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# Upwelling along the coasts of Java and Sumatra and its relation to ENSO

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**Abstract.** Upwelling along the Java-Sumatra Indian Ocean coasts is a response to regional winds associated with the monsoon climate. The upwelling center with low sea surface temperature migrates westward and toward the equator during the southeast monsoon (June to October). The migration path depends on the seasonal evolution of alongshore winds and latitudinal changes in the Coriolis parameter. Upwelling is eventually terminated due to the reversal of winds associated with the onset of the northwest monsoon and impingement of Indian Ocean equatorial Kelvin waves. Significant interannual variability of the Java-Sumatra upwelling is linked to ENSO through the Indonesian throughflow (ITF) and by anomalous easterly wind. During El Niño episodes, the Java-Sumatra upwelling extends in both time (into November) and space (closer to the equator). During El Nino (La Niña), the ITF carries colder (warmer) water shallowing (deepening) thermocline depth and enhancing (reducing) upwelling strength.

## 1. Introduction

Because of unique positions of the islands of the Indonesian maritime continent, they experience a strong response to monsoon and El Niño-Southern Oscillation (ENSO) climate phenomena. The monsoon and ENSO, and the complex interplay between the two, may be influenced by sea-air exchange processes and interocean throughflow within the Indonesian Seas [*Potemra and Lukas*, 1999; *Webster et al.*, 1999; *Godfrey*, 1996, *Tourre and White*, 1997]. During the southeast (SE) monsoon, southeasterly wind from Australia generates upwelling along the Java-Sumatra coasts. Conditions are reversed during the northwest (NW) monsoon. Understanding the spatial and temporal evolution of upwelling is an important factor for coastal fisheries. During the monsoon transition periods, i.e. April-May and October-November, equatorial westerlies generate equatorial downwelling Kelvin waves propagating eastward and become coastally trapped waves along the Sumatra and Java Islands [*Clarke and Liu*, 1993; *Sprintall*, 2000]. These waves play important roles in the upwelling and downwelling processes along these coasts.

The basic feature and the existence of upwelling along Java and Sumatra coasts have been documented by previous scientists [see i.e. *Bray et al.*, 1996; *Potemra and Lukas*, 1999]. Using numerical model, *Murtugudde et al.* [2000] showed analysis of the forcing mechanism responsible for this upwelling. *Saji et al.* [1999] argue that the interannual variability of cooler SST along the Java and Sumatra Islands is related to a dipole in the Indian Ocean, which is independent of ENSO and results from air-sea interaction inherent to the Indian Ocean. *Webster et al.*, [1999] concluded that the 1997/1998 anomaly, in spite of coincidence with the ENSO, may primarily be due to Indian Ocean internal dynamics, rather than a direct response to external influences. Meanwhile, *Venzke et al.,* [2000] and *Tourre and White* [1997] argue that although the Indian Ocean region exhibits ENSO-independent interannual variability, a considerable part of the interannual SST variability can be described as a response to interannual fluctuations over the Pacific Ocean related to ENSO. *Murtugudde at al.*, [2000] showed interannual variability in the region, while coincident with ENSO, is not controlled entirely by ENSO.

In this study, we present analysis of the seasonal evolution and interannual variability of upwelling along the southern Java-Sumatra coasts, and we quantify the west-northwestward propagation of the upwelling center during the course of the SE monsoon. We hypothesize that interannual variability of upwelling along the coasts of Java and Sumatra is coupled to ENSO, through atmosphere and ocean teleconnections.

In order to examine the detailed structure and evolution process of upwelling along the Java and Sumatra coasts, high-resolution data, both temporal and spatial, are needed. The following data sets are included: the gridded weekly optimal analysis of SST from November 1981 to July 1999 [*Reynolds and Smith*, 1994]; 10 days gridded sea surface height anomaly (SSHA) derived from TOPEX/Poseidon (T/P) altimeter from October 1992 to July 1999; and gridded weekly wind stress derived from ERS-1/2 (European Remote Sensing satellites) scatterometers from November 1991 to July 1999; and thermal structure from hydrographic and XBT/MBT data in the region (95°E to 115°E and –10°N to 1.5°N) from 1970 to 2000.

## 2. Monsoon Generated Upwelling

The standard deviation of monthly average SST (Fig. 1) reveals that the region of most variability is along the coasts of Java and Sumatra. The active feature propagates along the Java and Sumatra coasts toward the equator. SSHA and SST along the track (solid line in Fig. 2a), thermal structure, and wind off Java-Sumatra coasts are investigated. Time-longitude profiles of SSHA (Fig. 2b), SST (Fig. 2c), wind (Fig. 3), and thermal structure (Fig. 4) clearly reveal annual upwelling in June to October with cold SST and lower sea level. Therefore, we conclude that the region of high standard deviation in SST (Fig. 1) is associated with variable intensity of coastal upwelling.

The upwelling evolution as displayed in Figs. 1 and 2 corresponds very well to the SE monsoon cycle. In the SE monsoon, easterly alongshore wind (Fig. 3) in the southeastern tropical Indian Ocean starts to intensify. In June, alongshore wind is further intensified causing an upwelling and shoaling of the

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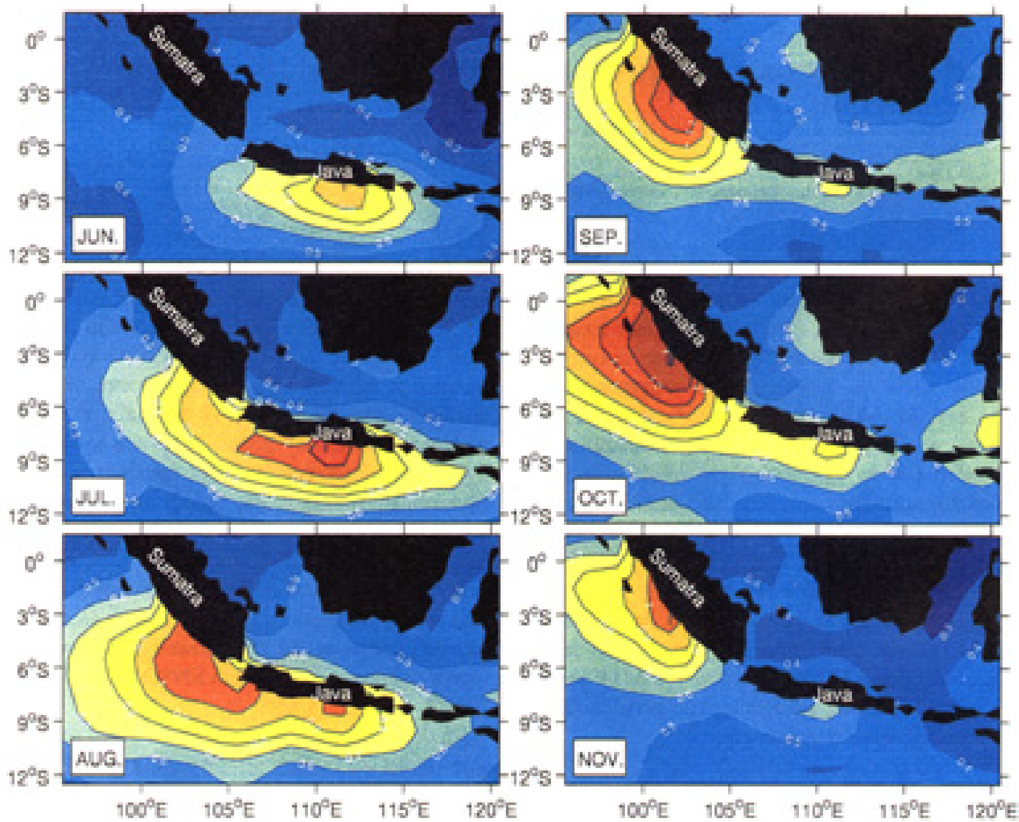


**Figure 1.** An image of standard deviation of monthly average SST from 1981 to 1999 during the SE monsoon period from June to November. Contour interval is 0.1°C.

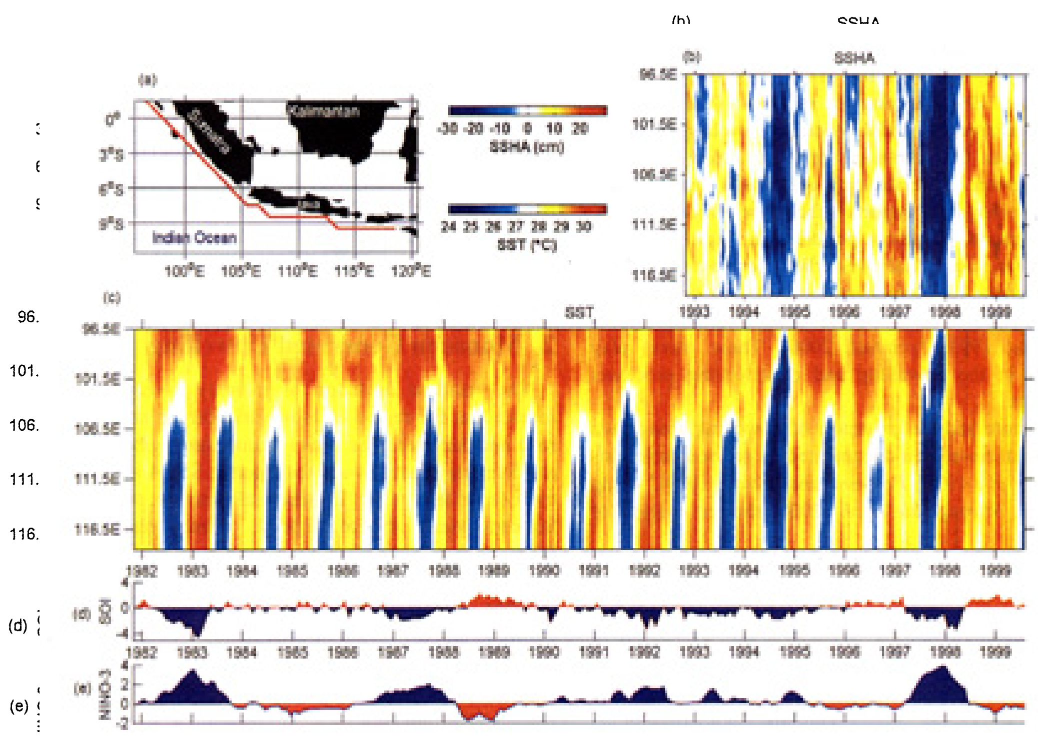


**Figure 2.** A track along the Java-Sumatra coasts (a), Time-longitude profile of SSHA along the track (b), Time-longitude profile of SST along the track (c), SOI (d), and SST anomaly at Nino-3 (e).

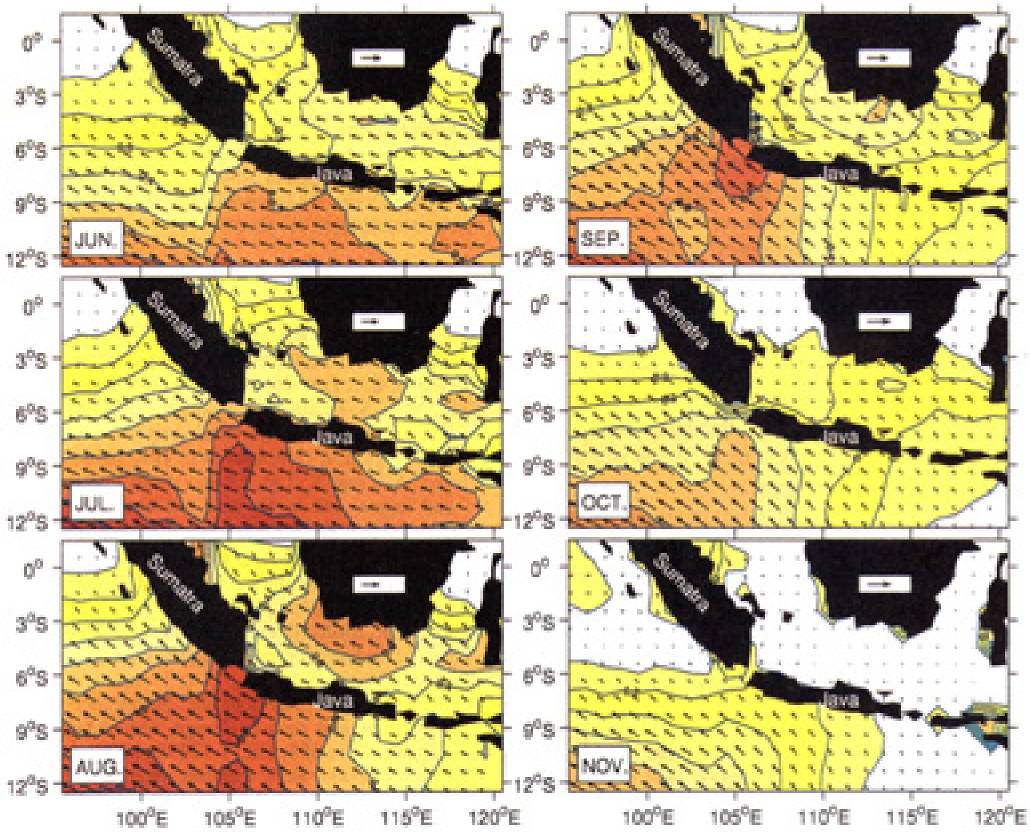


**Figure 3** Monthly mean wind stress derived from ERS scatterometer overlaid with alongshore wind stress parallel to the Java-Sumatra coasts. Contour interval of alongshore wind stress is 0.01N/m$^2$. Arrow scale for wind stress is 0.1 N/m$^2$.

thermocline off the east Java coast. Current meter data [Fig. 2, *Sprintall et al.*, 1999] from the Cilacap mooring (in south central Java) showed an eastward flow associated with semiannual coastally trapped Kelvin wave in May 1997 and a westward flow due to SE monsoon wind. The alongshore winds reach a maximum in July-August and are centered at 105° E (Fig.3). Even though the maximum wind parallel to the coast is just at the tip of the Sumatra coast, the upwelling center moves continuously northwestward with a northwestward propagation speed of 0.2 m/s and reaches 100°E and 2°S in October. By calculating the seaward Ekman transport along the coast of Java and Sumatra for the upwelling months, we find that westward shift of the upwelling center along the Java coast is consistent with the alongshore wind shift.

However, along the coast of Sumatra, where the coast has an angle to latitude, both alongshore wind and the Coriolis parameter changes with latitude are responsible for the northwest propagation of the upwelling. At the end of October, the monsoon transition starts to occur and easterly wind decreases (figure not shown), and soon will be replaced by westerly wind, reducing the upwelling strength. In addition, the equatorial westerlies generated downwelling Kelvin waves approach the Sumatra coast causes increasing sea level, deepening thermocline, and generates coastally trapped Kelvin waves. Hence, coastally trapped Kelvin waves and wind reversal block further equatorward propagation of the upwelling center and decrease the upwelling strength. Subsequently, NW monsoon induced causes coastal downwelling. The region of maximum downwelling is not visible during the NW monsoon.

## 3. Interannual features

It is apparent that interannual variability in the upwelling is present (Figs. 2 & 4), which is expected to be consequence of interannual atmosphere-ocean teleconnections. Over the Indian Ocean and Indonesian Seas, sea level and wind stress are correlated, and sea level and thermocline seasonal variations are negatively correlated (sea level rise corresponding to thermocline deepening) [*Bray et al.*, 1996]. Correlation coefficient between SSHA (Fig.2 ) and to both SOI and –Nino-3 is 0.72. Meanwhile, the correlation between SSTA and SOI and –Nino-3 is 0.67 and 0.65, respectively. In 1994 and 1997, the easterly wind was much stronger [*Saji et al.*, 1999; *Behera et al.*, 1999], SST was cooler, SSHA was lower, and thermocline depth shallower (40-60m, Fig.

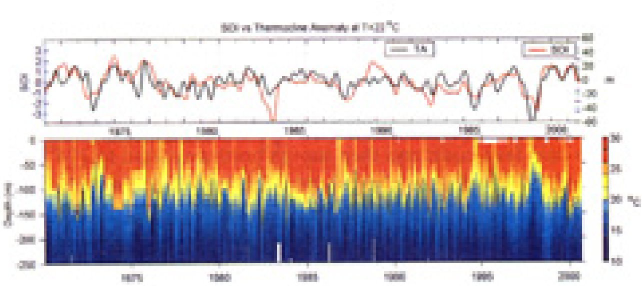

**Figure 4.** Temperature time-section from hydrographic and XBT/MBT data (bottom). Correlation between SOI and thermocline depth anomaly (annual mean has been removed) at T=22°C (top).

4) than the normal condition, and the maximum SST decrease was 4°C relative to the annual mean. In addition to a strong alongshore wind and changes in the Coriolis parameter, the anomalous easterly wind stress anomalies generated eastward upwelling Kelvin waves, thus, raised the thermocline off the Sumatra coast and enhanced the upwelling strength. During the months of October and November, upwelling was still very strong and extends further northwest along the Sumatra coast. The anomalous easterly wind also suppressed development of the northwest monsoon wind, which usually begins in November. The SST was much colder and the cold-water boundary approached closer to the Equator, and remained strong into November. SeaWifs data support this result (figure not shown). During the month of November 1997 (El Nino), chlorophyll-a concentration remains high along the coast of Java-Sumatra. On the other hand, in November 1998 (La Nina), there is no significant chlorophyll-a concentration in this region.

From longer time series of thermal structure along the coasts of Java and Sumatra (Fig 4), it is apparent that the upwelling is modulated by ENSO. The main path of the Indonesian Throughflow (ITF) from the Pacific to the Indian Ocean is by way of Makassar Strait. Based on 15 years XBT data, *Ffield et al.*, [2000] concluded that the Makassar thermocline temperature is highly correlated (r=0.77) to SOI. During the El Nino (La Nina), ITF transports colder (warmer) water to Indian Ocean via Lombok Strait and other straits in the Lesser Sunda Islands. Our study showed that the correlation between the thermocline temperature anomaly (at 22°C isotherm, and annual cycle has been removed) along the coasts of Java and Sumatra to SOI is 0.60 (Fig. 4). The correlation value implies that upwelling process mostly modulated by ENSO, and probably some part by the internal dynamics Indian Ocean. During El Nino events (72/73, 82/83, 86/87 94/95, 97/98) thermocline depth was 20 to 60m shallower. During the La Nina, Indonesian throughflow (ITF) transport is higher [*Meyers,* 1996; *Fieux et al.*, 1996; *Gordon and Susanto*, 1999; *Ffield et al.*, 2000], and warmer water from Indonesian Seas enters the Indian Ocean. Additional warm water due to ITF causes a deepening thermocline depth (about 20-30m) along Java coast. Instead of transporting cold water to the surface, the upwelling along the Java-Sumatra coasts caries warm water to the surface. In fact, in 1998-1999 SSHA much higher and thermocline deeper than normal and, hence, increases SST along Java and Sumatra coasts to greater than 28°C.

## 4. Conclusions

Characteristics of ocean upwelling Indian Ocean off the coasts of Java and Sumatra Islands are investigated. Our results shows that upwelling is mostly forced both locally by the alongshore winds associated with the SE monsoon and remotely by atmosphere-ocean circulation associated with ENSO. In the normal years, upwelling occurs from early June to mid October and starts off the east Java coast and then moves northwestward to 104°E at speed of 0.2m/s, due to alongshore wind and latitudinal changes in the Coriolis parameter. The correlation between thermocline depth anomaly and SOI is 0.60. During El Nino, ITF transports colder water shallowing thermocline depth (20-60m). Stronger easterly wind suppresses coastally trapped Kelvin waves and monsoon transition causes the upwelling extended both in time and space. During the La Niña periods, ITF transports warmer water, thermocline is deeper (20-30m), the SSHA is higher, and SST is warmer. Hence, upwelling intensity is reduced.

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