Correlation and coherence analysis between sea surface temperature (SST) and surface wind in the Equatorial Western Sumatra Waters

R B Hatmaja1, U J Wisha2, I M Radjawane1 and T Al Tanto2

1 Earth Sciences Study Program, Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Jl. Ganeca no. 10, Bandung – West Java 40135, Indonesia
2 Research Institute of Coastal Resources and Vulnerability, Ministry of Marine Affairs and Fisheries, Jl. Raya Padang-Painan KM. 16, Bungus, Padang – West Sumatra 25245, Indonesia

Email: rahadenbagas@gmail.com

Abstract. Equatorial Western Sumatra Waters have a tremendous dynamic in ocean characteristics. It directly faces the Indian Ocean exactly located below the equator. Consequently, Equatorial Western Sumatra waters are influenced by the tropical climatic factors such as monsoons and climate variabilities, such as Indian Ocean Dipole (IOD) and Madden Julian Oscillation (MJO) that control sea surface temperature (SST) fluctuation in the Indian Ocean regions. This study aimed to review the correlation and coherence of SST distributed by surface wind in the Equatorial Western Sumatra waters. Wavelet method (cross wavelet transforms and wavelet coherence) was used to analyze the correlation and coherence between SST and surface wind. The annual variation of SST for 365 days period is the strongest event throughout the year caused by either monsoon or the changes of wind speed in the surface. Otherwise, the strongest intra-seasonal SST variation of 35 - 60 days observed from December 2012 to March 2013. The highest surface wind speed occurs in the southern and western waters. The surface wind plays a role in evoking SST distribution of 35 - 60 days period (intra-seasonal variability). Besides, the surface wind with 6 months period (semi-annual variability) influences the SST distribution which is identified only in the southern waters and the Indian Ocean regions. These conditions are possibly predicted as the influence of monsoons.

Keywords: Equatorial Western Sumatra Waters, sea surface temperature, surface wind speed, wavelet methods

1. Introduction

Western Sumatra waters have a tremendous ocean dynamic due to its geographical position located between Asia and Australia. It directly faces the Indian Ocean which exactly positioned below the equator. Consequently, water characteristics are strongly influenced by monsoons (due to pressure differences between Asia and Australia) which varies every six months [1] such as global climate variability, the Indian Ocean Dipole (IOD) [2], solar warming intensity, and equatorial current system [1]. Moreover, Western Sumatra has a unique topography consist of many islands, headlands, bays, and the convergence of two large water masses (from the Indian Ocean and the Andaman Sea).
Sea surface temperature (SST) is a significant parameter representing the water conditions which is one of the dominant parameters that can detect the climate change variability regionally globally. The significant change in SST can cause several impacts on marine ecosystems such as coral bleaching, demised biota, and many others. For example, corals will be suffering bleaching due to the increase of SST. Every 0.1°C enhancement of normal temperature results in 35 - 42% chance of coral bleaching [3,4]. That phenomenon caused by the significant change of SST reached 33 - 34°C resulted from climate anomaly occurred from April to June 2016 in western Sumatra [1].

An assessment of surface wind in the study area is significant because it has a dominant influence on the distribution of surface water masses. Therefore, it affects the distribution of the SST as well [5]. Furthermore, surface wind also plays a role in inducing upwelling near the coast and IOD cycles [2]. The combination of surface wind and SST is certainly affecting the capacity and vulnerability of coastal resources because the study area positioned below the equator, influenced by the monsoon, and IOD. Therefore, a study regarding correlation and coherence between SST distribution and the surface wind is essential. This research can be useful for local government and fisherman to determine fishing ground area based on the existing SST distribution condition, as well as climate change mitigation due to the anomaly of SST distribution. In this study, we analyzed the distribution and variability assessment of SST and surface wind speed in West Sumatra waters. This study aimed to review the correlation and coherence of SST distributed by surface wind in West Sumatra waters.

2. Data and Methods

2.1. Data

Data used in this study were gridded from reanalysis ERA-Interim daily SST and 10 m surface wind (zonal (u) and meridional (v)) for 4 years (December 2012 - November 2016) in the West Sumatra Waters (1°N – 3°S and 97°E – 101°E) which the resolution is 0.125° × 0.125°. Data were retrieved from European Center for Medium-Range Weather Forecasts (ECMWF) (http://www.ecmwf.int/en/research/climate-reanalysis/browse-reanalysis-datasets) [6].

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

Figure 1. Research location and observation points (red pins)
Eight observation stations were selected to represent the condition of West Sumatra Waters. Station 1 - Station 4 are representing the waters between Sumatra Island and the Mentawai Islands, Station 5 - Station 7 are representing the waters near the Mentawai Islands which is directly adjacent to the Indian Ocean, and Station 8 represents the Indian Ocean. The position of these eight observation stations is shown in Table 1 and Figure 1. To obtain the wind speed value from the zonal \((u)\) and meridional \((v)\) components, the conversion formula was employed as follows:

\[
V = \sqrt{u^2 + v^2}
\]  

(1)

Where:
- \(V\) : wind speed (m/s)
- \(u\) : zonal wind component (m/s)
- \(v\) : meridional wind component (m/s)

2.2. Methods

To analyze the variability of SST and wind speed, spectral density is employed. The spectral density method will change the data from time series domain to frequency domain using Fourier Transform. Correlation and coherence analysis of SST distributed by surface wind was done using wavelet methods, which consist of cross-wavelet transform (XWT) and wavelet coherence (WTC) [7, 8].

2.2.1. Spectral Density. Spectral density is defined as the power of each frequency interval with amplitude as the investigated signal unit where the frequency is represented as a cyclic unit. The spectral density function \(G_x(f)\) from random data \(x(t)\) describes the frequency composition related to spectral density and the power of spectral density in the form of mean-square value. Mean-square value on the frequency scale \(f\) to \(f + \Delta f\) may generate data filter which bypasses the frequency characteristics and calculates the mean-root during filtering processes. The mean root value will approximate the mean square value as the infinite time of observation \(T\), therefore the mean square value can be derived from a mathematical equation [9], as follow:

\[
\psi(f, \Delta f) = \lim_{T \to \infty} \frac{1}{T} \int_{-T}^{T} x^2(t, f, \Delta f)dt
\]  

(2)

where, \(x(t, f, \Delta f)\) = The part of \(x(t)\) on the frequency scale \(f\) to \(f + \Delta f\). Spectral density function, \(G_x(f)\), can be defined as the following Equation 3 below.

\[
G_x(f) = 4\int_{-\infty}^{\infty} R_x(\tau) \text{e}^{-i2\pi \tau f} d\tau
\]  

(3)

where, \(R_x(\tau)\) = The self-correlation of \(x(t)\) which defined as \(x_{\tau}(t) = x(t), -T < t < T\)

2.2.2. Wavelet Methods. Wavelet method is used to analyze the data in time domain and time distribution information at a certain frequency. Wavelet Transform converts data from time domain to frequency domain which the information of the phenomena at a certain frequency will be obtained. Wavelet method is a way to decompose the time series into time-frequency domain simultaneously [8, 10]. This method calculates the spectrum energy in the form of time series data. The advantages of wavelet method are detecting transient periodic fluctuations and describing complex nonlinear dynamics processes demonstrated by the interaction of disturbances spatially temporally. The wavelet spectrum describes the results of data processing from wavelet method. The y-axis shows the time of incident and the x-axis shows the incident’s period or variability.
To assess the correlation between two time series data simultaneously, Cross Wavelet Transform (XWT) is used to identify relation and relative phase, as well as to analyze its covariance ($X_n$ and $Y_n$), as follows:

$$W_{XY} = W_X \cdot W_Y$$

(4)

where:

- $W_{xy}$: The power spectrum of XWT
- $W_x$: The power spectrum of $X_n$ time series data
- $W_y$: The power spectrum of $Y_n$ time series data

(the term * shows the complex conjugate)

Wavelet coherence (WTC) is used to analyze the coherence and phase lag between two types of time series data as a function of time and frequency [8, 10]. WTC is the coherence among wavelets of those data performed to find the significant coherence with low energy level. It involves the confidence level in the calculation. It defines as follows:

$$R^2_s(s) = \frac{|s(s^{-1}W_{xy}(s))|^2}{s(s^{-1}|W_x(s)|^2) \cdot s(s^{-1}|W_y(s)|^2)}$$

(5)

Where:

- $R^2_s(s)$ = the coherence between two variables
- $S$ = the spectrum values
- $W_n$ = the Wavelet Transform in n frequency.

3. Results and Discussions

3.1. Distribution and Variability of Sea Surface Temperature and Surface Wind Speed

Figure 2 shows the spatial distribution of mean SST and surface wind speed in the West Sumatra Waters for four years (from December 2012 to November 2016). The SST averages declined at Station 1 to Station 4, then terraced at Station 5, and decreased at Station 6 and 7, and terraced again at Station 8 (see Table 2), which the fluctuation is not more than 1°C. Based on its position, the SST in the south tends to be lower than in the north. It might be affected by the intense solar warming at the equator, so the value of SST is higher [11]. Otherwise, wind speed is quite random which increases during boreal summer season (June to August) and boreal autumn season (September to November). The speed ranged from 2 - 4 m/s. The average wind speed enhanced at Station 1 to Station 4, then decreased at Station 5, and eventually terraced at Station 8 (see Table 2). The wind speed closer to the equator is weak because the area near the equator is the convergence zone of trade winds well-known as Inter-Tropical Convergence Zone (ITCZ) [12]. Compared to the SST average in Table 2, the area with low SST tends to have strong surface wind speed due to higher air pressure in the deformation processes. Otherwise, a high temperature evokes air expansion. As a result, the wind becomes weaker inducing cloud convergence formations.

Figure 3 shows the annual variability domination of 365 days. The annual variations estimated induced by monsoon cycle. It can be affected by the changes of surface wind velocity that is stronger in the boreal summer season (June to August) and the boreal autumn season (September to November). The speed ranged from 2 - 4 m/s. The average wind speed enhanced at Station 1 to Station 4, then decreased at Station 5, and eventually terraced at Station 8 (see Table 2). The wind speed closer to the equator is weak because the area near the equator is the convergence zone of trade winds well-known as Inter-Tropical Convergence Zone (ITCZ) [12]. Compared to the SST average in Table 2, the area with low SST tends to have strong surface wind speed due to higher air pressure in the deformation processes. Otherwise, a high temperature evokes air expansion. As a result, the wind becomes weaker inducing cloud convergence formations.
by solar radiation in the equator occurred every 6 months. In general, seasonal to the semi-annual variations triggered by wind speed changing every 3-6 months (monsoon cycle).

Figure 2. Mean SST (a) and surface wind speed (b) in West Sumatra Waters from December 2012 to November 2016.

Table 2. Mean SST and wind speed for four years at each station points

|                | St. 1 | St. 2 | St. 3 | St. 4 | St. 5 | St. 6 | St. 7 | St. 8 |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Mean SST (°C)  | 29.74 | 29.42 | 29.34 | 29.33 | 29.60 | 29.54 | 29.49 | 29.52 |
| Mean wind speed (m/s) | 2.49  | 2.83  | 2.94  | 3.38  | 3.16  | 3.51  | 3.72  | 3.79  |

Figure 4 shows the spectrum density of daily variation which is very dominant, thus, the variance of wind speed in West Sumatra Waters is very high and random. Nevertheless, seasonal variations vary from 91 to 97 days, intra-seasonal variation over 35 to 90 days period, semi-annual variations within 183 to 209 days (6 months period monsoon), and annual variations of 365 days period.

The seasonal variation, which occurred for 3 months period, is caused by the change of wind speed between the boreal winter season (December to February) and the boreal spring season (March to May) and so on. The semi-annual variation shows the monsoon phenomenon between the boreal winter and boreal summer season. Those conditions caused by the fluctuations of wind speed occurred every year. In general, the dominant variation is 6-month period associated with monsoons.

3.2. Correlation and Coherency Analysis

The correlation between SST and wind speed within 32 to 60 days period (intra-seasonal variation domination) occurred in March to September 2013 which tend to be anti-phase. The annual variation correlation clearly detects for 365 days period dominating throughout 2014 until early 2015 which tend to be anti-phase as well. In addition, it correlates with semi-annual period (183 to 209 days or 6 months) occurred in October to November 2015 (anti-phase). Anti-phase term means that the wind speed leads the SST in which wind speed decreased when the SST increased. In this case, wind speed raised in the southern waters, resulting in declined SST in that region. It means that the wind distributes the warm water mass northward and westward. Otherwise, when the wind moves slowly, the warm water mass will be distributed by the other factors (currents, wave, pressure, or IOD).
Figure 3. Spectral density of SST at each observation point.
Figure 4. Spectral density of wind speed at each observation point.
Figure 5. Cross Wavelet Transform of SST and wind speed at each observation point.

The wavelet coherence indicates the coherence between SST and wind speed with 32 to 60 days period (dominant intra-seasonal variation) occurred in March to September 2013 which tend to be anti-phase (Figure 6). Coherence in the intra-seasonal variation is increasingly strengthened at Station 4 to Station 8 in the southern waters and the area adjacent to the Indian Ocean. During March to September 2013, the coherence in the intra-seasonal period occurred from September 2015 to February 2016, only observed at Station 6 to Station 8 (stations adjacent to the Indian Ocean). A strong coherence between SST and wind speed in the southern water and the open seas (directly adjacent to the Indian Ocean) is occurred.
Figure 6. Wavelet coherence of SST and wind speed at each observation points.

Coherence in the annual variation is obviously detected within 365 days period that predominated in June 2014 to early 2016 tend to be anti-phase, this event only occurs at Station 5 to Station 7. Thus, there is a coherence in the semi-annual period (183 to 209 days or 6 months) from October to November 2015 that tend to be anti-phase as well observed at Station 7 and Station 8.

In general, there is a correlation and coherence between SST and wind speed, but with different both period and variation. The dominant correlation and coherence are identified in intra-seasonal variation within 35 to 90 days period. The variability of SST is caused by the changes in wind velocity and intra-seasonal variability as well [14]. Those conditions show the influence of surface wind to the SST distribution within 35 to 90 days period (intra-seasonal variation). Besides intra-seasonal variation, the
correlation and coherence during semi-annual to annual period identified are quite strong in the southern waters and open seas adjacent to the Indian Ocean indicating the limited influence of monsoon wind to the SST distribution in that region because of several other stronger influences at Station 1 to Station 3. Moreover, the location is bordered by small islands and influenced by currents, waves, tides, and upwelling.

4. Conclusion
There are correlations and coherences between SST and surface wind speed, with a different period and variation. The dominant correlation and coherence are varying during intra-seasonal with 35 to 90 days period which tend to be anti-phase. The surface wind influences SST distribution within the period approximately 35 to 90 days (intra-seasonal variation). As well as the correlation and coherence of semi-annual to the annual period that was occurred quite strong in the southern waters and the open seas adjacent to the Indian Ocean (anti-phase) indicating the limited influence of monsoon wind in that region. It’s bordered by some small islands which the influences of freshwater runoff, currents, waves, tides, and upwelling take place.

This research can be useful for local government and fisherman by which it determines the fishing ground based on the existing SST condition, and climate pattern detection regarding the anomaly of SST and the surface wind. We suggest for future study to develop this information to be well implemented to the coastal communities.

Acknowledgement
Acknowledgement and gratitude are given to European Centre for Medium-Range Weather Forecasts (ECMWF) for providing the SST and wind data, and to everyone who helps, encourages, and supports us to finish this research. Cross wavelet transform and wavelet coherence software were provided by A. Grinsted (2004) [6].

References
[1] Wisha U J, T Al Tanto and Ilham I 2017 Geomatics 22 21–28
[2] Saji N H, B N Goswami, P N Vinayachandran and T Yamagata 1999 Nature 401 360–63
[3] Mc Williams J P, I M Côté, J A Gill, W J Sutherland and A R Watkinson 2005 Ecology 86 2055–60
[4] Lesser M P 2011 Coral bleaching: causes and mechanisms. In Coral reefs: an ecosystem in transition (Dordrecht: Springer) p 405
[5] Stramma L P, Cornillon, Weller R A, Price J F and Briscoe M G 1986 Large diurnal sea surface temperature variability: satellite and in situ measurements J. Physical Oceanography 16 827–837
[6] Dee D P et al 2011 Q J R Meteorol Soc 137 553–597
[7] Grinsted A, J C Moore and S Jevrejeva 2004 Nonlinear Processes in Geophysics 11 561–566
[8] Thomson R E and W J Emery 2014 Data analysis methods in physical oceanography (Oxford: Elsevier)
[9] Bendat J S and A G Piersol 2011 Random data: analysis and measurement procedures John Wiley & Sons Inc
[10] Bernal-Rusiel J L, Greve D N, Reuter M, Fischl B and M Sabuncu 2013 Neuroimage 66 249–60
[11] Sprintall J, A L Gordon, A Koch-Larrouy, Lee T, Potemra J T, Pujiana K and Wijffels S E 2014 Nature Geoscience 7 487
[12] Loo Y Y, L Billa and A Singh 2015 Geoscience Frontiers 6 817–23
[13] Syamsul R, Peter D, Mulyadi W, Jurgen S, Yopie I, Taufiq I and Muhammad M 2012 American Journal of Environmental Sciences 8 479–88
[14] Qu T, Du Y, Strachan J, Meyers G and Slingo J 2005 Oceanography 18 50–61