They calculated the mean transport volume with ADCP deployed in Karimata Strait from November 2008 to June 2015 as a part of the South China Sea-Indonesian Seas Transport/Exchange and Impact on Seasonal Fish Migration (SITE) Program. The observed current data indicates the transport volume the Karimata Strait exhibits significant seasonal variation. [33] reveals the mean transport volume is (-2.7±1.1) Sv during the boreal winter (December 2007 to March 2008) and (1.2±0.6) Sv during the boreal summer (May to September 2008). [33] calculated the winter-averaged transport (Dec-Feb) is -1.99Sv, while in the boreal summer (from June-
August), the averaged transport is 0.69Sv. From all of previous studies were conducted with several methods. [34] is in good agreement with present study especially with seasonal variation of SSTF through Natuna and Karimata section.

### 3.5 Power spectral density time series of SSTF through Natuna and Java section

Figure 5 showed the spectrum of energy density of transport volume in the two study areas namely Natuna section and Java section. Visually, the signal propagation among Natuna Sea and Java Sea can be seen from the peak of the spectrum of significant energy densities found in the periods of 341 day, 90 – 20 day, and 14.7 day, where the transport volume time series data are dominated by annual, intra-seasonal and baroclinic tide fluctuations. From figure, we can see that signal of Java Sea lead to signal of Natuna Sea.

![Power Spectral Density](image1)

**Figure 11.** Power Spectral Density time series of SSTF through Natuna and Java section

### 3.6 Coherence and phase of in Natuna and Java section

The cross-PSD analysis of transport volume time-series that the phase difference between signal fluctuations in Java Sea and Natuna Sea varied from 0.487 days to 0.5339 days. This indicates that SSTF at the transect of Natuna section (1.7°N) flowing to the SSTF – Java section at transect of (114.5°E) needs between 0.487 days to 0.5339 days.

![Coherence and Phase](image2)

**Figure 12.** Coherence and time series phase of transport volume between Natuna and Java section.
Besides that, the analysis results of cross-PSD time series of SSTF transport between Natuna and Java Sea shows that the significant coherence values occurred on annual, intraseasonal and forthnightly tidal time-scale, in 341 days, 146 days, 79 days, 60 days, 41 days, 33 days and 24 days. The highest coherence value (0.9962) occurs in a 341 days period with a 0.487 days different phase difference. In the periods of 146 days, 79 days, 60 days, 60 days, 41 days, 33 days, 24 days, coherence values of 0.9264 (0.4975 days), 0.8062 (0.4315 days), 0.8736 (0.4973 days), 0.8457 (0.5339 days), 0.8099 (0.4598 days) and 0.9759 (0.4709 days). This result indicated that the signal fluctuation in the Java Sea is out-of-phase to that appear in the Natuna Sea in term of flow direction (Table 3).

**Table 3.** Frequency, Period, coherence and phase of SSTF between Natuna Sea and Java Sea.

| No | Frequency (cpd) | Period (day) | Coherence | Phase (one circle equals to 1) |
|----|----------------|--------------|-----------|-------------------------------|
| 1  | 0.04102        | 24           | 0.9759    | 0.4709                        |
| 2  | 0.03027        | 33           | 0.8099    | 0.4598                        |
| 3  | 0.02441        | 41           | 0.8457    | 0.5339                        |
| 4  | 0.0166         | 60           | 0.8736    | 0.4973                        |
| 5  | 0.0127         | 79           | 0.8062    | 0.4315                        |
| 6  | 0.00684        | 146          | 0.9264    | 0.4975                        |
| 7  | 0.00293        | 341          | 0.9962    | 0.487                         |

**4. Conclusion**

The annual cycle of SSTF through the Sunda Shelf regions (Natuna Sea, Karimata Strait, Java Sea) are characterized by an intense southward flow at Natuna Strait and Karimata Strait and by a strong eastward flow at Java Sea in the Northwest monsoon. The mean transport volume of SSTF through Natuna section, Karimata section and Java section are (-0.529±0.964) Sv, (-0.494±0.919) Sv and (0.122±1.219) Sv, respectively. In boreal winter, the average transport volume of SSTF through Natuna section, Karimata section and Java section are -1.590Sv, -1.546Sv and 1.536Sv respectively. While in the boreal winter, the average transport volume of SSTF through Natuna section, Karimata section and Java section are 0.492Sv, 0.598Sv and -1.193Sv respectively. The transport volume of SSTF is dominated by annual, intra-seasonal and baroclinic tide fluctuations. The highest coherence (0.9962) occurs in the 341-days period with a phase difference of about 0.487. This means that the transport volume fluctuation in the Java Sea is out-of-phase to that in the Natuna Sea in term of flow direction.

**References**

[1] Roseli N M, Akhir M F, Husain M L, Tangang F and Ali A 2015 *Open Journal of Marine Science* 5 455-467

[2] Qu T, Song Y T and Yamagata T 2009 *Dynam. Atmos. Oceans* 47 3-14

[3] Fang G H, Wang Y, Wei Z X, Fang Y, Qiao F and Hu X 2009 *Dynam. Atmos. Oceans* 47 55-72

[4] Metzger E J and Hurlburt HE 1996 *Journal Geophys. Res.* 101(C5) 12331-12353

[5] Lebedev K V and Yaremchuk M I 2000 *Journal Geophys. Res.* 105 (C5) 11243 – 11258

[6] Fang G, Wei Z, Choi B H, Wang K, Fang Y and Wei L 2002 *Sci. China (Ser. D)* 32(12) 969-977

[7] Fang G, Susanto R D, Soesilo I, Zheng Q, Qiao F and Wei Z 2005 *Adv. Atmos. Sci.* 22 946-954

[8] Qu T, Du Y, Meyers G, Ishida A and Wang D 2005 *Journal Geophys. Res. Lett* 32

[9] Qu T, Du Y and Sasaki H 2006a *Journal Geophys. Res. Lett* 33

[10] Tuzuka T, Qu T and Yamagata T 2007 *Journal Geophys. Res. Lett* 34

[11] Yu Z, McCreary Jr J P, Yaremchuk M and Furure R 2008 *Journal Phys. Ocean*, 38 527-539

[12] Qu T, Gorton G and Whitehead J 2006b *Journal. Geophys Res* 111

[13] Wyrtki K 1961 *Physical Oceanography of the Southeast Asian Waters.*, Naga Report Vol. 2 Univ Of California Scripps Institution Oceanography

[14] Fang G H, Susanto R D, Wirasantosa S, Qiao F, Supangat A, Fan B, Wei Z X, Sulistyo B and Li S 2010 *J. Geophys. Res.* 115

[15] Cai S Q, Liu H L and Li W 2002 *Adv. Marine Sci.* 20 29-34

[16] Cai S Q, Liu H L and Li W 2005 *Acta Oceanol.Sin* 24 10-19
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