VARIABILITY OF SEA SURFACE TEMPERATURE (SST) AND CHLOROPHYLL-A (CHL-A) CONCENTRATIONS IN THE EASTERN INDIAN OCEAN DURING THE PERIOD 2002–2017

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Abstract. We analysed the variability of sea surface temperature (SST) and chlorophyll-a concentration (Chl-a) in the eastern Indian Ocean (EIO). We used monthly mean Chl-a and SST data with a 4-km spatial resolution derived from Level-3 Aqua Moderate-resolution Imaging Spectroradiometer (MODIS) distributed by the Asia-Pacific Data-Research Center (APDRC) for the period 2002–2017. Wavelet analysis shows the annual and interannual variability of SST and Chl-a concentration in the EIO. The annual variability of SST and Chl-a is influenced by monsoon systems. During a southeast monsoon, SST falls while Chl-a increases due to upwelling. The annual variability of SST and Chl-a is also influenced by the Indian Ocean Dipole (IOD). During positive phases of the IOD (2006, 2012 and 2015), there was more intense upwelling in the EIO caused by the negative anomaly of SST and the positive anomaly of Chl-a concentration.

Keywords: *sea surface temperature, chlorophyll-a, eastern Indian ocean, aqua MODIS, monsoon, upwelling, IOD.*

1 INTRODUCTION

The western seas of Sumatra and the southern seas of Java are part of the eastern Indian Ocean (EIO) (90-110°E and 10-0°S). The variability of sea surface temperature (SST) and Chlorophyll-a (Chl-a) concentration in this area is intriguing because the dynamics are influenced by various phenomena such as water mass mixing and the upwelling process. Variability in SST is closely related to the movement of currents that are generated by winds blowing over the sea surface. The difference in air pressure results in air mass movements that can affect the mixing of water masses, which in turn results in inhomogeneous temperature distribution and Chl-a concentration.

Indonesia is affected by the monsoonal system (Aldrian & Susanto, 2003). During a southeast monsoon, upwelling occurs in the EIO. This upwelling process increases the fertility of the water, which has a positive impact in terms of increasing phytoplankton abundance (Wyrtki, 1962; Lumban-Gaol et al., 2002).

The sea–atmosphere interaction in equatorial Indian Ocean regions is known as the Indian Ocean Dipole (IOD). The IOD has an index value called the Dipole Mode Index (DMI), where a negative value indicates the presence of wind gusts from east to west, while a positive value denotes the opposite (Saji et al., 1999). During a positive IOD phase, the Indian Ocean SST increases anomalously in the west while in

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general, the eastern part is cooler than the average temperature (Saji et al., 1999; Webster et al., 1999). Previous studies have shown SST and Chl-a concentration to be influenced by IOD and the El Niño Southern Oscillation (ENSO) cycle in the South Java Sea, Bali, Sunda Strait, Banda Sea, northwest Sumatra (Lumban-Gaol et al., 2002; Susanto & Marra, 2005; Susanto et al., 2001; Iskandar et al., 2009; Dipo et al., 2011; Ratnawati et al., 2017; Martono, 2016).

The aim of this study was to assess the variability of SST and chlorophyll concentrations in the EIO during the period 2002–2017.

2 MATERIALS AND METHODOLOGY

2.1 Study Area

The area for this study is the EIO (90-110°E and 10-0°S) The specific locations examined were the western seas of Sumatra and southern seas of Java, with five observation points for each (Figure 2-1).

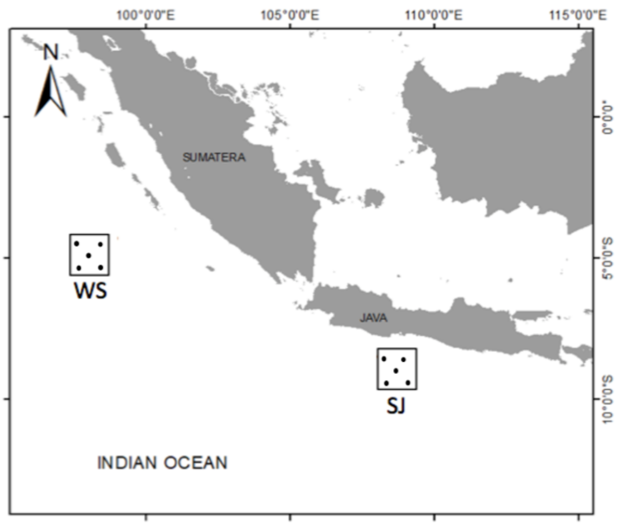

Figure 2-1: Study Area in the Eastern Indian Ocean (West Sumatra-WS and South Java-SJ).

2.2 Data Collection

SST and Chl-al concentration data were obtained from Aqua MODIS level-3 satellite imagery provided by Ocean Color and distributed by APDRC instant visualisation with ferret software (http://apdrc.soest.hawaii.edu/las/v6/ and https://coastwatch.pfeg.noaa.gov/).

The image level was corrected geometrically and radiometrically in the form of monthly composites for the 15 years from July 2002 to July 2017. The data used were monthly averages downloaded in ASCII format with a 4x4 km image resolution. The Indian Ocean Dipole Mode Index (DMI) 15-year monthly dataset used is from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) available at http://www.jamstec.go.jp/frcgc/.

2.3 Data Analysis

Continuous Wavelet Transform (CWT) was applied to analyse the time series SST and Chl-a concentration data (Torrence & Compo, 1998). The formula is given as follows:

$$W_n^X(s) = \sqrt{\frac{\delta t}{s}} \sum_{n'=1}^{N} x_{n'} \, \psi o \left[\frac{(n'-n)\delta t}{s}\right], \qquad (2\text{-}1)$$

In which x_n, n=1,..., N is a time series with equal time spacing δt and $n = 0 \dots N-1$ and ψ depend on non-dimensional 'time'. Wavelet transform can be used as a band-pass filter of uniform shape and width, as described in detail in Torrence and Webster (1999). The wavelet power could be defined as:

$$|W_n^X(s)|^2 \qquad (2\text{-}2)$$

In order to analyse for any significant coherency between cross-wavelet transforms, the wavelet coherence analysis, as described in Torrence and Webster (1999), is as follows:

$$R_n^2(s) = \frac{|S(s^{-1}W_n^{XY}(s)|^2}{S(s^{-1}|W_n^X(s)|^2) \cdot S(s^{-1}|W_n^Y(s)|^2} \qquad (2\text{-}3)$$

In which S is a smoothing operator. The S as described in Torrence and Webster (1999), is as follows:

$$S(W) = S_{scale}\left(S_{time}\left(W_n(s)\right)\right) , \qquad (2\text{-}4)$$

in which c_1 and c_2 are normalisation constants and S is the rectangle function. A factor of 0.6 is the empirically determined scale de-correlation length for the Morlet wavelet (Torrence & Compo, 1998).

3 RESULTS AND DISCUSSION

The fluctuations of SST and Chl-a off the west coast of Sumatra and south of Java during the period 2002–2017 are shown in Figures 3-1 and 3-2. There were fluctuations in SST in both South Java and West Sumatra. The range of SST in South Java (25–31°C) is lower than that in West Sumatra (28–32°C). During the southeast monsoon period (June to September), the SST in both South Java and West Sumatra was lower than the average, i.e. 28°C and 29°C respectively, whereas the SST during the northwest monsoon period was greater than the average. The monthly average of SST in the East Indian Ocean shows that the highest temperature occurred in March 2016 (31.1°C) and the lowest in September 2006 (24.7°C) (Figure 3-1).

The lowest SST value in southern Java was nearly 25°C while the highest was close to 31°C. This was not replicated in the western part of Sumatra, where the lowest temperature was only around 27°C. However, SST is always at its lowest during a southeast monsoon. In contrast, high SST values are seen during a northwest monsoon (Figure 3-2).

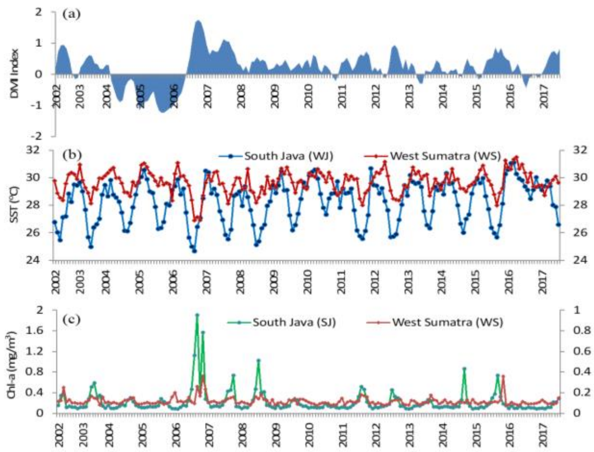

Figure 3-1: (a) Indian Ocean Dipole Mode Index, (b) monthly mean of SST and (c) Chl-a during the period 2002–2017.

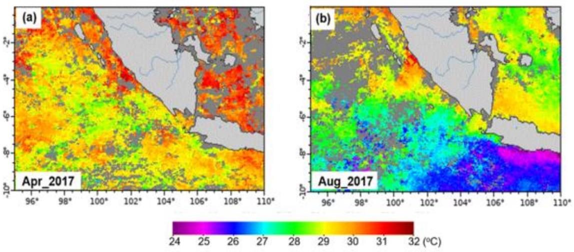

Figure 3-2: Distribution of SST during (a) Northwest and (b) Southeast Monsoon.

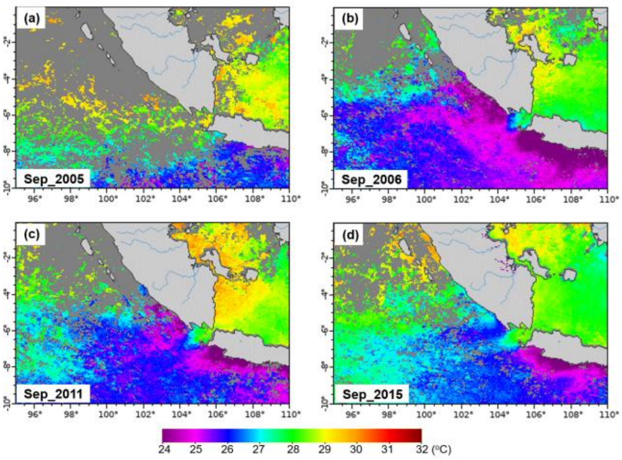

Figure 3-3: The distribution of SST (°C) in September during (a) 2005 (normal year), (b) 2006 (IOD+), (c) 2011 (IOD+), and (d) 2015 (IOD+).

During the IOD (+) phases, there was an increase in the intensity of upwelling in the area from southern Java to western Sumatra (Saji et al., 1999;

Webster et al., 1999). This phenomenon is the result of negative anomalous SST along the south coast of Java and West Sumatra (Figure 3-3).

For the three years during the period 2002–2017 in which an IOD (+) phase occurred, seemed the strongest effect is in 2006, compared to the year of 2011 and 2015. This is also evident from the lower average value of SST in 2016. Previous research has also pointed to a much stronger IOD in 2006 than the previous years. Sari et al. (2018) also observed a much higher SST along the western coast of Sumatra during the IOD (+) phase.

Wavelet power spectrum analysis shows significant variance in SST over the course of a one-year period in both West Sumatra and South Java (Figure 3-4). The one-year period is a reference to the significant influence of the monsoon wind on the variability of SST in the EIO.

Southeast monsoon winds produce seasonal upwelling along the south coast of Java and West Sumatra. This is the reason for the sharp decrease in SST. The results of the wavelet power spectrum analysis also show significant variance in SST during the 2–4-year period, which reflects the impact of the IOD phenomenon. During the IOD (+) phases, the intensity of upwelling in the EIO increased. SST variability during the 2–4-year period occurred in 2006, 2011 and 2015.

The cross-wavelet analysis (Figure 3-5a) revealed a high power spectrum between SST and the IOD in the 1–4-year period band during 2005–2010 and 2012–2015, as displayed within the red-yellow area.

The associate wavelet coherence plot confirms there was a significant period of association during 2005–2008 and 2012–2015, as shown by the negative correlation with a 1–4-year periodicity (Figure 3-5b).

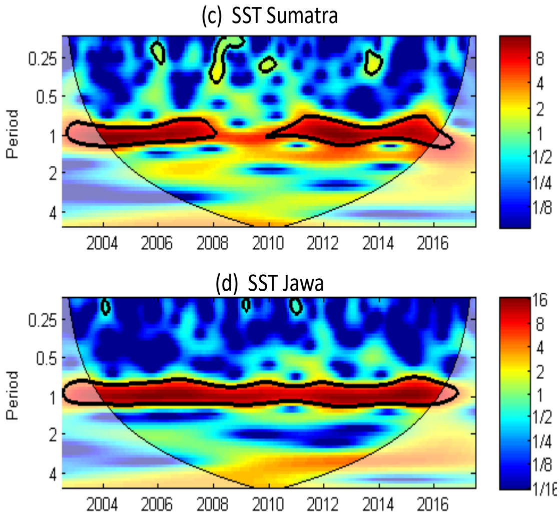

Figure 3-4: Wavelet power spectrum of SST (°C²) in the West Sumatra and South Java seas.

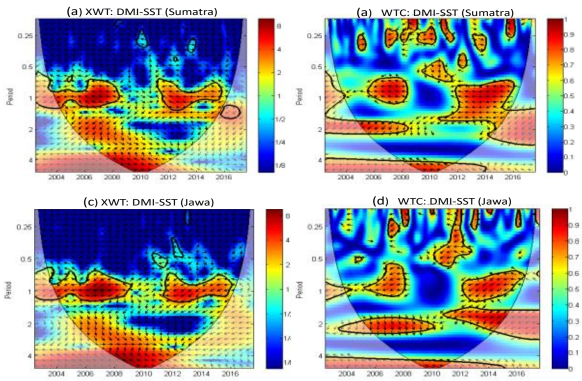

Figure 3-5: The wavelets of monthly SST and IOD mode index time series (2002–2017). (a) Cross-wavelet plot showing the common spectrum power of IOD mode index and SST time series, (b) Wavelet transform coherency plot of the IOD mode index and SST time series showing periods of coherency between the signals.

The Chl-a time-series data shows when a southeast monsoon occurs, since there is a higher Chl-a concentration at these times than during a northwest monsoon. This condition is also reflected in the pattern of SST, which is itself influenced by the upwelling process in the EIO. The highest Chl-a concentrations were 1.91 mg/m³ in the southern seas of Java (September 2006), and 0.365 mg/m³ in the western seas of Sumatra (November 2006), based on the time-series data (Figure 3-1c). Previous studies have shown a positive anomaly in Chl-a concentration in southern Java in 2006 (Kunarso et al., 2011; Iskandar, 2014). Figure 3-6 clearly shows a very high concentration of Chl-a in September 2006, 2011 and 2015 in both the south seas of Java and the west seas of Sumatra.

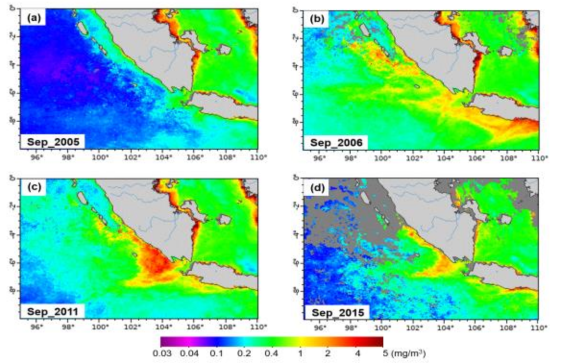

Figure 3-6: Distribution of Chl-a (mg/m^3) on September (a) 2005 (normal condition), (b) 2006, (c) 2011 and (d) 2015 (IOD+).

Wavelet power spectrum analysis reveals the presence of significant Chl-a variance over a one-year period both in West Sumatra and in the South of Java (Figure 3-7). The one-year period refers to the significant influence of the monsoon wind on the variability of the Chl-a. The wavelet power spectrum analysis also shows a significant SST variance over the course of the 2–3-year period, reflecting the impact of the IOD phenomenon. During the IOD (+) phases, the intensity of upwelling in the eastern Indian Ocean increased, producing an increase in water fertility. The variability of Chl-a on the west coast of Sumatra over a 2–3-year period was very clearly seen in the period 2006–2015 (Figure 3-7a), while to the south of Java Island it was seen in 2006 and 2015 (Figure 3-7b).

High concentrations of chlorophyll generally occur during the same month as low SST values, although the locations can be different. Low SST and high chlorophyll indicate upwelling, which as an event leads to a fall in nutrient levels and primary productivity that produces high Chl-a (Kunarso et al., 2011). Figure 3-4 shows the time-series graph of Chl-a concentration.

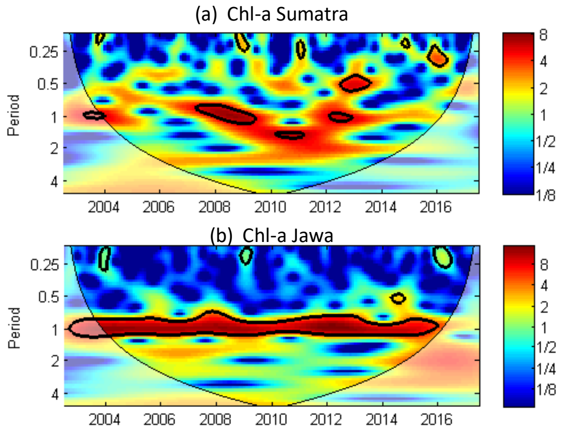

Figure 3-7: Wavelet power spectrum of Chl-a ((mg^3)^2) (a) in West Sumatra and (b) South Java.

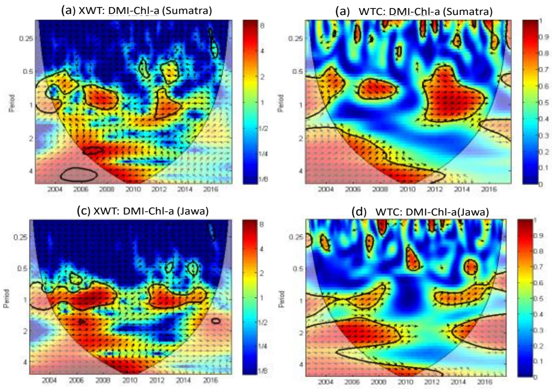

Figure 3-8: The wavelet of monthly Chl-a and IOD index (2002-2017). (a) Cross-wavelet plot showing common spectrum power of the IOD mode index and Chl-a time series, (b) Wavelet transform coherency plot of IOD index and Chl-a time series showing periods of coherency between the signals.

The cross-wavelet analysis (Figure 3-8a) shows a high power spectrum between Chl-a and IOD in the 1–3-year period band during both 2006–2011 and 2014–2015, as shown within the red-yellow area. The associate wavelet coherence plot confirms the significant period of the association during 2006–2012 (West Sumatra) and 2015–2016 (south Java Island), which shows a positive correlation with a 2–4-year periodicity (Figure 3-8b).

4 CONCLUSION

The Chl-a concentrations and SST variations during the period 2002–2017 were significantly influenced by the monsoon and IOD phenomena in the EIO. During a southeast monsoon, the SST decreases, and vice versa the concentration of Chl-a increases. During IOD (+) phases there was a negative anomaly in SST and a positive anomaly in Chl-a concentration. There were three IOD (+) phases during the period 2002–2017, namely 2006–2007, 2011–2012 and 2015–2016, while the lowest SST and highest Chl-a occurred in 2006–2007.

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