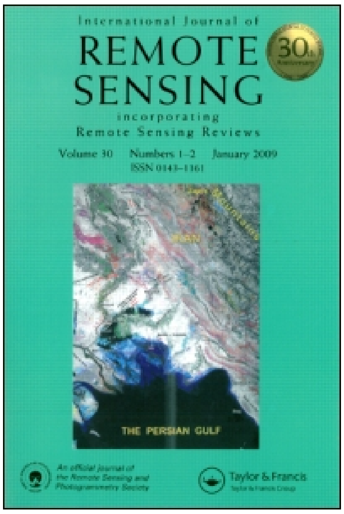

International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713722504

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Online Publication Date: 01 January 2009

To cite this Article Iskandar, I., Rao, S. A. and Tozuka, T.(2009)'Chlorophyll-a bloom along the southern coasts of Java and Sumatra during 2006',International Journal of Remote Sensing,30:3,663 — 671

To link to this Article: DOI: 10.1080/01431160802372309

URL: http://dx.doi.org/10.1080/01431160802372309

International Journal of Remote Sensing
Vol. 30, No. 3, 10 February 2009, 663–671

Chlorophyll-*a* bloom along the southern coasts of Java and Sumatra during 2006

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(*Received 14 December 2007; in final form 24 July 2008*)

Nine years of chlorophyll-*a* concentration data provided by the Sea-viewing Wide-Field of view Sensor (SeaWiFS) revealed an unusual bloom along the southern coastal area of Java and Sumatra during 2006. The bloom was generated by anomalous strong southeasterly winds along the coasts of Java and Sumatra associated with the Indian Ocean Dipole (IOD) event. The bloom evolution started in July 2006 and intensified during August 2006. Peak positive anomalies exceeding $4.0\,\mathrm{mg\,m^{-3}}$ were evident in September–November coinciding with the peak phase of the IOD. The blooms, thereafter, diminished rapidly in December 2006. In addition, there was an offshore intensification of chlorophyll-*a* distribution off eastern Java during November initiated by upwelling-favourable winds along the coast. Concurrent altimeter data show that the offshore intensification was co-located with the cyclonic eddies that further enhanced the intensification by increasing the concentration of nutrients in the euphotic zone.

1. Introduction

Seasonally varying monsoon winds over the Indonesian region (figure 1) have a great impact on the pattern of oceanic circulation along the southern coasts of Java and Sumatra (Wyrtki 1973, Quadfasel and Cresswell 1992). During the northwest monsoon (December–March), northwesterly winds along the coast drive the eastward surface current off Java, the so-called South Java Coastal Current (SJCC), bringing low-salinity, warm water from the eastern equatorial Indian Ocean off Sumatra. The circulation is reversed during the southeast monsoon (June–October) and the SJCC flows northwestwards, in parallel with the South Equatorial Current (SEC) due to the prevailing southeasterly winds along the coast (Wyrtki 1973, Quadfasel and Cresswell 1992, Sprintall *et al.* 1999). At the same time, the southeasterly winds drive offshore Ekman transport and produce upwelling off

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International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2009 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160802372309

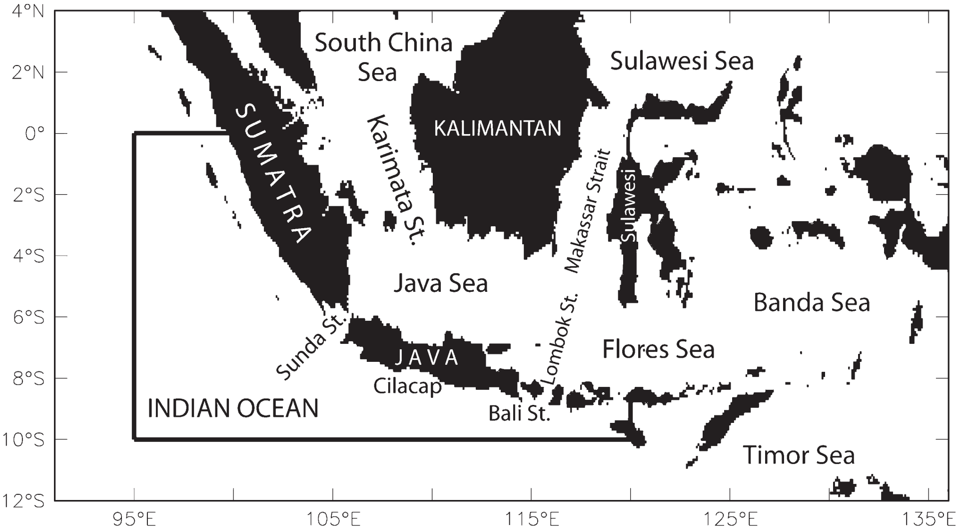

Figure 1. Topography of the southeastern tropical Indian Ocean, with names of the islands and straits discussed in the text. The study region is bounded by the black lines.

Java, which starts in June, reaches its peak in August, and diminishes in October–November (Susanto *et al.* 2001, Qu *et al.* 2005). Satellite-retrieved sea surface temperature (SST) and surface chlorophyll-*a* data show that the decrease in the SST off Java during the southeast monsoon is associated with the upwelling of nutrient-rich subsurface water supporting high primary productivity (Asanuma *et al.* 2003, Susanto *et al.* 2006).

Superimposed on this seasonal cycle, interannual oceanic variations associated with the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) events (Saji *et al.* 1999, Webster *et al.* 1999) may also influence oceanic conditions off Java and Sumatra. In particular, a typical IOD event is characterized by an extraordinarily low SST off Java–Sumatra and a higher SST in the central and western equatorial Indian Ocean off East Africa. The change in SST is associated with changes in wind patterns; anomalously strong southeasterly winds along the coasts of Java and Sumatra and anomalous easterly winds over the equatorial Indian Ocean are observed during the peak phase of the IOD (Saji *et al.* 1999). The IOD event is seasonally phase-locked; it develops at the beginning of the normal upwelling season (June–July), matures during October–November, and ceases during December. Therefore, in the presence of IOD events, the upwelling off Java and Sumatra becomes more intense, bringing more nutrients into the euphotic zone and leading to chlorophyll-*a* blooms (Murtugudde *et al.* 1999, Susanto and Marra 2005).

Many studies have interpreted the temporal variability of satellite-derived chlorophyll data using other satellite sensor data such as the SST, sea surface height (SSH) and wind fields (Murtugudde *et al.* 1999, Espinosa-Carreon *et al.* 2004, Thomas and Brickley 2006, Susanto *et al.* 2006). Using sea level data from TOPEX/Poseidon, sea surface wind data from the Special Sensor Microwave Imager (SSM/I) and surface chlorophyll data from the Sea-viewing Wide-Field of view Sensor (SeaWiFS), Murtugudde *et al.* (1999) demonstrated that the cold La Niña conditions during the boreal summer of 1998 were associated with upwelling equatorial Kelvin waves leading to a high chlorophyll concentration along the equatorial Pacific Ocean. In the eastern tropical Indian Ocean, however, the peak of the El Niño event in the boreal autumn–winter of 1997 caused an anomalous chlorophyll bloom off the coasts of Java and Sumatra.

In this study, we present evidence from ocean colour images of SeaWiFS for the occurrence of chlorophyll-*a* blooms along the southern coasts of Java and Sumatra during the 2006 southeast monsoon season. The bloom evolution is examined using multisensor remote sensing data.

2. Data

Eight-day composites of the SeaWiFS chlorophyll-*a* concentration data with a spatial resolution of 0.1° over the 9-year period from January 1998 to December 2006 were used in this study. The data were obtained using the National Aeronautics and Space Administration (NASA) Goddard Earth Sciences Data and Information Services Center (GES-DISC) Interactive Online Visualization and Analysis Infrastructure (Giovanni) (available at http://reason.gsfc.nasa.gov/Giovanni/).

The SST data used in this study were derived from the weekly Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) data for the period from January 1998 to December 2006. In addition, the weekly wind field data were obtained from a QSCAT scatterometer for the period from August 1997 to December 2006. Both the SST and wind field data were obtained at a spatial resolution of 0.25° (available at www.ssmi.com). The merged SSH data were derived from multiple satellite altimeters for the period from January 1998 to December 2006. The SSH data were obtained at a spatial resolution of 1/3° and are available at www.aviso.oceanobs.com.

Mean climatologies of chlorophyll-*a*, SST and SSH were calculated from time series over the period January 1998–December 2006, while those for wind fields were calculated over the period January 2000–December 2006. Anomaly fields for all variables were then constructed on the basis of deviations from their mean climatologies.

3. Results

3.1 *Seasonal variations of chlorophyll-a, SST and winds off Java and Sumatra*

Figure 2 shows the annual cycle of surface chlorophyll-*a* concentration and surface winds along the southern coasts of Java and Sumatra as monthly climatological series. The wind fields show distinct seasonal variation associated with the Asian–Australia monsoon. Upwelling-favourable (southeasterly) winds start in April–May (figures 2(*d*) and 2(*e*)). The winds intensify in June (figure 2(*f*)) and these southeasterly winds continue until October (figure 2(*j*)). On the contrary, the downwelling-favourable (northwesterly) winds prevail from December to March (figure 2(*l*–*c*)).

The oceanic response to the seasonally reversing monsoonal winds can be seen in the maps of chlorophyll-*a* distribution. Elevated concentrations of chlorophyll-*a* are first observed in June, with concentrations greater than $0.3\,\mathrm{mg\,m^{-3}}$ found in the eastern part and near the Sunda Strait (figure 2(*f*)). In July, there is an increase in chlorophyll-*a* concentration to a value of about $0.6\,\mathrm{mg\,m^{-3}}$ in the region along the southern coast of Java (figure 2(*g*)). The chlorophyll-*a* concentration increased significantly by August–September, forming a continuous band of high concentration

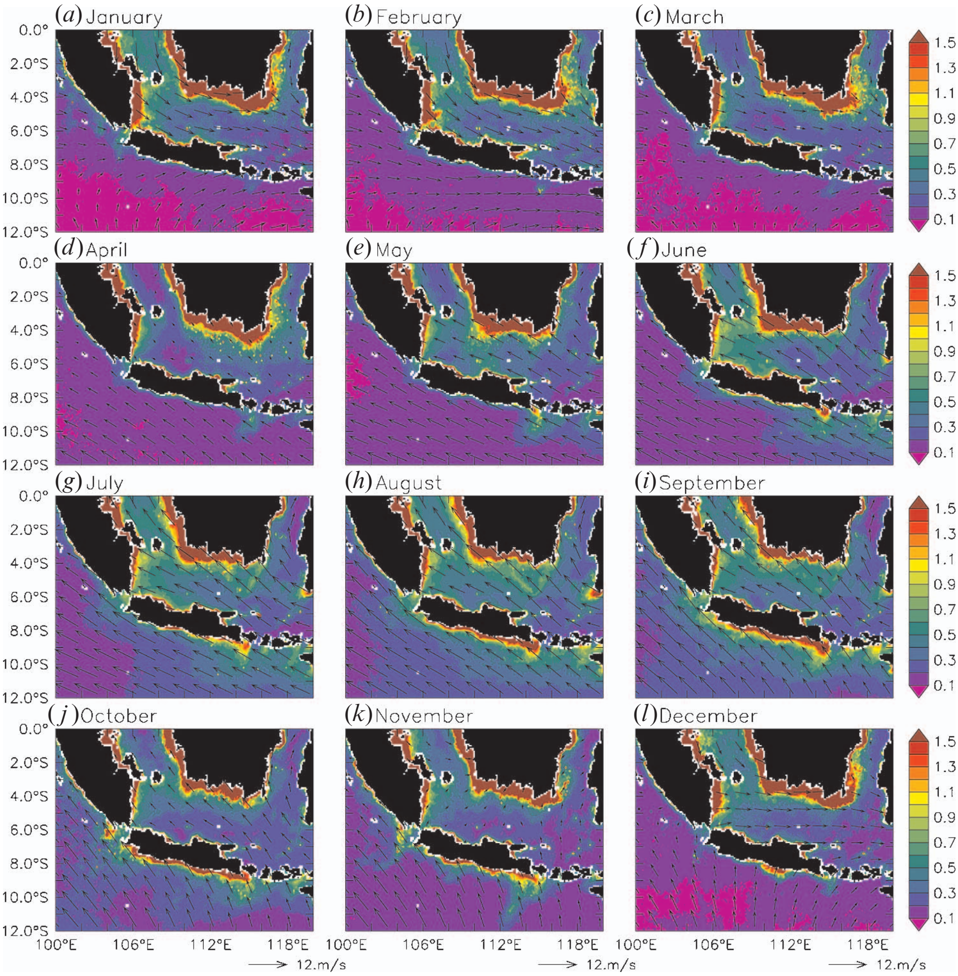

Figure 2. Monthly climatological maps of chlorophyll-*a* concentration (shaded, mg m^{-3}) and surface winds (arrows, m s^{-1}) in the southeastern tropical Indian Ocean.

(>1 mg m^{-3}) along the southern coast of Java (figures 2(*h*) and 2(*i*)). By November, the chlorophyll-*a* concentrations decrease progressively for the whole region (figure 2(*k*)). The prevailing northeasterly winds in December reduce the chlorophyll-*a* concentrations significantly and they remain low during the downwelling conditions (figures 2(*a*)–2(*c*)).

3.2 *Evolution of occurrence of anomalously strong chlorophyll-a bloom along the coasts of Java and Sumatra*

Surface chlorophyll-*a* anomalies along the southern coasts of Sumatra and Java over the 6-month period starting from July 2006 are shown in figure 3. The chlorophyll-*a* bloom started to develop in July, where positive anomalies (>0.5 mg m^{-3}) were first observed south of the Nusa Tenggara Islands chain in the vicinity of Sumba Island. In August, most of the study area from the south of Bali Island to the southern tip of Sumatra near the Sunda Strait shows positive anomalies (>1 mg m^{-3}). The anomalies intensified in September and expanded

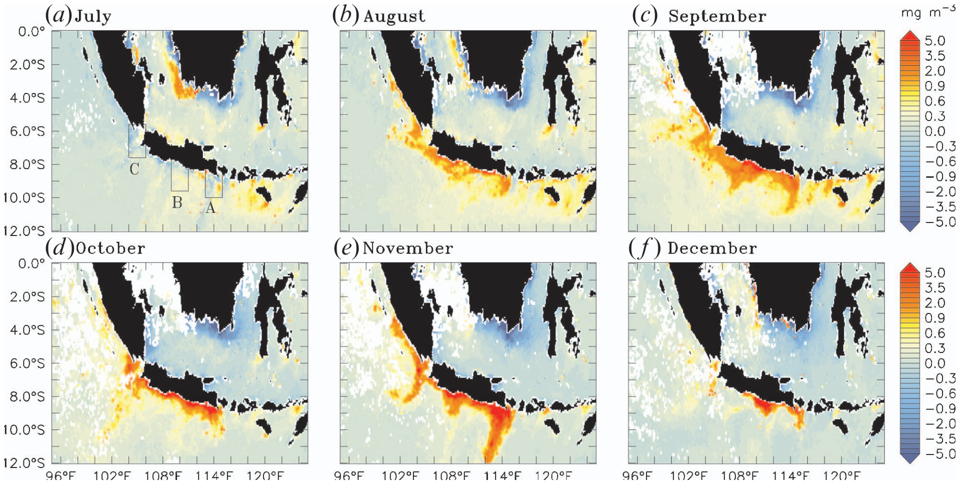

Figure 3. Monthly anomalies of SeaWiFS chlorophyll-*a* concentration (mg m^{-3}) along the southern coasts of Java and Sumatra for the period July–December 2006. The boxes shown in (*a*) are the regions in (A) Bali Strait, (B) Cilacap and (C) and Sunda Strait.

approximately 200 km offshore forming a continuous band of positive anomalies (>2 mg m^{-3}) from the south of Bali Island to the west of Sumatra. In October, a high chlorophyll-*a* concentration (>3 mg m^{-3}) was trapped towards the southern coast of Java. Then, positive anomalies (>3 mg m^{-3}) expanded further north and offshore in November. We note that there are three regions of high chlorophyll concentration with broader offshore extension: south of the eastern tip of Java, south of Cilacap in central Java, and south of Sunda Strait. The anomalies off the eastern tip of Java extended southwards to about 12° S. By December, positive anomalies (>1 mg m^{-3}) remained at the south of central and eastern Java, while the anomalies decreased significantly along the southern coasts of Sumatra and west Java.

3.3 *Chlorophyll-a bloom and the IOD*

The chlorophyll-*a* blooms during 2006 were evaluated in terms of coupled ocean–atmosphere dynamics. Figure 4 shows the time–longitude plot for chlorophyll-*a*, SST, SSH and wind anomalies along the southern coasts of Java and Sumatra during 2006.

Prior to the onset of the IOD, strong northwesterly winds from late January to early February were observed along the coast, leading to positive anomalies in SST and SSH and a negative anomaly in chlorophyll-*a* concentration. The northwesterly winds were weakened in mid-February and there were some minor episodic reversals in late February leading to negative anomalies in SSH and SST off Java. During March, the northeasterly winds again strengthened and a subsequent downwelling signal is shown by positive anomalies in SSH and SST off Java.

By early May, the northwesterly winds were weakened and gradually reversed direction in late May before setting to the southeast in June. This southeasterly wind excited upwelling off Java. However, in mid- to late July the evolution of the IOD was interrupted by incoming downwelling Kelvin waves generated in the equatorial Indian Ocean.

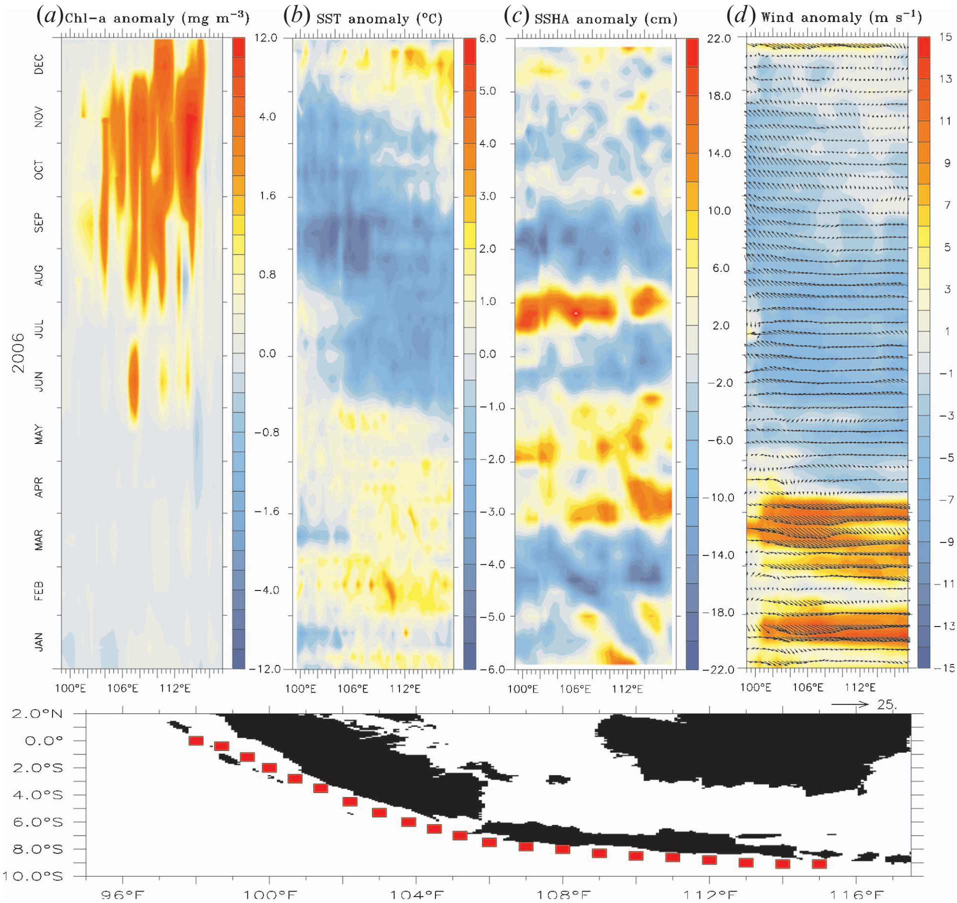

Figure 4. Longitude–time plots of anomalies of (*a*) chlorophyll-*a* concentration (mg m^{-3}), (*b*) sea surface temperature (°C), (*c*) sea surface height (cm) and (*d*) winds (arrows) superimposed over zonal wind speed (m s^{-1}; shaded) along the southern coasts of Java and Sumatra during January–December 2006. The path of sections is shown in the bottom panel.

In early August the southeasterly winds gradually strengthened and the IOD evolution started. Associated with these intensified southeasterly winds, the SST and SSH indicate a negative anomaly and the chlorophyll-*a* bloom started. The southeasterly winds reached their peak in September–October and the IOD was fully developed. They remained southeasterly until late November. Consequently, during this period a cold SST anomaly (SSTA) exceeding –3°C and a negative SSH anomaly (SSHA) of about –20 cm were observed off Java. A maximum chlorophyll-*a* concentration in excess of 4 mg m^{-3} was observed during this period.

The IOD was terminated in early December as the southeasterly winds episodically reversed direction before setting towards the southeast in late December. Corresponding changes were observed in the SSTA and SSHA, which indicate a positive anomaly off Java. The chlorophyll-*a* concentration off Sumatra and west Java also decreased significantly, but remained high off central and east Java.

It is also interesting to note that a very high chlorophyll-*a* concentration was observed at the eastern tip of Java (113–115° E) during late October to late

November, despite weak southeasterly winds along this region (see also figure 3(*e*)). Susanto and Marra (2005) also showed that a maximum chlorophyll-*a* concentration off Java during the upwelling season is located in the eastern tip of Java. This may suggest another forcing mechanism enhancing the upwelling of chlorophyll-*a* in this region.

To investigate the above intensification as well as its off-shore extension during November 2006, 8-day composites of chlorophyll-*a* concentration, weekly wind-stress curl and surface geostrophic currents are plotted in figure 5. This shows that the local cyclonic wind-stress curl (figures 5(*d*)–5(*f*)), by driving local upwelling, promoted the high concentration of chlorophyll-*a* away from the coast. Moreover, the offshore extension of the chlorophyll-*a* concentration is co-located with the northern flank of the cyclonic eddies observed along 12° S (figures 5(*d*) and 5(*g*)). These cyclonic eddies, which supply nutrients to the surface water, further enhanced the chlorophyll-*a* concentration. Asanuma *et al.* (2003) have shown that the Indonesian Throughflow (ITF) through the Lombok and Sumba straits further supplies nutrient-rich water to this region.

To analyse the interannual variability, time series of chlorophyll-*a* anomalies were extracted at three locations: south of the eastern tip of Java, south of Cilacap in Central Java, and south of Sunda Strait (as shown in figure 3). The time series are calculated by spatially averaging chlorophyll concentration over boxes centred at 105° E, 110° E and 115° E, respectively (figure 6). The temporal evolutions of spatial

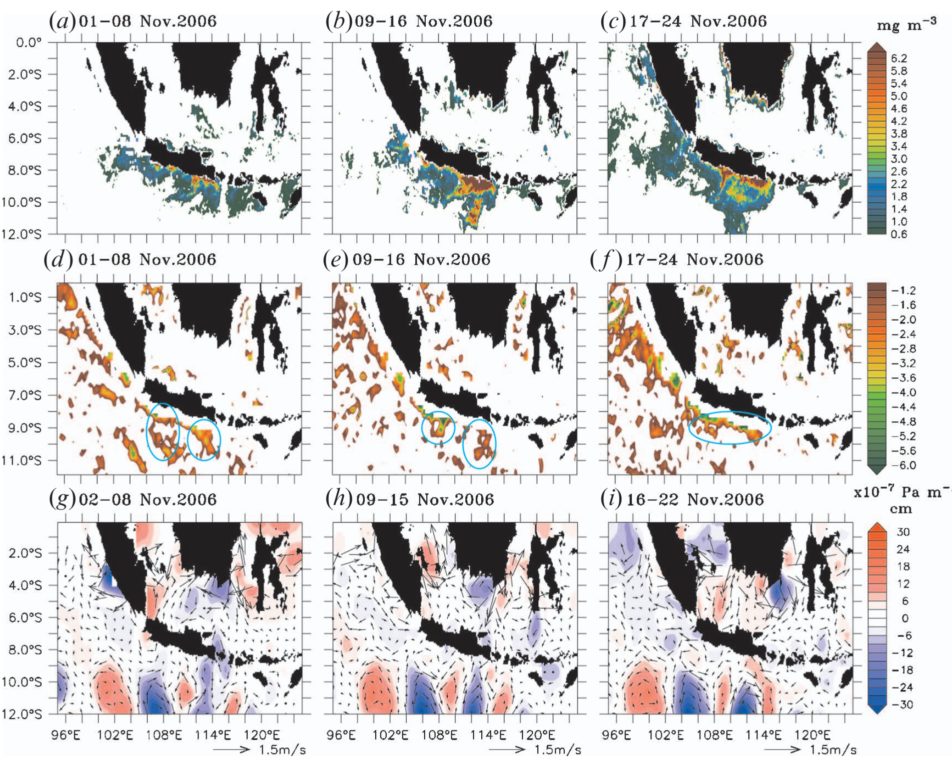

Figure 5. Distribution of (*a*–*c*) chlorophyll-*a*, (*d*–*f*) wind-stress curl and (*g*–*i*) sea surface height anomaly and geostrophic currents during November 2006. Only negative wind-stress curl (favourable for upwelling) is shown in (*d*–*f*).

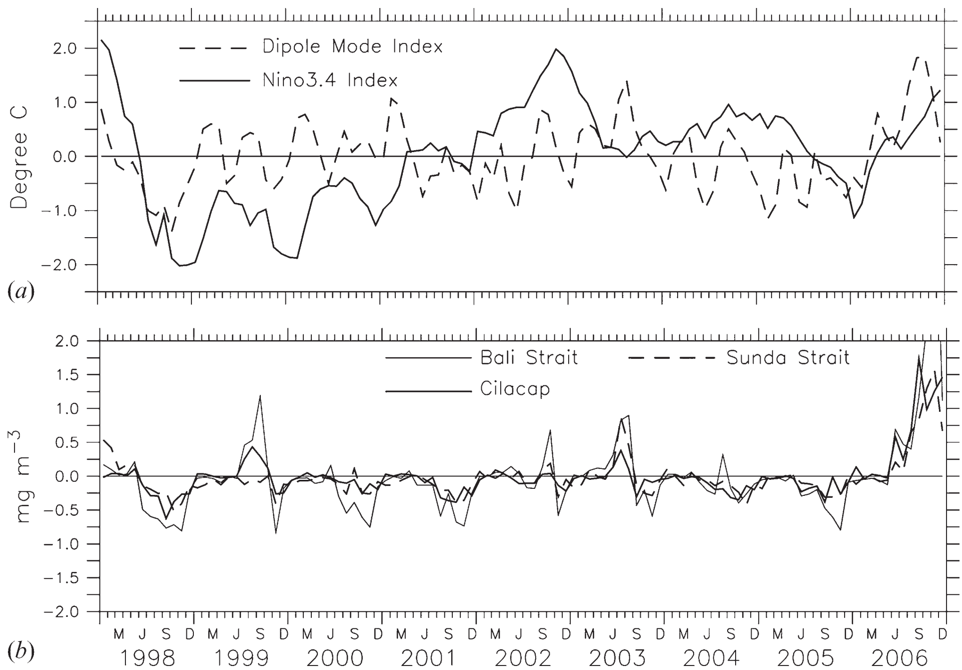

Figure 6. Time series of (*a*) the Dipole Mode Index (broken line) and the Niño3.4 Index (solid line) and (*b*) spatially averaged chlorophyll-*a* over the Bali Strait (thin line), Cilacap (thick line) and Sunda Strait (broken line) for the period January 1998–December 2006.

means clearly show interannual variations in chlorophyll-*a* concentration at all locations, where the anomaly in 2006 is the most prominent. The aborted IOD event in 2003 (Rao and Yamagata 2004) is also associated with a positive anomaly at all locations. In addition, positive anomalies with values exceeding $0.5\,\mathrm{mg\,m^{-3}}$ were evident at Bali Strait and Cilacap in 2002; the weak El Niño event. Similar blooms at Bali Strait and Cilacap were also observed during the southeast monsoon in 1999. Asanuma *et al.* (2003) attributed this bloom to the ITF, which brings nutrient-rich water from the Flores Sea during this period.

4. Conclusions

Chlorophyll-*a* concentration images from SeaWiFS show evidence for the occurrence of a chlorophyll-*a* bloom along the southern coasts of Java and Sumatra during the southeast monsoon of 2006. Stronger upwelling-favourable winds during this period associated with an IOD event promoted nutrient flux into the euphotic zone leading to a chlorophyll-*a* bloom. The evolution of the chlorophyll-*a* bloom followed the development of the IOD event, starting in July, peaking in September–October and diminishing in December. During the peak phase of the IOD, high chlorophyll-*a* concentrations exceeding $4\,\mathrm{mg\,m^{-3}}$ were observed off Java coinciding with negative SSTA and SSHA.

Although the upwelling-favourable winds along the coast initiated the offshore extension of chlorophyll-*a*, its intensification offshore was further enhanced by a series of westward-propagating cyclonic eddies. These cyclonic eddies, which are observed along 12° S, further promote nutrients to the euphotic zone. The time-series of spatially averaged cholorophyll-*a* concentration further showed that the region off eastern Java (Bali Strait) experienced greater variability compared to the other two regions. These inferences suggest that the relative control of winds and oceanic processes on chlorophyll-*a* distribution off Java and Sumatra are spatially dependent and their quantification will be a major challenge for future observational and modelling studies.

Acknowledgements
We thank Prof. T. Yamagata for valuable guidance throughout this study, and C. K. Tan for helpful discussion on the topic. Comments from two anonymous reviewers greatly helped to improve the quality of the manuscript. I.K. received support from the Japan Society for the Promotion of Science (JSPS). This work was supported by KAKENHI (19.07606). Ferret software was used for the graphics and analysis.

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