CORRELATION ANALYSIS OF SEA SURFACE TEMPERATURE (SST) AND ZONAL COMPONENT OF WIND IN THE WEST SUMATERA WATERS DURING 2012-2016

ANALISIS KORELASI SUHU MUKA LAUT DAN KOMPONEN ANGIN ZONAL DI PERAIRAN SUMATERA BARAT SELAMA PERIODE 2012-2016

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ABSTRACT

West Sumatera waters is a strategic water area where it directly faces the Indian Ocean and exactly located below the equator. Consequently, West Sumatera waters are influenced by the tropical climatic factors such as monsoons and climate variability, and strongly related to the influence of the Indian Ocean Dipole (IOD) that controls the sea surface temperature (SST) fluctuation in the Indian Ocean regions. This study aims to review the correlation and coherence between SST and $\boldsymbol{V}$ component of wind in West Sumatera waters. We use the wavelet methods (cross wavelet transforms and wavelet coherence) to examine the correlation and coherency of those two parameters. The annual SST variation with a period of 365 days is the strongest event throughout the year. This is caused by both monsoon and the changes in the wind regime at the surface. We also identify that the strongest intra-seasonal SST variation of 35-60 days from December 2012 to March 2013. The highest surface wind speed occurred in the southern and western waters. During the positive dipole mode in October 2015, the surface wind speed was slightly high, resulting in a decline in SST. Nevertheless, during the negative dipole mode in July 2016, the condition was inversely proportional. Surface wind plays a role in evoking the SST distribution in the period of 35 - 60 days (intra-seasonal variability). Furthermore, surface wind with a period of 6 months (semi-annual variability) strongly influences the SST distribution that was identified both in the southern waters and the Indian Ocean regions. These conditions are likely influenced by monsoon.

Keywords: Sea surface temperature, zonal wind component, West Sumatera, wavelet methods

ABSTRAK

Sumatera Barat merupakan wilayah perairan yang stategis dimana secara langsung berhadapan dengan Samudera Hindia dan tepat berada pada dibawah Garis Katulistiwa. Oleh karena itu, Perairan Sumatera Barat dipengaruhi oleh faktor-faktor iklim tropis seperti monsun dan variabilitas iklim, sangat terkait dengan Indian Ocean Dipole (IOD) yang mengendalikan fluktuasi suhu permukaan laut (SPL) di Samudera Hindia. Tujuan dari penelitian ini adalah menelaah korelasi dan koherensi antara parameter SPL dan komponen kecepatan angin V di perairan Sumatera Barat. Metode wavelet (cross wavelet transform dan wavelet coherence) digunakan untuk menganalisa korelasi dan koherensi dari kedua parameter yang diuji. Variasi tahunan dari SPL pada periode 365 hari merupakan kejadian terkuat sepanjang tahun yang disebabkan oleh monsun atau perubahan pengaruh angin dipermukaan. Sebaliknya, variasi musiman terkuat dari SPL pada periode 35-60 hari ditemukan terjadi pada bulan Desember 2012 hingga Maret 2013. Kecepatan angin tertinggi terjadi di perairan selatan dan barat. Selama dipole mode positif pada bulan Oktober 2015, kecepatan angin permukaan sedikit meningkat yang mengakibatkan penurunan suhu perairan. Namun, selama dipole mode negatif pada bulan Juli 2016, kondisinya berbanding terbalik. Angin permukaan memainkan peran pada peningkatan distribusi suhu permukaan laut pada periode 35-60 hari (variabilistas musiman). Selain itu, angin permukaan dengan periode 6 bulan (tengah tahunan) sangat mempengaruhi distribusi suhu yang teridentifikasi pada wilayah selatan dan Samudera Hindia. Kondisi tersebut diperkirakan sebagai pengaruh dari monsun.

***Kata kunci**: Suhu Permukaan laut, komponen angian zonal, Sumatera Barat, metode wavelet*

1. Introduction

West Sumatera waters is a strategic water area because of its ocean dynamic and geographical position which directly faces the Indian Ocean and exactly located below the equator. Consequently, the water characteristics are strongly influenced by monsoons (seasonal reversing wind accompanied by corresponding changes in precipitation) which blows approximately six months from the southwest and six months from the northeast [1]. Monsoon patterns affect the global climate variability such as the Indian Ocean Dipole (IOD) [2], solar warming intensity, and equatorial current system [1]. Furthermore, West Sumatera has a unique topography consist of many islands, headlands, bays, and becomes the area of two large water masses confluence (from the Indian Ocean and the Andaman Sea).

As a result of the climate variability influence, the physical condition in West Sumatera waters is severely erratic. The parameter directly affected is the temperature of the waters. Sea surface temperature (SST) is a significant, easily observable parameter which can detect climate variability and climate both regionally and globally. A significant increase in SST can have several impacts on marine ecosystems such as coral bleaching, demised biota, and biogeochemical cycle disruption. Corals will tend to be bleach due to the increase in SST with every 0.1^{o}C increase in normal temperature results in the 35-42% chance of coral bleaching [3]. For example, according to [4], the condition of the coral reefs in the Mentawai Islands Coastal Conservation Area (KKPD) continues to deteriorate where the healthy coral covered only 18.2% in 2016. This phenomenon is caused by a significant increase in SST that reached 33 to 34^{o}C as a result of climate anomaly that occurred during April-June 2016 [5].

At the surface, the distribution of temperature is strongly related to the influence of wind, which is the main factor that plays a role in the water masses distribution [6]. Therefore, assessing surface wind in the study area is essential. Moreover, the surface wind also plays a role in inducing upwelling near the coast [7], [8] and IOD cycle as well [2]. By examining SST-influenced wind in West Sumatera waters, we can obtain a good depiction of their distribution and period related to the IOD cycle [2]. A correlation and coherence study between SST distribution and V component of wind is essential in which this research can be useful for predicting upwelling areas, as well as identification of climate change in the form of anomalies in seawater temperature [9]. [10] have determined the correlation and coherence analysis of SST and surface wind speed in West Sumatera waters. In this study, we analyze the distribution and variability of SST and V component of wind in the West Sumatera waters because the variability of SST in the western Sumatera waters is not only influenced by wind speed but also wind direction. The SST-wind interaction strongly relates to the upwelling event in which the wind regime takes place [11]. The same wind speeds in different directions may play a different role in evoking SST response [12]. This study aims to review the correlation and coherence of SST-distributed wind in West Sumatera waters.

2. Data and Methods

Data. We used gridded datasets ERA-Interim reanalysis of daily sea surface temperature and 10-m V component of wind (zonal) for four years (December 2012 - November 2016) in West Sumatera Waters (1^{o}N – 3^{o}S and 97^{o}E –101^{o}E) with resolution $0.125^{o} \times 0.125^{o}$. The data were retrieved from the European Center for Medium-Range Weather Forecasts (ECMWF) (http://www.ecmwf.int/en/research/climate-reanalysis/browse-reanalysis-datasets) [13]. Furthermore, DMI data are provided by the Australian Bureau of Meteorology [7].

Eight points were chosen representing significant areas where interactions between SST and zonal wind component are most likely to occur. Point 1 up to 4 are located in the Mentawai Strait, while Point 5 up to 7 are positioned closer to Mentawai Islands, and the Point 8 represents the Indian Ocean. The coordinates of these eight observation stations are shown in Table 1 and spatially shown in Figure 1.

Table 1. Representative point coordinates

Station Point	Latitude	Longitude
Point 1 (St. 1)	0.5^{o} N	98.75^{o} E
Point 2 (St. 2)	0.5^{o} S	99.25^{o} E
Point 3 (St. 3)	1.5^{o} S	99.75^{o} E
Point 4 (St. 4)	2.5^{o} S	100.25^{o} E
Point 5 (St. 5)	0.75^{o} S	98.0^{o} E
Point 6 (St. 6)	1.75^{o} S	98.5^{o} E
Point 7 (St. 7)	2.75^{o} S	99.0^{o} E
Point 8 (St. 8)	2.5^{o} S	97.5^{o} E

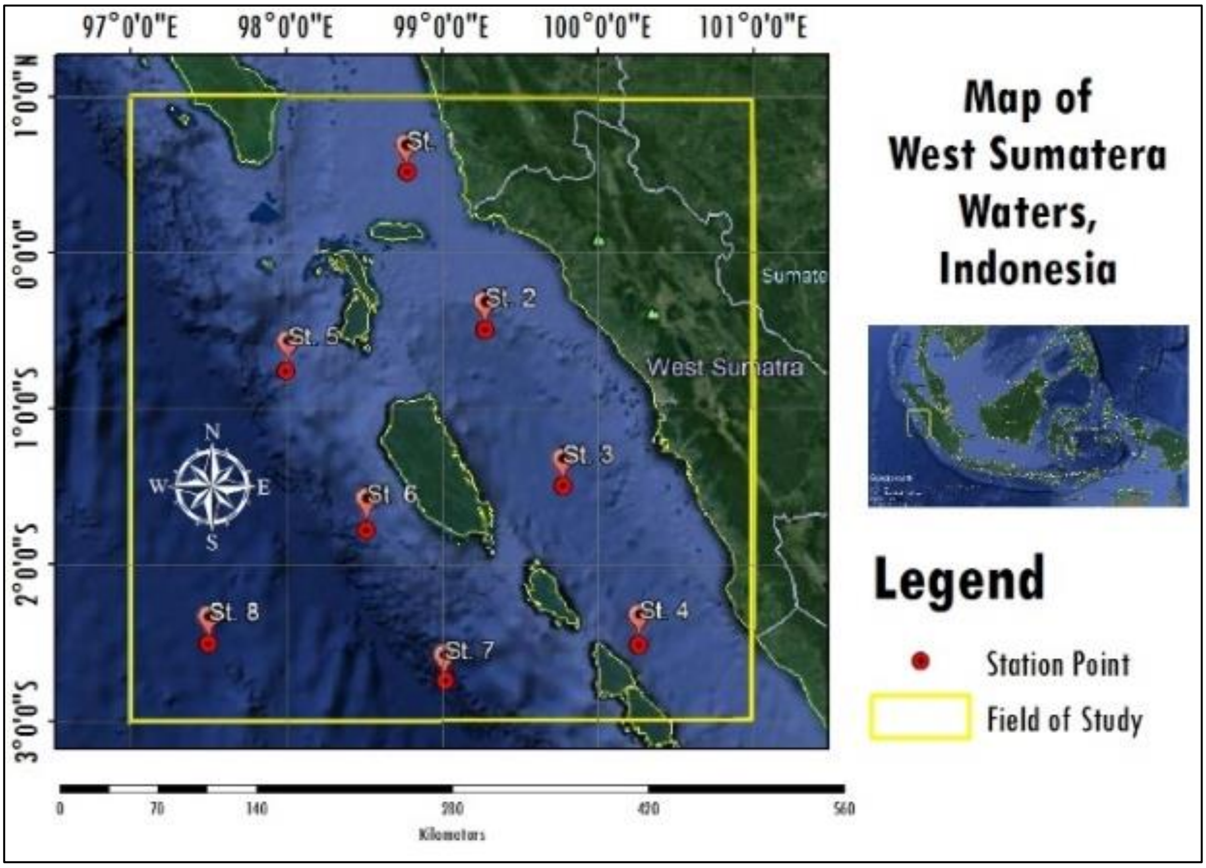

Figure 1. The study area (bordered by the yellow square) and station points (red pins) (Google Earth, 2017)

Methods. To analyze the variability of SST and wind, we use *spectral density* and *S-Transform*. The first method converts the data from time series domain to frequency domain using the *Fourier Transform* while the random data are filtered from a particular window using *S-transform*. These steps can improve the data quality in which the bias data can be sophisticatedly reducted and detect the phenomenon with a specific period variation at the time of its occurrence. Thus, it will result in a better time in either period or frequency domain.

Correlation and coherence of SST-influenced wind are examined using cross-wavelet transform (XWT) and wavelet coherence (WTC) [14]. To analyze the IOD cycle per year, we use Dipole Mode Index (DMI), derived from the differences in average SST anomaly between the Tropical Western Indian Ocean (10^{o}N - 10^{o}S and 50^{o}E - 70^{o}E) and the Tropical South Eastern Indian Ocean (0^{o}N - 10^{o}S and 90^{o}E - 110^{o}E) [2]. It helps to determine the phase of IOD during its positive and negative phases. Positive dipole mode indicates that the SST in the East Coast of Africa is higher than in the West Coast of Sumatera, whereas the negative dipole mode shows that a warm phase occurs in the West Coast of Sumatera, increasing convection [5].

Spectral Density. Spectral density is defined as the power of frequency interval with amplitude as the investigated signal unit wherein the frequency is represented as a cyclic unit [15]. The spectral density function $Gx(f)$ of the random data $x(t)$ describes the data composition of frequency associated with the power of spectral density in the mean-square value.

Mean-square value data in the frequency scale off and $f + \Delta f$ will generate data filter which exceeds the frequency characteristics. The root mean is calculated during filtering process whereby the value will approximate the infinite time of observation (T), therefore, those processes can be derived from a mathematical equation [16], as follow:

$$\psi(f, \Delta f) = \lim_{T\to x} \frac{1}{T}\int_0^T x^2(t, f, \Delta f)dt \qquad (2)$$

where,

$x(t, f, \Delta f)$ = The part of $x(t)$ on the frequency scale of f up to $f + \Delta f$

Spectral density function, $G_x(f)$, can be defined as:

$$G(f) = 2\int_{-\infty}^{\infty} R_x(\tau)e^{-i2\pi ft}dt \qquad (3)$$

where,

$R_x(\tau)$ = The self-correlation of $x(t)$, defined as $x_T(t) = x(t), -\mathrm{T} < t < \mathrm{T}$

Thus,

$$R_x(\tau, \mathrm{T}) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x(t).x(t+\tau)d\tau \quad (4)$$

and the *Fourier Transform* of $R_x(\tau)$ when T → ∞ is given by:

$$S(f) = \int_{-\infty}^{\infty} R_x(\tau) e^{-i2\pi f\tau} d\tau \quad (5)$$

The relationship between $G_x(f)$ and $S(f)$ can be written as:

$$G_x(f) = 2S_x(f), \qquad 0 < f < \infty \quad (6)$$

Hence,

$$G_x(f) = 4 \int_{-\infty}^{\infty} R_x(\tau) e^{-i2\pi f\tau} d\tau \quad (7)$$

S-Transform. S-Transform method is used to analyze the distribution of a datum in either frequency or period and time domain. This method was developed in 1994 by Stockwell for analyzing geophysical data. *S-Transform* is a variable window for data filtering in the *Short Time Fourier Transform* (*STFT*) or an extension of continuous wavelet transform method. The formula of *S-Transform* is derived from *STFT* of signal $h(t)$ as follow:

$$STFT\ (\tau, f) = \int_{-\infty}^{\infty} h(t) g(\tau - t) e^{-i2\pi ft} dt \ (8)$$

where,

τ : Spectrum localization time
f : Fourier frequency (day^{-1})
$g(t)$: Window function for data filtering

By replacing the window function $g(t)$ with the Gaussian function

$$g(t) = \frac{|f|}{\sqrt{2\pi}} e^{\frac{t^2 f^2}{2}} \quad (9)$$

we obtain the equation of *S-Transform*:

$$STFT(\tau, f) = \int_{-\infty}^{\infty} h(t) \frac{|f|}{\sqrt{2\pi}} e^{\frac{(\tau-t)^2 f^2}{2}} e^{-i2\pi ft} dt \ (10)$$

Therefore, *S-Transform* is another form of STFT with Gaussian function as the window for data filtering [17].

The Wavelet Method. The wavelet method is used to analyze data in a specific time domain and time distribution information at a particular frequency. Wavelet Transform converts data from a time domain to a frequency domain by which the information of examined phenomena at a certain frequency would be obtained. The wavelet method is one of the ways to decompose time series into a time-frequency domain simultaneously [18]. In this method, the spectrum energy in the form of time series data would be calculated. It can detect the transient periodic fluctuation thereby describing the complex nonlinear dynamics processes spatially illustrated by the interaction of spectrum disturbances. The wavelet spectrum describes the results of data processing from the wavelet method by which the y-axis shows the period and x-axis shows the monthly variability.

To examine the correlation between two types of time series data simultaneously, we use Cross Wavelet Transform (XWT) to identify the relationship and relative phase between those time series data in the time-frequency domain, as well as to analyze the covariance of those data (Xn and Yn), as follow:

$$W^{XY} = W^X W^{Y*} \quad (11)$$

where:

W^{xy} : The power spectrum of XWT
W^x : The power spectrum of Xn time series data
W^y : The power spectrum of Yn time series data
(the term * shows the complex conjugate)

The wavelet coherence (WTC) is employed to analyze the coherence and phase lag between two types of time series data as a function of time and frequency [19]. WTC is the coherence among wavelets of those data performed to find the significant coherence with low energy level. It involves the confidence levels in the calculation defined as follow:

$$R_n{}^2(s) = \frac{|S(s^{-1}W_n^{XY}(s))|^2}{S(s^{-1}|W_n^X(s)|^2).S(s^{-1}|W_n^Y(s)|^2)} \quad (12)$$

where:

$R_n{}^2(s)$ = The coherence between two variables
S = Spectrum value
Wn = The Wavelet Transform in n frequency.

3. Results and Discussions

SST and *V* Component of Wind Distributions and Variabilities. To analyze the significant role of IOD in controlling seawater temperature, we compare the fluctuation of IOD phase and SST data for four years where positive modes occurred during September-November 2015 while negative modes occurred during June-September 2016. Figure 2 shows that the SST increased significantly from March till June in each year ranging from 28.5 up to 30°C. Besides, there are anomalies, wherein the temperature decreased in October 2015 and then drastically increased in mid-2016 (March - July 2016). The IOD may strongly trigger the SST anomaly (SSTa) [4].

The dipole mode dramatically increased in October 2015, showing the emergence of positive IOD (low-temperature predomination in the West Sumatera) (Figure 2). A significant decrease in dipole mode was identified during June-September 2016, indicating the occurrence of negative phase (higher sea surface temperature in the West Sumatera). Based on these results, the SST is most likely related to the IOD cycle as shown by the relatively opposite variation between SST and IOD data.

Zonal component of wind shows the opposite conditions in which the component velocity is positively following the fluctuation of DMI. The more positive the dipole mode condition, the higher the wind velocity occurred, and vice versa (Figure 2). Those relations are not applicable during DMI low values. Extreme anomalies were identified during the last 2012 and early 2013. This might result in SST being distributed by wind close to the ocean surface [2].

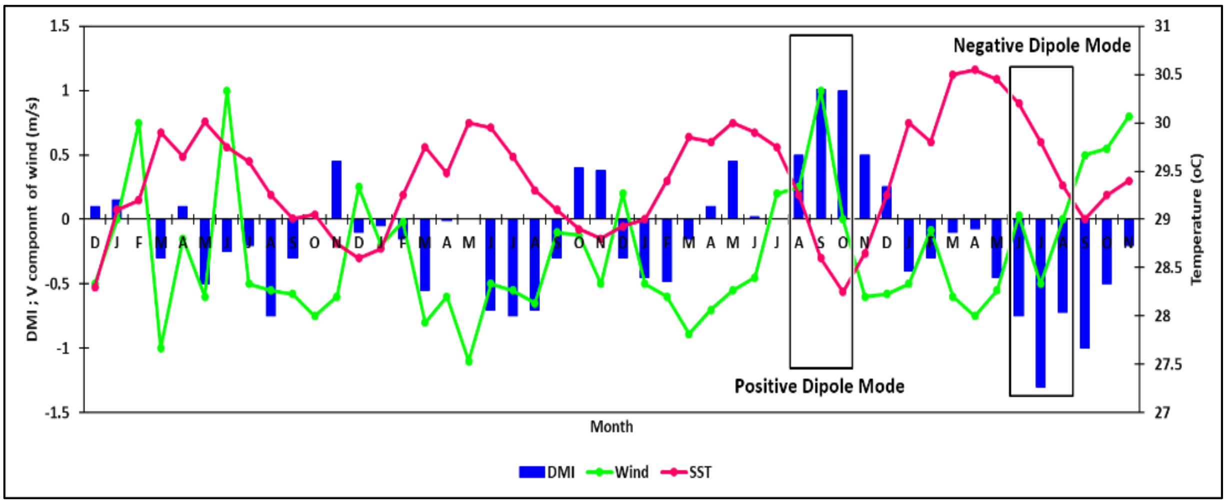

Figure 2. Time series of monthly average SST and V component of wind compared with DMI in West Sumatera Waters for four years (December 2012 to November 2016)

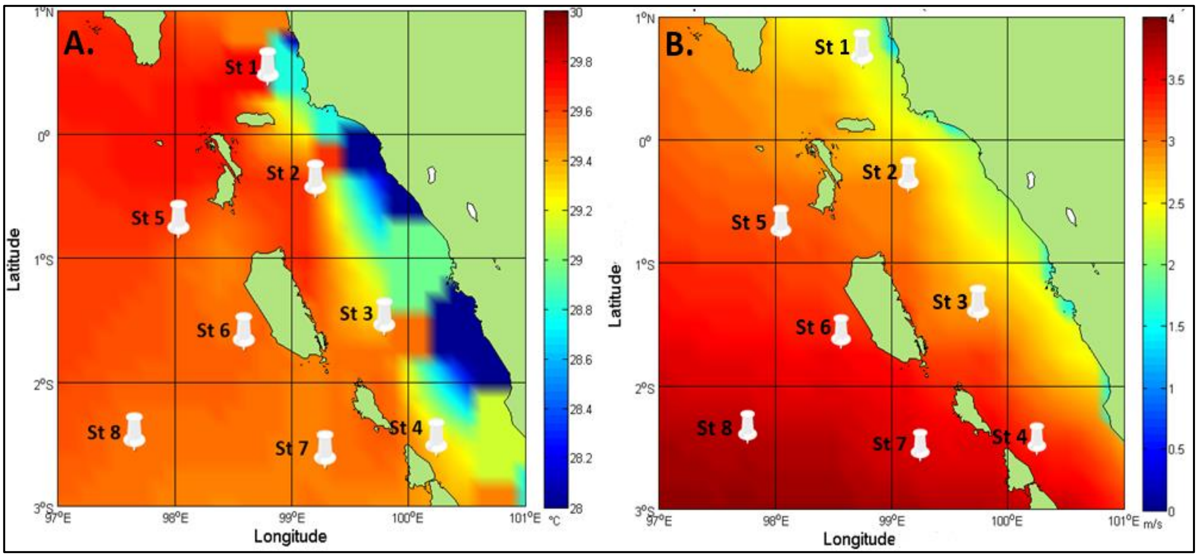

Figure 3. The spatial distribution of mean SST interpolated from monthly SST data (A) and average wind velocity (B) in the West Sumatera Waters during December 2012 to November 2016.

Figure 3a shows that the mean SST declines at Station 1 to Station 4, then flatten at Station 5, decreases at Station 6 and 7, and flatten again at Station 8 (Table 2). The fluctuation is <1°C. SST in the southern region tends to be lower than the northern region, which might be affected by the intense solar warming at the equator [20].

The spatial distribution of wind velocity is shown in Figure 3b and Table 2. Generally, wind velocity increases at Station 1 to Station 4, then decreases at Station 5, and eventually flatten at Station 8. The wind velocity at regions near the equator tends to be weak due to the convergence zone of trade winds, which is well-known as the Inter-Tropical Convergence Zone (ITCZ) [21].

Table 2. The average of SST and wind velocity for four years at each station

Station	SST (^oC)	Wind velocity (m/s)
Station 1	29.74	2.49
Station 2	29.42	2.83
Station 3	29.34	2.94
Station 4	29.33	3.38
Station 5	29.60	3.16
Station 6	29.54	3.51
Station 7	29.49	3.72
Station 8	29.522	3.79

The area with low SST tends to have stronger surface wind. This may be influenced by the higher air pressure in the formation of wind. Otherwise, a high temperature evokes the air expansion. The wind becomes weaker, inducing cloud formation in the convergence zone [22].

Figure 4a illustrates the SST annual variability domination of 365 days period and inter-annual variations of 730 (two years) to 1461 days period. The annual and inter-annual variations of SST estimated induces by monsoon cycle [4]. It can be affected by the changes of surface wind velocity that is stronger in the southwest monsoon (June-August) and the 2nd transitional season (September-November).

Besides the annual variations, there are a seasonal variation of 91 to 97 days period (3 months), intra-seasonal variation over 35 to 90 days period, and semi-annual variation of 183 to 209 days period (6 months). Seasonal to semi-annual variations occurred because the SST distribution is influenced by local phenomena such as wind, surface current, and waves [23]. Furthermore, the semi-annual variation (6 months period) is more dominant than the seasonal variation. This is caused by solar radiation in the equator that occurs every 6 months. Generally, seasonal to semi-annual variations are triggered by changes in wind speed that occurs every 3-6 months (monsoon cycle).

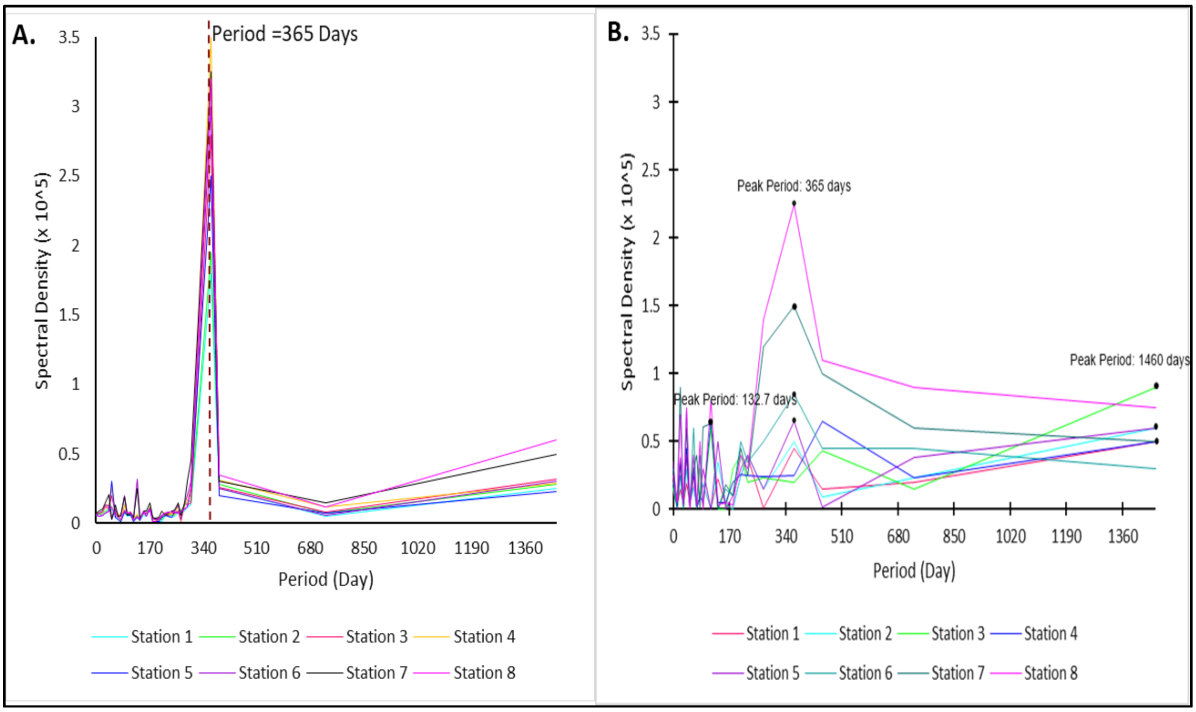

Figure 4. Spectral density of SST and V component of wind at each station. The strongest annual SST variation is uniform in the 365 days period (A), while the zonal component is more erratic by which the peak period varies at all stations (B).

Figure 4b shows the dominant spectral density of daily zonal wind component variation in which its variance in the West Sumatra Waters is very high and erratic. Nevertheless, seasonal variation varies from 91 to 97 days, intra-seasonal variation over 35 to 90 days period, semi-annual variation of 183 to 209 days (6 months period monsoon), and annual variation of 365 days period.

The seasonal variation which occurs for three months period is caused by the changes in wind velocity between the northeast monsoon (December to February) and the first transitional season (March to May) and so on. The semi-annual variation shows the monsoon phenomenon between the southwest and northeast monsoons [20]. Those conditions are caused by the fluctuations in wind speed that occur every year. In general, the dominant variation period is a 6-month period that is associated with the monsoon.

Figure 5 shows the period of 30 to 1461 days used to analyze the seasonal-interannual variations occurrence. It was done by ignoring daily-weekly variations (period of 2 to 28 days). The annual variation is very strong in 365 days period that occurs throughout the year. Moreover, there is an intra-seasonal variation with a period of approximately 35-60 days that occurred during December 2012 - March 2013, especially at Station 1 and Station 2. Freshwater runoff with low temperature (anthropogenic factors) may influence the intra-seasonal variation of SST.

Correlation and Coherency Analysis. Figure 6 shows the correlation between SST and *V* component of wind in the period of 32-60 days (intra-seasonal variation domination) that occurred in March-September 2013 tended to be anti-phase. The annual variation correlation clearly detects that the period of 365 days dominating throughout 2014 until early 2015 tended to be anti-phase as well. Furthermore, it correlates with the semi-annual period (183-209 days or 6 months) that occurred in October - November 2015 (anti-phase).

The term of anti-phase means that the wind velocity decreases when the increase in SST emerges. In this case, wind speed increases in the southern waters, resulting in declined SST in that region. It means that the wind distributes the warm water mass towards the north and west. Otherwise, when the wind moves slowly, the warm water mass will be distributed by other factors such as currents, wave, pressure, and IOD [9].

The wavelet coherence indicates the coherence between SST and wind velocity component with the period of 32 to 60 days (dominant intra-seasonal variation) that occurred in March-September 2013 tended to be anti-phase (Figure 7). The coherence in the intra-seasonal variation strongly increases at Station 4 to Station 8 in the southern waters and the area adjacent to the Indian Ocean.

During March-September 2013, the coherence in the intra-seasonal period that occurred from September 2015 to February 2016 was only observed at Station 6 to Station 8, stations that are located adjacent to the Indian Ocean. We identify a strong coherence between SST and zonal wind component in the southern waters and the open seas (directly adjacent to the Indian Ocean).

The coherence in the annual variation at the period of 365 days that predominated from June 2014 to early 2016 tended to be anti-phase. This event only occurred at Station 5 to Station 7. In addition, there was a coherence in the semi-annual period (183 - 209 days or 6 months) from October to November 2015 that tended to be anti-phase as well observed at Station 7 and Station 8.

Generally, there is a correlation and coherence between SST and wind velocity whereby several data are lack of either period or variation. The dominant correlation and coherence are identified in intra-seasonal variation with a period of 35-90 days. The variability of SST is caused by the changes in wind velocity and intra-seasonal variability, and this relates to the upwelling occurrence [24].

The correlation and coherence during semi-annual to annual periods are correlated to the southern waters and open sea adjacent to the Indian Ocean, indicating the limited influence of monsoon wind to the distribution of SST in that region due to some other stronger influences at Station 1 to Station 3. Moreover, the location is bordered by small islands and influenced by strong currents, waves, and tides [8].

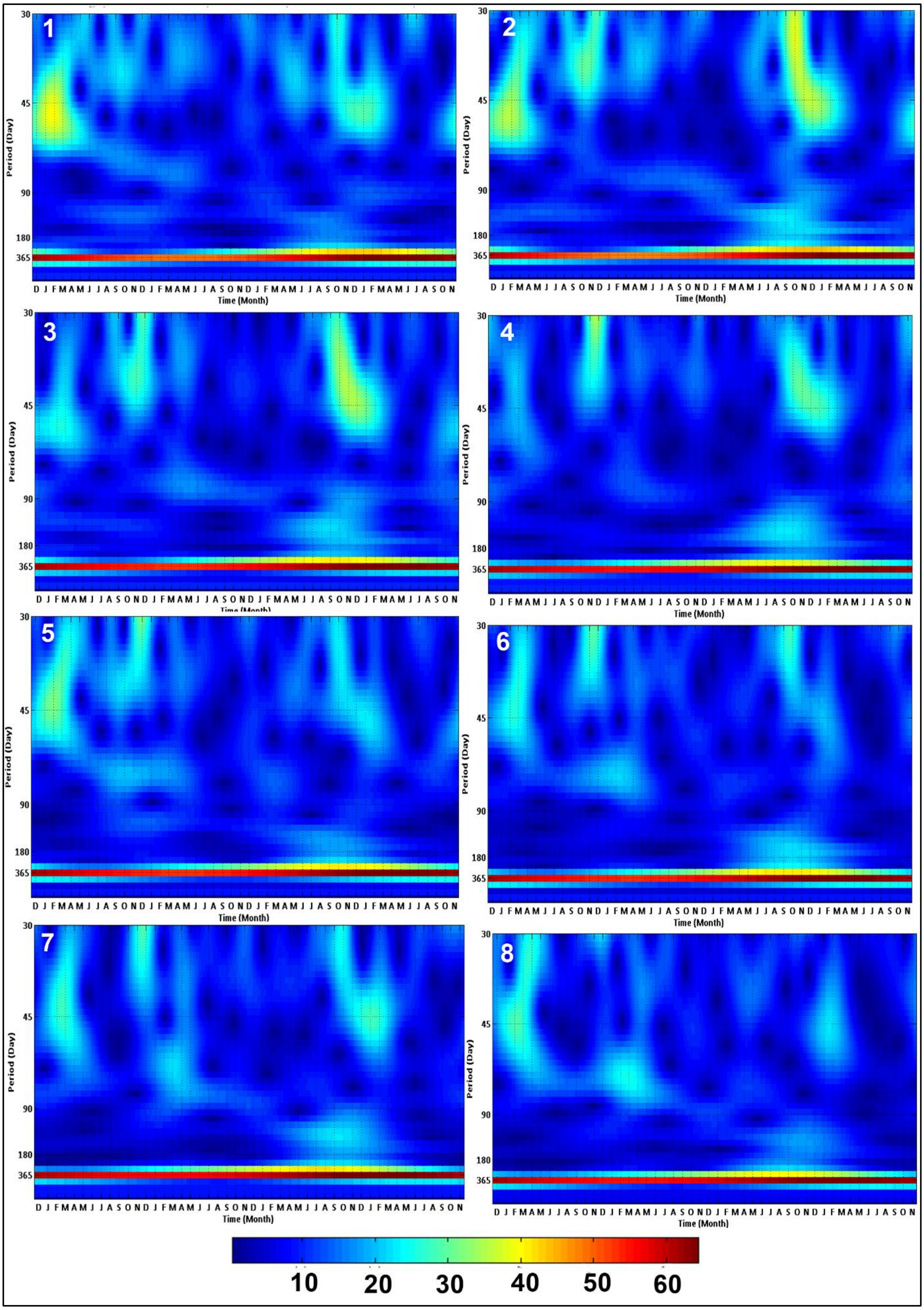

Figure 5. ***S-Transform*** **of SST data at each station**

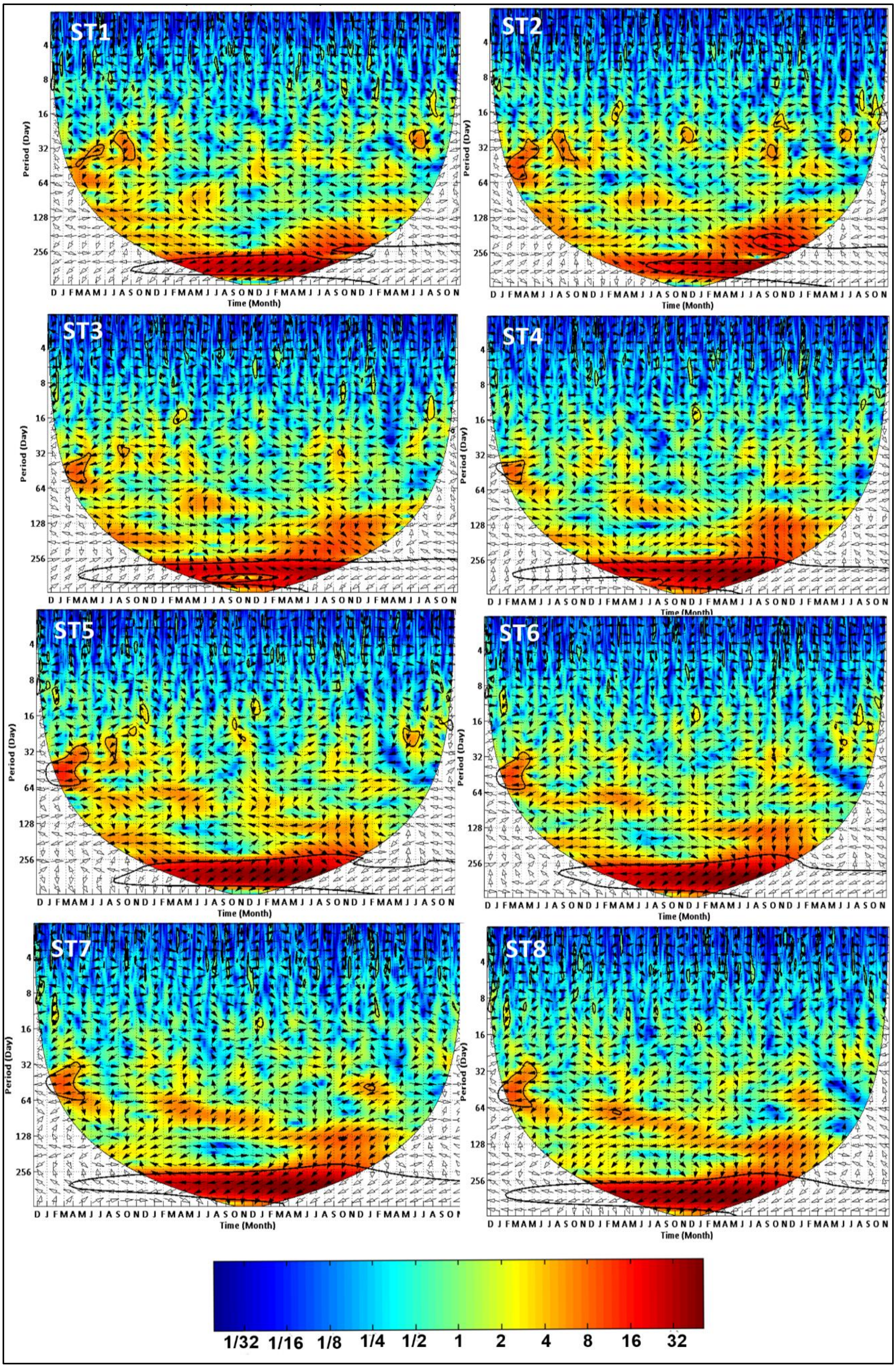

Figure 6. Cross Wavelet Transform of SST and *V* component of wind in each station

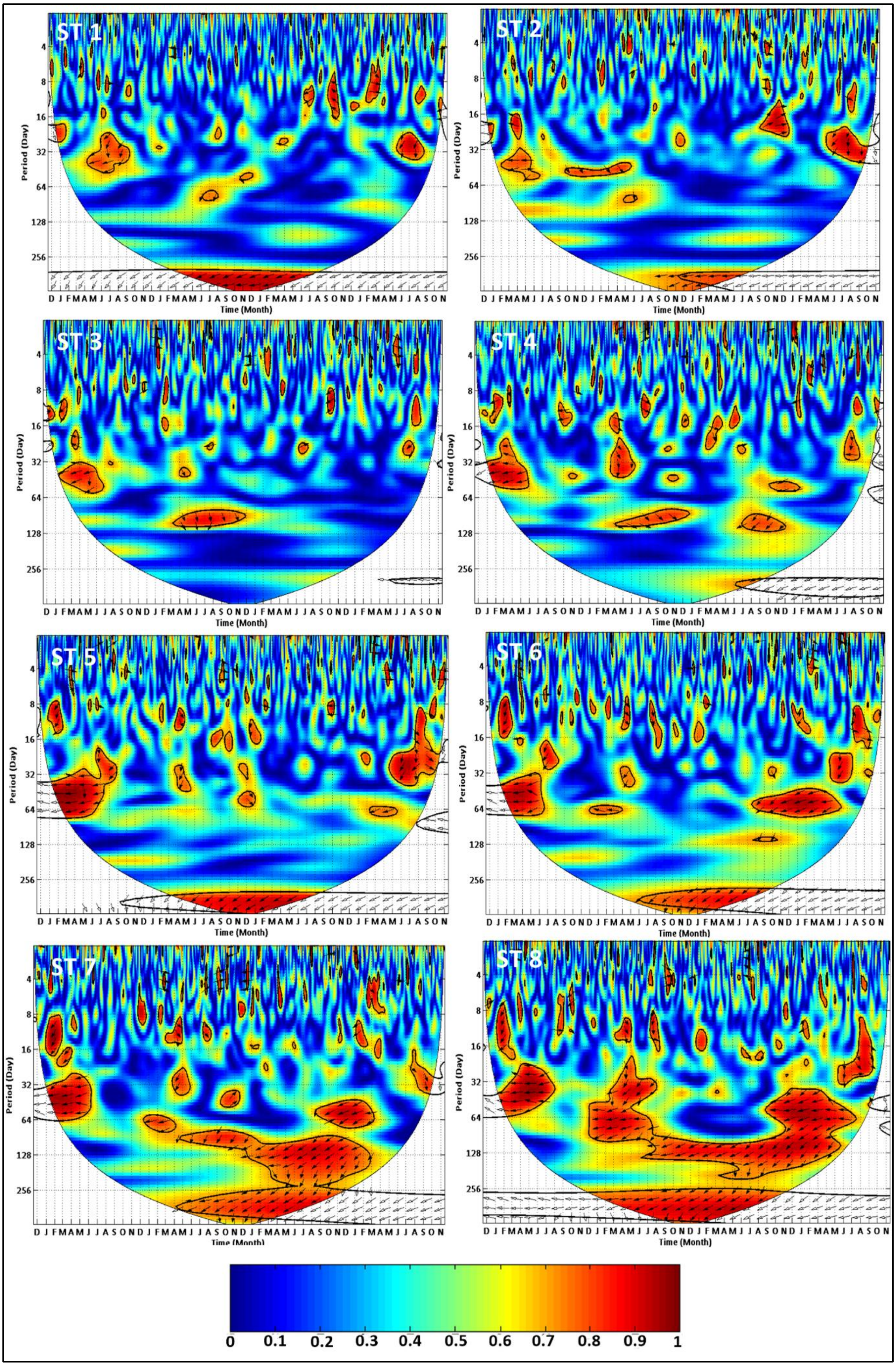

Figure 7. Wavelet coherence of SST and V component of wind in each station

4. Conclusion

There are correlation and coherence between SST and the velocity of zonal component of wind, with various periods and variations. The predominant correlation and coherence that vary during intra-seasonal with a period of 35 to 90 days tend to be anti-phase. Wind regimes influence the distribution of SST with a period of approximately 35-90 days (intra-seasonal variation). The correlation and coherence of semi-annual to the annual period that was strongly occurred in the southern waters and the open sea adjacent to the Indian Ocean (anti-phase) indicates the limited influence of monsoon wind in that region.

The Sumatera Waters are bordered by several small islands where the influences of freshwater runoff, currents, waves, tides, and upwelling take place. During the positive IOD event in October 2015, the surface wind velocity tended to be high as the lower SST than the normal condition and vice versa for negative mode.

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