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Variability of Chlorophyll-*a* Distribution Off Pahang Coastal Waters Using Satellite Images

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ABSTRACT

Determination of chlorophyll-*a* (Chl-*a*) distribution in the coastal waters is important to understand the physical conditions of the area. This study was conducted to understand the spatial and temporal dynamic of Chl-*a* in the coastal waters off Pahang, Malaysia and to determine factors influencing its variability. Five years of Aqua MODIS satellite data from January 2006 to December 2010 of Chl-*a* distribution and sea surface temperature (SST) were analysed. Daily Level 1A data (1 km spatial resolution) were processed to monthly composites Level 3 data using SeaDAS and ERDAS Imagine software. Variability of the time series of monthly Chl-*a* and SST images were determined using Empirical Orthogonal Function (EOF) analysis. Four modes explained the variability for Chl-*a* distribution and SST in this region with total variance of 83.63 % and 97.49 % respectively. First mode for the distribution of Chl-*a* (76.0 % of variance) explained the seasonal cycle. Mode 2 (4.18 % of variance) showed high distribution of Chl-*a* off Sg. Pahang river mouth and along the coast during the Southwest and Northeast monsoon respectively. Mode 3 (2.08 % of variance) indicated distribution of Chl-*a* along the coast which explained the Northeast monsoon and subsequently mode 4 (1.37 % of variance) indicated the inter-monsoon periods at the river mouth and along the coast. Meanwhile EOF variance for SST showed that the first mode (97.0 % of variance) explained the seasonal cycle. Mode 2 (0.18 % of variance) indicated the inter-monsoon periods indicating variability along coast towards offshore. Mode 3 (0.17 % of variance) and Mode 4 (0.14 % of variance) explained the variability during the Northeast monsoon (along coast and offshore) and Southwest monsoon (offshore and south of river mouth) respectively. This study showed that the Chl-*a* distribution off Pahang coastal water region was influenced by SST and wind stress direction during monsoons period.

Keywords : Empirical Orthogonal Function (EOF), Coastal water, Chlorophyll-*a*, Satellite images.

1.0 Introduction

Understanding the chlorophyll-*a* (Chl-*a*) distribution provides a good method to explain the environmental conditions. Concentration of these pigments in the water column is mainly caused by the abundance of phytoplankton in the water column (Yoder et al. 2001). Chlorophyll can be observed through a sensor by analyzing the ocean color data in the visible spectrum wavelength between 400-700 nm (Chauhan et al. 2002, Radiarta & Saitoh, 2008).

The temporal variability of phytoplankton biomass appears to depend primarily on physical processes occurring on wide spatial and temporal scales (Wahbah & Zughul 2001). The observed data provide information of Chl-*a* at the ocean surface either seasonally or between a certain period and may vary due to input from land and influence of oceanographic physical processes such as surface wind. There are various sources of chlorophyll and nutrients input to the ocean, discharge from the river, estuarine, coastal pollution from land brought by current and also from the atmosphere (Huang et al. 2003).

Chlorophyll data is also used as an indicator for primary productivity and to understand the changes in certain places (Ledrew & Richardson, 2006). High phytoplankton abundance and productivity will lead to enhanced concentration of green pigments in the water column (Tang et al. 2003).

This study focuses on the Pahang coastal region (between 2.5° to 4.5°N and from 103.0° until 104.45°E) in east Peninsular Malaysia. This area is influenced by river discharge from Sg. Pahang, the longest river in Peninsular Malaysia (495 km long) and also aquaculture farms which are sources of nutrients to the coastal area. Understanding the spatial and temporal pattern of Chl-*a* in this region is important because the presence of these organic matter will affect the marine ecosystem especially in the enhancement of productivity in the coastal region. The objectives of this study are to understand the spatial and temporal dynamic of Chl-*a* in the coastal waters off Pahang, Malaysia and to determine factors influencing its variability.

2.0 Methods

2.1 Satellite imageries

Level 1 (Chl-*a* and sea surface temperature) of MODIS images with 1 km^2 spatial resolution at nadir, intersecting the region between 0.0° to 10.0°N and from 100.0° until 120.0°E for the period of 1st January 2006 to 31st December 2010 were downloaded from the NASAs GSFCs Distributed Active Archive Center (DAAC). We used the SeaWiFS Data Analysis System (SeaDAS) software (O'Reilly et al. 1998, Chavula et al. 2009) to process the data. Generated Level 3 products were subset from the images to geographic extents of 2.5° to 4.5°N and 103.0° to 104.45°E. The data were then processed to monthly composites data using ERDAS Imagine (Version 9.1) software.

2.2 Empirical orthogonal function (EOF)

Empirical orthogonal function (EOF) analysis was applied to the time series of the monthly averaged Chl-*a* and sea surface temperature (SST) images. This method will extract the datasets into a series of orthogonal functions that describe the spatial and temporal variability within this study region (Baldacci et al. 2001, Lihan et al. 2008, Mustapha et al. 2011). The dataset is presented by a few spatial modes with a total variance which explains the variability in a series of time.

Monthly composite images were standardized by ignoring the monthly mean from the time-series and decomposed using the method of Polovina and Howell (2005):

$$F(x,t) = \sum_{i=1}^{N} a_i(t)c_i(x) \quad (1)$$

where $a_i(t)$ are the principal component time-series or the expansion coefficients of the spatial components $c_i(x)$. The temporal and spatial components are calculated from the eigenvectors and eigenfunctions of the covariance matrix **R**, where $\mathbf{R}=\mathbf{F}'\cdot\mathbf{F}$. This analysis results in N statistical modes, each with a vector of expansion coefficients related to the original data time-series by $a_i=Fc_i$ and a corresponding spatial component map c_i.

EOF give the best result when applied to a series of no missing data. Interpolation was conducted to the images with missing data using the Distance Weighting function, which uses a set of reference data points that weighted by a value corresponding with the distance between each point and the pixel to measure a pixel value inside the AOI. Maps were reconstructed using the basic monthly 1 km x 1 km to the Chl-*a* and SST products.

2.3 Surface wind data

Wind data were downloaded from the Southeast Fisheries Science Center, NOAA Fisheries Service Environmental Research. The zonal and meridional ArcView gridded wind speed data were processed to obtain the magnitude and direction of sea wind stress patterns of the region. These components were calculated to wind stress, τ (kg m^{-1} s^{-2}), using the equation of Nezlin & DiGiacomo (2005):

$$\tau = C_D \rho_{air} U^2 \quad (2)$$

where C_D is dimensionless drag coefficient (0.0013), ρ_{air} is air density (1.22 kg m^{-3}) and U is wind speed at 10 m above surface. The images were mapped using ArcGIS.

3.0 Results

The first EOF mode explains 76 % of the total variance distribution of Chl-*a* (Figure 1A). Spatial pattern indicated the seasonal cycle with high variability in the coastal region. The spatial patterns of this mode showed high Chl-*a* concentration distributed along the coastline towards offshore region. High variability was also observed from the river mouth to the South. The time series associated with mode 1 showed positive signals. Low positive signal was detected in June 2006, August 2007, early October in 2008, August 2009 and July 2010. This explained the variability during the Southwest monsoon. While strong positive signals occurred in December 2006, November 2007, January 2008, November 2009, and during December 2010. This pattern also explained by EOF of SST which showed 97 % of variance explaining seasonal cycle (Figure 2A). Strong positive signal explained the Southwest monsoon at the coastal area and low positive signal during Northeast monsoon at the offshore area.

The second EOF mode explains variability during Southwest and Northeast monsoon with 4.18 % of variance (Figure 1B). The temporal amplitude showed strong negative signals in April 2006, June 2007, July 2008, September 2009 and June 2010. This signal was detected off Sg. Pahang river mouth during Southwest monsoon and was explained by EOF SST mode 4 (0.14 % of variance) (Figure 2D). Negative signal occurred offshore from the river mouth (April 2006, June 2007, July to September 2008 and September 2009) showed by the annual time-series of these two EOF results. Northeast monsoon showed a strong positive signal for Chl-*a* EOF that occurred along the coast (January 2006, January and December 2007, January 2008, January 2009 and January 2010).

The third EOF mode explained about 2.08 % of total Chl-*a* variance (Figure 1C). Strong positive signal occurred in March 2006, February 2007, February 2008 and January 2010 indicating the Northeast monsoon which is associated with mode 3 SST EOF which explains 0.17 % of total variance and showed variability along the coast (Figure 2C). The spatial pattern of Chl-*a* was distributed along-shelf direction. Meanwhile, mode 4 of Chl-*a* EOF explained the inter-monsoon period with 1.37 % of total variance (Figure 1D). Variability was observed at the river mouth (positive signal) and along coast (negative signal). High positive peak was detected in April 2006, April 2007, March 2008, March 2009 and April 2010. Strong negative signal occurred in November 2007, September 2010 and low positive signal in October 2008 indicating the transitional period from Northeast to Southwest monsoon. This pattern was also explained by EOF SST mode 2 with 0.18 % of total variance showing a negative signal during this period (Figure 2B). Negative signal was detected in April 2006, April 2007, March 2009, April 2010, November 2007, and September 2010 which is associated with inter-monsoon period.

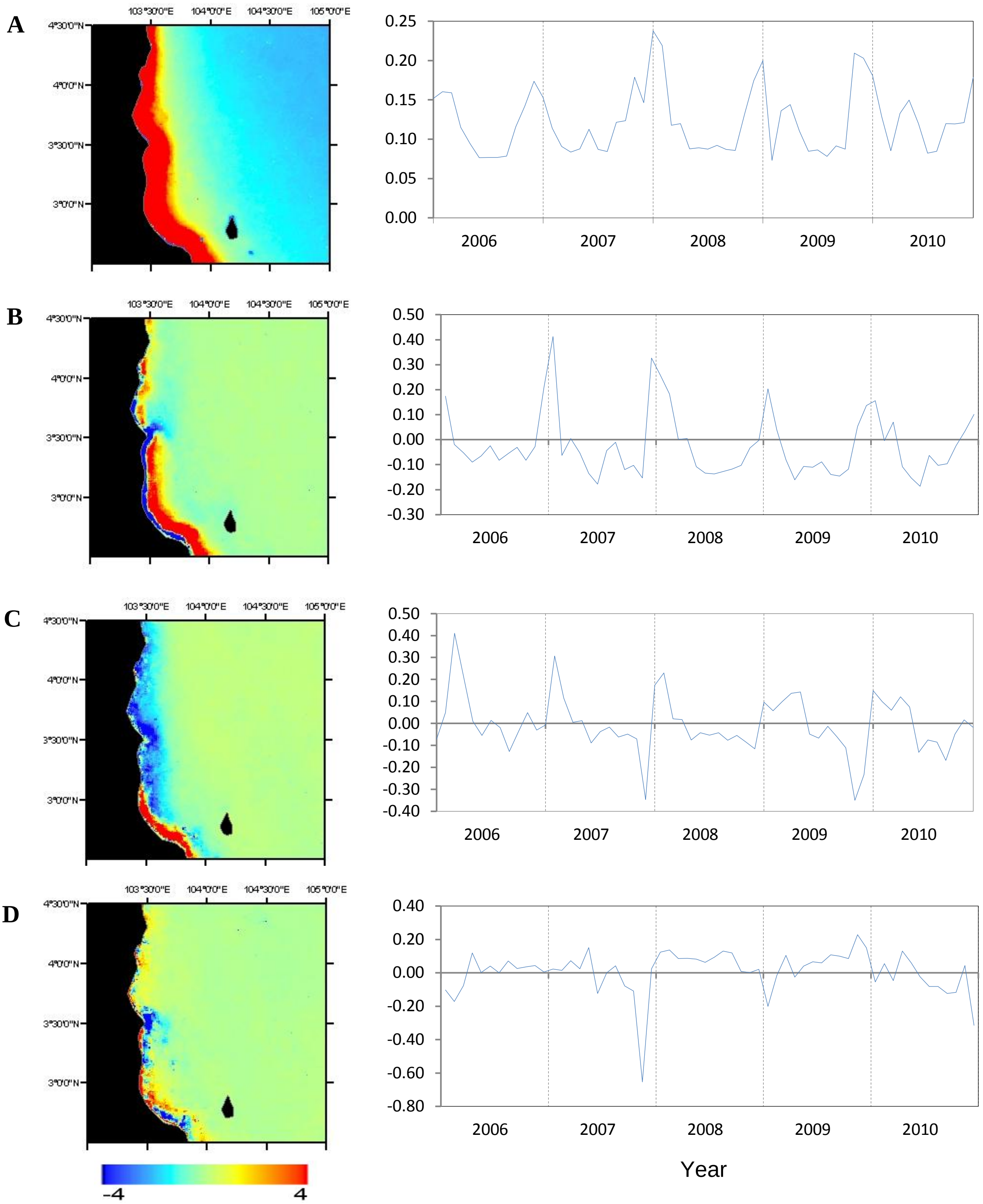

Figure 1. EOF analysis showing inter-annual variability of chlorophyll-*a* (Chl-*a*) off Pahang coastal water: Each mode consist of spatial pattern (left) and the time-series (right). (A): First mode represents 76 % of variance indicating seasonal cycle, (B): second mode 4.18 % of variance explaining the Southwest and Northeast monsoon, (C): third mode 2.08 % explaining the Northeast monsoon, and (D): fourth mode 1.37 % of variance indicating the inter-monsoon period.

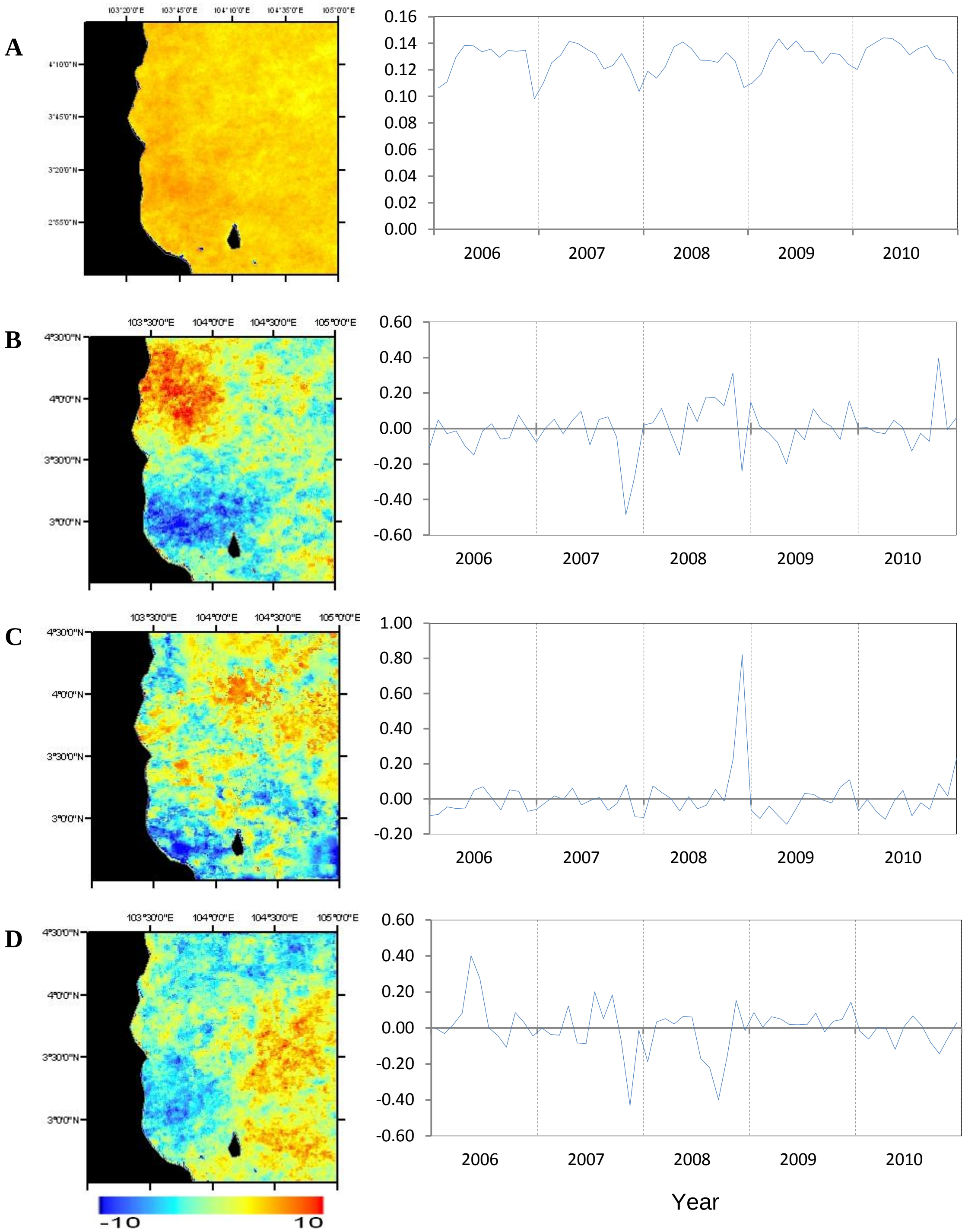

Figure 2. EOF analysis showing inter-annual variability of sea surface temperature (SST) off Pahang coastal water: Each mode consist of spatial pattern (left) and the time-series (right). (A): First mode represents 97 % of variance indicating seasonal cycle, (B): second mode 0.18 % of variance explaining inter-monsoon period, (C): third mode 0.17 % explaining the Northeast monsoon, and (D): fourth mode 0.14 % of variance indicating the Southwest monsoon.

The spatial distribution of Chl-*a* from the monthly composite images of MODIS were affected by wind direction and magnitude during Northeast, Southwest, and inter-monsoon period.

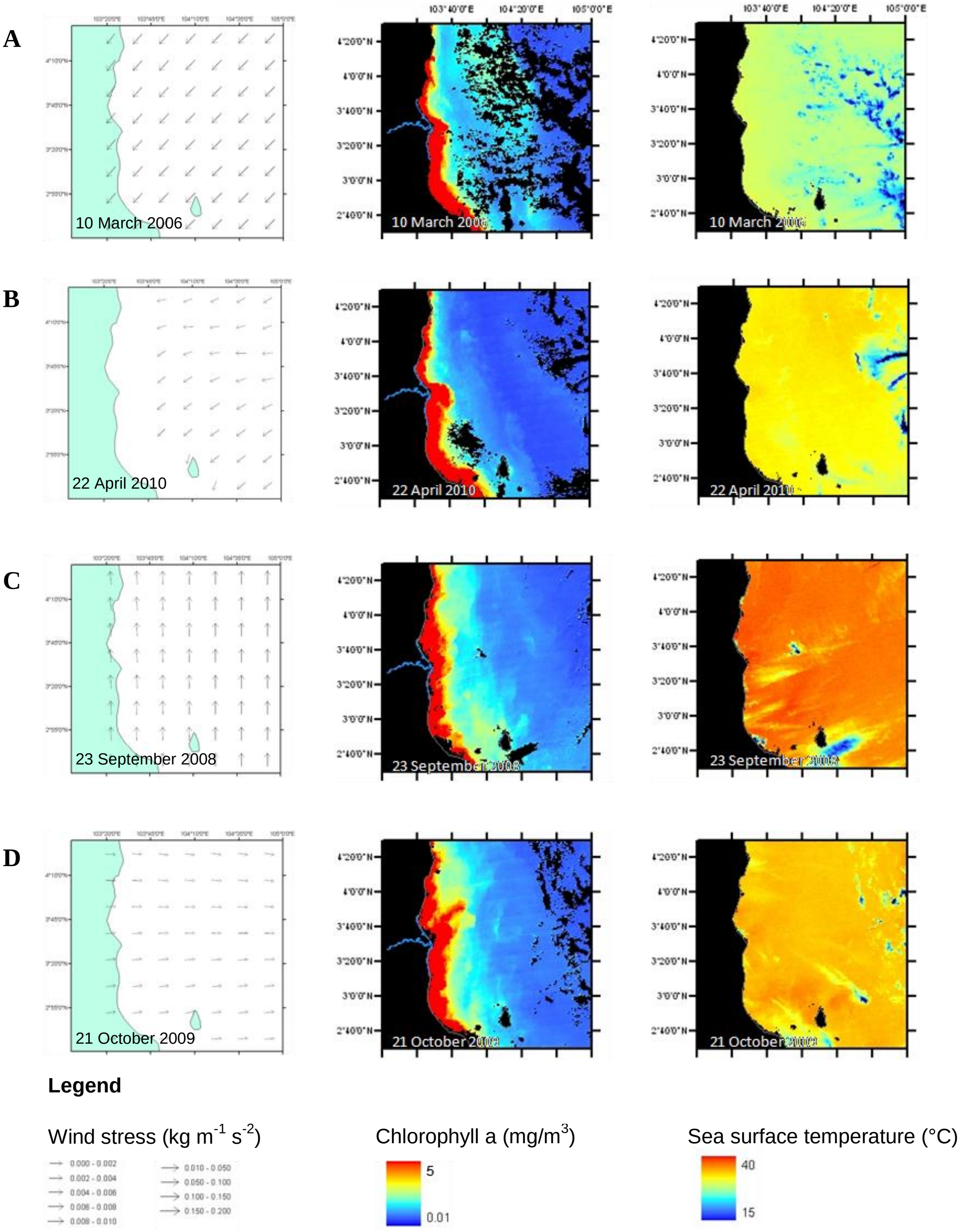

Figure 3. Influence of wind stress and its direction (left panel) to the chlorophyll-*a* distribution (middle panel) and sea surface temperature (right panel). On (A): Northeast monsoon, (B): Inter-monsoon April, (C): Southwest monsoon, and (D): Inter-monsoon October.

4.0 Discussion

The variability of the distribution Chl-*a* in Pahang coastal water was explained by the Empirical orthogonal function (EOF) analysis of MODIS monthly composite images. Optical properties of the near-surface water depend on the spectrum that is reflected by the constituent in water. Understanding variability of this constituent provides information on the dynamic distribution and concentration of Chl-*a* in the environment.

EOF analysis mode 1 showed occurrence of seasonal cycle of Chl-*a* distribution in this region influenced by the Northeast and the Southwest monsoon. During this period wind forcing condition brings the circulation of low and high SST to the South China Sea region (Wang et al. 2009). This condition was explained by EOF SST mode 1 indicating low and high signals detected during wet and dry seasons. High surface water temperature was detected during Southwest monsoon and low water temperature detected during Northeast monsoon. According to Kueh and Lin (2010), the transition and onset of these two major systems happens due to atmospheric internal dynamics, intra-seasonal oscillation, and sea/land surface conditions.

The distribution of Chl-*a* was higher near the coast due to discharge from the river and urban area as showed by the spatial pattern of EOF mode 3 (highest signal in March of 2006) (Figure 1C). Sg. Pahang discharge measured at Lubok Paku was 596 m^3/s during wet season of Northeast monsoon (Tachikawa et al. 2004). As observed in Figure 3A, high Chl-*a* concentration occurred off the river mouth of Sg. Pahang and along the coast. Variability of SST was also observed to influence the along coast pattern of Chl-*a* distribution. During this period SST is also low due to movement of cooler waters from the North following the Northeast winds. Apart from that, precipitation was maximum during November and December in this region (Wang et al. 2009). This result in discharge water that is usually higher in nutrient during the Northeast monsoon.

Meanwhile, spatial distributions of Chl-*a* during Southwest monsoon is affected by the wind magnitude that moves the water to the Northward direction. As shown by Figure 3C, dispersion of Chl-*a* off the river mouth of Sg. Pahang and to the offshore direction was clearly seen due to presence of surface Northward flow, wind was weak and observed to move Northward. Due to transition between major circulation systems over the Indian Ocean and the western Pacific, South China Sea summer monsoon period was occupied with high sea surface temperature that occurred in this region (Chang et al. 2006, Kueh and Lin, 2010). As indicated by the negative signal in the temporal amplitude of SST EOF mode 4, occurrences of high SST around the South China Sea was observed.

The seasonal transition of monsoon circulation was also affected by the wind direction and SST in South China Sea. During transition period from Northeast to Southwest monsoon in April, Chl-*a* distribution was observed high along the coast. Chl-*a* variation indicated that this period was accompanied by a warm SST indicating the transition from Northeasterly wind to Southwesterly wind. The Intertropical Convergence Zone (ITCZ) becomes its weakest and the South China Sea is its driest during the pre-monsoon period from March to mid-May (Wang et al. 2009). Onset of rainy season during inter-monsoon period is a transition from Southwest to the Northeast monsoon in October, wind directions were reverse from Southwesterly to Northeasterly. Chl-*a* distribution was influenced by wind stress direction, high at river mouth (Figure 3B and Figure 3D) and its level are in between summer and winter (Tang et al. 2003).

5.0 Conclusions

For the whole 5 years study period (January 2006 - December 2010) the spatial and temporal signature of this parameter was summarized. Variability of Chl-*a* distribution was affected by wind and SST and demonstrated by EOF analysis (76 % variance of mode 1, 4.18 % variance of mode 2, 2.8 % variance of mode 3 and 1.37 % variance of mode 4). Inter-annual variability of spatial and temporal dynamic of Chl-*a* in Pahang coastal water was influenced by monsoon periods. Northeast monsoon brings the Northeasterly wind that moves the water to the Southwest direction with low sea surface water temperature. While, a Southwest monsoon associated with Southwesterly wind moves the water to the Northward direction in this region. Inter-monsoon period occurred moves the water with Chl-*a* in pursuance of wind stress direction, along shore in April and to the off-shore direction in October. Inter-monsoon periods show the changing between Northeast and Southwest flow in this region.

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