Satellite–measured spatial and temporal variability of the Pahang River plume.

Amizam Jabbar, Zulfahmi Ali Rahman, Sahibin Abd.Rahim,
Muzzneena Ahmad Mustapha & Tukimat Lihan.

School of Environmental and Natural Resource Sciences,
Faculty of Science and Technology,
Universiti Kebangsaan Malaysia,
43600 Bangi, Selangor
Email:amizam_oasis@yahoo.com

Pahang River plumes leads to important variations of suspended matter concentrations and pollutants. Understanding of Pahang River plume dynamics and dispersal patterns are important for management of coastal water quality and biological productivity. This study aims to determine the variability of Pahang River plume at coastal area. We analyze 1-km spatial-resolution normalized water-leaving radiance, (nL_w 551) obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) on Aqua satellite from the period of 2005-2010. Empirical orthogonal function (EOF) was used to express the spatial and temporal variability of plume using anomalies of nL_w (551) monthly average images. The EOF analysis shows there are five modes to express the spatial and temporal variability of river plume with a total of 74% from the total variance. The first mode (59% of variance) shows that the plume distributed along the coastal area has the highest variability of the spatial pattern and indicate the seasonal cycle. Meanwhile the second mode explains about 8 % of the temporal and spatial variability. The plume which appeared to propagate along the coast and offshore indicates the dominance effect of Northeast Monsoon. Third mode (6.2% variance) describes the plume distribution offshore during October and November which is associated with the inter-monsoon of Southwest to Northeast. Fourth mode (4.8% variance) which is related to the inter-monsoon of Northeast to Southwest explains the movement of river plume from the river mouth to the south. Meanwhile, the fifth (4.4% variance) mode shows the distribution of the plume to the north which could be associated with the Southwest Monsoon phenomena. The high variability of the plume distribution along the coastal area is influenced by the wind direction and magnitude.

Keywords: Pahang River; River plumes; Remote sensing; Ocean color; Spatial and Temporal

INTRODUCTION

Estuaries and coastal ecosystems are important areas and they are relatively sensitive to changes. Information about the processes which occur in coastal areas is important to further study about the ecosystem preservation. River discharge being the major source of pollutants flows out to the sea to form a plume in front of river mouths. River plume is a mass of water with different spectral reflectance of the actual mass (Nezlin et al. 2008; Lihan et al., 2008). Plumes are also identified by looking at the water body that has lower salinity than seawater (Nezlin et al. 2008). Total reflection spectrum is dependent on the content of suspended sediments and colored dissolved organic matter (CDOM) in plume.

As shown by several studies, the dynamic of river plumes presents a complex behavior due to the high temporal variability (Broche et al., 1998) and simultaneous influence of different factors (Garvine, 1999). The high variability of the plume distribution in time and space at the coastal environment is influenced by a number of factors such as wind stress and river discharge. The use of remotely sensed data is significant to provide synoptic and frequent regional overviews. This enables more effective analysis of the spatial and temporal distribution by using surface parameters that can be measured from space (Nezlin et al., 2005).

The Pahang River system is important in the irrigation of agriculture area in Pahang Basin consists of 16 major rivers with a total length of 440 km. It is the longest river in Peninsular Malaysia and flows into South China Sea at Pekan (Figure 1). The South China Sea sustains two major monsoons throughout the year which are North East Monsoon (October to Mac) and South West Monsoon (April to September). This monsoonal climate strongly affects its circulation and wind which in turn influence the spatial and temporal distribution of Pahang River plumes. The river plumes that flow to the sea eventually influence the coastal ecosystem surrounding. Freshwater input from rivers carries along natural and anthropogenic contaminants and pollutants. Consequently, it will directly deplete the ecosystems and fishery resources. Suspended sediment in the river plumes limits the productivity in coastal area due to the reduction in the photic zone. Therefore it is important to understand the spatial and temporal distribution of Pahang River plume area. This study aims to determine the variability of the Pahang River plume using satellite images. This can be achieved by using MODIS images to clarify the spatial and temporal dynamics of the river plume.

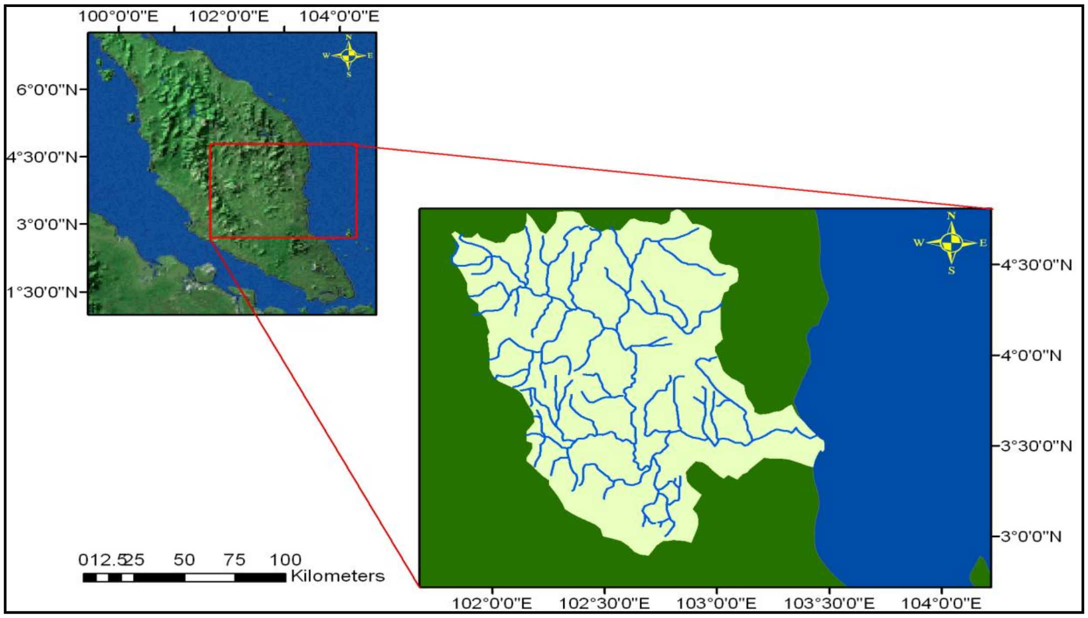

Figure 1. Shows the study area at the coastal of Pahang River mouth.

MATERIAL AND METHODS

MODIS-Aqua Level 1A images data were obtained from NASA Goddard Space Flight Center and processed to level 2 (normalized water-leaving radiance: nL_w) using the NASA's SeaWiFS Data Analysis System (SeaDAS version 6.1) software. The normalized water-leaving radiances nL_w 551 with 1000m spatial resolution were calculated. The atmospheric correction was based on an aerosol model utilizing the shortest infrared wavelength at 1240 nm and the longest infrared wavelength at 2130 nm (Wang & Shi., 2005; Wang, 2007; Lahet & Stramski, 2010). Level 2 local area coverage (LAC) images with 1 km swaths intersecting the region of 10-0° N, 100-120° E were analyzed for period of 1 January 2005 to 31 December 2010 with a total of 898 MODIS images. The coastline of the study region was used as a base map to project the data. In order to map, data were projected with a cylindrical system identical using ArcGIS. Meanwhile the wind data were downloaded from NOAA Earth System Research Laboratory website (www.esrl.cdc.noaa.gov). These files contain regular grids of zonal and meridonal wind speeds at 10m above the earth surface. The direction and magnitude of the wind surface were displayed and plotted using The Grid Analysis and Display System (GRADS) and this data would be related to the variability of the plume river.

The empirical orthogonal function (EOF) analysis was applied to the times series of the anomaly on nL_w 551 monthly average images to investigate the spatial and temporal variability of Pahang River plumes. Studies have proved that the optical property of nL_w 551 is a good proxy to describe the contents of freshwater discharge at coastal areas. Images with missing data were interpolated using Kriging interpolation method, which uses weights of the values surrounding the measured value to calculate a prediction for the missing data location (Goovaerts, 1997;

Lihan et al., 2008). The times series of the anomaly of nL_w 551 monthly average images were de-trended and stabilized by removing the monthly mean from the time series and decomposed following the approach used by Polovina & Howell (2005).

RESULTS AND DISCUSSIONS

EOF analysis is a common multivariate analysis technique used to derive the dominant patterns from a statistical field. For this study EOF analysis organizes a temporal and spatial series of 6 years of monthly images period from nL_w 551 into a set of orthogonal functions that compactly describes the covariability of the variability of Pahang River plumes. The EOF analysis results show that only the first five modes describe the variability of spatial and temporal of the Pahang River plumes which covers 74% of the total variance (Figure 2).

The first mode of EOF analysis of nL_w 551 (Figure 2. A) explains 54% variance of spatial and temporal variation. The first mode explains the spatial pattern of the plumes which contained suspended solid that were widely spread along the coast, starting from the mouth of the Pahang River to Kuantan River and south part of this coastal area. A strong positive signal from this mode indicates the plume distribution along the coast (along-shelf direction). Temporal series which was associated with the first mode shows high temporal variation. Positive temporal amplitude shows a strong signal in October, November and December 2005 and 2010. Meanwhile weak signal is shown in February, March and April 2007, 2008, 2009 and 2010; May, Jun, August and September 2006, 2007 and 2010. This first mode explains the distribution pattern of plume during Northeast Monsoon in October, November and December and Southwest Monsoon in May, Jun, August and September. This is a proof that the first EOF mode indicates a pattern of seasonal cycles over the study period.

The second mode of EOF analysis (Figure 2. B) explains about 8% of spatial and temporal variability. The positive signal showed that plume appeared to propagate along the coastal area and offshore. Meanwhile, negative signal of temporal amplitude describes the distribution of the plume to the north and south of the river mouth. The second mode of temporal amplitude show that the positive signal can be observed during December and January 2006 and 2007 and November 2007, 2008 and 2009. Strong negative signal meanwhile occurred in October 2005 and 2006; November 2006, 2008 and 2010; December 2009; January 2005 and 2008. This mode explains the dominance effect of Northeast Monsoon which influences the distribution pattern of plume along the coast, offshore, north and south of the river mouth.

The third mode of EOF analysis (Figure 2. C) explains 6.2% variation. This mode shows the positive signal patterns spread in front of the river and continental shelf, while the negative signal indicates the plume spread along the coast. The temporal for this mode shows a positive signal during October 2007, 2008 and 2009; November, 2006, and 2008; December 2006 and 2009. The negative signal, on the contrary, occurred during October 2005 and 2006, November 2007, 2009 and 2010. Based on the temporal amplitude, this mode describes the distribution patterns of plume during the inter-monsoon of Southwest to Northeast.

The fourth mode of EOF (Figure 2. D) explains about 4.8% variance with positive signal exhibited southward direction of plume distribution from the mouth river. However the negative signal indicates that the plumes were moving out of the estuary to the north. Based on the amplitude of the fourth mode, Pahang River plumes provide a positive signal in April 2006, 2007, 2008, 2009 and 2010; May 2007 and 2008; June 2005 and 2010. However negative signal of temporal amplitude were observed in December 2006, 2007; November 2009 and 2010. This mode describes the distribution pattern of plume that tends to propagate to the south of river mouth during the transition of Northeast Monsoon to Southwest Monsoon.

Fifth mode (Figure 2. E) explains about 4.4% variance in the spatial and temporal variability. Positive signal indicates the movement of the plumes tends to propagate offshore and northward during Southwest Monsoon. Meanwhile negative signal exhibits the pattern of plumes settling down of plume at the south of coastal area. The positive amplitude signal can be observed in May and June 2006 and 2006; April 2005; July 2007 and 2008; August 2008 and 2009. Negative signal of temporal amplitude for this mode were observed during January 2006 and 2008; September 2008 and 2010; November 2006 and 2007.

Based on the wind data analysis, there are five types of wind direction at South China Sea and along the East Coast. Five types of wind that were identified are East Wind, Northeast Wind, West Wind, Southwest Wind, and the South Wind which could indirectly be associated with the spatial and temporal variability of Pahang River plumes.

Annually South China Sea and East Coast are influenced by two distinct monsoons, which are Northeast (November to March) and Southwest Monsoon (May to September) (Fien & Stephens, 1987). They are interspersed by two transition monsoon between them in April and October. During Northeast Monsoon, a strong Northeast Wind and East Wind (2.5 ms^{-1}-7.9 ms^{-1}) blows East Coast (Figure 3. A). During this monsoon, East Coast of Peninsular Malaysia will experienced a heavy rain episode for a period of time. Besides, this monsoon results in high cloud cover, which affects the availability of satellite data especially in December and January. The intensity of Northeast and East Wind during this monsoon explains the distribution patterns of plume in second mode of EOF analysis. The strong affects of both winds which, can exceed to > 8 ms^{-1}, will eventually force the plume propagates from the river mouth to the offshore and disperse along the coast due to the re-suspension by strong wind mixing.

However Southwest Monsoon which occurs in May to September is different from Northeast Monsoon because it carries along a dry wind (Ku Kassim et al., 2007). East Peninsular usually having a constant dry season during this period and Southwest Wind, West Wind and South Wind are dominance but relatively weaker than Northeast Monsoon wind (1.2 ms^{-1} – 4.5 ms^{-1}). The distribution pattern of EOF mode five might be associated with the influences of Southwest Wind, West Wind and South Wind. The wind force during Southwest Monsoon will force the plume to form at the Northward of coastal area (Figure 3. D). Meanwhile during the monsoon transition in April and October the direction and magnitude of wind pattern will changed. In April the direction of the wind will shift from Northeast to Southwest (Figure 3. C). Plumes was seen distributed along the south of coastline in this month as shown by EOF mode 3. In October the wind direction changes from Southwest to Northeast with higher force of wind magnitude (Wang et al.,2009). Based on EOF mode three, plumes tends to propagate offshore during this period (Figure 3. B).

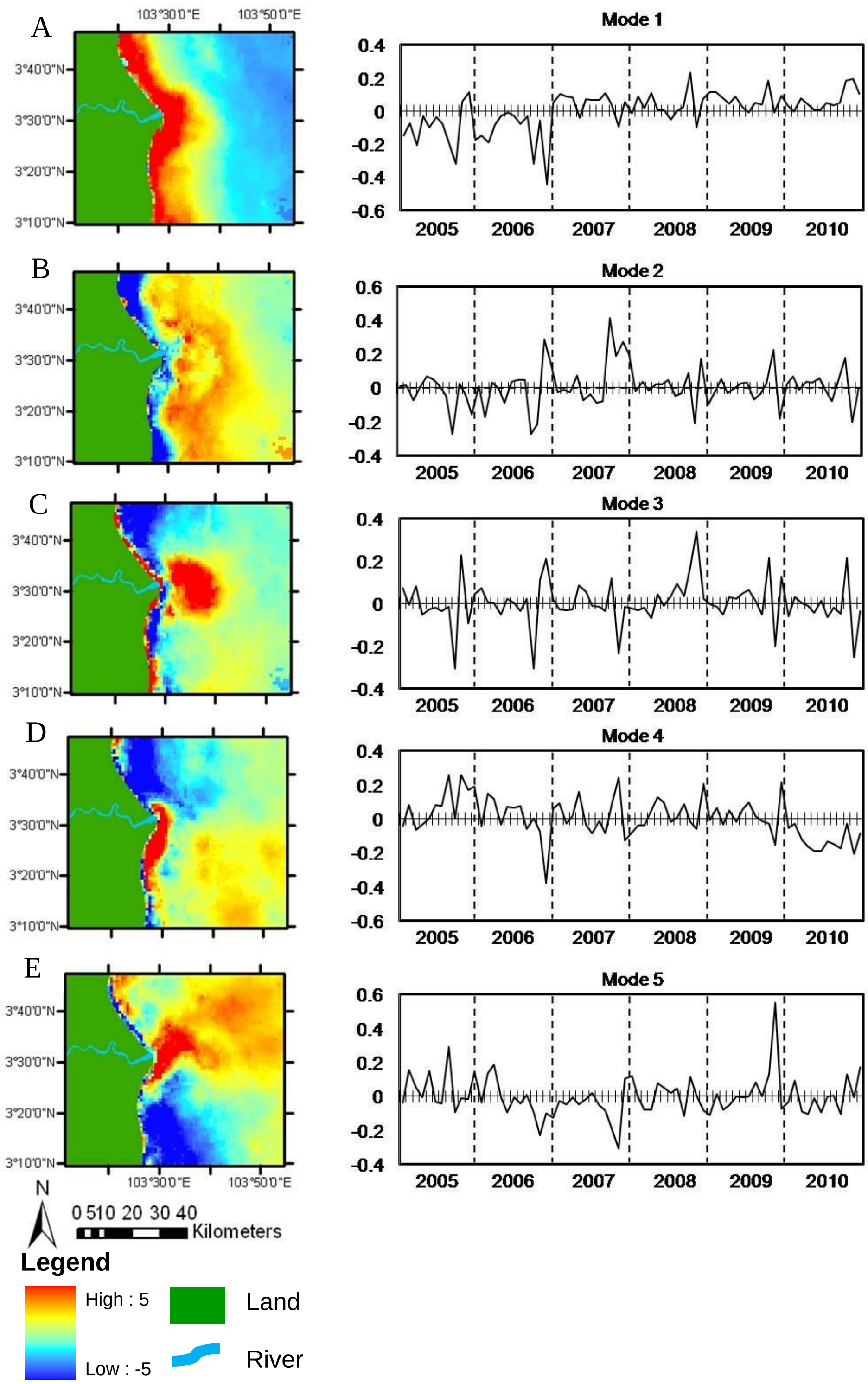

Figure 2. EOF analysis showing the spatial and temporal variability of Pahang River plume, first mode (A), second mode (B), third mode (C), fourth mode (D) and fifth mode (E) which

describing 74% of total variance. Each mode represent spatial pattern (left) and temporal amplitude (right).

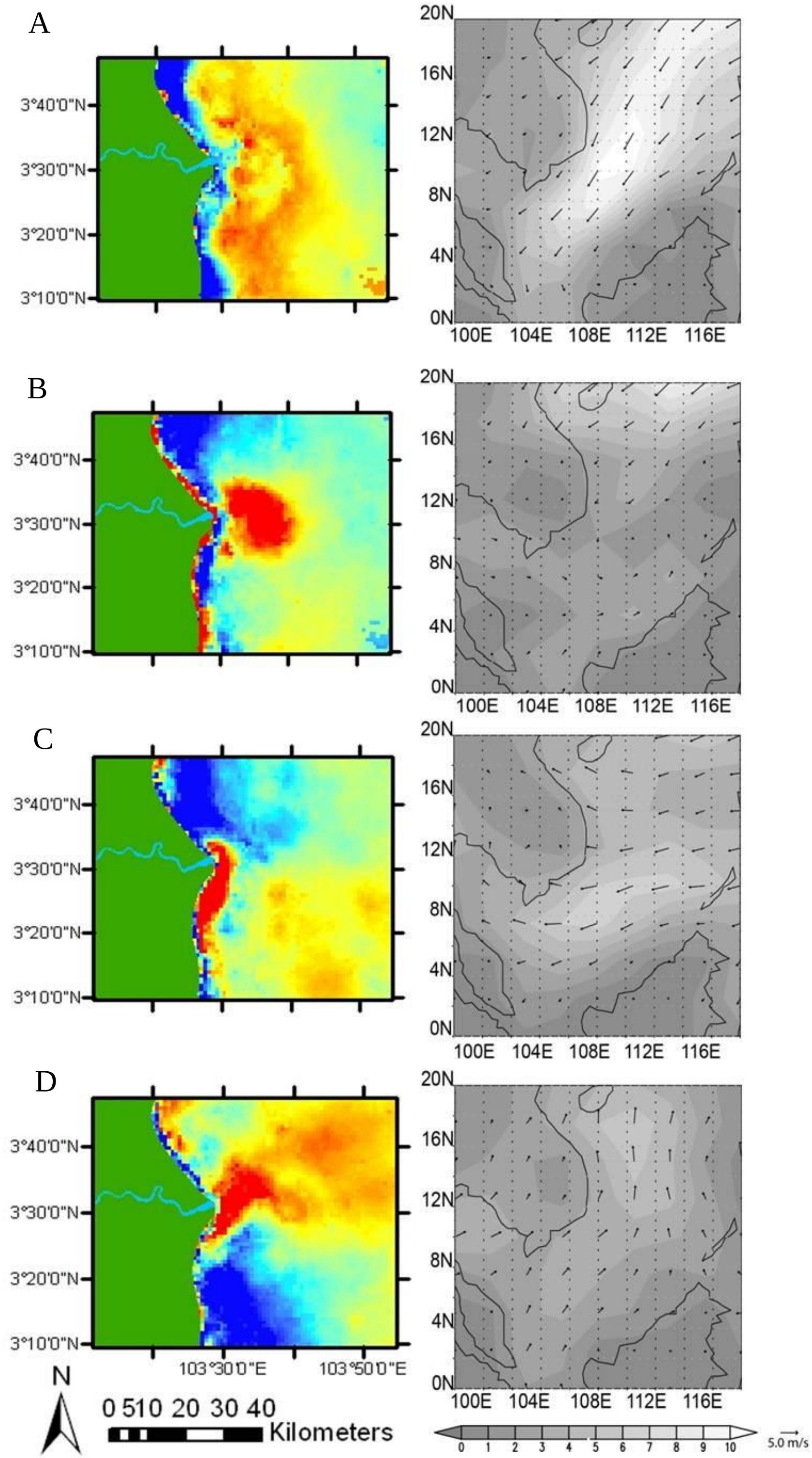

Figure 3. Relationship between plume spatial patterns (left) with wind speed force (right) in distinct monsoon. Northeast Monsoon (A), Inter-monsoon from Southwest Monsoon to Northeast Monsoon (B), Inter-monsoon from Northeast Monsoon to Southwest Monsoon (C) and Southwest Monsoon (D).

CONCLUSION

The use of remote sensing and satellite images is the best approach in observing and assessing the characteristics of the formation and distribution of plumes at estuary and coastal areas. This study also provides the best conceptual ocean color to understand the seasonal and variability of the Pahang River plumes. Pahang River plumes showed high spatially and temporally variability through the investigation of EOF analysis. During the study period the plumes tends to distribute along the coast. During the Southwest and Northeast Monsoon the plume propagates to the north and to the south of study area. High spatial variability of plume patterns was influenced by wind direction and magnitude that came along during both dominance seasons.

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Name of presenter: Mohamad Amizam Bin Abdul Jabbar

Author affiliation: National University of Malaysia

Mailing address: amizam_oasis@yahoo.com

Telephone number: +60133014033

Biography: Bachelor Science in Environmental Science (UKM)

Currently pursuing Master Science in Environmental Science (UKM)