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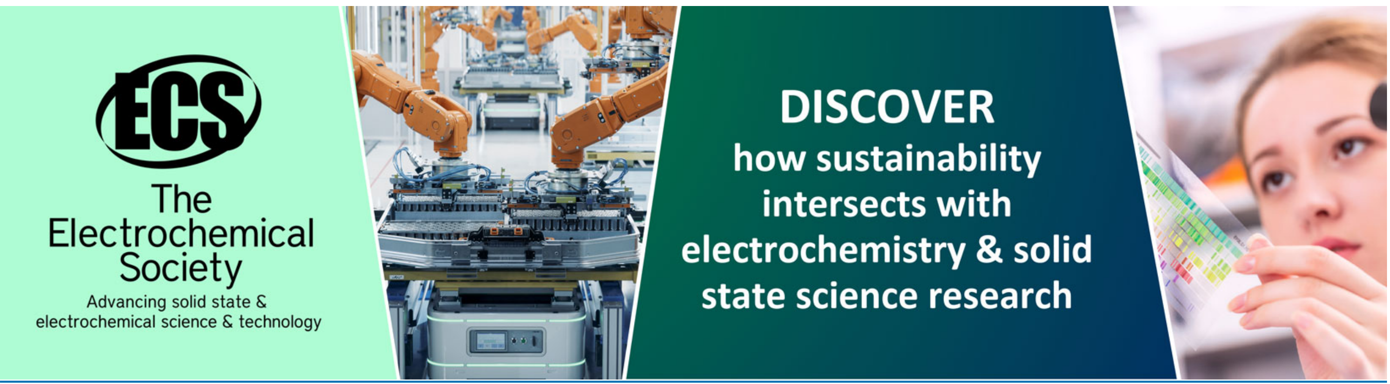

Detection of SST Wake in Belitung Island Induced by The Monsoon Wind

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Abstract. The Java Sea is one of the monsoon wind path blowing over Indonesia Seas. Belitung Island is located in the center of the monsoon path in the Java Sea. Although the topography Belitung Island relatively flat, the existence of mountainous with 200-300m height in the center of the Island may form the island wake during the strong wind event. Island wake phenomena in Belitung Island was investigated by using MODIS SST Lv3. From 2003 to 2016 period of observation, 245 cases of SST wake were found with the distribution for each season are 39, 35, 135 and 36 cases for NW monsoon, Transition I, SE monsoon and Transition II, respectively. The direction of SST wake depends on the direction of the surface wind. During NW monsoon and Transition I, the direction of SST wake is southeastwardly while during SE monsoon and Transition II is northwestwardly. The high Chl-a concentration outside the SST wake patch indicates that the occurrence of SST wake in the seas of Belitung Island may influence biological productivity in that area.

Keyword: Belitung Island, monsoon, SST wake, topographic effect, blocked wind

1. Introduction

In geophysics "island wakes" is a definition used to refer to atmospheric effects induced by the island mountains' (atmospheric wakes), as well as ocean effects induced by the island's bathymetry (ocean wakes). Ocean wakes, can be grouped into two main categories (i) wakes induced by atmospheric phenomena (e.g. wind induced wakes), and (ii) wakes induced by the oceanic phenomena (e.g. ocean current wakes). Both atmospheric and oceanic wakes have been the subject of intense study by the scientific community. The most robust evidence of island wake phenomenon is found in the Hawaiian Islands which has been reported by many studies [e.g., 1,2,3,4].

Island wake in the Hawaiian Islands is generated by the existence of easterly trade wind that persistently blowing throughout the year. The trade wind is blocked by the islands creating wind shadow in the lee of the islands. Using satellite data, [1] detected a wind wake trailing westward behind the Hawaiian Islands for 3000 kilometers, a length many times greater than observed anywhere else on Earth. This wind wake drives an eastward ocean current that draws warm water from the Asian coast 8000 kilometers away, leaving marked changes in surface and subsurface ocean temperature. Moreover, [4] revealed that the distributions of high SST, low wind and high concentration of cloud liquid water (CLW) in the lee of Hawaiian Islands are caused by the Hawaiian Lee Counter Current (HLCC) and that this current is driven by the wind-curls induced by the orographic effect of the islands. It is also shown that wind changes around the Hawaiian Islands can further affect the speed of the North Equatorial Current (NEC) and SST over the current, and intra-annual variability in CLW to the west of the islands is governed, not only by SST but also by wind speed. Thus, island wake in the Hawaiian Islands has an important role in regulating the global climate through ruling the speed of NEC which is a part of the north Pacific Gyre.

Lying on the confluence of the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate is the Indonesian Archipelago. The Indonesian region is also known as the "Maritime Continent" [5]. Because of its unique position, the Indonesian maritime continent experiences seasonal (i.e., monsoons) to inter-annual (i.e., El Nino-Southern Oscillation, ENSO) climate variations. There is two monsoon seasons every year, i.e. southeast (SE) monsoon and northwest (NW) monsoon. The SE monsoon (dry season) is associated with easterlies from Australia that carry warm and dry air over the region. On the other hand, the NW monsoon (rainy season) is associated with westerlies from the Eurasian continent that carry warm and moist air to the Indonesian region [6]. The pathways of the monsoon wind across Indonesian Seas is illustrated in Fig. 1. As an archipelagic state, Indonesia has 16.056 islands, spread over 5.180.053 km^2 area (http://www.big.go.id). This large number of the island may interact with the monsoon wind creating typical island wakes phenomena which may differ from the Hawaiian Islands due to the change of monsoon wind direction in every half year which makes the island wake is not persistence throughout the year.

Belitung Island is the second largest island after Bangka Island in Bangka Belitung Province. Besides the two mainlands, this province possesses a number of small islands like Sellu Island, Mendanau Island, Nangka Island ring, Memperak, Buku Limau, Sekunyit and Long Island ring. Belitung Island lies on the strategic location in trading and economic position in within trading and economic route in South East Asia region, Asia, and Indonesia. Belitung Island is located at the one of the monsoon path i.e., Karimata Strait with an areal size of 4.800 km^2. Although the topography of Belitung Island is relatively flat with mainly less than 100 m height, in the center of the Island, as shown by the red arrow, mountainous area exists with approximately 200-300 m height (Fig.1). This high topography is potential for blocking the monsoon wind for creating island wake in its lee. Since monsoon wind changes its direction seasonally, the island wake may also occur not only on one side of the island which makes the island wake in Belitung Island is different with it in the Hawaiian Island. Thus, Belitung Island is the potential area for island wake study in Indonesia. In this study, we identified the high SST appearances in the lee of Belitung Island referred as the SST wake phenomena influenced by the bidirectional monsoon by using infrared based SSTs.

2. Data and Method

Since SST wake is the air-sea-land interactions, the topography is the important parameter. We used a 10m resolution of Digital Elevation Model and the Global 30 arc sec elevation (GTOPO30) for topography**.** For island wake identification, we use Sea Surface Temperature (SST) from Moderate Resolution Imaging (MODIS) Level 3 onboard Aqua and Terra satellites with 4 km of spatial resolution [7] Terra passes over the equator at approximately 10:30 am and 10:30 pm each day, while Aqua satellite is at approximately 1:30 pm and 1:30 am. Thus, we can get 2 images of SST during daytime which is important for identifying SST wake in the Belitung Island. Moreover, because this SST data is generated based on an infrared sensor, it has the advantage to observe SST only during clear sky condition which is favorable for the generation of SST wake.

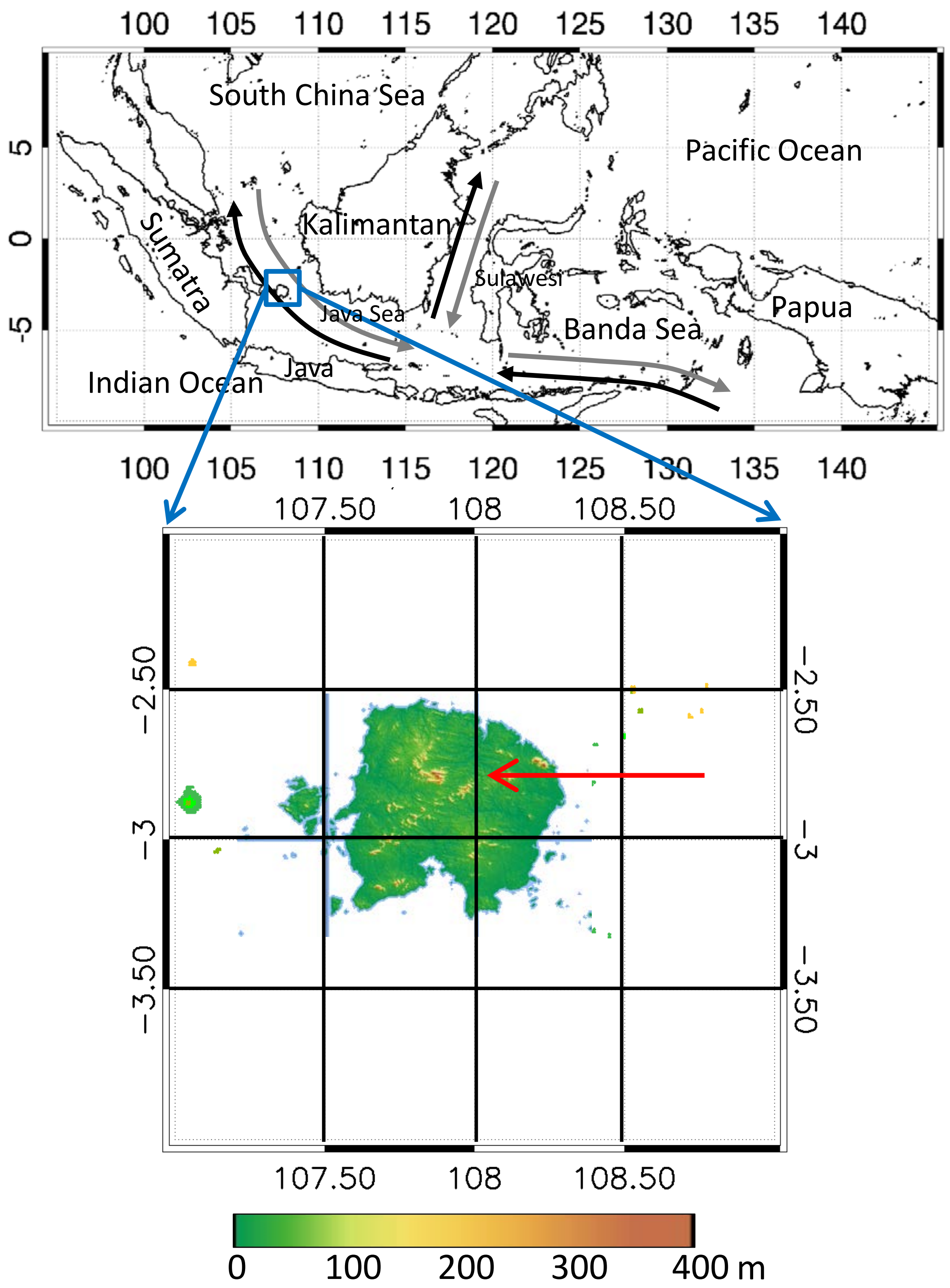

Figure 1. Monsoon wind path of Indonesian Archipelago (Upper figure) and the Topographic map of Belitung Island (Lower figure). Black arrows denote the paths of southeast monsoon season (Jun, July, and August) and gray arrows denote the paths of Northwest monsoon season (December, January February).

For investigating the mechanism of the SST wake, we used The Cross-Calibrated Multi-Platform (CCMP) gridded surface vector winds [8]. This product is produced using satellite, moored buoy, and model wind data, and as such, are considered to be a Level-3 ocean vector wind analysis product. The new CCMP V2.0 dataset now available from Remote Sensing Systems (RSS). The V2 CCMP processing now combines Version-7 RSS radiometer wind speeds, QuikSCAT and ASCAT scatterometer wind vectors, moored buoy wind data, and ERA-Interim model wind fields using a Variational Analysis Method (VAM) to produce four maps daily of 0.25 degree gridded vector winds. For diurnal SST data, we used deltaSST_v7.1.3 produced by Tohoku University, Japan with grid interval of 0.1°. The method to estimate diurnal SST amplitude is explained in [9] following the parametric model described in [10]. For investigating the oceanic response on island wake, surface chlorophyll-a distribution was investigated. We used daily MODIS Chlorophyll-a Lv3, with spatial resolution 4 km [11]. All parameters derived from remote sensing and reanalysis data were composted into monthly climatology to obtain seasonal pattern following [12]. First, all parameters were calculated into monthly means and we derived monthly climatologies by using this formula:

$$\bar{X}(x,y) = \frac{1}{n}\sum_{i=1}^{n} xi\,(x,y,t) \qquad (1)$$

where $\bar{X}(x,y)$ is monthly mean value or a monthly climatology value at position (x,y), $xi(x,y,t)$ is i^{th} value of the data at (x,y) position and time t. Furthermore, n is number of data in 1 month and the number of monthly data in 1 period of climatology (i.e., from 2003 to 2016 = 14 data) for monthly calculation and monthly climatology calculation respectively. Pixel xi is excluded in the calculation if it is a hollow pixel. The investigation of island wake was conducted by displaying all semi-daily data of SSTs for 14 years observation (i.e., 2003-2016). Then, island wake phenomena were detected manually by eye. The robust cases were chosen for further analysis, investigating the oceanic response.

3. Result and Discussion

3.1. Seasonal variation of SST in the seas around the Belitung Island

The seasonal variation of SST in the seas around the Belitung Island is shown by the monthly climatology of SSTs in Fig. 2. The NW monsoon, the transition I, SE monsoon and transition II are represented by December, January, February; March, April, May; Jun, July, August; and September, October, November, respectively. In NW and SE monsoon, SST tends to be low ranges about 27°C to 29°C. Lowest SST was detected in the north-western part of the study area in January. In April and November, SST increased to more than 29°C. The peak of SST cooling (warming) occurred in NW and SE monsoon (Transition I and II) season. Thus, semi-annual variation characterizes the SST variation in the seas around the Belitung Island. This result is consistent with the distribution of SST in the Java Sea observed by the previous studies [e.g., 13, 14]. The SST wake phenomena were not detected by using climatological analysis. The short occurrence period of this phenomenon was dissembled by the averaging process in the climatological analysis. Thus, daily data observation is needed to capture the SST wake phenomena.

The physical parameters underlying the SST climatology distribution in the seas around the Belitung Island is surface wind speed. Fig. 3 shows the monthly climatology of surface wind. The minimum SST occurs during NW and SE monsoon was related to the maximum wind speed during that season. Conversely, during transition season, the SST increased due to the minimum wind speed. Thus, the stronger wind speed induced stronger mechanical mixing and heat release which reduced SST. This wind-driven mechanism is similar as found in Maluku Sea as found by [12, 15].

3.2. Detection of SST wake in the seas of Belitung Island

The detection of SST wake in the seas of the Belitung Island was conducted by investigating semi-daily MODIS SST onboard Aqua and Terra satellite visually from 2003 to 2016. Thus, about 18.000 scenes of SST was investigated to obtain SST wake.

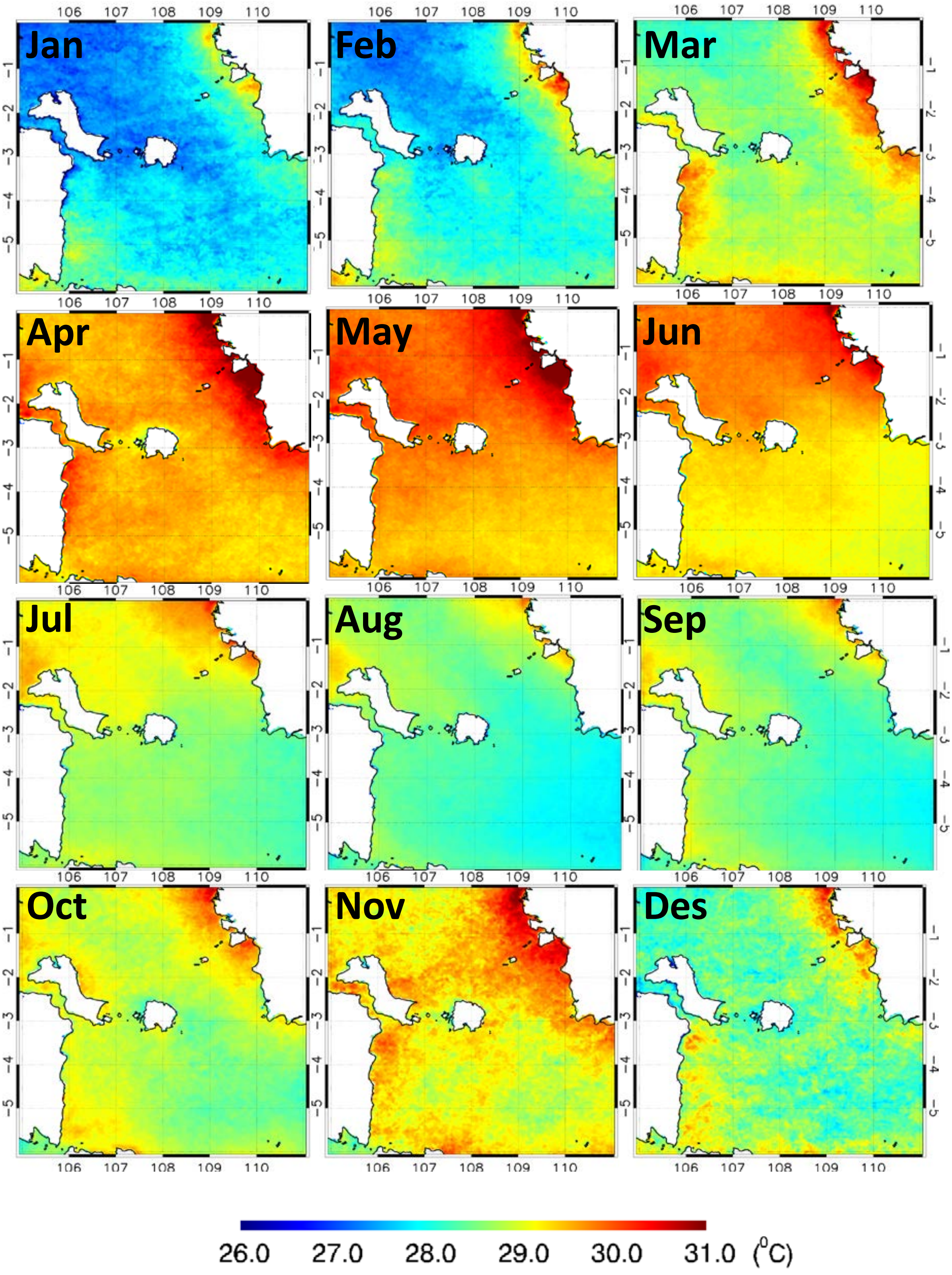

Figure 2. Monthly climatology of SST in the seas around Belitung Island calculated from semi-daily MODIS SST Lv3 from 2003 to 2016

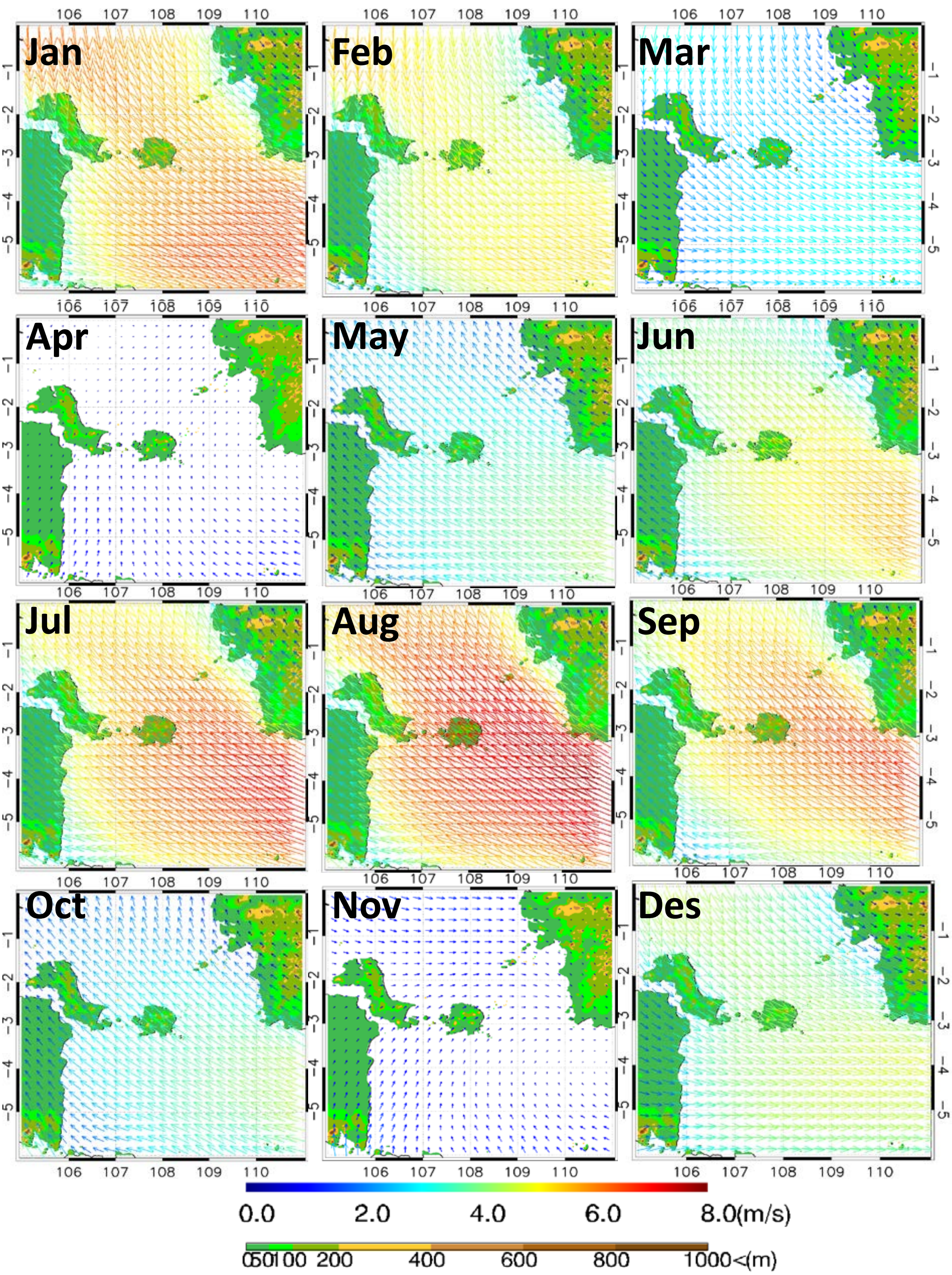

Figure 3. Monthly climatology of surface wind around Belitung Island calculated from semi-daily CCMP wind product from 2003 to 2016

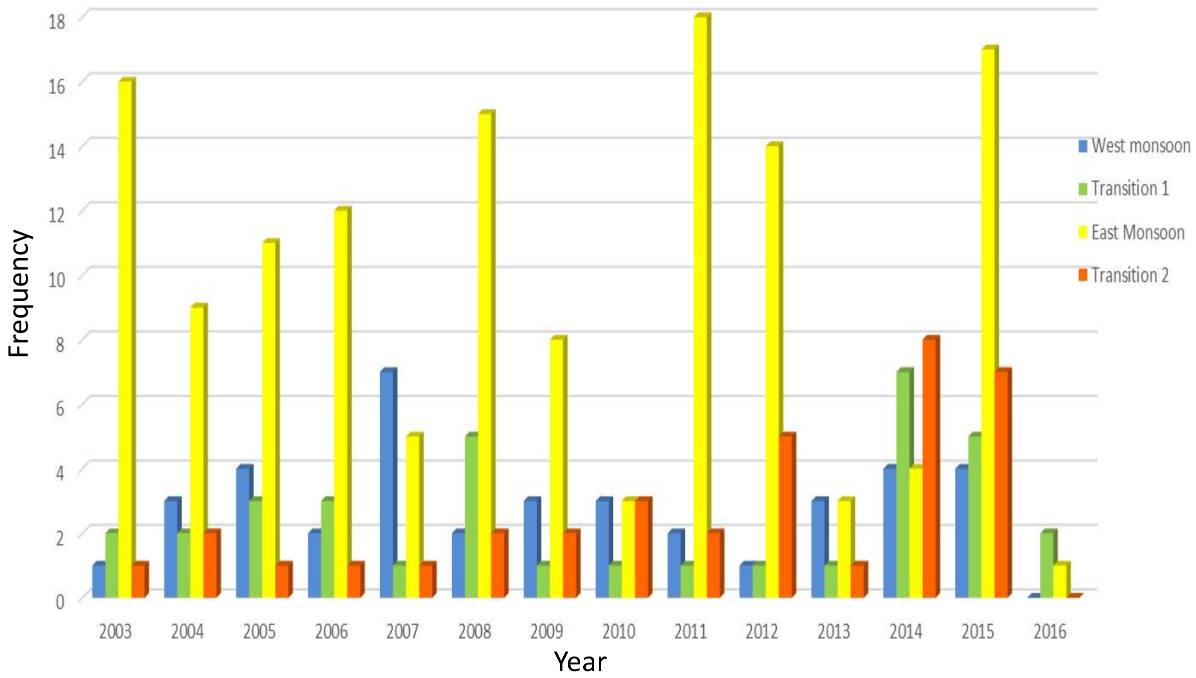

Figure 4. Number of detected SST wake in the seas around Belitung Island from 2003 to 2016

Because MODIS SST product is collected by an infrared sensor, it has the advantage that SST is observed only during clear sky condition which is favorable for the generation of SST wake. The result is shown in the histogram in Fig. 4. We found 245 SST wake cases from 2003 to 2016 period. Each season distributions were 39, 35, 135 and 36 cases for NW monsoon, Transition I, SE monsoon and Transition II, respectively. The highest occurrence of SST wake during SE monsoon may be related to the dry season which occurs during this period. During the dry season, less cloud was formed caused the high solar radiation frequently occurred during this season. The high solar radiation was needed for the generation of high SST as well as SST wake. Conversely, NW monsoon is a rainy season. Thus, the cloud formation increased during this season, reduced the solar radiation penetrating to the sea surface. During transition season, wind direction intermittently changed which SST wake was difficult to be generated. The detection of SST wakes indicates that the high topography in Belitung Island was able to block the monsoon wind, created SST wake in its lee.

The examples of SST wake cases are shown in Fig. 5,6,7 and 8 for NW monsoon, Transition I, SE monsoon and Transition II, respectively. The SST wake phenomena are denoted by the high SST patchiness (i.e., more than 29°C) extended from the lee of the island toward the sea. The length of SST wake was more than 100 km and the longest one was observed during the Transition I for more than 200 km. Thus, comparing to the SST wake in Hawaiian Island as found by [1,3,4], SST wake in Belitung Island is much shorter which is caused by the much lower topography and wind speed.

During the NW monsoon and Transition I (SE monsoon and Transition II) season, the direction of SST wake was southeastwardly (northwestwardly). This direction was related to the surface wind direction which wes southeastwardly (northeastwardly) during the NW monsoon and Transition I (SE monsoon and Transition II) season. Moreover, SST wake was located in the lee of the Island where the wind speed was low due to the existence of mountainous. However, the wind wake phenomena are not clearly seen in the result. This may be caused by the spatial resolution of wind data is not sufficient to observe the braking effect of the wind in the lee of the island. For more detail analysis of the wind effect on the generation of SST wake, the much higher spatial resolution of wind data is needed. This is left for future study.

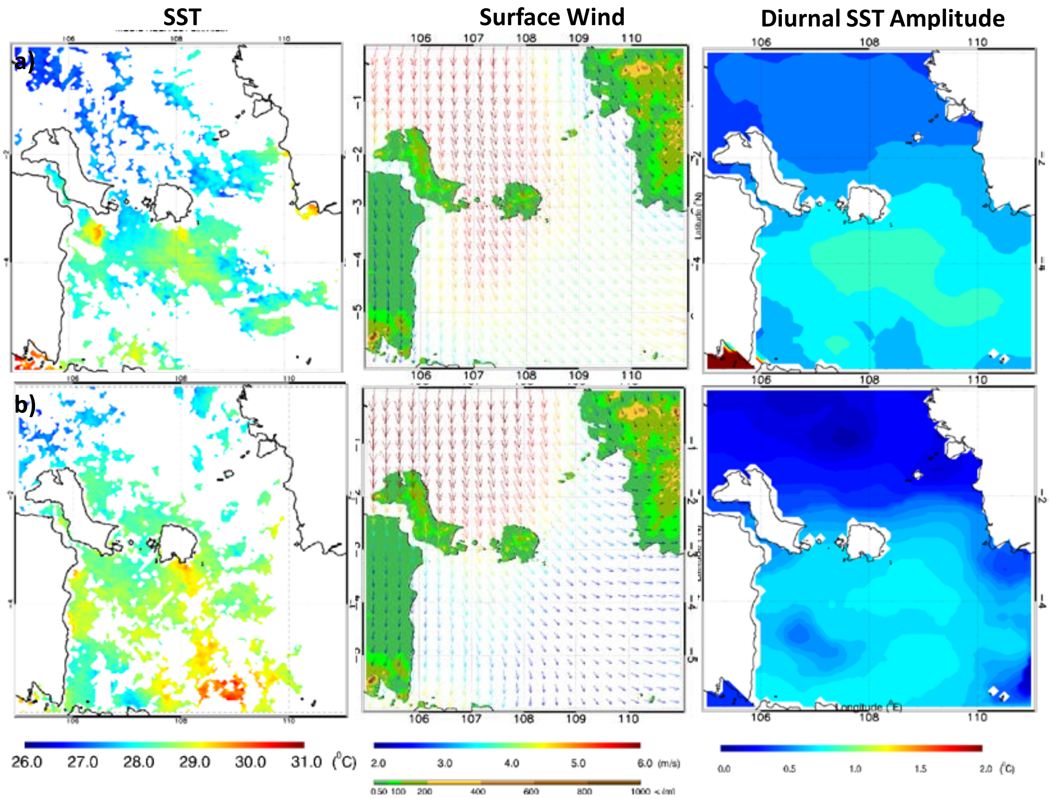

Figure 5. Example cases of SST wake during NW monsoon on (a) 07 Feb. 2007 and (b) 22 Jan. 2004.

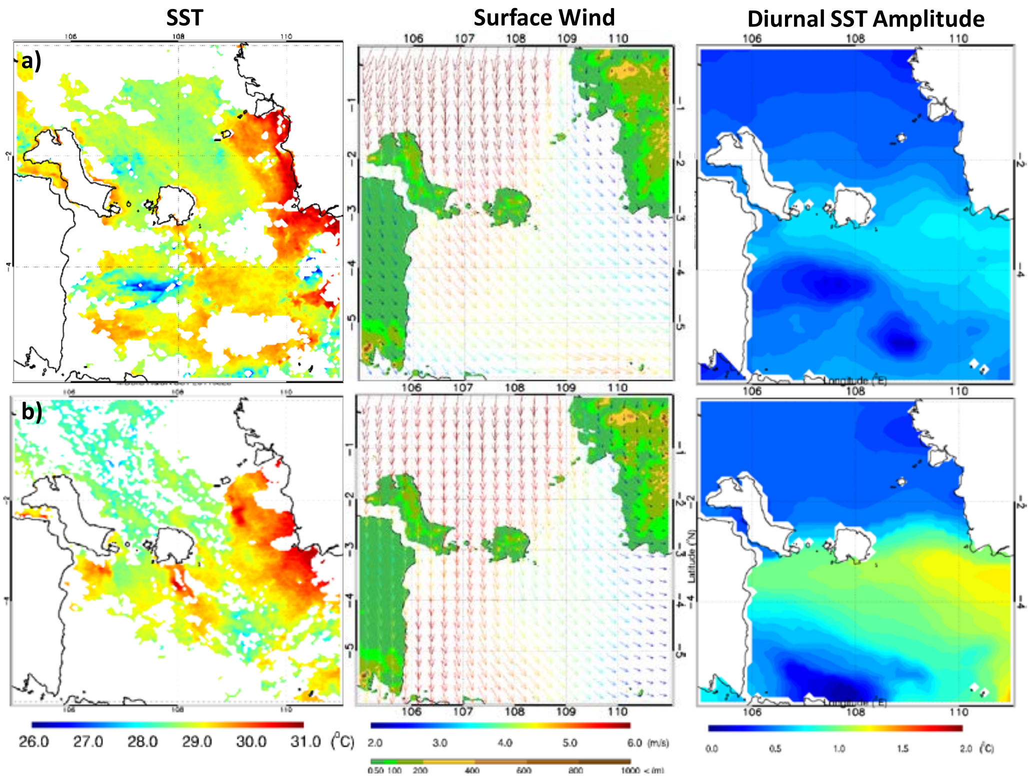

Figure 6. Example cases of SST wake during Transition I on (a) 14 March 2005 and (b) 23 March 2014.

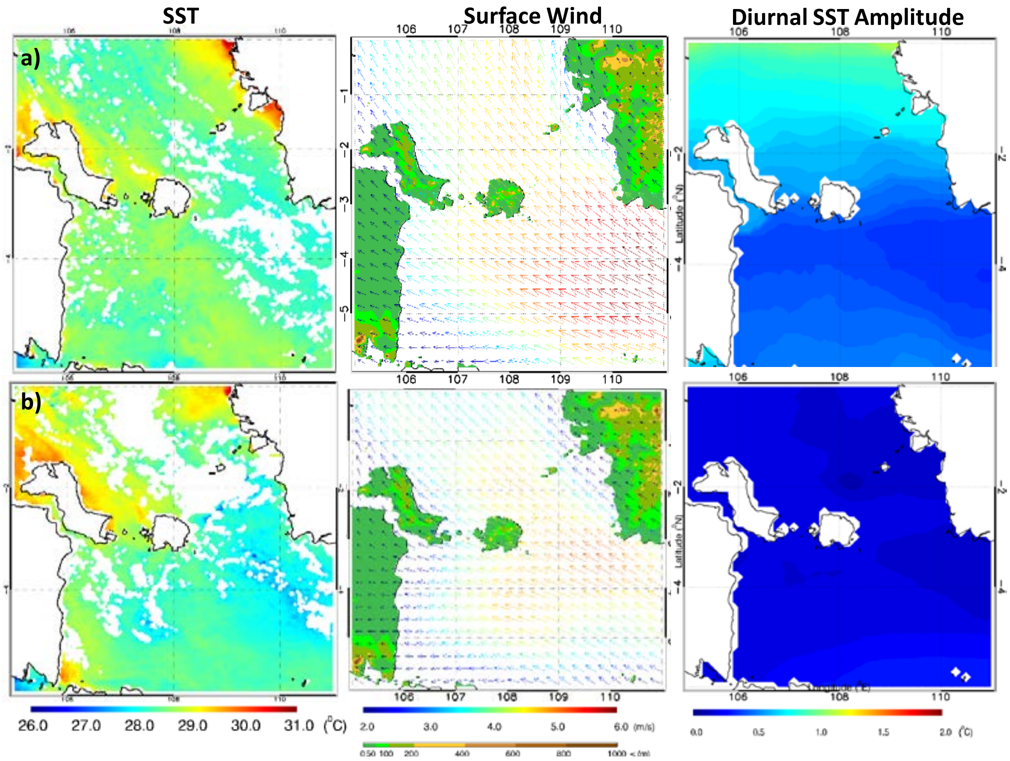

Figure 7. Example cases of SST wake during SE monsoon on (a) 01 Aug. 2008 and (b) 13 Aug. 2003.

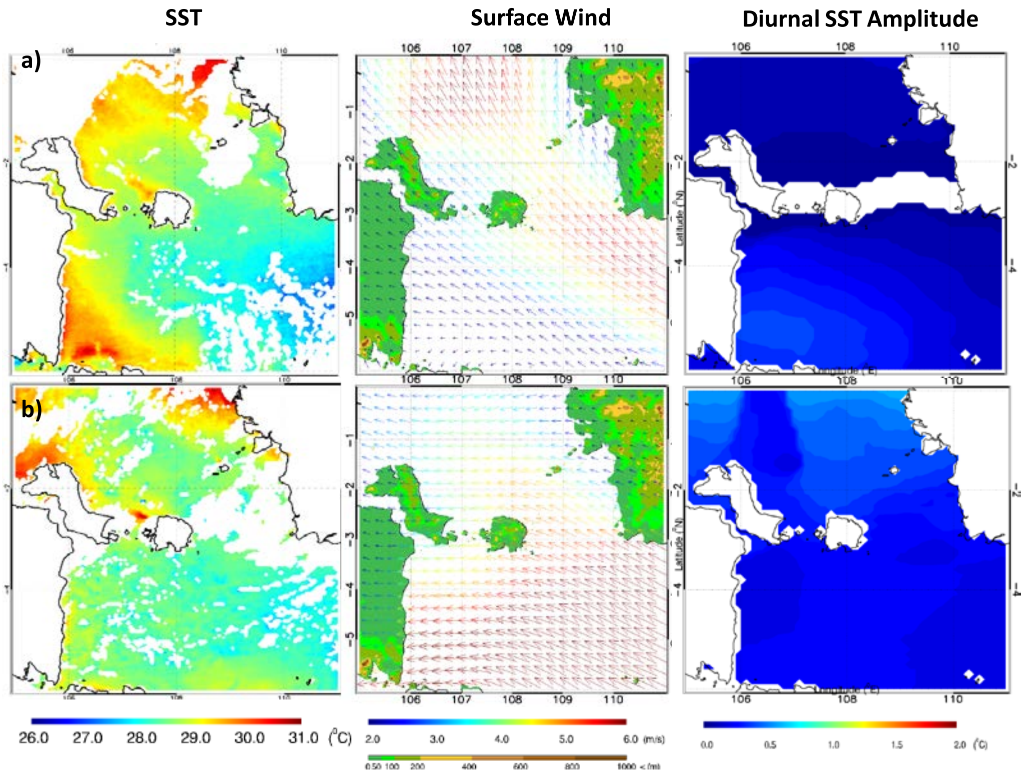

Figure 8. Example cases of SST wake during Transition II on (a) 09 Sep. 2015 and (b) 19 Sep. 2014

The diurnal SST amplitude data also demonstrate the same tendency with the surface wind. High diurnal SST amplitude means that the SST difference between the maximum and minimum SST within a day is high. High diurnal SST amplitude is caused by high solar radiation and low wind speed. Thus, lee of the island is potential for generating high DSST amplitude. Fig. 5-8 show that although the SST wake was located at the high DSST area of more than 0.5°C, the area of SST wake was not well coincided with the area of high DSST amplitude. The area of high DSST amplitude coincides with the low wind speed area. This is caused by the calculation of DSST amplitude data used partly the surface wind data as CCMP wind.

3.3. Effect of SST wake on the biological productivity

To investigate the effect of SST wake on the biological productivity of the seas around the Belitung Island, we plotted the Chl-a distribution during the SST wake event. An example of Transition I season is shown in Fig. 9a. It is clearly seen that the low Chl-a concentration coincided with the SST wake patch on 7 February 2007. Outside SST wake area, Chl-a concentration was higher. The high Chl-a concentration may be generated due to the occurrence of eddies around the SST wake patch. This phenomenon also has been reported in other areas with the more robust signal. Island wakes are also related to the concept of ''island mass effect.'' which was first described by [16] as an increase in ''biological productivity,'' that is, chlorophyll concentration, on the east side of Oahu Island in the Hawaiian Archipelago. Subsequently, the effect of island bathymetry on ambient oceanography was generalized to include island effects around entire islands [17] and island mass effects now include differences in phytoplankton, zooplankton and fish biomass due to the formation of island-induced wakes, eddies, fronts, filaments and upwelling processes [see also 18-22]. Thus, the blocky wind induces the high potential vorticity at the lateral island, triggering the eddy formation and finally transporting the nutrient from the deeper layer to the sea surface which increases Chl-a. However, the occurrence of SST wake was not always followed by the increase of biological productivity. Fig. 9b shows that on 10 March 2006, there was no indication of Chl-a bloom during the event of SST wake. This may be related to the different response of blocky wind by the high topography on inducing the eddy generation in the seas around the island. Nevertheless, this indication should be examined further in the Belitung Island by using a much higher resolution of surface wind data for calculating the wind curl and Ekman pumping velocity. This is left for future study.

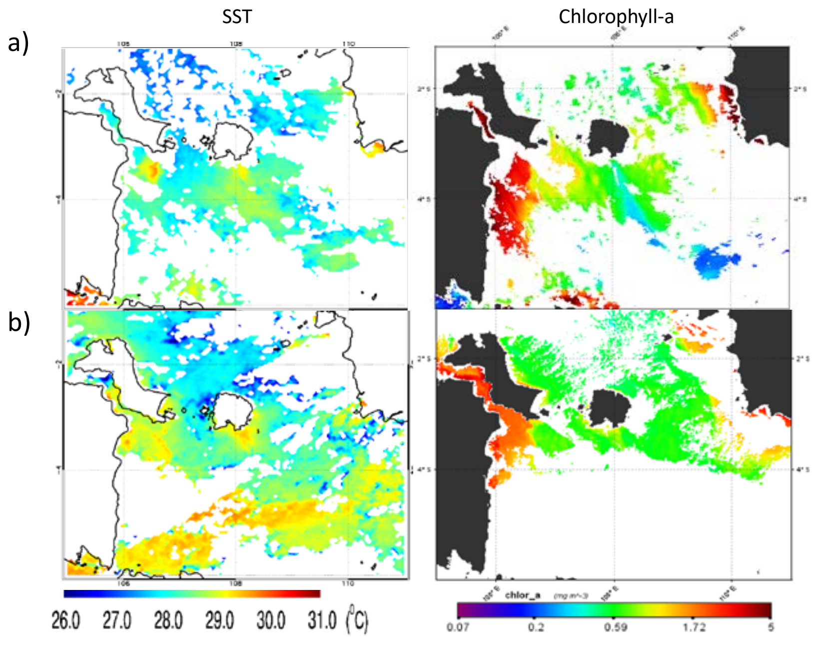

Figure 9. SST and Chl-a concentration on (a) 07 February 2007 and (b) 10 March 2006

4. Summary

Island wake phenomena in Belitung Island has been investigated by using MODIS SST. The result can be summarized as follows :

a. Although the topography Belitung Island relatively flat, the existence of mountainous with 200-300m height in the center of the Island may form the island wake during the strong wind event.
b. The peak of SST cooling (warming) occurs in NW and SE monsoon (Transition I and II) season following the wind speed distribution. The higher wind speed the lower SST occur in the seas around Belitung Island.
c. From 2003 to 2016 period of observation, 245 SST wake cases were found with the distribution for each season are 39, 35, 135 and 36 cases for NW monsoon, Transition I, SE monsoon and Transition II, respectively
d. The direction of SST wake depends on the direction of the surface wind. During NW monsoon and Transition I, the direction of SST wake is southeastwardly while during SE monsoon and Transition II is northwestwardly.
e. The high Chl-a concentration outside the SST wake patch indicates that the occurrence of SST wake in the seas of Belitung Island may influence biological productivity in that area.

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Acknowledgments
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