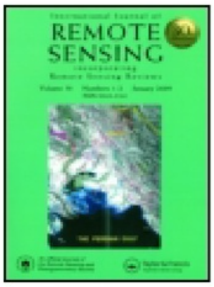
Surface chlorophyll-a variations in the Southeastern Tropical Indian Ocean during various types of the positive Indian Ocean Dipole events

By Qurnia Sari



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Surface chlorophyll-a variations in the Southeastern Tropical Indian Ocean during various types of the positive Indian Ocean Dipole events

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ABSTRACT

Surface chlorophyll-a (chl-a) variation in the Southeastern Tropical Indian Ocean (SETIO) shows different patterns in response to the various types of the Indian Ocean Dipole (IOD) events. Thirteen years of remotely sensed surface chl-a data from the Moderate-resolution Imaging Spectroradiometer (MODIS) were used to evaluate interannual surface chl-a variation in the SETIO. During the period of analysis (January 2003-December 2015), there were three canonical positive IOD (pIOD) and four pIOD Modoki events. It is found that the spatial patterns of surface chl-a variation were coherent with the pattern of surface wind anomaly, and the sea surface temperature anomaly (SSTA). During canonical pIOD events, high chl-a concentrations were observed in the vicinity of the Sunda Strait and along the coast of western tip of the Java Island around the Cilacap region. Meanwhile, during pIOD Modoki event, surface chl-a concentration was relatively higher and distributed wider than those observed during canonical pIOD event. The analysis shows that relatively weak upwelling event indicated by a deep isothermal layer depth (ILD) during pIOD Modoki events combined with thin barrier layer thickness (BLT) and deep mixed layer provides a favourable condition for an increase in surface chl-a in the SETIO region. Meanwhile, strong upwelling as indicated by shallow ILD combined with thick BLT and shallow mixed layer prevents surface chl-a to increase during canonical pIOD events.

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1. Introduction

The seasonal variability of Indonesian ocean and atmosphere is dominantly influenced by the monsoonal wind (southeast monsoon and northwest monsoon). Meanwhile, the coupled ocean-atmosphere modes in the tropical Indo-Pacific, namely the El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) events, regulate the interannual variation. In particular, previous studies have shown that IOD events strongly influence the oceanic circulation in the southeastern tropical Indian Ocean (SETIO)

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region, including the distribution of surface chlorophyll-a (chl-a) (Iskandar, Rao, and Tozuka 2009; Iskandar et al. 2010).

Early studies have proposed a typical IOD type characterized by a zonal sea surface temperature (SST) gradient between the western and the SETIO (Saji et al. 1999; Saji and Yamagata, 2003; Webster et al. 1999). In particular, Saji et al. (1999) have shown that the positive IOD event is associated with positive SST anomalies observed in the western (10°S-10°N, 50°E-70°E) and negative SST anomalies found in the SETIO (0°-10°S, 90°E-110° E). Recently, Du, Cai, and Wu (2013) have proposed three types of the IOD events based on the development phase of events. They named the events as the normal IOD, unseasonable IOD and prolonged IOD. A more recent study has classified the events based on their SST pattern and proposed two types of the IOD events, namely the canonical/normal IOD and the IOD Modoki (Endo and Tozuka 2016). In particular, they suggested that the IOD Modoki is characterized by warm SST anomalies in the central equatorial Indian Ocean and cold SST anomalies in the SETIO.

Previous studies have examined the impact of the IOD events on the ocean circulation in the tropical Indian Ocean (Iskandar et al. 2008; Gnanaseelan, Deshpande, and McPhaden 2012; Yuhong et al. 2013; Ying et al. 2016), as well as on the climate variations over the surrounding continents (Guan and Yamagata 2003; Yamagata et al. 2004; Behera et al. 2006). In addition, several early studies have also examined the impact of IOD event on the chl-a distributions in the SETIO off south Java and Sumatra (Susanto and Marra 2005; Iskandar, Rao, and Tozuka 2009; Iskandar et al. 2010). However, those early studies did not classify the different types of the IOD events and their possible influence on the chl-a distribution. Therefore, this study is designed to evaluate the impact of various types of the IOD events and their associated ocean-atmosphere dynamics on the chl-a distribution in the SETIO off south Java and Sumatra.

2. Data and methods

The study area is in the SETIO region off the south of Java and the west of Sumatra from 0° to 15°S and 98°E to 122°E (Figure 1). The surface chl-a concentration data were obtained from the Moderate-resolution Imaging Spectroradiometer (MODIS) Aqua satellites. Level 3 monthly data of surface chl-a at 9 km spatial resolution from January 2003 until December 2015 were downloaded from the Ocean Colour website. Note that the original chl-a data have missing value due to cloud covers. Therefore, we reconstructed the chl-a data using empirical orthogonal function-based data interpolation (DINEOF) to remove the cloud effects (Alvera-Azcárate et al. 2007).

The SST dataset was derived from the daily Optimum Interpolation Sea Surface Temperature (OI-SST) of the National Oceanographic and Atmospheric Administration (NOAA) (Reynolds et al. 2007). The data cover a period from January 2003 to December 2015. Monthly averages were calculated from these daily fields. The spatial resolution of the SST data is 0.25° × 0.25°. Meanwhile, the surface wind data obtained from the ECMWF Re-Analysis (ERA)-Interim of the European Centre for Medium Range Weather Forecasts (ECMWF). The data have a spatial resolution of 0.25° × 0.25° and are available from January 2003 to December 2015. In addition, the monthly mixed layer depth (MLD) and isothermal layer depth (ILD) data were obtained from the Array for Real-Time Geostrophic Oceanography (ARGO) gridded products of the Asia-Pacific Data-Research

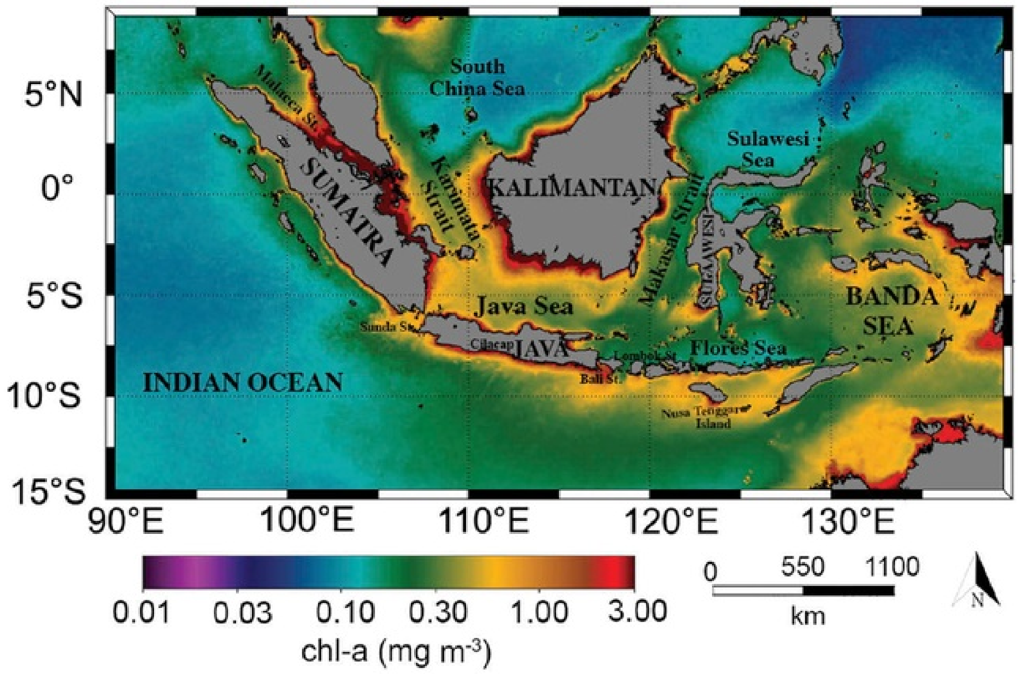

Figure 1. Mean surface chl-a concentration in the SETIO during June–August (2003–2015). The area of interest is bounded by white line (0° to 15°S and 90°E to 125°E).

Center (APDRC) University of Hawaii. The data have a spatial resolution of 1.00° × 1.00° and are calculated for a period from January 2005 to December 2015. Note that the MLD is defined as a depth on which the density increases from that of the reference point (10 m depth) to the value equivalent to the potential density ($\Delta\rho$) criterion by 0.125 kg m^{-3}. Meanwhile, ILD is defined as the depth on which the temperature differs from the reference temperature (10 m depth) by 0.20°C (Toyoda et al. 2017; Zeng and Wang 2017). The barrier layer thickness (BLT) is calculated as a difference between ILD and MLD. If the value is less than or equal to zero, then the BL does not exist (Zeng and Wang 2017).

The monthly climatology of all parameters was calculated by taking the long-term monthly mean of each parameter from January 2003 to December 2015, except for the MLD and ILD, which were calculated from January 2005 to December 2015. Then, the anomalies were defined as a deviation from their climatological values. In this study, the time series of DMI (Dipole Mode Index) is used as a reference for evaluating the occurrence of the IOD event in which the IOD is defined when the DMI value is larger (smaller) than its one positive (negative) standard deviation for three consecutive months (Saji et al. 1999) (Figure 2).

By following the definition of Endo and Tozuka (2016), we have three (three) canonical positive IOD (pIOD) events, four (four) pIOD Modoki events, one (one) canonical negative IOD (nIOD) event, and one (one) nIOD Modoki event (Table 1.). However, in this study, we only focus on the distribution of surface chl-a during pIOD events. Note that the pIOD Modoki event is characterized by negative SST anomalies observed in the eastern and western tropical Indian Ocean and positive SST anomalies found in the central tropical Indian Ocean. Furthermore, based on this definition, the 2006 event was classified as a weak IOD Modoki event. In order to evaluate the spatial and temporal variations of the

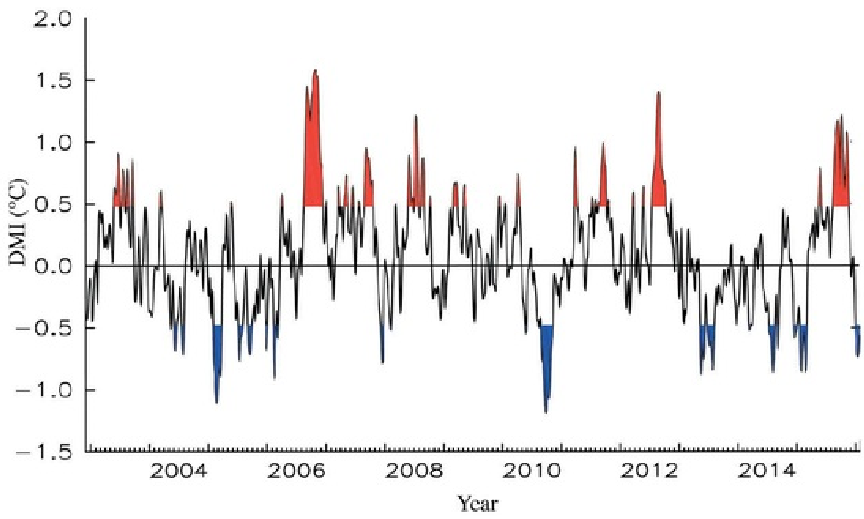

Figure 2. Time series of the DMI from January 2003 to December 2015. Positive value (red colour) indicates positive IOD events, while negative value (blue colour) represents negative IOD events based on early studies.

Table 1. Classification of the types of IOD events, 2006 is weak Modoki (Du, Cai, and Wu 2013; Endo and Tozuka 2016).

Type of IOD	Canonical IOD	IOD Modoki/Unseasonal IOD
Positive	2011, 2012, 2015	2003, 2006, 2007, 2008
Negative	2010	2005

surface chl-a associated with various types of the pIOD events, we divided the study area into four regions, namely the western coast of Sumatra, the Sunda Strait, the southern coast of Java, and the southern coast of Nusa Tenggara Island Chains.

3. Results

3.1. Spatio-temporal variation of chl-a distribution anomalies

Figure 3 presents the chl-a distribution during the canonical pIOD in 2011, 2012, and 2015. Among those three pIOD events, we observed that the highest positive anomalies of the surface chl-a appeared during the 2015 pIOD event. Note that the 2015 pIOD event co-occurred with a strong El Niño event that took place in the tropical Pacific Ocean (Liu et al. 2017; Iskandar et al. 2017, 2018; Utari et al. 2019). It was suggested that the unique pattern of SST anomalies in the tropical Pacific Ocean associated with strong 2015/2016 El Niño event has modulated the evolution of 2015 pIOD event (Liu et al. 2017). The surface chl-a increase started in June 2015 and it was observed off south Nusa Tenggara Islands. In the following months, the increase was extended westward and toward offshore. The chl-a increase peaked in September and October 2015 and gradually disappeared in November 2015. Note that a similar timing of chl-a evolution was also observed during other canonical pIOD events, but with lower amplitude. In

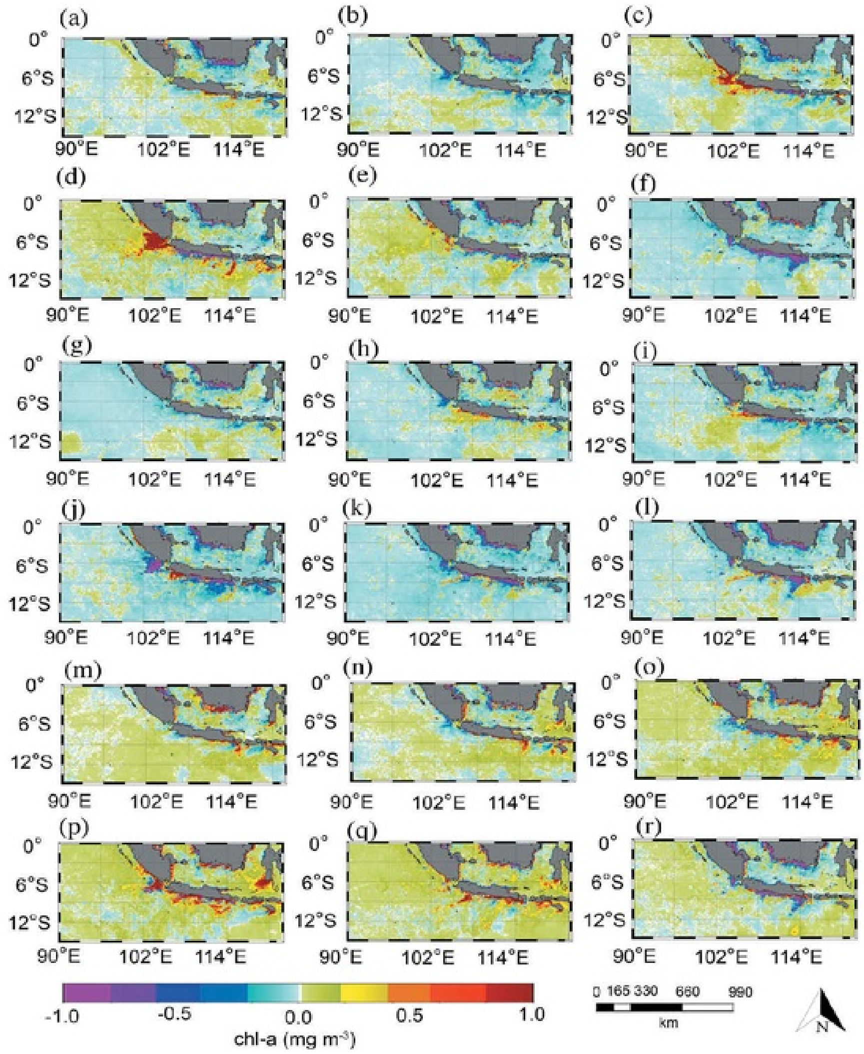

Figure 3. Monthly anomalies of chl-a distribution during the canonical IOD events for period June–November in 2011 (a)–(f), 2012 (g)–(l), and 2015 (m)–(r), respectively.

addition, we also noted that the chl-a evolution during 2012 pIOD event was shorter and covered smaller region compared to 2011 and 2015 pIOD events.

Figure 4 shows monthly anomalies of the chl-a distribution during the pIOD Modoki events in 2003, 2006, 2007 and 2008. It is shown that the development of chl-a distribution is different for each pIOD Modoki years. Generally, the area with enhanced chl-a concentration extends from the south of the Nusa Tenggara Island towards the western coast of Sumatra and is highly concentrated over a wide area in the western coast of Sumatra and the southern coast of Java. Among those four pIOD Modoki events, the 2006 pIOD Modoki event, which was attributed as the weak Modoki event, has shown the highest chl-a concentration compared to other pIOD Modoki events (Figure 4(g–l)). The highest chl-a concentrations were observed along the southern coast of Java during September – November 2006 as shown in previous studies (Iskandar, Rao, and Tozuka 2009; Iskandar et al. 2010). Southwestward offshore extension of chl-a

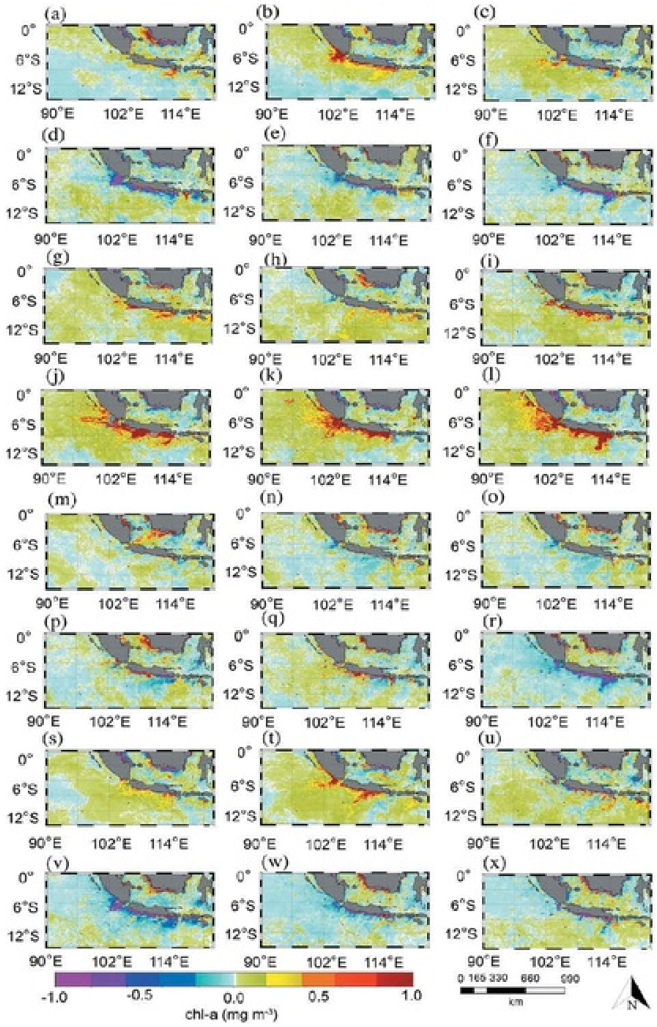

Figure 4. Same as Figure 3 except for the positive IOD Modoki events in 2003 (a)–(f), 2006 (g)–(l), 2007 (m)–(r), and, 2008 (s)–(x).

concentration was also revealed during this period and it was attributed to the enhanced cyclonic activities during the pIOD event (Iskandar et al. 2010). In contrast to the 2006 event, a short-lived chl-a increase was observed during the 2003, 2007 and 2008 pIOD Modoki events. During these three pIOD Modoki events, high chl-a concentration was only observed during June – August (southeast monsoon season). It has been suggested that those three pIOD Modoki events were early aborted; developed in late spring, peaked in summer and terminated in late summer/early fall (Rao and Yamagata 2004; Iskandar, Irfan, and Saymsuddin 2013; Iskandar et al. 2014).

3.2. Spatio-temporal variations of surface winds and SST anomalies

In order to obtain a better interpretation of underlying mechanism affecting the surface chl-a increase during each pIOD event, we first examine the surface winds as the dominant forcing of surface chl-a increase in SETIO. Figure 5 illustrates the

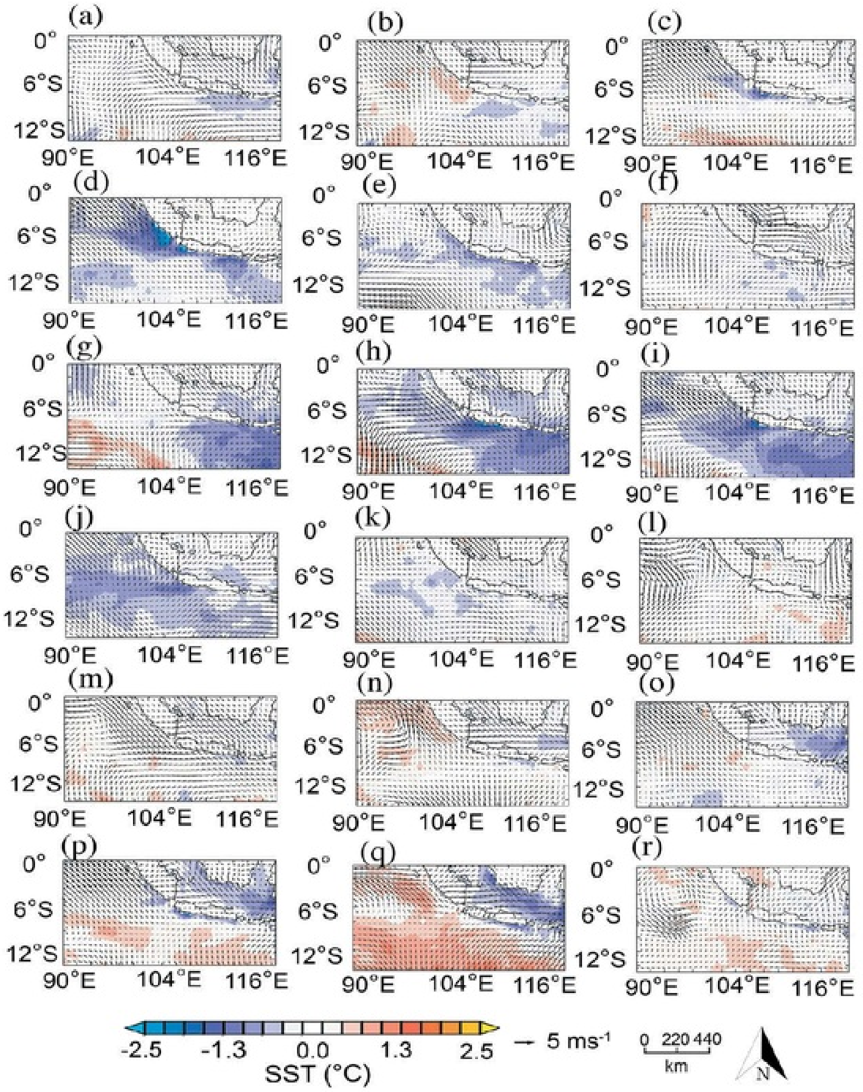

Figure 5. Monthly surface wind anomalies superimposed on the SST anomalies of the canonical pIOD events for period June–November in 2011 (a)–(f), 2012 (g)–(l), and 2015 (m)–(r).

surface wind and SST variability during the canonical pIOD events. It is shown that there is no uniform pattern of the surface wind and SST evolution for the events. However, it should be noted that strong southeasterly wind anomalies accompanied by high negative SST anomalies were observed during the peak phase of the event in August – September (Figure 5(d,i,p)). The region covered by negative SST anomalies indicates the presence of coastal upwelling that leads to the positive chl-a anomalies (Figure 3).

Figure 6 illustrates the spatiotemporal evolutions of the surface winds and SST anomalies during pIOD Modoki events in 2003, 2006, 2007, and 2008. Similar to the canonical pIOD events, the pIOD Modoki events also show different spatio-temporal evolutions of the surface wind and SST anomalies for each event. The 2006 pIOD Modoki events showed a distinct characteristic; developed in summer, peaked in fall

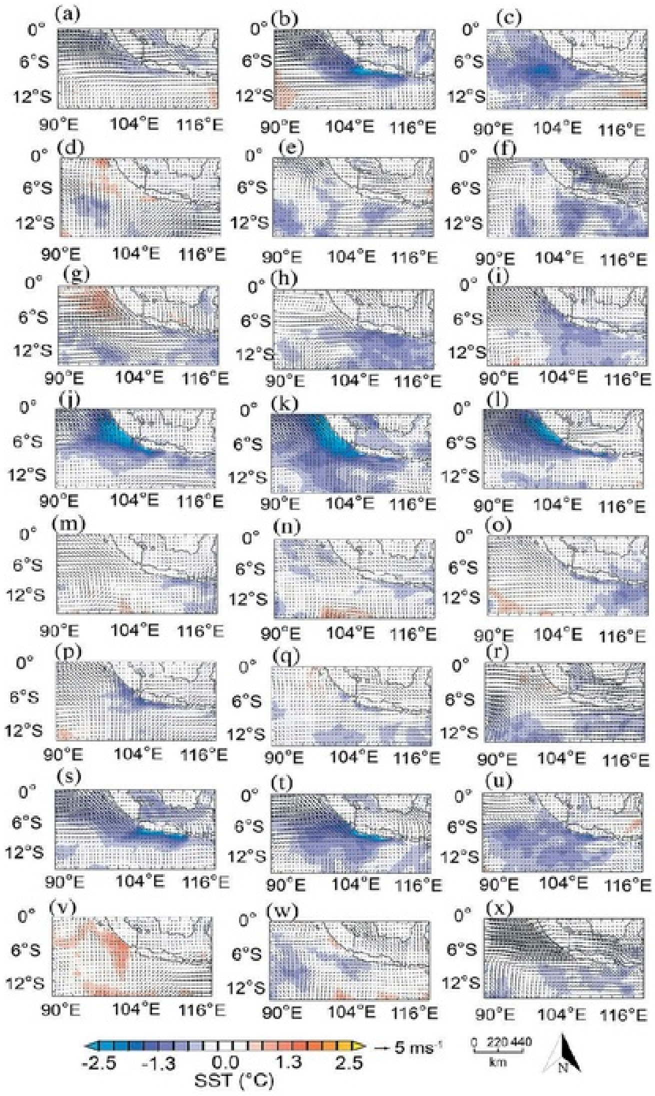

Figure 6. Same as Figure 5 except for the pIOD Modoki events in 2003 (a)–(f), 2006 (g)–(l), 2007 (m)–(r), and, 2008 (s)–(x).

and terminated in early winter (November). Meanwhile, as suggested in previous studies (Rao and Yamagata 2004; Iskandar, Irfan, and Saymsuddin 2013; Iskandar et al. 2014), the 2003, 2007 and 2008 events were abruptly terminated. The evolutions of the events were very fast and they were fairly short-lived. The 2003 and 2008 pIOD Modoki events developed in June, peaked in July–August, and terminated in September, while the evolution of the 2007 event showed one month lag. As we observed during the canonical pIOD events, strong southeasterly wind anomalies associated with high negative SST anomalies were observed during the peak phase of the pIOD Modoki events. Strong southeasterly winds and SST anomalies co-occurred with high chl-a concentration as shown in Figure 4.

3.3. Variability of barrier layer thickness, isothermal layer depth and mixed layer depth

In order to explain the mechanism of an intensification of chl-a concentration in the SETIO, we first evaluated the variabilty of BLT. Note that the BLT, an intermediate layer between ILD and MLD, appeared to be a factor that limits increasing of chl-a concentration during pIOD events. In general, Figures 7 and 8 show that the BLT was observed in June, it got thinner during the peak phase of pIOD events (July–August) and it disappeared at the end of the evolution of the pIOD events, in particular in the southern area of the Java and Nusa Tenggara Island Chains (October–November). Monthly analysis of the BLT on each event clearly described the role of BLT on the surface chl-a varitions. For example, strong upwelling forced by anomalous southeasterly winds (Figure 5(g–l)) combined with thick barrier layer (Figure 7(g–l)) during canonical pIOD in 2012 lead to fairly low chl-a anomaly (Figure 3(g–l)) over most area from the southern Nusa Tenggara Island Chains to the southwestern area of Sumatra. On the other hand, during the peak phase of 2015 canonical pIOD event, relatively weak upwelling (Figure 5(m–r)) combined with thin barrier layer (Figure 7(m–r)) allows an increase of surface chl-a concentration in the southern area of Java (Figure 3(m–r)). The influence of BLT on the surface chl-a variation is more robust during pIOD Modoki events (Figure 8). Relatively thinner BLT observed

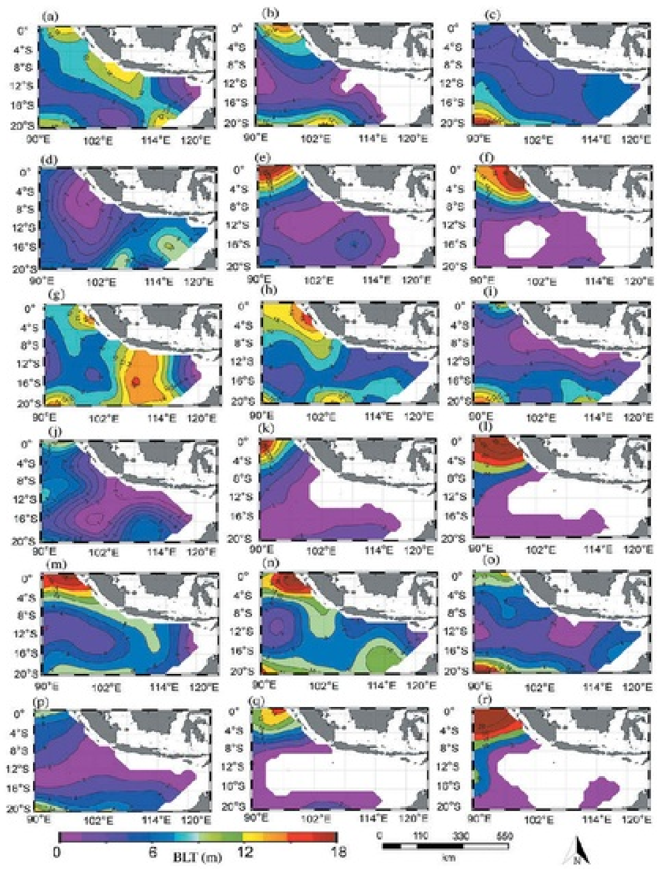

Figure 7. Spatio-temporal variations (June–November) of BLT during canonical pIOD events in 2011 (a)–(f), 2012 (g)–(l), and 2015 (m)–(r), respectively.

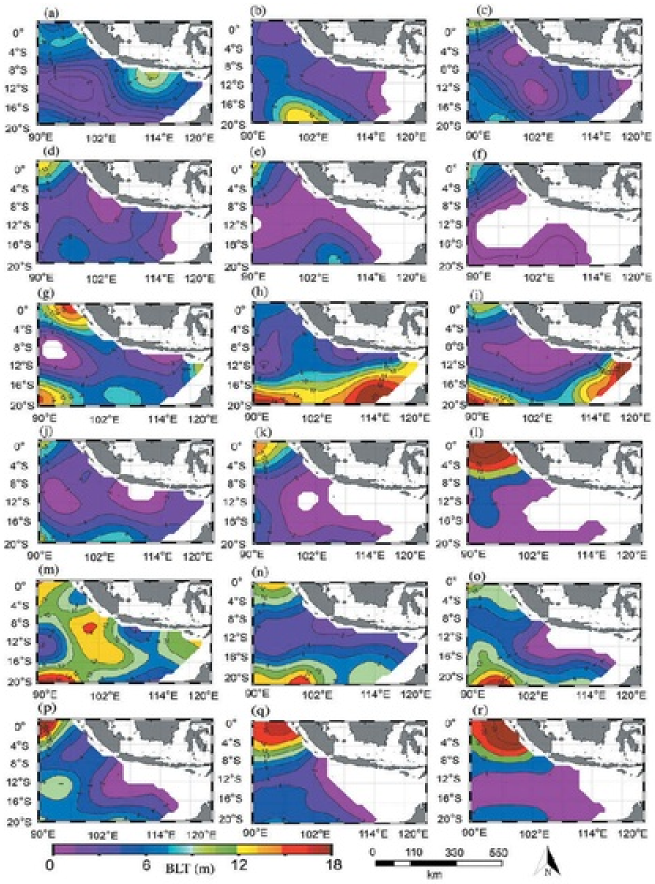

Figure 8. Same as Figure 7 except during pIOD Modoki events in 2006 (a)–(f), 2007 (g)–(l), and 2008 (m)–(r), respectively.

during pIOD Modoki events than that observed during canonical pIOD events has allowed an increase of surface chl-a concentration during pIOD Modoki events. Therefore, we argue that the difference in observed BLT during those two types of the pIOD events leads to a different impact on surface chl-a concentration in the SETIO region. We found that relatively weak upwelling combined with thin BLT observed during pIOD Modoki events caused a high surface chl-a concentration in the SETIO region. On the other hand, anomalously strong upwelling combined with thick BLT observed during canonical pIOD events prevented increase in surface chl-a concentration in the SETIO region.

To further evaluate the role of BLT on the surface chl-a variation in the SETIO associated with the pIOD events, we show the composite time-series of the BLT, ILD and MLD averaged over the SETIO as shown in the white box in Figure 1. It is clearly shown that the BLT during pIOD Modoki events is thinner than that observed during canonical pIOD events almost all year around except during March and September (Figure 9(a)). It is interesting to note that during pIOD Modoki events the ILD is much deeper than that during the canonical pIOD events (Figure 9(b)). This indicates that the upwelling process during pIOD Modoki is weaker than that during canonical pIOD events. Moreover, the MLD time series also revealed an interesting feature. Shallower MLD indicating a more stratified layer was observed during canonical pIOD events, while

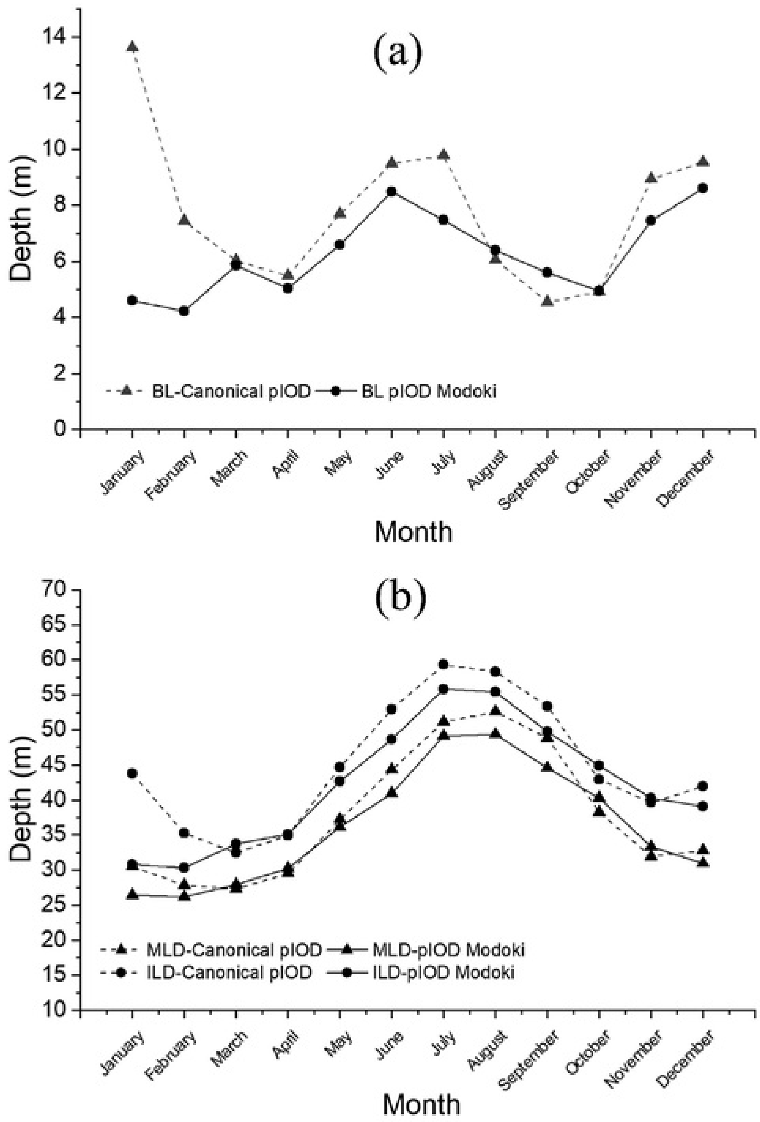

Figure 9. Monthly composite time series of (a) BLT during canonical pIOD events (dashed line-triangle symbol) and pIOD Modoki events (solid line-circle symbol) and (b) mixed layer depth and isothermal layer depth during canonical pIOD events (triangle symbol) and during pIOD Modoki events (circle symbol).

deeper MLD was observed during pIOD Modoki events. As discussed in previous study, a deeper MLD may erode deep chl-a maximum allowing upwelling process to bring subsurface chl-a to the surface layer (Iskandar et al. 2010). Therefore, we may conclude that relatively weak upwelling event indicated by a deep ILD during positive IOD Modoki events combined with thin BLT and deep MLD provides a favourable condition for an increase in surface chl-a in the SETIO region. Meanwhile, strong upwelling as indicated by shallow ILD combined by thick BLT and shallow MLD prevents surface chl-a to increase during canonical pIOD events.

4. Summary

The surface chl-a concentration in the SETIO tends to increase during the southeast monsoon season and decrease during the southwest monsoon season (Asanuma et al. 2003). The southeasterly winds associated with the southeast monsoon-induced coastal upwelling along the southern coast of Java and Nusa Tenggara Island Chains. The upwelling drives subsurface dense, cooler and nutrient-rich water toward the ocean surface leading to surface chl-a bloom (Susanto and Marra 2005; Iskandar, Rao, and Tozuka 2009). This study evaluated ocean response in term of surface chl-a variation in response to various types of pIOD events, namely the canonical pIOD and the pIOD Modoki events, although the upwelling during pIOD Modoki events was weaker than that during canonical pIOD events (Figures 3 and 4). This indicates that surface chl-a variation in the SETIO is not solely driven by the upwelling, instead other ocean dynamics may play a role in causing the different strength of the surface chl-a increasing.

Here, we propose that spatiotemporal variations of BLT influence the surface chl-a variations in the SETIO (Figures 7 and 8). We found that the observed BLT during pIOD Modoki events is shallower than that during canonical pIOD events. Although the BLT patterns do not show a linear variation, in general, we found that the BLT observed during pIOD Modoki events was thinner than that observed during canonical pIOD events. We argue that the presence of thick barrier layer during canonical pIOD events hampered the upward motion of subsurface nutrient-rich water to the ocean surface. Previous modelling study has shown that the depth of mixed layer is critical for the surface chl-a variation (Iskandar et al. 2010). They showed that increase in surface chl-a concentration only occurs when the MLD erodes the deep chl-a maximum. The analysis showed that the MLD during pIOD Modoki events is deeper than that during canonical pIOD events. Therefore, we suggest that relatively weaker upwelling during pIOD Modoki events combined with thin BLT and deep-mixed layer has provided favourable condition for an increase of surface chl-a concentration. Meanwhile, the presence of relatively thick BLT and shallow-mixed layer during strong upwelling event prevents the surface chl-a increasing as seen during the canonical pIOD events.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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