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Spatial and temporal variability of chlorophyll-*a* concentration in Makassar Strait using Empirical Orthogonal Function analysis of satellite images

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Nine years of monthly data of MODIS derived chl-*a* around Makassar Strait of Indonesia were used to investigate the spatial and temporal variability of chl-*a* concentration. The variability was further analyzed by empirical orthogonal function (EOF). The first mode (62.08% of variance) showed variability of seasonal pattern. The second mode (5.75% of variance) showed variability during the Northwest monsoon and the Southeast monsoon. Meanwhile, the third mode (2.72% of variance) and the fourth mode (2.25% of variance) showed variability during the Transition monsoon I and II, respectively.The variability of chl-*a* along the Borneo Island is influenced by river runoff during the Northwest monsoon, while the variability of chl-*a* along the Sulawesi Island is induced by strong wind and current during the Southeast monsoon.

[Keywords: monsoon; SST; current; wind; MODIS]

Introduction

Makassar Strait is a high productive region[1], within the most productive region on the planet, namely the ocean between 10°N to 10°S[2]. This region which is located between the Pacific and Indian oceans, and also between Asia and Australia continents, is strongly influenced by monsoonal climate.

Monsoon is a major wind system that seasonally reverses its direction. The monsoon system that affects this region is known as the "Asian-Australian Monsoon System", which is characterized by seasonal changes in wind speed and directions[3]. It consists of the Northwest monsoon (November-March) which is associated with the westerlies from Asia that brings warm air and high moisture, and causes rainy season in this region. The Southeast monsoon (May-September) which is associated with the easterlies from Australia, brings warm and dry air, and causes dry season in this region. There are also the Transition monsoon I (April) and the Transition monsoon II (October), which are characterized by lower wind speed[2].

Chl-*a* pigment concentration is a convenient index of phytoplankton biomass[4,5], and it is the most important pigment required in the photosynthesis process. The variability of chl-*a* is related to seasonal monsoons[1,5-7], which are interrelated to wind, current, rainfall, and river discharge. Chl-*a* is also related to Sea Surface Temperature (SST) in upwelling processes. These physical and biological processes in the marine ecosystems vary depending on various space and time scales.

Advancement of remote sensing technology contributes to efficient ways in providing important information on oceanographic conditions compared to survey methods that are costly, require time, and have limited coverage areas. Remote sensing technology provides near real time and reliable global ocean coverage data with relatively high spatial and temporal resolution. It also has the advantages of synopticity and repetitive coverage and cost effective which are ideally appropriate to support environmental monitoring and assessment[8]. This becomes an effective approach in monitoring change of marine ecosystem globally[9].

Satellite estimates have been useful to study spatial and temporal variability of chl-*a*[1,6,8,10-16]. Satellite-derived chl-*a* provides a measure of the areas of enhanced biological production[4,17]. This enables more effective analysis of the spatial and temporal distribution of chl-*a* that can be measured from space[18]. It offers the sole means by which concurrent patterns of biological variability can be systematically quantified across the entire region[19]. This provides a new perspective and can assist in improving our understanding of the biological processes and its variability in the oceans. Present study is to understand the spatial and temporal distribution of chl-*a* concentration in Makassar Strait and its influencing factors using MODIS satellite imageries.

Materials and Methods

The study was conducted in Makassar Strait (Fig. 1) which is located between Borneo and Sulawesi Island, at the western coast of Sulawesi Indonesia. Waters of Makassar Strait is highly dynamic because it is strongly influenced by monsoons. Additionally, the existence of several large rivers from Borneo Island i.e. Barito River, Kapuas River and Kahayan River also influences this area.

Level 3 (4 km) monthly Standard Mapped Image (SMI) data of chl-*a* and SST were derived from the Moderate Resolution Imaging Spectroradiometer Satellite (MODIS-Aqua) throughout July 2002 to June 2011. The data were downloaded from the ocean color website (http://oceancolor.gsfc.nasa.gov/). SeaWiFS Data Analysis System (SeaDAS) version 6.1 software was used to extract the data. Images were subsampled to the geographic extent of the study area of 115.00 – 119.90 E and 2.00 N – 6.30 S using ERDAS Imagine version 10.0 software. Monthly averaging data from multiple years was implemented to produce a climatological monthly seasonal cycle of the study area[5,8].

Daily sea surface wind speed data were obtained from the Southwest Fisheries Science Centre, NOAA Fisheries Service Environmental Research website (http://las.pfeg.noaa.gov/).

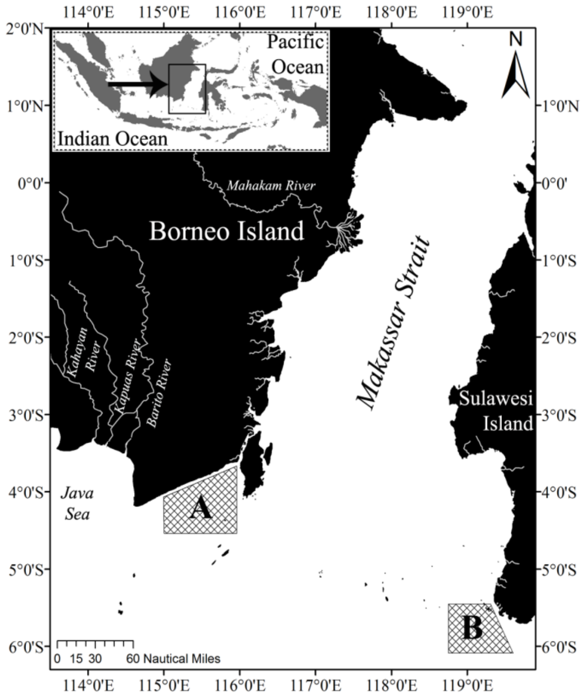

Fig. 1-The study area in Makassar Strait, Indonesia. Polygon (A) at the southern part of Borneo Island and polygon (B) at the southwestern part of Sulawesi Island indicates the location where MODIS chl-*a* data was extracted.

The data were recalculated to wind stress ($kgm^{-1}s^{-2}$) using the conventional equation[18]:

$$\tau = C_d \rho_a |U| U \qquad (1)$$

where C_d is the dimensionless ''drag coefficient'' (0.0013), ρ_a is air density (1.2 kg m^{-3}) and U is wind speed (ms^{-1}). Monthly wind speed data were downloaded from the NOAA Earth System Research Laboratory website (http://www.esrl.noaa.gov/). While, monthly mean sea surface current data were downloaded from the NOAA Ocean Surface Current Analysis (OSCAR) website (http://www.oscar.noaa.gov/). The data were processed using the Grid Analysis and Display System (GrADS) version 2.0 software.

EOF analysis is commonly used to study temporal and spatial patterns in geophysical data and to describe and quantify oceanic variability[11]. Numerous studies have used EOF analysis in determination of chl-*a* variability using ocean color data (*e.g.,* 10-12; 14-16; 20). EOF is a helpful technique for compressing the variability of time series data[16] and decomposing space and time distributed data into modes ranked by their temporal variance[8,21]. This method will extract the datasets into a series of orthogonal function that describes the spatial and temporal variability within the study area[8,20]. In this study, EOF analysis was applied to the monthly time-series data of chl-*a*. Monthly images were decomposed following the method of Polovina & Howell[22]:

$$F(x,t) = \sum_{i=1}^{n} a_i(t)c_i(x) \qquad (2)$$

where $a_i(t)$ are the principal component time-series with the expansion coefficients of the spatial components $c_i(x)$. Temporal and spatial components are calculated from the eigenvectors and eigenfunctions of the covariance matrix **R**, where **R=F'*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. The analysis was carried out using MATLAB R2011a software.

Results and Discussion

Makassar Strait sustains high biological productivity but is vulnerable to the surrounding environmental factors. Information on its status is important to assess the productivity of the area. However, the knowledge of the spatial and temporal variability of the chl-*a* and factors influencing its variability are lacking in this region.

Dominant spatial and temporal pattern of chl-*a* variability over the study area during the 9 years were summarized quantitatively using an EOF analysis. A total of 108 images were selected. Seasonal variability in spatial and temporal patterns of chl-*a* was observed (Fig. 2). Generally, there were two distinct patterns of chl-*a* variability around Makassar Strait. Variability was observed in the area at the western part of Makassar Strait along the Borneo Island (polygon “A” in Fig. 1). The chl-*a* concentration was higher during the Northwest monsoon and the Transition monsoon I and it occurred along the coast to the offshore of the eastern and southern part of Borneo Island. During the Southeast monsoon and the Transition monsoon II, chl-*a* concentration was lower (Fig. 2). Seasonal cycle of chl-*a* concentration in this area is shown in Fig. 3 (dash line). The chl-*a* concentration peaked during the Northwest monsoon (in January 2005, 2006; February 2009 to 2011; and March 2003, 2004, 2007, 2008) with the highest concentration (5.76 mg m^{-3}) occurring in March 2003 and the lowest (2.71 mg m^{-3}) in March 2008. During the Transition monsoon I, chl-*a* concentration was still high (>1.00 mg m^{-3}). Meanwhile, during the Southeast monsoon, chl-*a* concentration was low (<1.00 mg m^{-3}) throughout the year. Chl-*a* concentration remained below 1.00 mg m^{-3} during the Transition monsoon II except in 2005 and 2010. Variability was also observed in the area at the eastern part of Makassar Strait along the Sulawesi Island (polygon “B” in Fig. 1). The chl-*a* concentration was higher during the Southeast monsoon and it occurred along the coast to the offshore of the southwestern part of Sulawesi Island. However, during the Northwest monsoon and the Transition monsoon, the chl-*a* concentration was lower (Fig. 2).

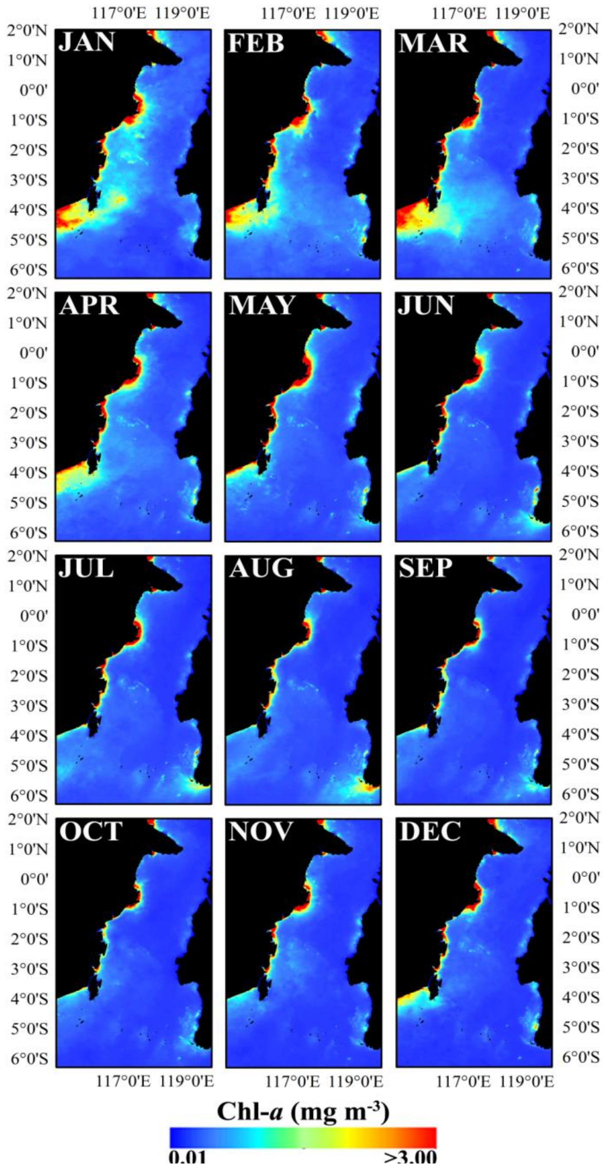

Fig. 2-Climatological monthly composite of MODIS chl-*a* (mg m^{-3}) from July 2002 to June 2011 at the Makassar Strait of Indonesia. Occurrence of high chl-*a* concentration during the Northwest and the Transition monsoon I in comparison to the Southeast and the transition monsoon II

Seasonal cycle of chl-*a* concentration in this area is shown in Fig. 3 (solid line). The chl-*a* concentration peaked during the Southeast monsoon (in June 2003, 2006, 2010, 2011; July 2005, 2007; and August 2002, 2004, 2008, 2009) with the highest concentration (5.19 mg m^{-3})

occurring in August 2004 and the lowest (1.44 mg m^{-3}) in August 2009. Meanwhile during the Northwest monsoon and the Transition monsoon, chl-*a* concentration was low (<1.00 mg m^{-3}) throughout the year.

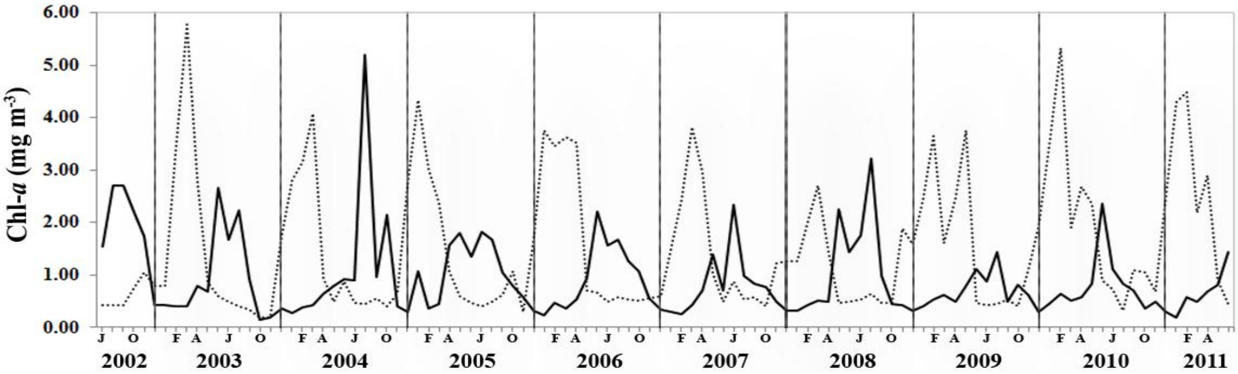

Fig. 3-MODIS chl-*a* concentration (mg m^{-3}) at the area in the southern part of Borneo Island (polygon A in Fig.1) which showed high chl-*a* concentration during the Northwest monsoon and the Transition monsoon I (indicated by the dash line) and the area in the southwestern part of Sulawesi Island (polygon B in Fig.1) which showed high chl-*a* concentration during the Southeast monsoon (indicated by the solid line). The data were extracted from the monthly time series of MODIS chl-*a* concentration throughout July 2002 to June 2011

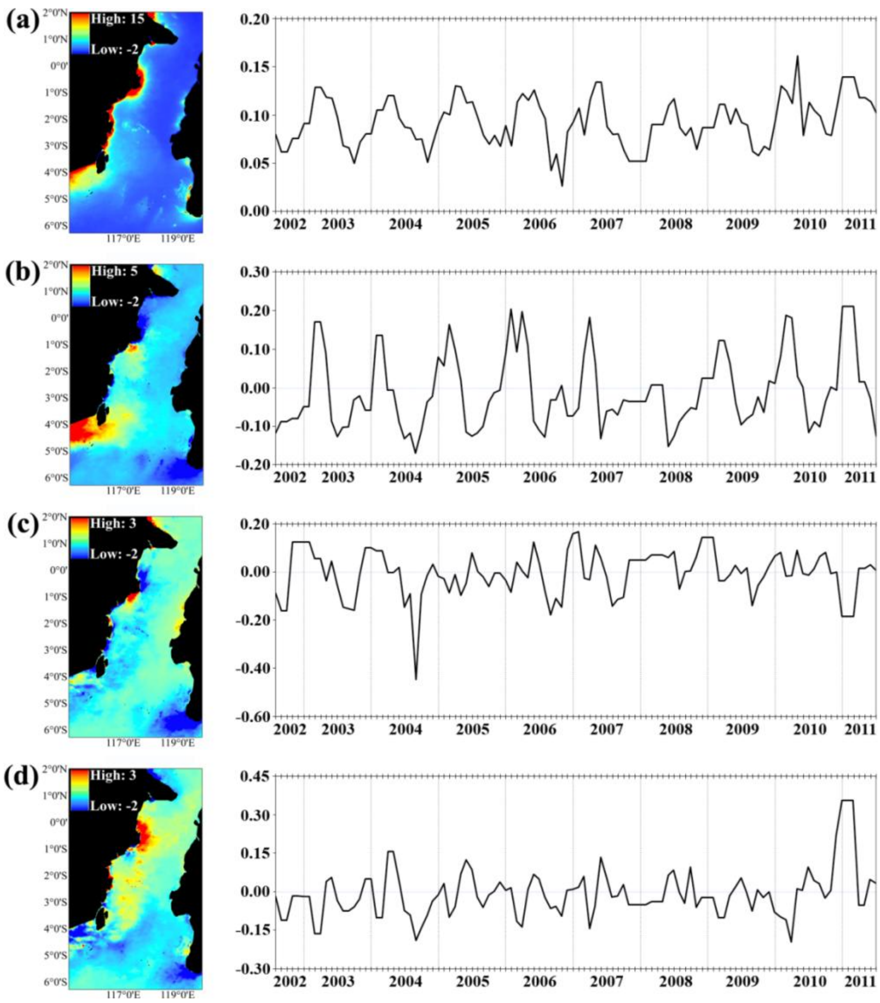

Fig. 4-EOF analysis shows the inter-annual variability of chl-*a* in Makassar Strait. Each mode consists of spatial pattern (left panel) and time-series (right panel) of (a) mode 1 (62.08% of variance) indicated the seasonal pattern, (b) mode 2 (5.75% of variance) demonstrated the variability during the Northwest and the Southeast monsoon, (c) mode 3 (2.72% of variance) showed the variability during the Transition monsoon I, and (d) mode 4 (2.25% of variance) showed the variability during the Transition monsoon II

Overall, it appeared that chl-*a* concentration was highest during the Northwest monsoon (Fig. 2). This was evident in the EOF analysis of chl-*a* mode 1 which explained 62.08% of the variance (Fig. 4a). The spatial pattern of the first mode showed high signal along the coast of Borneo Island and slightly high signal along the coast of Sulawesi Island, particularly in the southwestern part, while low signal was observed at the centre of the strait. Temporal amplitude showed high positive signals during the Northwest monsoon (throughout January to March) and the Transition monsoon I, while low positive signals were observed during the Southeast monsoon (throughout July to August) and the Transition monsoon II. Its associated amplitude function demonstrated that the variability of chl-*a* in Makassar Strait indicated the seasonal cycle and was greatly influenced by the monsoon. Generally, this first few EOF modes with higher variance may describe the dominant patterns and will be an efficient representation of the main patterns of chl-*a* in this region.

During the Northwest monsoon, chl-*a* concentration in Makassar Strait was higher compared to the Southeast monsoon and the Transition monsoon. It occurred along the coast, particularly at the mouth of several large rivers in Borneo Island. Meanwhile during the Southeast monsoon, chl-*a* concentration was slightly lower than the Northwest monsoon. However, during the Southeast monsoon, high chl-*a* concentration occurred in the southwest coast of Sulawesi Island (Fig. 2). Variability during both monsoons was evident in the EOF analysis of chl-*a* mode 2 which explained 5.75% of the variance (Fig. 4b). Spatial pattern of this mode showed high signal in the south coast of Borneo Island which was associated with high chl-*a* concentration during the Northwest monsoon, while low signal occurred in the southwest coast of Sulawesi Island which was associated with high chl-*a* concentration during the Southeast monsoon. Temporal amplitude showed strong positive signal that occurred through the year (except in 2008), while strong negative signal occurred in August 2004.

High chl-*a* concentration along the coast of Borneo Island still occurs during the Transition monsoon I. The pattern seems to resemble that of the Northwest monsoon (Fig. 2a).This was evident in the EOF analysis of chl-*a* mode 3 which explained 2.72% of the variance (Fig. 4c). Spatial pattern showed low signal along the coast of Borneo Island and in the southwest coast of Sulawesi Island. Temporal amplitude was described by negative signal in April 2003 to 2006 while in April 2008 and 2011, it was described by weak positive signal. Furthermore, during the Transition monsoon II, the chl-*a* concentration was lower compared to the Southeast monsoon, the Northwest monsoon and the Transition monsoon I throughout the year (Fig. 2a). This was evident in the EOF analysis of chl-*a* mode 4 which explained 2.25% of the variance (Fig. 4d). Spatial patterns showed low signal in the southern part of the strait. Temporal amplitude was by negative signal in October (except 2005 and 2010).

The first mode was heavily dominant and a very steep drop in variance followed the next few modes. This indicated that the chl-*a* in Makassar Strait were dominated by a unique spatial pattern. Typically, the spatial and temporal patterns of the lower modes will be the easiest to interpret[16].

Makassar Strait is a large channel system and passageway between the Pacific and the Indian Ocean[23]. It is located right on the equator causing this area to receive relatively high solar energy (sunlight) throughout the year, which creates favorable conditions for the photosynthesis of phytoplankton. It is also located between two major islands, the Borneo Island in the western part and Sulawesi Island in the eastern part (Fig. 1). Borneo Island has extensive forest and mangrove area and shallower coastal waters. Activities from these forest flow to the coastal area through the several large rivers. This complexity may influence the variability of chl-*a* in Makassar Strait. Higher chl-*a* concentration in the coastal zone of Borneo Island compared to Sulawesi Island, is likely to be a combination of river runoff, coastal environments, and water depths which are important ingredients to the climatology of ocean color in the region[1].

During the Northwest monsoon, our results show that chl-*a* concentration in Makassar Strait becomes higher along the coast to the offshore[1]. Highest chl-*a* concentration, especially during January to March, occurs throughout the year along the coast to the offshore of Borneo Island, particularly in the area near the river mouth (Fig. 2a). Large riverine inputs can modify the hydrographic patterns along the coast[24]. This may have been due to suspended sediment from river runoff. Land based runoff inputs nutrients to the coastal ecosystem[25]. During the Northwest monsoon, the region experiences rainy season which causes maximum runoff from the mainland. During that process, nutrients which are indispensable material in the photosynthesis process would flood the coastal areas, especially at the mouth of rivers. High chl-*a* concentration along the coast (near the river mouth) was also reported in the Gulf of Tonkin[6] and Funka Bay[16], respectively. Factors that affected the variability of chl-*a* in coastal waters were rainfall[14,26] and river discharge[6,9,14]. Strong wind and heavy rainfall might have a direct negative effect on phytoplankton growth because of turbulence in the water column, but they favour chlorophyll concentration in the future by importing nutrients into the euphotic zone[26].

Meanwhile during the Southeast monsoon, chl-*a* concentration was lower than during the Northwest monsoon. However, chl-*a* bloom developed in the southwest coast of Sulawesi Island (Fig. 2). This event could be caused by the upwelling process because of the high magnitude of wind and strong current[1,7]. Upwelling in Indonesian Seas is a response to regional wind associated with the monsoon and larger scale wind from the Pacific Ocean[27]. In Makassar Strait, wind is northwesterly during the Northwest monsoon and southeasterly during the Southeast monsoon. Stronger wind develops during the Southeast monsoon. Southeasterly wind may induce coastal upwelling along the Sulawesi Islands[28]. The water masses rise from the bottom layers which are characterized by rich nutrient and cooler temperature, enhancing nutrient at the surface layer. These nutrients support chl-*a* bloom[6,24]. At the same time, SST becomes colder because strong wind and current will enhance vertical mixing and also reduce the SST. It appeared that there is a relationship between SST and chl-*a*. Cool water is an indicator of high nutrient. SST and nutrients are two important factors affecting phytoplankton growth[6]. When upwelling occurs, the bottom layer with colder water and rich nutrient will rise to the surface and encourage chl-*a* bloom[29]. Therefore, there is negative correlation (inversely) between SST and chl-*a*, which means if SST decreases, the chl-*a* concentration will increase, and vice versa[4,10,12,16,30]. This can be observed in Fig 5. The relationship of both SST and wind forcing to chlorophyll variability is through stratification and its role in light limitation and vertical nutrient flux into the euphotic zone[12]. The seasonal variation of chl-*a* concentration and SST distribution is associated with the seasonal monsoon[6]. During the Southeast monsoon, the influence of wind forcing was quite dominant. This is due to the longer duration of wind compared to the period during the Northwest monsoon and the Transition monsoon[1].

Wind speed may affecting the concentration of chl-*a*. However, strong wind did not simultaneously affect the chl-*a* bloom. The timing of the highest wind speed did not coincide with the highest chl-*a* concentration[16]. This process requires time and suitable environmental condition.

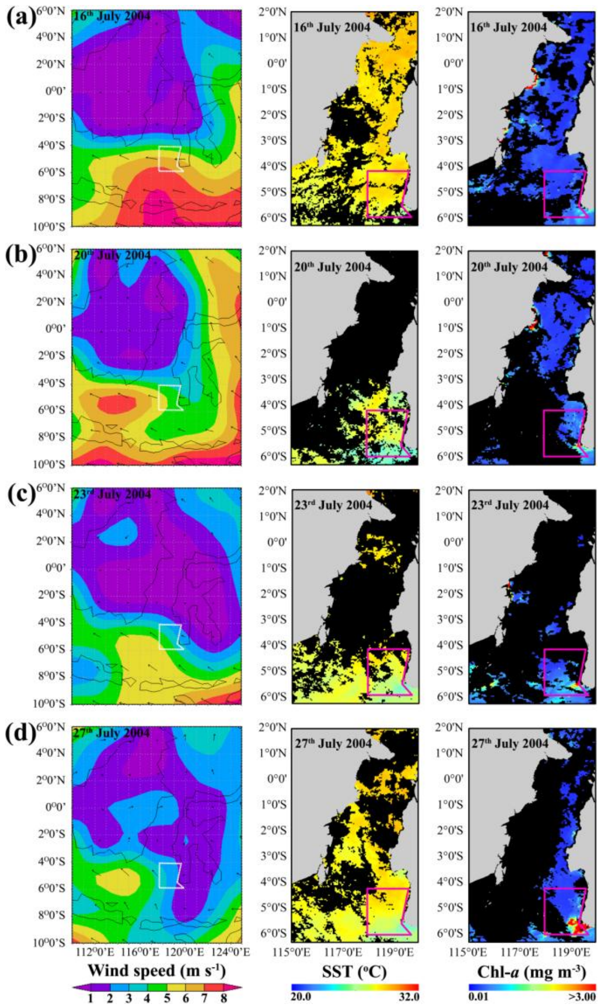

Fig. 5-Influence of wind speed (left panel) on SST (middle panel) and chl-*a* (right panel) in Makassar Strait during the Southeast monsoon. Peaked of wind caused cooler SST, while the relaxation of wind was developed high chl-*a* concentration. Box area indicates the location of extraction of wind data

The upwelling process during the month of July 2004 can be observed in Figs. 5 and 6. It appears that when the wind forcing began to increase (0.106 kg m^{-1} s^{-2}) on July 16th and reached its peak (0.135 kg m^{-1} s^{-2}) on July 17th (Fig. 6), this could immediately initiate the mixing process. During this process, warmer SST and low chl-*a* concentration occurred in this area (Fig. 5a). Subsequently, when the wind forcing decreased (0.106 kg m^{-1} s^{-2}) on July 20th (Fig. 6), nutrient associated with colder water was liftedup which induced high nutrient and cooler SST at the surface layer (Fig. 5b). Furthermore, when the relaxation of wind continued (0.090 kg m^{-1} s^{-2}) to July 23rd (Fig. 6), the stratification of water started to develop and with enough solar energy and stratification that developed well, the process of photosynthesis occurred. During this time, SST became warmer again and small blooms began to develop (Fig. 5c). The optimum condition persisted and chl-*a* bloom occurred on July 27th (Fig. 5d). The areas of weak wind stress facilitated the development of stratification of the water column and enhancement of chl-*a* bloom[15].

High chl-*a* concentration up to the offshore in certain parts of Makassar Strait during the Northwest monsoon and the Southeast monsoon can be explained by Fig. 7. During the Northwest monsoon, chl-*a* concentration was high at the area in the southern part and eastern part of Borneo Island because of the movement of the wind and the current flow which distributed the chl-*a* from the mouth of the Barito River, Kapuas River and Kahayan River, moving eastward to the Java Sea and turning to the North into Makassar Strait (Fig. 7a). Similarly, during the Southeast monsoon, chl-*a* concentration was high in the southwestern part of Sulawesi Island because of the movement of the wind and the current flow which distributed chl-*a* concentration that moved westward and partly turned to the North, entering Makassar Strait (Fig. 7b).

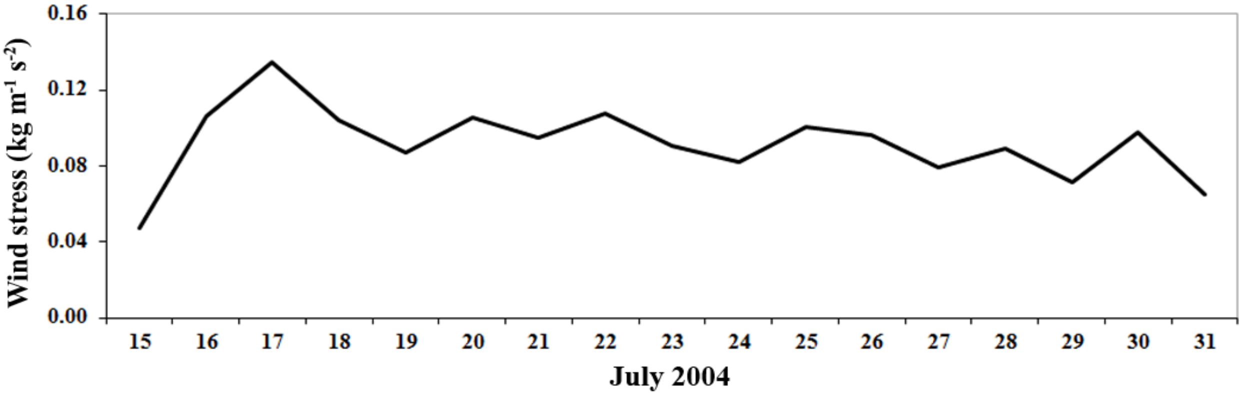

Fig.6-Timing of strong and relaxation of wind stress (kg m^{-3} s^{-3}) during the month of July 2004. Wind forcing began to increase on July 16th and reached its peak on July 17th, which then starts to decrease on July 18th and relaxation of wind was observed throughout the month

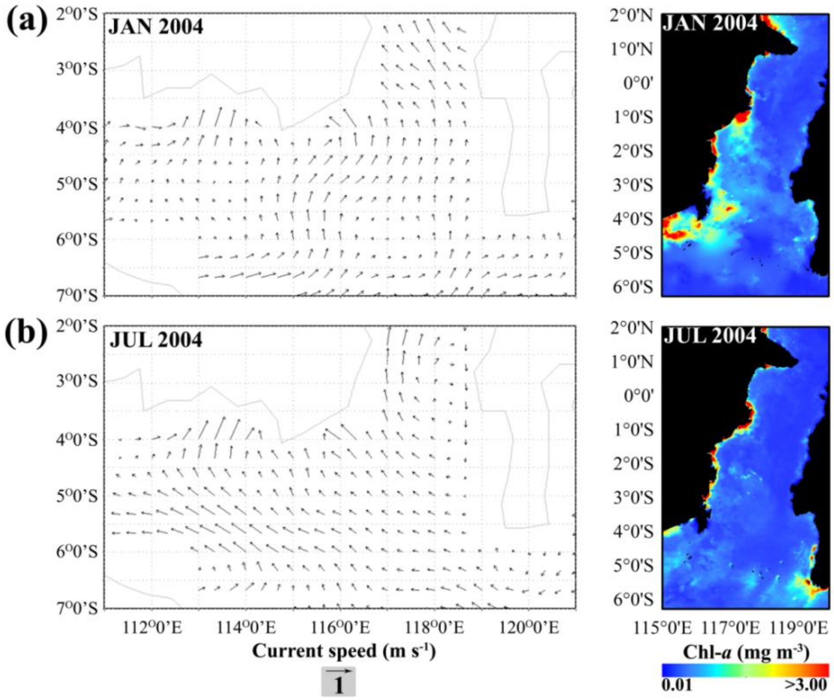

Fig. 7-Influence of current speed and its direction (left panel) on the chl-*a* distribution (right panel) in Makassar Strait during: (a) the Northwest monsoon and (b) the Southeast monsoon. High chl-*a* concentration at the western and the eastern part of the strait was distributed by current flow to the center part of the strait

Runoff and wind conditions appeared to influence the seasonal variability of chl-*a*, while surface current distributed chl-*a* around Makassar Strait. However, strong current may also develop upwelling in the coastal area. Strong current flow may cause emptiness on the surface layers that will be replaced by water masses from the bottom layers[29].

EOF analysis using MODIS remote sensing data was able to determine the spatial and temporal variability of chl-*a* concentration in Makassar Strait. However, further analysis and integration of several other environmental variable data, for example Sea Surface Height (SSH), geostrophic current, ekman upwelling, are necessary for a better understanding of the chl-*a* variability in this region.

Conclusion

The results presented in this paper showed that the chl-*a* variability in Makassar Strait followed the seasonal cycle and was greatly influenced by the monsoon. Four EOF analysis of chl-*a* modes explained the pattern and variability of chl-*a* concentration in this region. Chl-*a* concentration during the Northwest monsoon was higher compared to the Southeast monsoon and the Transition monsoon. High chl-*a* occurred mainly along the coastal area to the offshore while lower chl-*a* occurred along the centre of Makassar Strait.The variability of chl-*a* was influenced by river runoff, strong wind and current.

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