Different responses of chlorophyll-a concentration and Sea Surface Temperature (SST) on southeasterly wind blowing in the Sunda Strait

by Lilik Maslukah

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Different responses of chlorophyll-a concentration and Sea Surface Temperature (SST) on southeasterly wind blowing in the Sunda Strait

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Abstract. During southeast monsoon, along the western coast of Sumatra Island and southern coast of Java Island are known as the coastal upwelling areas denoted by the occurrence of Sea Surface Temperature (SST) cooling and chlorophyll-a blooming. Located between Sumatra and Java Islands, Sunda Strait waters may give different response to the southeasterly wind blowing above. Using SST and chlorophyll-a data obtained from daily MODIS level 3 during 2006–2016, this study demonstrated the evidence on how bathymetry and topography modified the effect of southeasterly wind on the spatial variability of SST and chlorophyll-a. All datasets were composed into monthly and monthly climatology. The area in the center of Sunda Strait had the lowest chlorophyll-a concentration and the warmest SST during the peak of upwelling season. The deep bottom topography and the absence of barrier land prevented the generation of wind driven coastal upwelling. However, the chlorophyll-a concentration in this area had the highest correlation with the wind speed which means that the variation of chlorophyll-a concentration in this area was highly depended on the variability of wind. On the other hand, the areas with shallow bathymetry and in front of Panaitan and Java Islands had higher chlorophyll-a concentration and cooler SSTs.

1. Introductin

Upwelling is known as the lifting of water mass from the deep water column to the sea surface. In the sea surface, upwelling can be indicated by lower SST and higher chlorophyll-a (Chl-a) concentration since the lifting of water mass carries cold water and rich in nutrient which is required for the growth of phytoplankton. The high Chl-a concentration during upwelling period is often followed by the increase in fisheries productivity [1, 2, 3]. Thus, SST and Chl-a are important indicators for determining the fishing ground and season.

The area along southern coast of Java and Sumatra is well known as the upwelling area occurs during the southeast monsoon [4, 5, 6]. The southeasterly wind blowing along the southern coast of Java Island and Sumatra Island generates Ekman transport which carries water mass away from the coast. The water mass loss in the coastal area is then filled by the water mass from the deeper layer. Thus, the upwelling along the coast of Java and Sumatra Islands is classified as the coastal upwelling.

The Sunda strait is a narrow channel separating the Java and Sumatra Islands. As a whole entity, the Sunda Strait has been investigated by [6] which demonstrated as one of the three strongest upwelling

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areas along the southern coast of Java and Sumatra in 2006. The positive Chl-a anomaly of greater than 3 mg/m^3 extended offshore for more than 200 km from October to November 2006. Nevertheless, the smaller scale pattern of Chl-a concentration and SST in the south side of the Sunda Strait mouth was neglected in the previous studies. With the width of mouth passage of about a hundred kilometers, varied bottom topography and the existence of small islands, the southeasterly wind blowing over the Sunda Strait may give various impact on the pattern of Chl-a concentration and SST distribution. It has been known that, wind speed is the most important factor for the development of coastal upwelling along the southern coast of Java and Sumatra Islands [1, 2, 3]. In the present study, we demonstrated on how the same speed of southeasterly wind can give the various impact on the Chl-a and SST distribution in a relatively narrow area i.e. the Sunda Strait.

Because of the wide-ranging spatial and temporal coverages, satellite remote sensing has often been used to investigate the ocean surface conditions in the Indonesian Seas [1, 2, 4, 5, 6, 7, 8, 9]. The ocean surface dynamics like upwelling, SST front, and eddies can be monitored by using satellite remote sensing technology. Utilizing the advantage of remote sensing technology, the present study investigates Chl-a and SST variability in the Sunda Strait.

2. Materials and Methods

The main dataset used in this study were MODIS Aqua Lv3 for Chl-a and SST with spatial resolution of 0.04° × 0.04° and observation period from 2006 to 2016 [10]. For SST, we used MODIS SST 11 μm which cover the observation both for day and night. These datasets are developed and distributed by the Ocean Biology Processing Group. The algorithm for generating MODIS SST is described in [11] while for MODIS Chl-a is in [12, 13]. These datasets have been examined and validated against *in situ* data to ensure the best accuracy [14, 15, 16, 17, 18].

To investigate the formation mechanism of Chl-a and SST pattern in the Sunda Strait, we used surface wind data obtained from six hourly ERA interim data with grid interval of 0.125° [19]. We composed SST, Chl-a, and surface wind parameters into monthly and monthly climatology following [20]. We also calculated Ekman Depth following this equation [21]:

$$\boldsymbol{D_E} = \frac{\mathbf{4.3}\boldsymbol{W}}{\sqrt{\mathbf{sin}|\emptyset|}} \qquad (1)$$

where D_E is the Ekman depth (m), W is wind speed (m/s) and ϕ is latitude (°).

To obtain the bottom topography, we used Shuttle Radar Topography Mission (SRTM 30) with the spatial resolution of 30 seconds or equal to one km. SRTM 30 data is developed by National Aeronautics and Space Administration and can be accessed at http://topex.ucsd.edu/.

3. Results and Discussion

3.1. Spatial distribution of Chl-a and SST during upwelling season in the Sunda Strait

The spatial pattern of Chl-a, SST, and surface wind in the Sunda Strait during September is shown in figure 1. We show the period of September since the peak of upwelling season occurs in this month. During September, surface wind blew southeasterly. This condition was favourable for coastal upwelling generation. Outside the strait mouth, wind speed was about 6–7 m/s and decreased entering the strait.

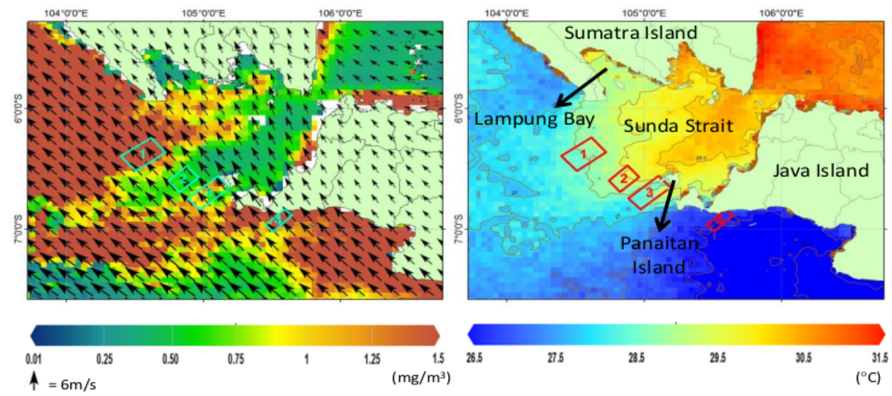

Figure 1. Distribution of Chl-a concentration and surface wind vector (left) and SST (right) in the Sunda Strait in September (2006–2016). Boxes in the figure denote the area for temporal analysis shown in figure 2. Detail coordinates of the areas are described in text.

The upwelling area was observed along the southern coast of Java Island until southwestern coast of Sumatra Island indicated by the high Chl-a (SST) bands of greater than 1 mg/m^3 (less than 27.5 °C).

Focusing at the mouth of the strait, we can easily capture the distinctive spatial pattern of Chl-a and SST. The area in the center of the Sunda Strait shows the lowest Chl-a concentration and the warmest SST during the peak of upwelling season. On the other hand, near the tip of Sumatra Island and in front of the Panaitan Island and Java Island exhibit higher Chl-a concentration and cooler SSTs. The absence of barrier land in the center of the Sunda Strait prevents the formation of coastal upwelling. However, a contradictive fact is found at the southern tip of Sumatra Island. Although there is no barrier land, the Chl-a concentration (SST) was high (low). For further analysis, we chose 4 areas at the mouth of the Sunda Strait, which represent the different characteristic of Chl-a and SST distribution in the Sunda Strait, to investigate their temporal variation as shown in figure 1. The areas are:

1. Southern tip of Sumatra Island, the corners are as follows: 104.616 °E, -6.242 °N; 104.722 °E, -6.364 °N; 104.510 °E, -6.518 °N; 104.396 °E, -6.394 °N.
2. The center of the Sunda Strait, the corners are as follows: 104.744 °E, -6.598 °N; 104.878 °E, -6.473 °N; 104.963 °E, -6.570 °N; 104.824 °E, -6.693 °N.
3. In front of the Panaitan Island, the corners are as follows: 105.104°E, -6.559 °N; 105.192 °E, -6.656 °N; 104.974 °E, -6.838 °N; 104.884 °E, -6.747 °N.
4. In front of the Java Island, the corners are as follows: N: 105.454 °E, -6.964 °N; 105.589 °E, -6.837 °N; 105.648 °E, -6.884 °N; 105.508 °N, -7.020°N.

3.2. *Temporal variability of Chl-a and SST in the Sunda Strait*

The temporal variation of Chl-a, SST, and wind speed in 4 areas is presented in figure 2. Figure 2a shows that the minimum (maximum) wind speed was about 1 m/s (6 m/s) which occurred in April (September). It also obviously shows that the wind speed variabilities among four areas were almost similar both in pattern and amplitude. The variation of Chl-a and SST followed the variation of wind speed. From January when the wind blew northwesterly to Jun when the wind speed was minimum, the Chl-a concentration (SST) was low (high). This is due to the absence of coastal upwelling which only generated under the condition of strong southeasterly wind. Despite the different amplitudes, the maximum (minimum) Chl-a concentration (SST) was reached during the southeast monsoon in

September. Thus, there was a different response on Chl-a and SST for each area toward the southeasterly wind blowing in the Sunda Strait.

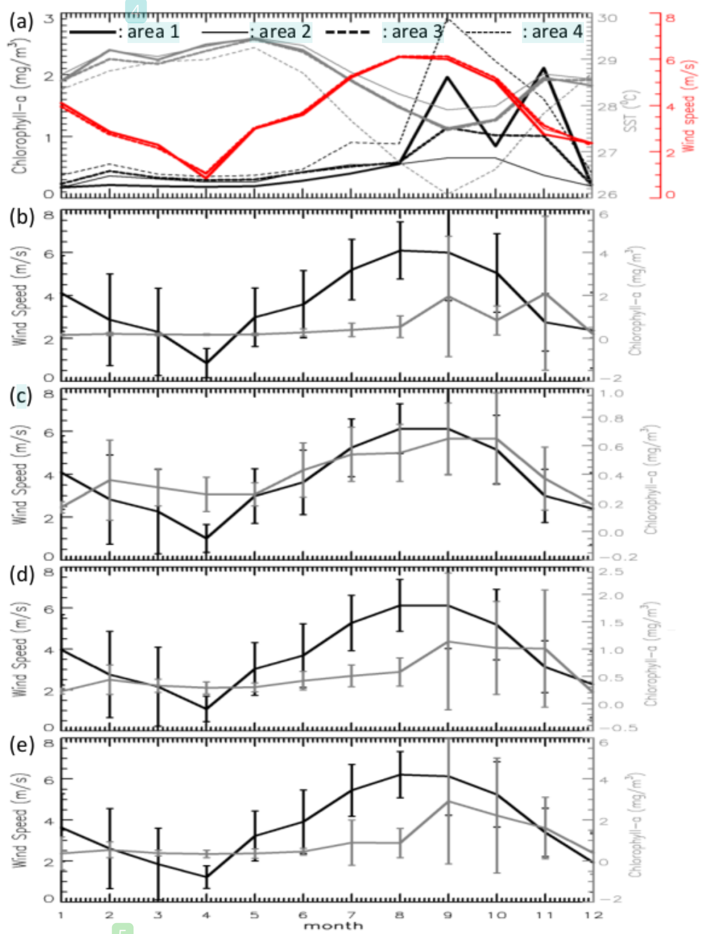

Figure 2. (a) Time series of wind speed, Chl-a, and SST in four areas as shown in figure 1. Adjusted scale of time series graphic in figure 2a and standard deviation for Chl-a and wind speed in (b) area 1, (c) area 2, (d) area 3, and (e) area 4.

The different responses of Chl-a and SST amplitudes in 4 areas toward the same wind speed blowing in the Sunda Strait are described as follows. As explained in the previous section, during the southeast monsoon the area 4 had the highest Chl-a concentration i.e., about 3 mg/m^3 and the lowest SST i.e. about 26 °C; area 2 had the lowest Chl-a concentration i.e. 0.5 mg/m^3 and highest SST i.e. 28 °C; and area 1 and 3 was in between. There was almost no fluctuation of Chl-a concentration in area 2. Furthermore, figure 2b-e shows the adjusted scale of wind speed and Chl-a axis with their standard deviation for area

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1 to 4. The standard deviation of wind speed for 4 areas were only about 2 m/s which means that from 2006 to 2016 the monthly wind speed blew in the Sunda Strait were relatively stable. During the southeast monsoon, the standard deviation of Chl-a in area 1, 3, and 4 was high, i.e. maximum of about 4 mg/m^3, 1.5 mg/m^3 and 2 mg/m^3 for area 1, 3, and 4 respectively. This means that the monthly Chl-a concentration in area 1, 3, and 4 was highly variable. After scale adjustment, we can see the variation of Chl-a in area 2 clearer than presented in figure 2a. The variation of Chl-a in area 2 followed the variation of wind speed and it has the lowest standard deviation i.e. 0.2 mg/m^3. This means that although the amplitude of variation is not as large as in area 1, 3 and 4, area 2 has the most stable monthly variation of Chl-a concentration. Moreover, it has been confirmed by statistical analysis, the Chl-a concentration in area 2 has the highest correlation with the wind speed. The correlation of Chl-a and wind speed for 4 areas were 0.35, 0.80, 0.60, and 0.66 for area 1, 2, 3 and 4, respectively. Thus, the Chl-a concentration in area 2 was highly depended on the wind speed.

3.3. Relation between Chl-a and SST distribution with the bottom topography

Back to the question on how the high Chl-a and low SST in area 1 occurred without the existence of barrier land, we used bathymetry data presented in figure 3 to examine the relation between bottom topography and the distribution of Chl-a and SST. Areas 1, 3 and 4 are located at the shallow areas. Despite no barrier land, the upwelling may still occur in area 1, since water mass loss due to the southwestward Ekman transport cannot be compensated by the water mass in the shallow area. Thus, the deeper water mass should replace that water mass loss through upwelling mechanisms.

In contrast, the deep bottom topography in area 2 prevented the generation of coastal upwelling. The physical process regulated the high correlation between wind speed and Chl-a concentration in area 2 may be related to the wind generated mechanical mixing instead of coastal upwelling. With the wind speed of about 6 m/s, the Ekman depth in area 2 in September was only about 73 m. This is not comparable with the depth of area 2, i.e. about 2000 m (figure 3b). As shown by many researchers at various seas, the concentration of nutrients increases significantly with depth until about 1000 m and remain stable after that [22, 23]. Thus, although this mixing process still can entrain the nutrients from the deeper layer to the surface, it cannot reach the richest nutrient layer which is located near the bottom of the sea. Thus, the amplitude of Chl-a variation in area 2 was lower than the other three areas.

The previous section shows that although the amplitudes of Chl-a variation in area 1, 3 and 4 were higher than area 2, they were highly variable denoted by high standard deviation. Moreover, the correlation with the wind speed was lower than area 2. This means that there are other possible factors influence the Chl-a concentration instead of surface wind. Since they are shallow and located near land, freshwater discharge which bring nutrients from the land may also influence the Chl-a concentration in these 3 areas. The variable anthropogenic effect and freshwater discharge influenced by precipitation to this three areas may cause the monthly Chl-a concentration in these 3 areas become variable. As discussed by [1, 2] the anthropogenic factor such as trading harbour, agricultural rice field, and fishpond activities, all together contribute to the nutrient dynamics of the Lampung Bay which is located in the northern part of area 1. These possibilities are left for future studies. In contrast, these factors may be neglected for area 2 since it is deep and located far from the land. Thus, this indication supports the statement in the previous section i.e. the variability of Chl-a in area 2 was strongly depended on the wind speed.

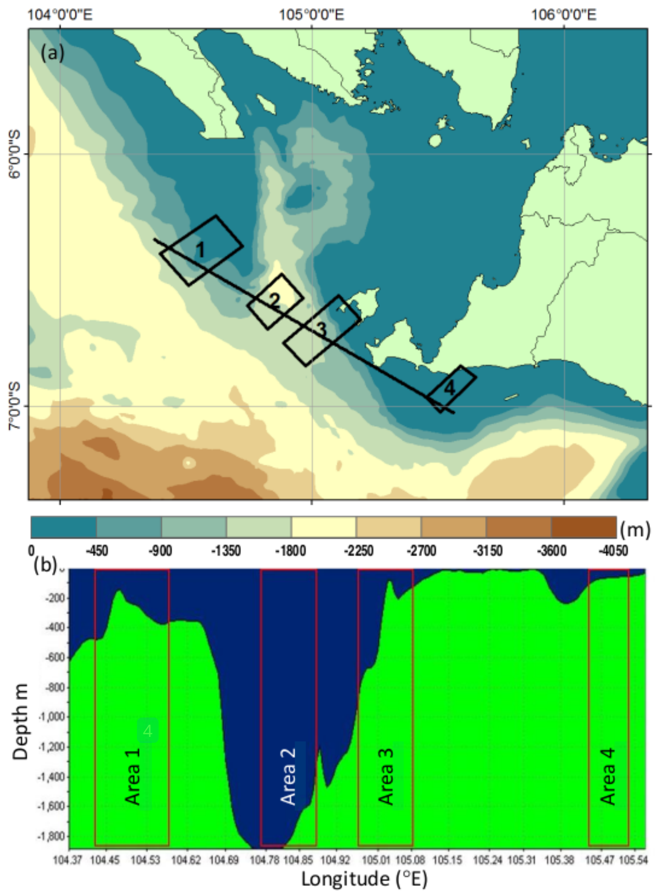

Figure 3. (a) Bathymetry of the Sunda Strait, (b) depth profile of the black line in figure 3a.

4. Conclusion

The detailed features of Chl-a concentration and SST in the Sunda Strait during the southeast monsoon has been investigated by using long-term observation of MODIS data (2006-2016). The results are concluded as follows:

1. Although the speed of surface wind is the same, the different characteristics of bottom topography and the existence of barrier land caused different distribution of Chl-a and SST in the mouth of the Sunda Strait.
2. The area with shallow bathymetry in the southern tip of Sumatra Island and the areas in front of the Panaitan and Java Islands demonstrates higher Chl-a concentration and cooler SSTs. Southeasterly wind generated the coastal upwelling in these areas may entrain more nutrients from the sea floor to the surface than the deep area without barrier land in the center of the Sunda Strait.

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3. The variability of chlorophyll-a concentration in the areas with shallow bathymetry and in front of the Panaitan Island and Java Island indicates lower correlation with the wind speed. This means that there are other possible factors influence the chlorophyll-a concentration instead of surface wind.
4. The area in the center of the Sunda Strait depicts the lowest Chl-a concentration and the warmest SST during the peak of upwelling season. The deep bottom topography and the absence of barrier land prevented the generation of wind driven coastal upwelling. Surface wind may only generate mechanical mixing instead of upwelling which made the intensity of the Chl-a blooming and SST cooling was less than the other areas.
5. The Chl-a concentration in the center of the Sunda Strait reveals the highest correlation with the wind speed which means that the variation of Chl-a concentration in this area was highly depended on the variability of wind speed.

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