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The Coherency and Correlation between Sea Surface Temperature and Wind Velocity in Malacca Strait: Cross Wavelet Transform and Wavelet Coherency Application

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Abstract

This study tried to observe the correlation and coherency between sea surface temperature (SST) and wind velocity in the Malacca Strait at the year of 2015. The SST and wind velocity data with 6 hours interval step have been used in this study. S-Transform, the Cross Wavelet Transform, and the Wavelet Coherency were applied to observe the influence of the variation of sea surface temperature to the wind velocity in Malacca Strait. These methods could produce the phase lag and the time of occurrence between them. S-Transform was used to show the spectrum energy of the sea surface temperature variation. The strongest correlation between them has the period of 32 days during July to August and October to November at each point with significance level of 95 %. The coherency of them has the range of 4 to 64 days at each point. The last result is the spectrum energy of SST variation that has the period of 5 to 50 days at each point. It was similar to the result of the correlation and coherence period between the wind velocity and the SST data.

Keywords: Sea surface temperature, Malacca strait, Wind velocity, Coherency, Correlation.

1. Introduction

The Malacca Strait has been located in the coordinate of 96 to 106 E and 2 N to 8 S. It is directly connected to Andaman Sea and Indian Ocean (Amiruddin et al., 2011). The Indian Ocean climate has influence to the Malacca Strait climate. Monsoonal condition is the potential thing to affect the Northern Indian Ocean condition (Tomzcak, 2001). Instead of that, the monsoonal condition can be shown by the wind reversing in two times a year, and also there are two conditions of monsoon climate, northeast monsoon (winter monsoon) and southwest monsoon (summer monsoon) (Wyrtki, 1961; Rao and Sivakumar, 2000; and Susanto et al., 2001). In the Indian Ocean, Asian monsoon intensity has also influenced to control the basin-margin instability (Lin et al., 2010). The Malacca Strait has been affected by the seasonal conditional. These were northeast monsoon and southwest monsoon (Hii et al., 2006). It affect to several parameters in the Malacca Strait. The temperature and salinity in the Malacca Strait have the lowest condition at the winter monsoon and highest condition during summer monsoon (Peralta and Yusoff, 2014). In addition, the Malacca Strait has the shallow bathymetry. It was an average of 53.38 m (Hii et al., 2006). And also, the Malacca Strait water mass has been influenced by the rivers in the west Sumatra and west coast of Peninsular Malaysia (Chua et al., 1997; Hii et al., 2006; Amiruddin et al., 2011). The water mass of the Malacca strait has been moving southwesterly towards to the Indonesian seas during southwest monsoon (Amiruddin et al., 2011 and Hii et al., 2006).

In this study, we show an analysis about the variation and correlation of the sea surface temperature (SST) and wind velocity in the year of 2015 in the Malacca Strait. Importantly, we also considered the influence of monsoonal condition. We also quantify the phase lag between them using cross wavelet transform and wavelet coherency. To show the variation of SST in Malacca Strait we were using the S-Transform method. In addition, using these methods, we can identify the dominant period and its variation.

2. Data and Method

This research used the gridded reanalysis ERA Interim daily SST and wind velocity data in the Malacca Strait area in the year of 2015 by six hourlies interval step. They have the resolution as big as 0.125° and 0.5°, and it was downloaded by European Centre for Medium-Range Weather Forecasts (ECMWF) in the region of 8°N – 2°S and 96°E – 106°E. It would be processed by the methods of S-Transform to observe the dominant period of sea surface temperature, Ocean Data View as a visual analytic, Cross Wavelet Transform, and Wavelet Coherency by Morlet Wavelet with significance level 95 % (Grinsted et al., 2004).

2.1 S-transform

The first method to observe the dominant period of SST is the S-Transform. It was a window variable from Short Time Fourier Transform (STFT) or it would be extension from wavelet transform (WT) (Wang, 2010). The time series spectrum component could be shown by the Fourier Transform and only contains the information about the time series spectrum components, but can't to identify the time distribution at different frequencies. Wavelet Transform either to extract the data information in time and frequency domains. However, the wavelet transform is sensitive to noise. Equation 1 shows the correlation between S-Transform and STFT. The STFT equation to h(t) signal is shown in the below:

$$STFT(\tau,f) = \int_{-\infty}^{\infty} h(t)g(\tau-t)e^{-j2\pi ft}dt \tag{1}$$

Where:

τ : Spectrum localization time

f : Fourier frequency

$g(t)$: *Window* function

Changing $g(t)$ value is the one of the way to determine *S-transform* with the Gaussian function, such as:

$$g(t) = \frac{|f|}{\sqrt{2\pi}}e^{\frac{t^2f^2}{2}} \tag{2}$$

From the Equation 1 and 2, can be identified to S-Transform and it becomes the Equation 3:

$$S(\tau,f) = STFT(\tau,f) \tag{3}$$

$$= \int_{-\infty}^{\infty} h(t)\frac{|f|}{\sqrt{2\pi}}e^{\frac{(\tau-t)^2f^2}{2}}e^{-j2\pi ft}dt$$

In the other words, the S-Transform is the other form of STFT with Gaussian window.

2.2 Wavelet Coherence

Using Wavelet coherence, the highest coherence between the correlated time series data can be observed in the time-frequency domain. Torrence and Webster (1998) in Grinsted *et al.* (2004) have formulated the equations for the wavelet coherency as follows:

$$R_n^2(s) = \frac{\left|S(s^{-1}W_n^{XY}(s))\right|^2}{S\left(s^{-1}\left|W_n^X(s)\right|^2\right).S\left(s^{-1}\left|W_n^Y(s)\right|^2\right)} \tag{4}$$

Using S as a smoothing operator and its equation become:

$$S(W) = S_{scale}(S_{time}(W_n(s))) \tag{5}$$

The S_{scale} is the notation of the *smoothing* along the *wavelet* scale and S_{time} is the *smoothing* in time. The smoothing operator which suitable to *Morlet wavelet* as follows:

$$S_{time}(W)\big|_s = \left(W_n(s) * c_1^{\frac{-t^2}{2s^2}}\right)\Bigg|_S, \tag{6}$$

$$S_{time}(W)\big|_s = \left(W_n(s) * c_2\prod(0{,}6s)\right)\Big|_n$$

Whereas c_1 and c_2 are used to normalization. Using numerical method is one of the way to determine the normalization coefficient. To determine the confident level of wavelet coherence can be solved by Monte Carlo method. The squared of coherence is used to estimate the frequency. It has the range between 0 and 1 to indicate the correspondent of x and y value. The squared of coherence can be arranged as follows:

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \tag{7}$$

Whereas the $P_{xx}(f)$ and $P_{yy}(f)$ are the power spectral density of x and y data, and also the $P_{xy}(f)$ is the cross power spectral density of x and y data.

2.3 Cross Wavelet Transform

Morlet Wavelet shows a good relation between time and frequency localization. Cross wavelet transform is the result of a band pass filter of a time series data (Grinsted *et al.*, 2004). The formulation for cross wavelet transform can be written as follows:

$$W_n^X(s) = \sqrt{\frac{\delta t}{s}}\sum_{n'=1}^{N} x_{n'}\psi 0[(n'-n)\frac{\delta t}{s}] \tag{8}$$

The $W_n^X(s)$ value is a local phase and $|W_n^X(s)|^2$ is a wavelet power. Cross wavelet transform correlate two time series data, whereas can be defined as:

$$W^{XY} = W^X W^{Y*} \tag{9}$$

So we can define which the value of $|W^{XY}|$ is a cross wavelet power and the value of W^{XY} can be interpreted as a local relative phase between the value of X_n and y_n at time – frequency domain.

To determine the influence of the wind velocity to SST distribution, we decided to choose 3 sampling points, that is quite represent the research area, they are A, B, C point (Fig.1). Point A is located between Northern of Lhokseumawe and Langkawi

Island, these point is still under the big influence from Andaman Sea, point B is located between Eastern waters of Medan and Western of Malaysia, and point C is located between Bagansiapiapi waters and Western of Kuala Lumpur, the coordinates of point A, B and C are shown at Table 1.

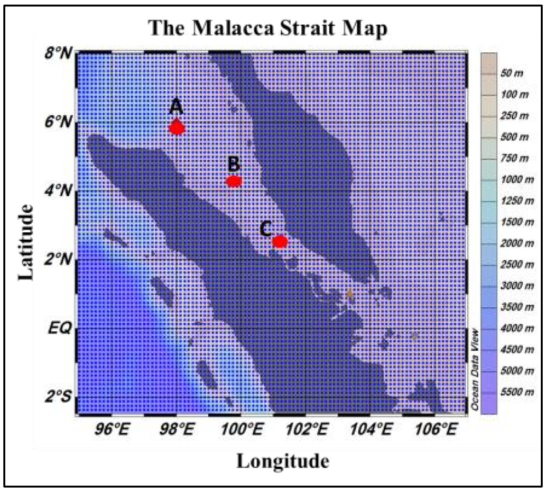

Fig. 1. Study area in Malacca Strait with A, B, and C point.

Table 1 Sampling point coordinates

Point	Longitude	Latitude
A	6° 4' 12" N	97° 58' 48" E
B	4° 12' 0" N	99° 49' 48" E
C	2° 33' 36" N	101° 13' 48" E

3. Result and Discussion

3.1 The Variation of Sea Surface Temperature and Wind Velocity

Fig 2. shows that the SST variation in the straits changed seasonally. In January, the highest temperature has the value of 303.36 K or 30.21°C, whereas the highest temperature value in July is 304.28 K or 31.18°C. It shows the SST is lower when the western monsoon (December-February) than the eastern monsoon (June to August).

The condition of SST is depended on monsoon cycles, the change of monsoon is quietly influence the SST condition in Malacca Strait, specifically the change of the wind speed and direction significantly affect the distribution of SST that is come from heat waste and solar heating intensity, SST in the Malacca Strait is transported by the wind, surface current, wave, tide and the other physical factors (Syamsul *et al.*, 2012). The change of STT value in every monsoon condition is not too significant ± 1°C (Table 2).

Table 2. The maximum value of SST

Monsoon	Range of SST (°C)
Northeast monsoon	31.18 – 33.06
Northwest monsoon	31.51 – 34.29
Southwest monsoon	32.20 – 34.14
Southeast monsoon	30.81 – 33.58

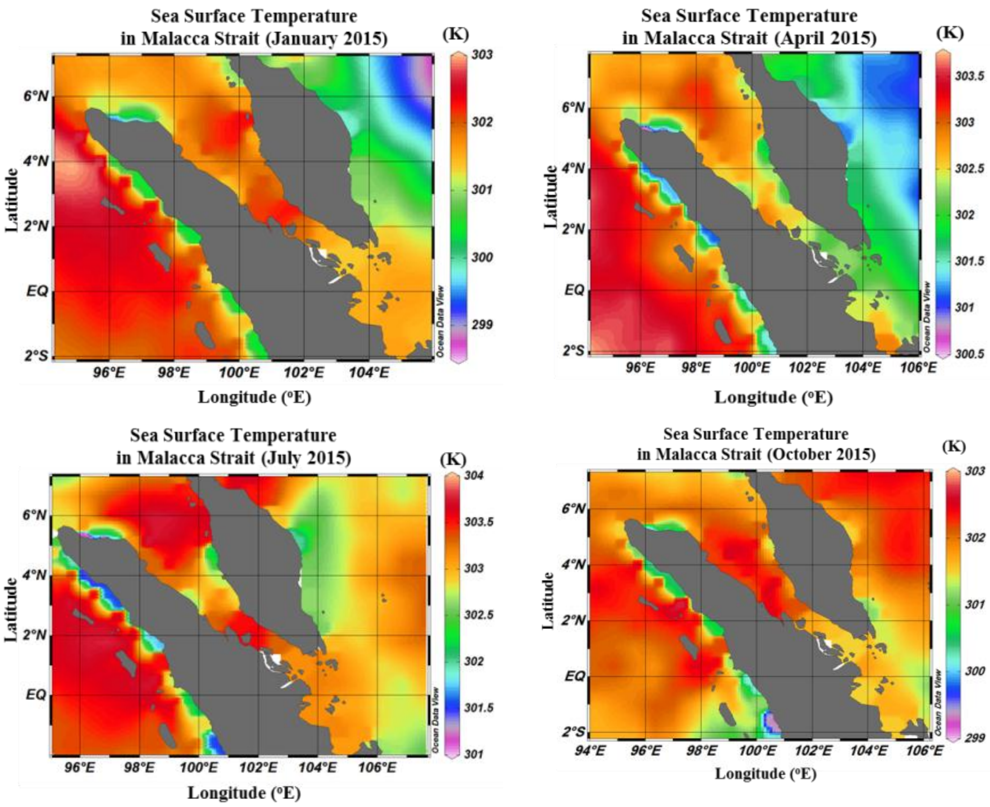

Fig 2. Spatial SST distribution in the Malacca Strait (a) northeast monsoon (b) northwest monsoon (c) southwest monsoon (d) southeast monsoon.

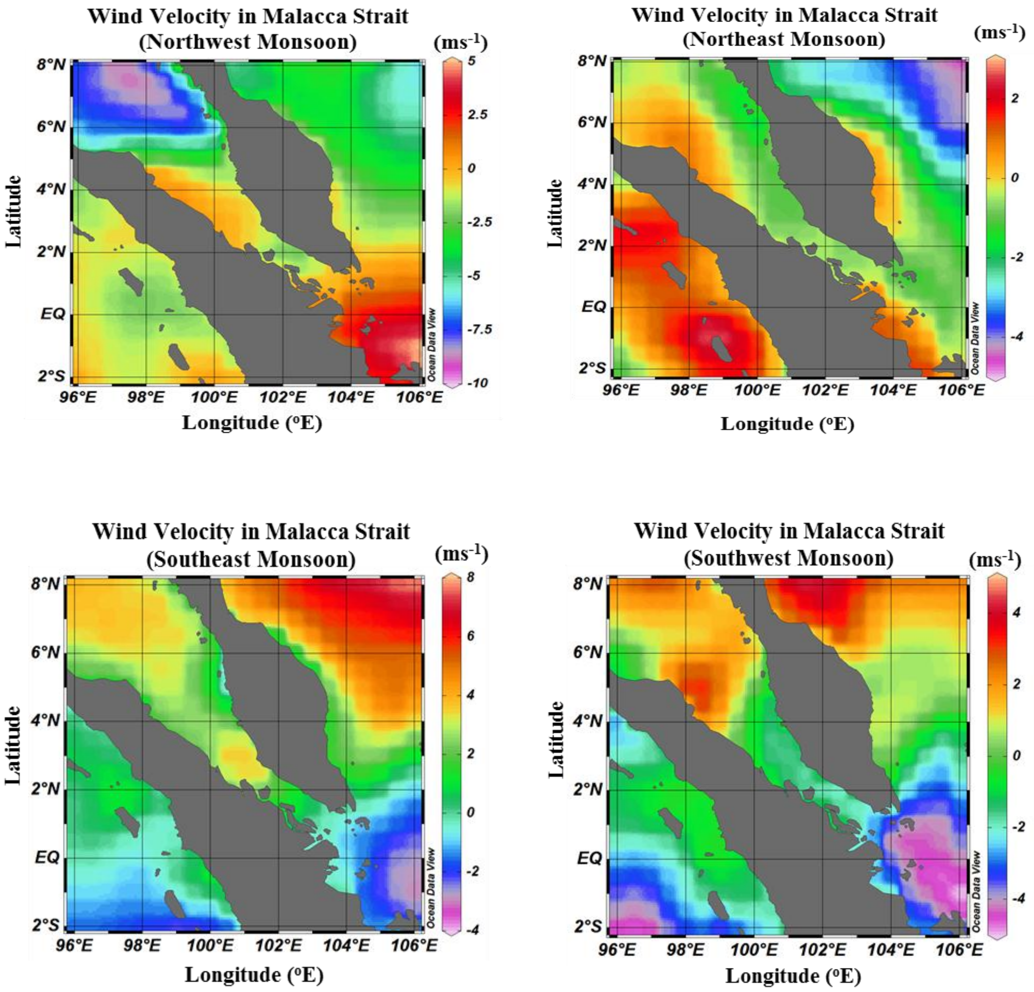

Fig. 3. Spatial wind velocity distribution in the Malacca Strait (a) northeast monsoon (b) northwest monsoon (c) southwest monsoon (d) southeast monsoon

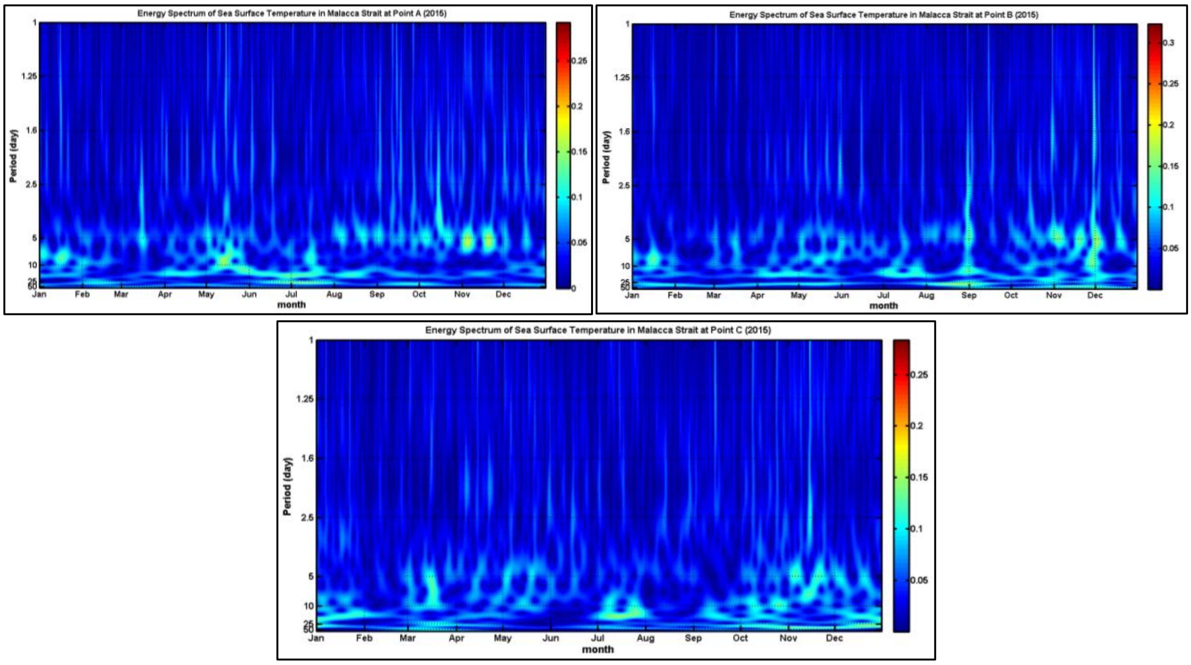

Fig. 4. The SST energy spectrum on the A, B, C point in the Malacca Strait using S-Transform during 2015.

Table 3. The maximum value of wind velocity

Monsoon	Range of wind velocity (m/s)
Northwest monsoon	0.05 – 10.84
Northeast monsoon	0.03 – 9.22
Southeast monsoon	0.03 – 10.09
Southwest monsoon	0.05 – 9.15

It suggests that seasonal factor affected the variation of SST in the Malacca Strait. The result of S-Transform shows the variation of 5-50 days in SST at points A, B, and C does exist (Fig 3). Susanto (2000) said that the intra-seasonal variations have the period of 35 to 90 days. The influence of seasonal factors can also be seen from the changes in the Malacca Strait wind speed at different seasons.

During western monsoon (December to February), the wind velocity in the southern of Malacca Strait is higher than the wind velocity in the northern of Malacca Strait. Meanwhile, during the southeast monsoon, the condition of wind velocity in the southern of Malacca Strait is lower than the wind velocity in the northern Malacca Strait (Fig 3). It shows that the wind velocity condition in the Malacca Strait is affected by monsoon conditions. Based on Table 3, during the eastern monsoon, the wind velocity has the highest condition, such as 13 m/s. It shows that the SST has the correlation to the wind velocity.

3.2 The correlation between the wind velocity and the SST

Fig 4. indicated that the correlation between SST and wind velocity has a period of 4-64 days at the points of A, B, and C. The strongest correlation occurred in July-August and October-November with a period of 32 days. These results are consistent with a dominant period of SST, which is 50 days. It proves that the variation of SST has influenced by wind velocity. The arrow indicates the phase lag between wind velocity and SST. In Fig 5. is shown that the wind velocity and SST has a phase lag as long as 18 days in July-August and October-November at point C. While at points A and B, the wind velocity has a phase lag of 8 and 24 days. Grinsted (2004) said that the calculation of the correlation between wind velocity and SST using cross wavelet coherency has a significance level greater than 95%.

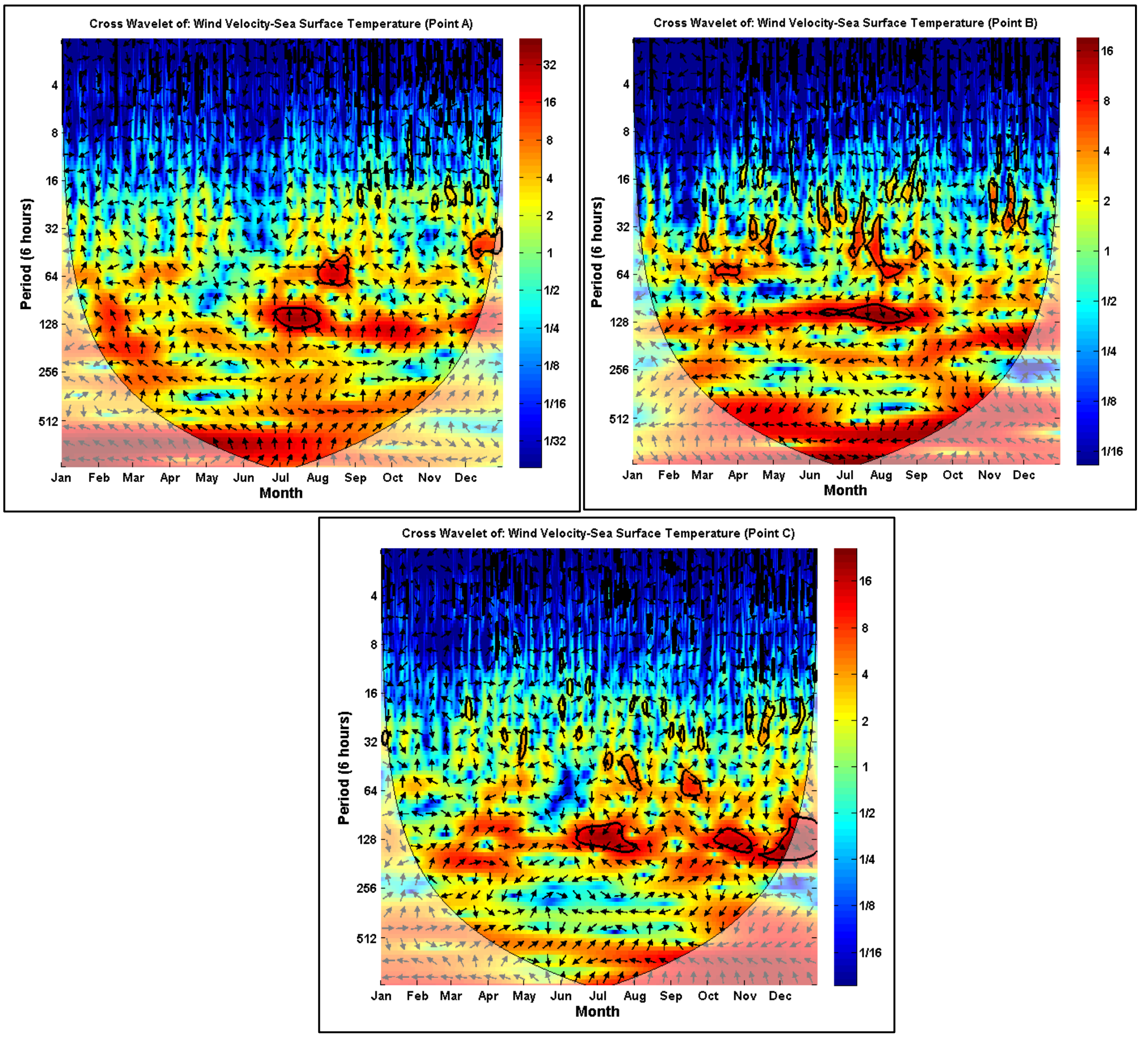

Fig. 5. The correlation between the SST and wind velocity at the points of A, B, and C in the Malacca Strait using Cross wavelet transform.

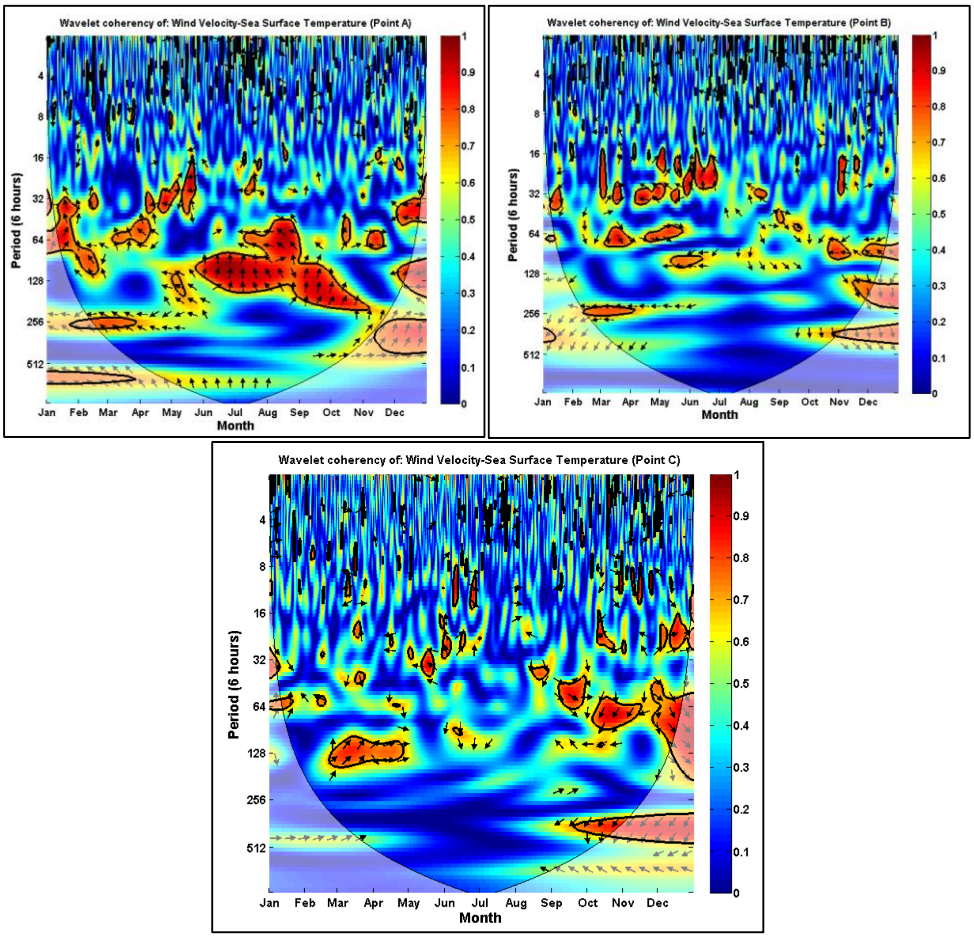

Fig 6. The coherence of SST and wind velocity at the points of A, B, and C in the Malacca Strait using the Wavelet coherency.

3.3 The coherence between the wind velocity and SST in the Malacca Strait

Fig 1. showed that the points of A, B, and C are the sample to observe the correlation and coherence of wind speed and SST. This study proves the coherence between the wind velocity and SST (Fig 6). Figure 6 provided the coherence between wind velocity and SST, it has the period of 4-64 days at the points of A, B, and C. These results illustrate that the SST variations with a period of 4-64 days is influenced by wind velocity. This proves that the intra-seasonal variation of the SST in the Malacca Strait is influenced by the local wind velocity.

4. Conclusion

The SST data in the Malacca Strait have a correlation and coherence to the wind velocity. It correlation has a period of 4-64 days. In addition, the strongest correlation occurred in July-August and October-November with a period of 32 days, and its confidence level is greater than 95%. The wind velocity and SST in the Malacca Strait has a phase lag of 8-24 days. In addition, there was a coherency between the wind velocity and the SST data with a period of 4-64 days at the points of A, B, and C in July-August and October-November. These correlation and coherence have a similar period with the variation of SST, i.e. 5-50 days. It should be the intra-seasonal variation. The strongest energy spectrum of SST occurred in July-August and October-November. It suggests that the intra-seasonal SST variation (35-90 days) affected the wind velocity.

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