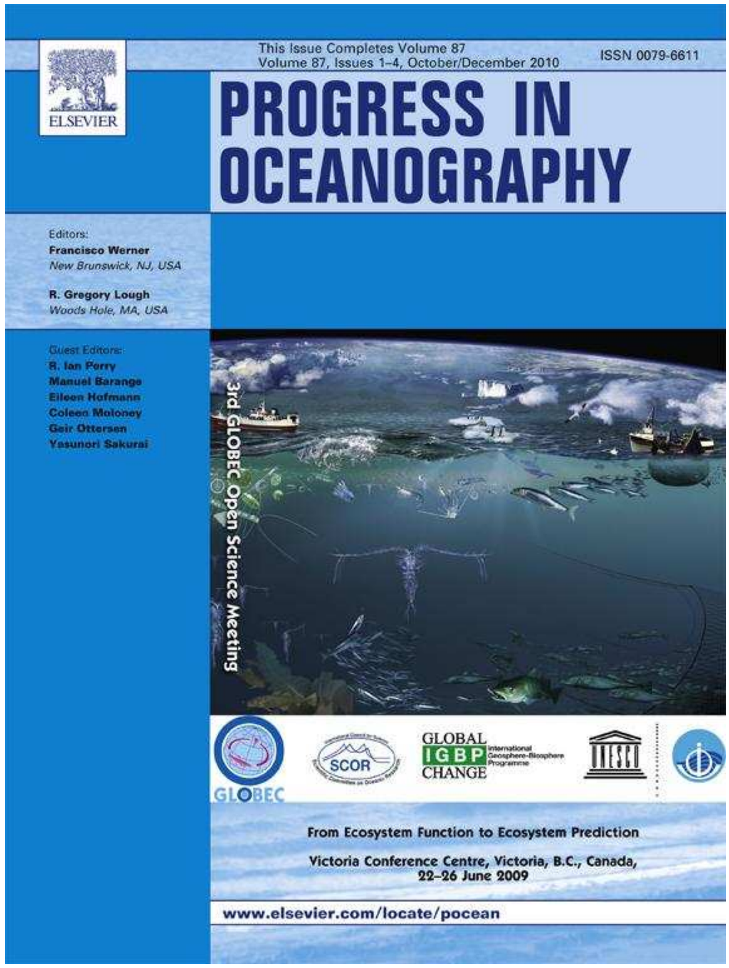
This Issue Completes Volume 87
Volume 87, Issues 1–4, October/December 2010
ISSN 0079-6611
ELSEVIER
PROGRESS IN OCEANOGRAPHY
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Victoria Conference Centre, Victoria, B.C., Canada,
22–26 June 2009
www.elsevier.com/locate/pocean

Progress in Oceanography 87 (2010) 168–174

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

# Variations in chlorophyll-a concentration and the impact on *Sardinella lemuru* catches in Bali Strait, Indonesia

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ARTICLE INFO

*Article history:*
Available online 19 September 2010

ABSTRACT

The variation of chlorophyll-a concentration during 2003–2007 was studied in Bali Strait, Indonesia, using Aqua-Modis satellite data, and their relationships with catch per unit of effort (CPUE) of *Sardinella lemuru*, sea surface temperature (SST) and indices of climate variability (Niño 3.4 and Indian Ocean Dipole Mode Index) were analyzed. An inverse relationship was found between SST and chlorophyll-a anomalies. Chlorophyll-a anomalies significantly increased at the end of 2006, reaching 1 mg/m$^3$ above normal. This increase corresponded with upwelling processes represented by a drop of SST during the El Niño event that coincided with changes in the Indian Ocean Dipole at the end of 2006. There was an unlagged response between chlorophyll-a and SST. However, there was an integrated response between chlorophyll-a and the CPUE of *S. lemuru*, such that increased catches (and CPUE) of *S. lemuru* were most highly correlated with increased chlorophyll-a in the prior three months.



## 1. Introduction

Bali Strait is located between Java Island and Bali Island, about 1200 km eastward from Jakarta, Indonesia (Fig. 1). As an upwelling area (Hendiarti et al., 2005; Susanto and Marra, 2005), it is nutrient rich with strong biological and fishery productivity. Increases of chl-a concentration occur due to upwelling events during Southeast Monsoons (Hendiarti et al., 2004). Anomalous easterly winds during the strong 1997/1998 El Niño followed by a La Nina coincided with an Indian Ocean Dipole (IOD) event to produce higher chlorophyll-a along the southern coast of Java (including Bali) and Sumatra (Susanto and Marra, 2005). Whether high chlorophyll concentrations have direct or indirect impacts on *Sardinella lemuru* catches is not clear from previous studies.

Bali Strait is characterized by cool temperatures and low salinity and is affected by both Indonesian through flow and mixing in the Pacific Ocean (Gordon, 2005). The mechanisms that generate and maintain sea surface temperature (SST) within the Indonesian Sea occur as a consequence of the complex topography and connectivity between the Pacific and Indian Oceans. In addition to surface heat fluxes, intense tidal mixing of surface and thermocline water driven remotely by winds over the Pacific and Indian Oceans plays an important role in generating and maintaining SST. SST variability in the region is generally small compared with that in the tropical eastern Pacific due to a lack of strong equatorial upwelling. However, higher variability (>4.0 °C) occurs along and offshore of the Java (including Bali Strait) and Sumatra Coasts, indicative of a strong remote influence of the equatorial Indian Ocean combined with local upwelling (Qu et al., 2005). The strong tidal mixing and seasonal upwelling also influences chl-a concentration in this area (Hendiarti et al., 2005). The variability of SST and chl-a are affected by monsoon cycles. As explained by Susanto and Marra (2005), during Southeast monsoons (April–October), southeasterly winds from Australia generate upwelling, bringing cooler waters and increased nutrients to the surface along the south coast of Java (including Bali) and Sumatra. Conditions are reversed during the northwest monsoon (October–April).

*Sardinella lemuru* is the dominant species (more than 90% of total catch) in the pelagic fishery of Bali Strait (Merta, 1992a,b; Hendiarti et al., 2005). *S. lemuru* is a coastal schooling species and is also known as a strong migratory species. Its distribution includes the Eastern Indian Ocean (Thailand, southern coast of East Java and Bali, Western Australia) and the western Pacific (Java Sea north to the Philippines, Hong Kong, Taiwan, and southern Japan) (Carpenter and Niem, 1999; Pauly ad Martosubroto, 1996). The fish come to shore especially in the northern part of the Bali Strait where salinity is low (during the rainy season) for spawning (usually September–February, but the peak is in December–January). Growing fish move towards the shelf of Bali closer to the Indian Ocean, while mature fish are caught in the south of Bali Strait (Indian Ocean) (modified distribution map, Fig. 2) (Carpenter and Niem, 1999; Pauly and Martosubroto, 1996; Dwiponggo and Burhanuddin, 1980; Martosubroto and Pauly, 1976). Seasonal

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doi:10.1016/j.pocean.2010.09.002

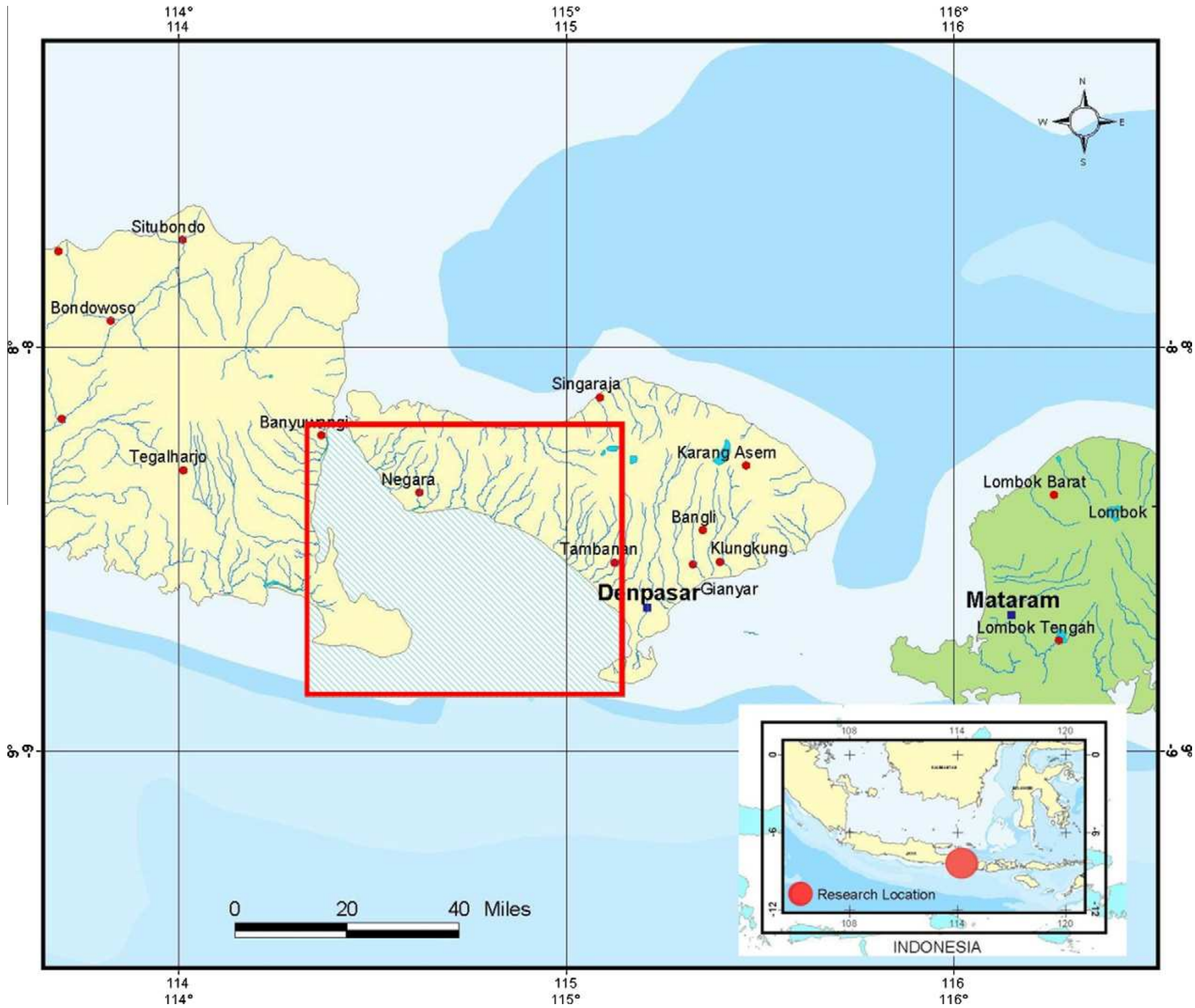


**Fig. 1.** The study area (red square). Bali Strait (latitude 8.1°S, 9.2°S; longitude 114.2°E, 115.3°E) is located between Java Island and Bali Island, Indonesia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fluctuations of catches are highly correlated with changes in oceanographic conditions (Hendiarti et al., 2005).

The variability of chlorophyll-a concentration may play an important role in the *Sardinella lemuru* catches in Bali Strait. The existence of such a link in the Bali Strait, between chlorophyll-a concentration and *S. lemuru*, is not clear from the existing literature. Although several studies in the last decades have discussed *S. lemuru* in Bali Strait, Java Sea and the Indian Ocean (Dhulkhed, 1962; Kagwade, 1964; Burhanuddin and Praseno, 1982; Carpenter and Niem, 1999; Merta et al., 1995), there are only a few studies that describe its food habits (Carpenter and Niem, 1999; Burhanuddin and Praseno, 1982; Merta et al., 1995), and the variability of chl-a and the fishery for *S. lemuru* in Bali Strait (Hendiarti et al., 2005).

We hypothesized that changes in chl-a abundance due to upwelling during ENSO and IOD events indirectly affects the *S. lemuru* catches in Bali Strait. By using satellite-derived chl-a, SST, two indices of climatic variability (Niño 3.4 and IOD), and *S. lemuru* catch time series data, we investigated the variability of chl-a concentration and its impact on *S. lemuru* catches in 2006.

## 2. Methods

This study focused on fishing locations of *S. lemuru* in the Bali Strait area as shown in Fig. 1. Since there is a lack of data of environmental data for these fishing locations, satellite data were used. Monthly average sea surface temperature (SST) (2003–2007) data derived from the Terra-Modis level 3 (version 4) (Terra-Moderate-resolution Imaging Spectroradiometer) satellite and chlorophyll-a data derived from the Aqua-Modis level 3 satellite were downloaded from the NASA Goddard Space Flight Centre (GSFC) through the following website http://oceancolor.gsfc.nasa.gov/cgi/. These data are 4-km pixel resolution products in hdf format.

Monthly average Niño 3.4 and Indian Ocean Dipole (IOD) indices were used to examine the possible relationships of climate variability with chl-a and *Sardinella lemuru* in Bali Strait. Niño 3.4 defines an average of sea surface temperature anomalies within the tropical western Indian Ocean (50°E–70°E, 10°S–10°N) and the tropical southeastern Indian Ocean (90°E–110°E, 10°S–Equator) (Saji et al., 1999; Susanto and Marra, 2005). Positive and negative Niño 3.4 values indicate El Niño (SST low) and La Niña (SST high), respectively. Niño 3.4 values were downloaded from the NOAA website: http://www.cpc.noaa.gov/data/indices. The Indian Ocean Dipole (IOD) is an ocean–atmosphere coupled phenomenon between the Indian Ocean and the equator (Saji et al., 1999), which is also known as the Indian Ocean Zonal (IOZ) mode (Webster et al., 1999). The positive phase of the IOD is characterized by an east–west dipole pattern in SST anomalies spanning the Indian Ocean basin (between Africa and Indonesia). A positive IOD is usually accompanied by heavy

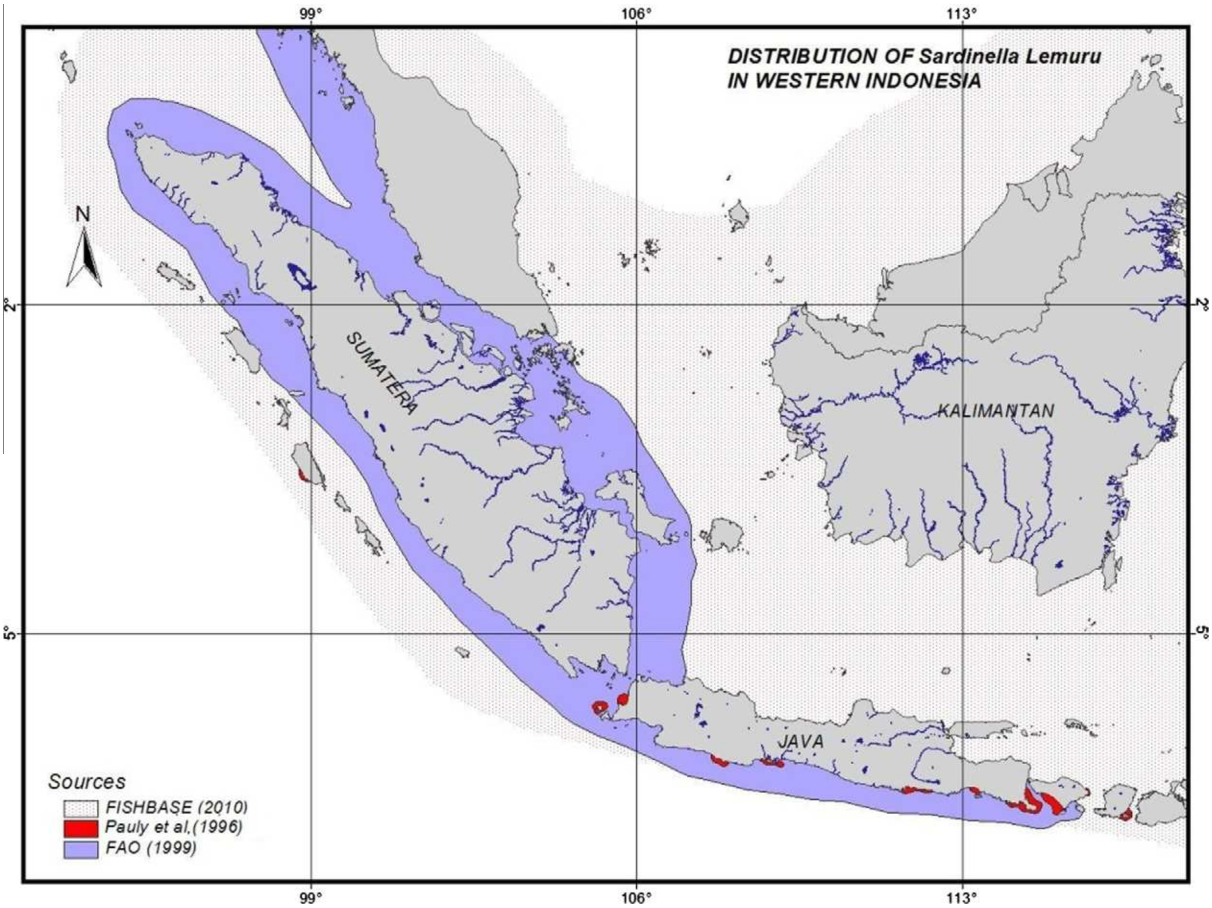


**Fig. 2.** Map of *S. lemuru* distribution in Western Indonesia, modified from FAO (Carpenter and Niem, 1999, light blue); Pauly et al. (1996, red); and Fishbase (2010, light gray). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

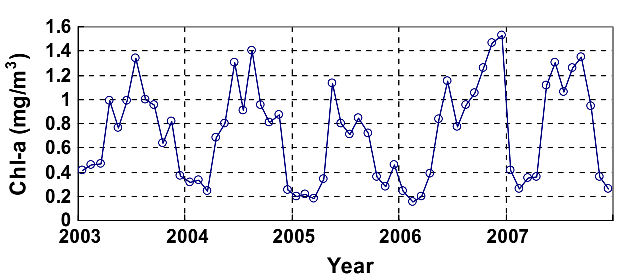


**Fig. 3.** Time series of monthly mean chlorophyll-a concentration (2003–2007).

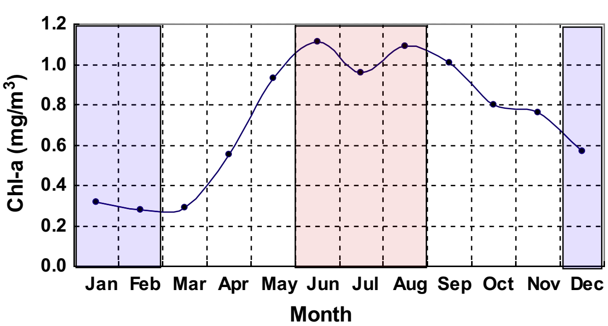


**Fig. 4.** Seasonal variation of chlorophyll-a concentration in Bali Strait. Its seasonal variation follows a monsoonal pattern, Southeast monsoon (June–August), Northwest monsoon (December–February), transition I (March–May), and transition II (September–November).

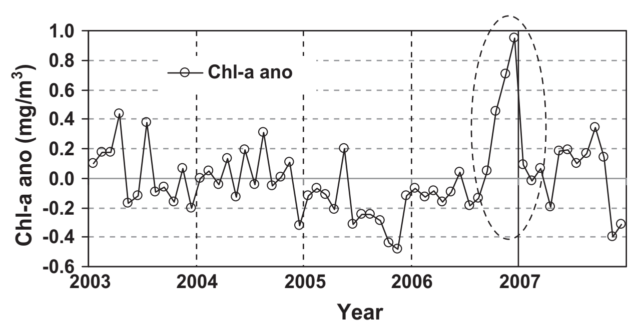


**Fig. 5.** Time series of chlorophyll-a anomalies. During the 5 years studied (2003–2007) chlorophyll-a showed the highest anomalies at the end of 2006, reaching five times above average.

rainfall in eastern Africa and droughts in Indonesia. Like the Pacific ENSO, the evolution of the IOD is strongly locked to the annual cycle. In active years, cold SST anomalies off Java and Sumatra typically develop in June–August and peak in September–October, while warm SST anomalies in the western Indian Ocean occur later (Qu et al., 2005). IOD data were obtained from http://www.jamstec.go.jp/frsgc/research/d1/iod/jamstec.

The monthly mean catches (2003–2007) of adult *Sardinella lemuru* (about 18–20 cm standard length) were provided by the Marine and Fisheries Agency of Jembrana, Bali and the Fisheries Harbour of Muncar, Banyuwangi (Indonesia). Catch per unit of effort (CPUE) was used in this study in order to minimize problems in catch data collection.

Monthly mean SST, chl-a, and CPUE of *S. lemuru* in Bali Strait were plotted as time series from 2003 to 2007. To investigate unusual phenomena in these time series, the anomaly method was used. This method indicates deviations from normal monthly values (Davis, 1976; Emery and Thomson, 1997). The 3 month moving average method was applied to understand the relationship between the chl-a and CPUE time series. Correlations between SST and chl-a, and for chl-a (after applying a 3-month moving average) and CPUE were examined using Pearson's correlation coefficient.

To understand possible effects of climate variability on the chl-a and CPUE of *S. lemuru* in Bali Strait, we used Principal Components Analysis (PCA), which is a common way of identifying and expressing patterns in the data in such way as to highlight their similarities and differences.

## 3. Results and discussion

### 3.1. Variability of chl-a concentration

Analysis of 5-year (2003–2007) composite monthly mean chl-a showed that there was seasonal variability of chl-a in Bali Strait (Fig. 3). The maximum and minimum chl-a concentration occurred in December 2006 (about 1.526 mg/m$^3$) and February 2006 (about 0.150 mg/m$^3$), respectively. According to Hatta (2002), this is categorized as a high (>0.14 mg/m$^3$) concentration of chl-a for this region. Seasonal variation of chl-a in Bali Strait follows a monsoonal pattern (Fig. 4; Realino, 2007): Southeast monsoon (June–August), Northwest monsoon (December–February), transition I (March–May), and transition II (September–November). To understand the characteristics and abnormal pattern of chl-a concentration at Bali Strait, anomaly analysis was used. Positive/negative values of chl-a anomalies indicate the chl-a concentration is above/below normal, respectively (Fig. 5). Prominent low abundance of chl-a occurred in 2005 and at the end of 2007, whereas prominent high abundance of chl-a occurred at the end of 2006, when it reached nearly 1 mg/m$^3$ above normal.

### 3.2. SST and chl-a

Fig. 6 shows that most declines in SST were followed by increases of chl-a in Bali Strait during the study period (2003–2007). This indicates that the increase in chl-a is strongly influenced by upwelling processes. Prominent high chl-a concentrations (nearly 1 mg/m$^3$ above normal) appeared in 2006 when SST dropped about −0.6 °C below normal. However, prominent low chl-a concentrations occurred in 2005 and at the end of 2007. The correlation between SST and chl-a concentration is shown in Fig. 7a. There is a significant negative correlation between SST and chl-a in Bali Strait ($r = 0.56$; $p < 0.005$).

### 3.3. Chl-a and CPUE of S. lemuru

Hendiarti et al. (2005) mentioned that Bali Strait is dominated by small pelagic species including *S. lemuru*, due to the inflow of recently upwelled water. The maximum of the *S. lemuru* fishing

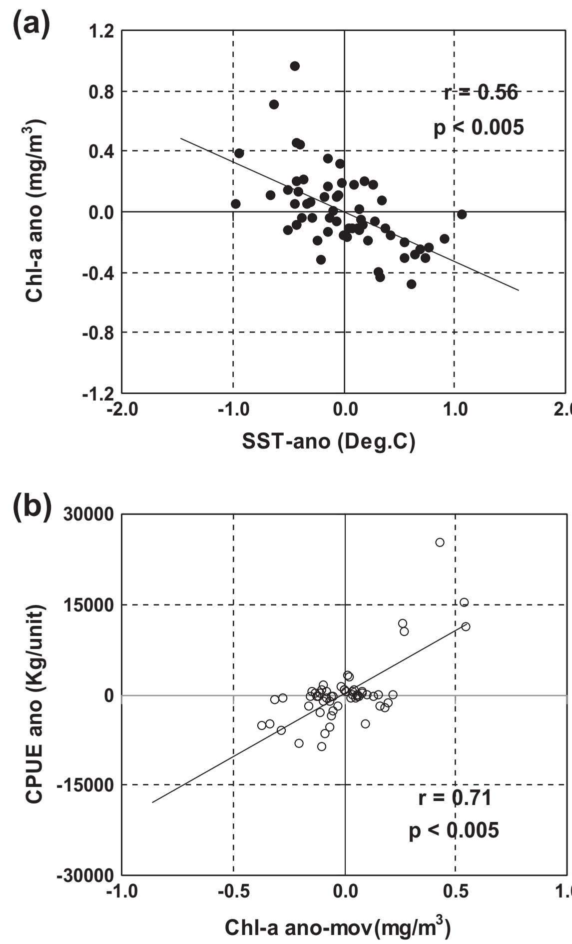


**Fig. 7.** Significant correlation between chl-a anomaly and SST anomaly (a) and between chl-a anomaly (with a 3 month moving average) and CPUE anomaly of *Sardinella lemuru* (b). Dynamics of chl-a follow the dynamics of SST, in which drops of SST are followed by increases in chl-a (a) while increases in chl-a generated increased CPUE of *S. lemuru* three months later (b).

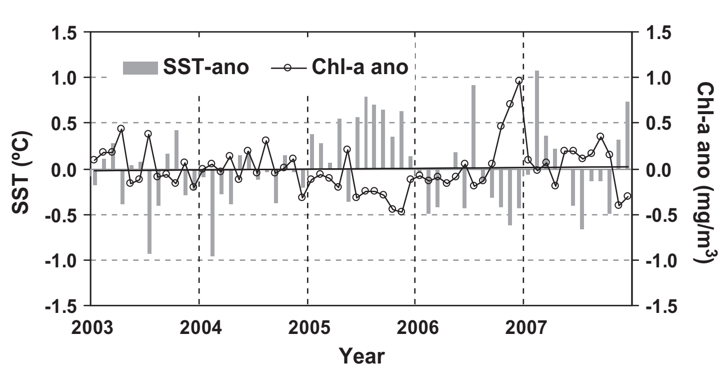


**Fig. 6.** Chlorophyll-a and SST variation at Bali Strait (2003–2007). Decreased SST due to strong anomalous easterly winds during El Niño and Indian Ocean Dipole events in 2006 generated anomalous upwelling and produced high chl-a.

season is in September–November, while the minimum is in March–April. In 2006, there was an indirect response of chl-a on *S. lemuru* CPUE. After applying a 3-month moving average to the chl-a, the result showed that chl-a and CPUE of *S. lemuru* were well matched (Fig. 8). This significant positive correlation is shown by Fig. 7b, with $r = 0.71$, $p < 0.005$.

The highlight event during the 5-year study occurred in 2006 because of unusually high chl-a concentration. Relationships among satellite derived SST, chl-a, and CPUE of *S. lemuru* are shown in Supplementary Fig. 1. In September 2006, when SST = 25.91 °C, chl-a = 1.055 mg/m$^3$, the CPUE of *S. lemuru* reached 18256.6 kg/unit. In October 2006, when SST = 26.96 °C, chl-a = 1.256 mg/m, the CPUE of *S. lemuru* reached 34853.4 kg/unit. In November 2006, when SST = 28.21 °C, chl-a = 1.468 mg/m$^3$, the CPUE of *S. lemuru* reached 15251.2 kg/unit. In December 2006, when SST = 29.25 °C, chl-a = 1.526 mg/m$^3$, the CPUE of *S. lemuru* reached 3200.9 kg/unit. In comparison, the low chl-a concentration in 2005 (Supplementary Fig. 2) resulted in the following values: in January 2005, when SST = 30.07 °C, chl-a = 0.201 mg/m$^3$, the CPUE of *S. lemuru* reached 2431.5 kg/unit; in February 2005, when SST = 30.57 °C, chl-a = 0.214 mg/m$^3$, the CPUE of *S. lemuru* reached 2289.2 kg/unit; in March 2005, when SST = 30.06 °C, chl-a = 0.177 mg/m$^3$, the CPUE of *S. lemuru* reached 2433.9 kg/unit; and in April 2005, when SST = 30.28 °C, chl-a = 0.340 mg/m$^3$, the CPUE of *S. lemuru* reached 2982.0 kg/unit.

### 3.4. Effect of climate variability on SST, chl-a, and CPUE S. lemuru

The steep increase of chl-a in 2006 may be particularly important to the climate variability issue. The time series of climate indices (such as Niño 3.4 and IOD), SST anomaly, and chl-a anomaly are shown in Fig. 9. High chl-a concentrations occurred with upwelling during the Southeast monsoon cycle. Strongly positive Niño 3.4 in 2006 indicated an El Niño event (SST low). This event coincided with a strong positive Indian Ocean Dipole (SST low). Connections between the strong El Niño and IOD strengthened the Southeast monsoon generated upwelling, producing higher chl-a concentrations at Bali Strait in 2006 than in other years. A similar process occurred in 1997/1998 along the southern coast of Sumatra and Java (including Bali) as reported by Susanto and Marra (2005).

Ocean-colour variability in Indonesian waters is affected by the monsoonal wind system and interannual forcing associated with ENSO and the IOD, particularly in the upwelling region along the coasts of Java (including Bali) and Sumatra, and the Banda Sea (Susanto and Marra, 2005; Susanto et al., 2006). The Northwest monsoon (December–February) is characterized by low chlorophyll-a, while the Southeast monsoon (June–August) is characterized by high chlorophyll-a concentration. El Niño events which coincide with positive IOD (low water temperatures in South Indonesia including Bali) produce significant departures of chl-a

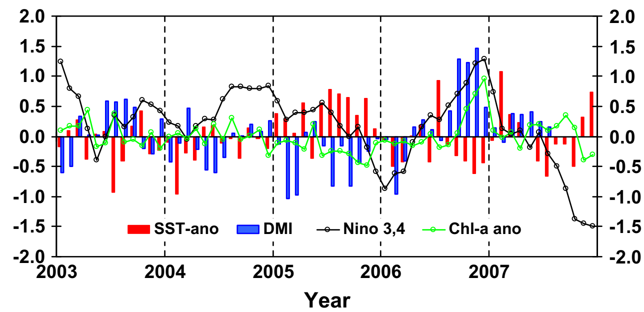


**Fig. 9.** Temporal variability of chl-a anomalies (green line) and SST anomalies (red bar) at Bali Strait, overlaid with climate indices: Niño 3.4 (black line) and Indian Ocean Dipole (Dipole Mode Index-DMI, blue bar). High anomalies of chl-a at the end of 2006 occurred with strong positive values of the El Niño and Indian Ocean dipole indices, and strong negative SST anomalies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in both magnitude and timing of the seasonal response to the Southeast monsoon. During these events, ocean colour intensifies in the upwelling region along the south coasts of Java and Sumatra. The area of increased ocean colour extends westward and prolongs the Southeast monsoon period. Supplementary Fig. 2 shows the high chl-a concentration derived from Aqua-MODIS during the transition II period (September–November) and beginning of the northwest monsoon (December), with high chl-a spreading southward and westward of Bali Strait to the south coast of Java and Sumatra even into the Indian Ocean. As a result, the impacts of the Southeast monsoon (June–August) were prolonged until November. High chl-a was followed by increased CPUE of *S. lemuru* in Bali Strait (more than 15,000 kg/unit) during the positive Niño 3.4 and IOD. In comparison (Supplementary Fig. 2), when the IOD was negative in 2005 (high water temperature in South Indonesia, including Bali Strait), the chl-a concentration was low followed by low CPUE of *S. lemuru* in Bali Strait (less than 5000 kg/unit) . Principal component loadings from the correlation matrix of PCA analysis among IOD, Niño 3.4, chl-a and CPUE of *S. lemuru* in Bali Strait (Table 1) showed that IOD, chl-a, and CPUE of *S. lemuru* were located in PC 1, whereas Niño 3.4 was in PC 2. This means that the

**Table 1**
Principal component analysis. Principal component loadings from the correlation matrix among the Indian Ocean Dipole (IOD), Niño 3.4, chl-a and CPUE of Sardinella lemuru in Bali Strait, Indonesia, during 2003–2007. Chl-a and CPUE were mainly affected by IOD and strengthened by Niño 3.4.

| Components | Comp. 1 | Comp. 2 | Comp. 3 | Comp. 4 |
|---|---|---|---|---|
| IOD | 0.56 | −0.63 | 0.51 | −0.09 |
| Niño 3.4 | 0.42 | 0.78 | 0.45 | 0.03 |
| Chl-a | 0.89 | −0.11 | −0.21 | 0.36 |
| CPUE | 0.86 | 0.14 | −0.34 | −0.33 |

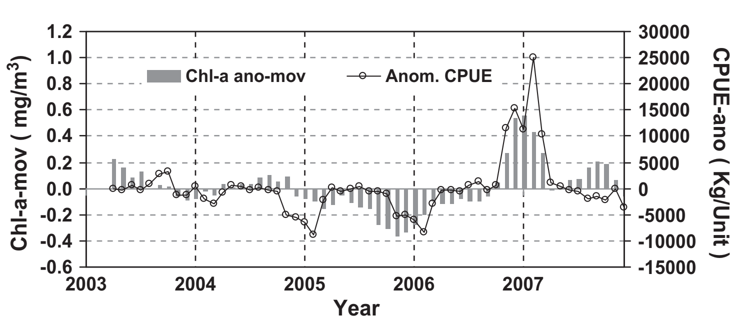


**Fig. 8.** Time series of chl-a anomaly (with a 3 month moving average) and *S. lemuru* CPUE anomaly at Bali Strait (2003–2007). At the end of 2006 and early 2007, chl-a anomalies match well with the CPUE anomaly after applying a 3-month lag.

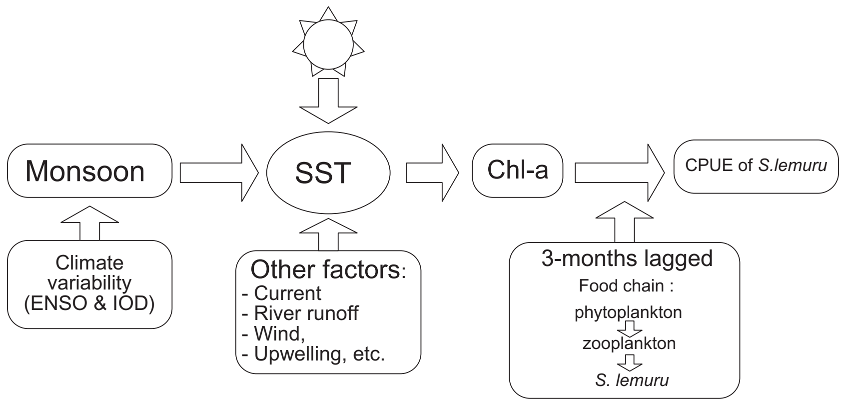


**Fig. 10.** Schematic of possible impacts of climate variability on catch per unit of effort (CpUE) of *S. lemuru*. It requires about 3-months to transfer energy from chl-a to *S. lemuru* in their food chain. IOD: Indian Ocean Dipole.

variability of chl-a and CPUE of *S. lemuru* was mainly affected by IOD events, and strengthened by Niño 3.4.

Schematically, the possible effect of climate variability on *S. lemuru* CPUE in Bali Strait is presented in Fig. 10. Chlorophyll-a concentration in Bali Strait follows the monsoonal patterns: Southeast monsoon, transition I, northwest monsoon, and transition II. Southeast/northeast monsoon defines upwelling/downwelling processes which bring cooler/warmer water to the surface of Bali Strait. Water temperature depends on solar intensity and other factors (e.g. currents, river runoff, wind, upwelling, etc.). Climate variability (as indexed by El Niño and IOD) tend to prolong the monsoon period intensifying upwelling events, followed by increased chl-a concentrations. Increased chl-a does not directly increase the CPUE of *S. lemuru*, as there is approximately a 3 month integration between high chl-a concentration and high *S. lemuru* CPUE. There is some confusion regarding the food habits of *S. lemuru*, since it is reported that *S. lemuru* feeds on both phytoplankton and zooplankton (Carpenter and Niem, 1999). Dhulkhed (1962) and Kagwade (1964) mentioned that *S. lemuru* feeds on phytoplankton (diatoms and dinoflagellates) and then copepods, while Burhanuddin and Praseno (1982) and Merta et al. (1995) found that *S. lemuru* feeds mostly on zooplankton (about 90–95%, mainly copepods). The last two references are more suitable for the feeding habits of *S. lemuru* in Bali Strait, and indicate that more time is needed to transfer chl-a to *S. lemuru* via the food chain. We conclude that *S. lemuru* caught in Bali Strait were mature fish and preferred to feed on zooplankton rather than phytoplankton. Larink and Westheide (2006) mentioned that the peak production of zooplankton follows the peak production of phytoplankton by about two months. If it is assumed that another month is needed to transfer energy from zooplankton to *S. lemuru*, then a 3 month integration between chl-a and *S. lemuru* CPUE in Bali Strait is reasonable.

There is no mention in available studies of *S. lemuru* of the effect of weather on catches of *S. lemuru* and the changes in circulation patterns during unusual phenomenon (such as El Niño), whereas changes of chl-a concentration due to El Niño have been reported by Susanto et al. (2006). The relatively calm weather and water circulation patterns do not seem to be a threat for fishermen who fish in Bali Strait compared to the difficult weather conditions, water circulation, and high waves of the Indian Ocean.

## 4. Conclusion

The variability of chlorophyll-a concentration in Bali Strait, Indonesia, follows monsoonal patterns: Southeast monsoon (June–August), transition II (September–November), Northwest monsoon (December–February), and transition I (March–May). Southeast monsoons are characterized by high chl-a due to southeasterly winds from Australia leading to upwelling, which causes cooler waters and increased nutrients at the surface along the south coast of Java (including Bali) and Sumatra, while northwest monsoons produce the inverse conditions. The year 2006 was a special case for Bali Strait because of an unusual increase of chl-a concentration (about 1 mg/m$^3$ above normal). It coincided with an El Niño event and was modified by the IOD. During this event, ocean colour derived from satellite (Aqua-MODIS) showed a westward spreading of chl-a. This is the first study that found a 3-month lag response between chl-a and catch per unit effort of *S. lemuru* in Bali Strait. This discovery has altered our understanding of indirect effects of climate variability on this marine ecosystem. If, as it appears, *S. lemuru* feeds mostly on zooplankton rather than phytoplankton, then approximately three months are needed to transfer energy from chl-a (phytoplankton) to zooplankton and then to *S. lemuru*. Understanding these mechanisms will aid forecasting of possible biological responses and assist in marine resource management practices in this area.

## Acknowledgments

We thank the National Oceanic and Atmospheric Administration (NOAA) for the production and distribution of the Indian Ocean Dipole Index and Nino 3.4 data, Aqua-Modis for chlorophyll-a data, Terra-Modis for SST data, Marine and Fisheries Agency of Jembrana, Bali (Indonesia) and Coastal Fisheries Harbour of Muncar, Banyuwangi (Indonesia) for lemuru catch data. We are grateful to BROK-SEACORM-Bali staff for their help with satellite data, Dr. Ian Perry and other three anonymous reviewers for their valuable comments. This study was supported by University of Brawijaya, Indonesia and Globec IPO, UK. This paper was presented at the 3rd Globec Open Science Meeting on "From ecosystem function to ecosystem prediction" held on June 22–26, 2009, in Victoria, BC, Canada.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.pocean.2010.09.002.

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