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Ocean color variability in the Indonesian Seas during the SeaWiFS era

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[1] More than 6 years of satellite-derived ocean color (SeaWiFS) and 7 years of sea surface temperature (AVHRR) and sea surface wind (ERS1/2, NSCAT, and QuikSCAT) are investigated for the Indonesian Seas. Harmonic analysis and monthly means in ocean color indicate that during the southeast Asia-Australia monsoon southeasterly wind from Australia generates upwelling and brings cooler and nutrient-rich water near the surface, enhancing productivity and increasing ocean color in the Banda Sea and the southern coasts of Jawa (Java)-Sumatra. Conditions are reversed during the northwest monsoon. The northwest wind induces downwelling and produces a weaker biological response in terms of ocean color. Anomalous winds associated with the 1997–1998 El Niño/La Niña events coinciding with the Indian Ocean Dipole (IOD) produced significant departures from the 6-year monthly mean in both magnitude and timing of the seasonal response to the southeast monsoon. Ocean color intensified in the upwelling region along the southern coast of Jawa-Sumatra, and the area of increased amplitude extended westward and prolonged the southeast monsoon period. In addition, localized minimum values of ocean color are observed along the exit pathways of the Indonesian Throughflow.

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1. Introduction

[2] The majority of the ocean's productivity occurs within the tropics, that is the zone of 10°N to 10°S [*Longhurst*, 1993], and Indonesia, because of its longitudinal extent (90°–141°E longitude), will be a significant fraction of tropical ocean productivity. The Indonesian Seas (Figure 1) play an integral part in the global thermohaline circulation and global climate, as well as being a center of biological diversity [*Veron*, 1995] and the site of important fisheries. The Indonesian Seas, with their unique geographical location and complex coastal geometry are the only low latitude inter-ocean communi-

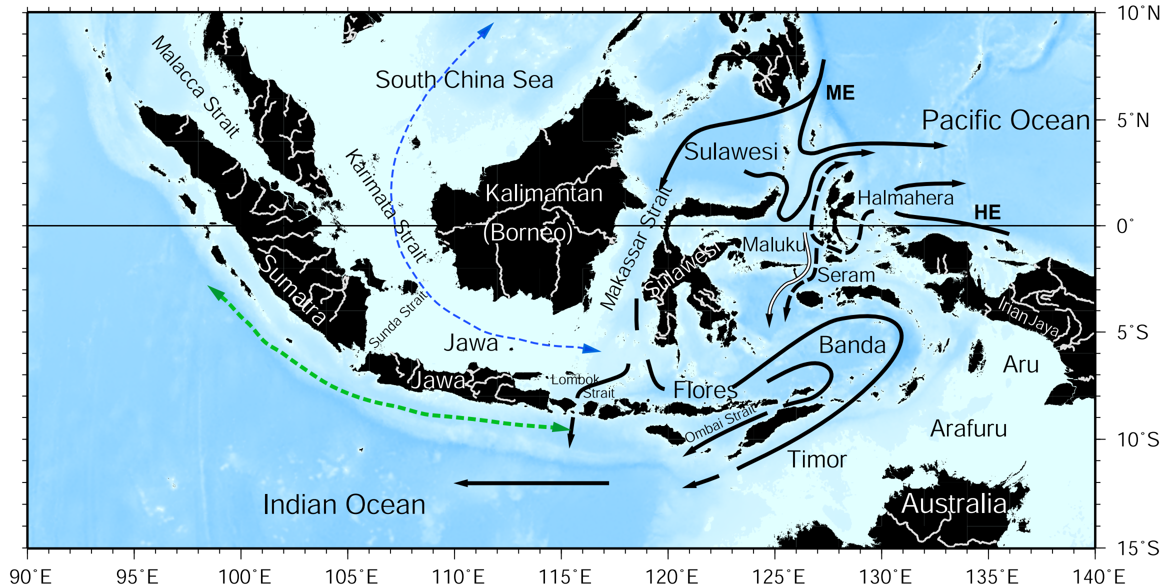

Figure 1. Map of Indonesian Seas with major rivers and throughflow pathways. The solid arrows represent North Pacific thermocline water; the dashed arrows (black) are South Pacific lower thermocline water. The dashed arrows (green and blue) along the north and south Sumatra-Nusa Tenggara Island chain are seasonally reversed surface water flow due to the Asia-Australia monsoon. The Indonesian throughflow transport is estimated to be 9 Sv (1 Sv = 10^6 m^3/s).

cation between the Pacific and the Indian Oceans. This communication between oceans is known as the Indonesian throughflow (ITF).

[3] Because of the influences of coastal geography, and ocean bottom topographical variations, variability in the ITF can be expected to be associated with variability in ocean color. Aside from the ITF, ocean color in the Indonesian Seas is strongly affected by the Asia-Australia (AA) monsoon system: the southeast and northwest monsoon. The southeast monsoon (April–October) is associated with easterlies from Australia that carry warm and dry air over the region. On the other hand, the northwest monsoon (wet season) is associated with westerlies from the Asian continent that carry warm and moist air to the region. During the wet northwest monsoon, river discharges may also affect ocean color through not only the delivery of nutrients, but also an increase in both inorganic particulate material and colored dissolved organic matter (CDOM), especially in the western Indonesian region [*Asanuma et al.*, 2003; *Hendiarti et al.*, 2004].

[4] Because Indonesia is affected by the El Niño-Southern Oscillation (ENSO), it is hypothesized that, on interannual timescales, ocean color variability in the Indonesian Seas will also be strongly influenced by the ENSO phenomenon. Other forcings that may have influence on ocean color which have been shown to affect the Indonesian Seas are the Indian Ocean Dipole (IOD) [*Saji et al.*, 1999; *Webster et al.*, 1999; *Feng and Meyers*, 2003], the Madden-Julian Oscillation (MJO) [*Madden and Julian*, 1994], and Kelvin and Rossby waves, and tides [*Ffield and Gordon*, 1996; *Sprintall et al.*, 2000; *Susanto et al.*, 2000]. To date, there is no consensus among scientists as to whether the IOD is dependent on or independent of ENSO but we acknowledge that these two large-scale forcings will have some effect on the Indonesian Seas. This collection of oceanic and atmospheric forcings affects sea surface temperature (SST), sea surface height anomaly, and winds, and can therefore be expected to affect the variability in ocean color.

[5] Remotely sensed ocean color observations often include the estimation of chlorophyll-a concentration which becomes more difficult as the relative optical contributions of suspended material, CDOM, and bottom reflectance increase with respect to the contribution from phytoplankton [*Sathyendranath*, 2000]. Given that the Indonesian Seas have waters that may be optically complex; we recognize that the variability in ocean color has qualitative aspects. Here, following convention, we express ocean color as chlorophyll-a but we are more interested in the patterns of variability in ocean color and how physical processes affect

those patterns on seasonal and longer timescales. Also, we choose to include regions where it might be expected that other optically absorbing constituents will affect satellite retrievals of ocean color, the so-called "Case-2" waters. Thus ocean color may be unreliable in terms of the magnitude of the chlorophyll-a signal, but more reliable in terms of the patterns. Because we are interested in the variability throughout the region, we evaluate all the areas, and retain the use of ocean color as the measure of variability.

[6] We note that while there have been several analyses of the variability in ocean color, globally [e.g., *Gregg and Casey*, 2004; *Yoder and Kennelly*, 2003], none of these includes other satellite information with which to aid in the interpretation of the ocean color variability. Thus we also present satellite-derived SST data from the Advanced Very High Resolution Radiometers (AVHRR), and sea surface winds from ERS1/2, NSCAT and QuikSCAT. We have examined sea surface height anomaly (SSHA) data from the TOPEX/Poseidon and Jason-1 mission. However, SSHA data are unreliable for our use because they have a longitudinal resolution of 2.8° (~300 km) at the equator, and also require a regional tidal model, and the proximity of land affects the signal. As of yet, there is no a high resolution tidal model for the Indonesian Seas. For these reasons, we have not included SSHA data in our analyses. We will focus on the analysis of ocean color, SST, and winds in the context of annual variability associated with the AA monsoon and interannual variability associated with the 1997/1998 El Niño.

[7] Though the variability of chlorophyll-a in the Indonesian Seas is expected to have a strong relationship with the AA monsoon and ENSO, in situ chlorophyll-a measurements are limited, even more so in terms of validation for satellite estimates. The only shipboard survey of chlorophyll-a undertaken for the Indonesian Seas as a whole was the *Arlindo* Program of 1993-1994 [*Kinkade et al.*, 1997]. *Arlindo* measured surface concentrations at about 50 stations for each of two cruises conducted during the southeast and northwest monsoons. The *Arlindo* surveys showed that the highest chlorophyll-a concentrations were associated with the southeast monsoon (August), from 1–6 mg m^{-3}. In addition, the surveys showed an east-west gradient in the variability with the eastern seas showing the highest concentrations of chlorophyll-a during the southeast monsoon. During the northwest monsoon (February), surface chlorophyll-a concentrations were lower overall, but higher in the west compared to the east. Because of the lower overall chlorophyll-a concentrations, the gradient, west to east, during the northwest monsoon was substantially less than for the southeast monsoon. There are a few validation data points from a research cruise in 1998 [see *Moore et al.*, 2003], and these are within typical SeaWiFS match-up errors for oceanic waters.

[8] This paper is organized as follows. The next section gives an overview of the data used in this study. Harmonic analysis and seasonal variability of ocean color, SST and zonal wind stress are presented in section 3. Section 4 describes the effect of 1997/98 El Niño on ocean color, SST and zonal wind stress. The results are discussed in section 5.

2. Data

2.1. Ocean Color (Chlorophyll)

[9] The primary data used in the present study are estimates of phytoplankton chlorophyll concentration derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). The remotely sensed chlorophyll data-files are 292 GAC (Global Area Coverage) 8-day composites with a spatial resolution of 9 km. These files cover a time frame from 2 September 1997–31 December 2003 and were provided on tape from NASA's GSFC (Goddard Space Flight Center) in a compressed HDF (Hierarchical Data Format) format.

[10] The chlorophyll estimates have been processed under the "4th reprocessing" protocols [*Patt et al.*, 2003]. The 4th SeaWiFS reprocessing (along with SeaDAS 4.3) has in situ chlorophyll-a match-up errors that range from 23.77–31.35% (Sean Bailey, NASA/GSFC, personal communication, 2003). The atmospheric correction applied to these data uses a multiscattering aerosol correction with the 765/865 model and NIR correction for non-zero normalized water-leaving radiances.

[11] Monthly averages are calculated for each given month. To avoid bias due to skewness (total number of September–December months is longer than the rest of the months) and due to 1997/98 El Niño effect, the monthly mean climatology is calculated from January 1998 to December 2003. The results are 12 monthly representations of the climatological mean of chlorophyll variability. Residual chlorophyll data are calculated by subtracting the 6-year climatological mean from the monthly

averaged data for September 1997 to December 2003.

2.2. Sea Surface Temperature (SST)

[12] We use the latest version (Version 5.0, or V5) of SST from the NOAA/NASA AVHRR Oceans Pathfinder data product, which is derived from the 5-channel AVHRR on board the NOAA −9, −11, −14 and −16 polar orbiting satellites. It has high spatial resolution of 4 km and data flagging.

[13] The quality flag varies from 0 (lowest) to 7 (highest) [*Kilpatrick et al.*, 2001]. Here, we use quality flag greater or equal to 4. The monthly SST data are available from January 1985 to December 2003. To be consistent with the temporal availability of the SeaWiFS data, the monthly climatological means are calculated on the basis of monthly means for six years (January 1998–December 2003) of SST data. Residual SST data are calculated by subtracting the monthly climatological mean from the monthly data for January 1997 to December 2003.

2.3. Ocean Winds

[14] Wind products (zonal and meridional wind speeds, stresses, curl, and divergence) are derived from the ERS-1/2, NSCAT and QSCAT scatterometers and obtained from the CERSAT-IFREMER, France. The NSCAT and QSCAT wind data has a spatial resolution of 0.25° by 0.25° (longitude × latitude). Meanwhile, the ERS-1/2 wind data spatial resolution is 0.5° by 0.5° (longitude × latitude). Before we combine the NSCAT and QSCAT with the ERS data, both data sets are decimated into 0.5° by 0.5° (longitude × latitude). Monthly winds are available from March 1991 to December 2003. To be consistent with the temporal availability of the SeaWiFS data, the monthly climatological means are calculated on the basis of the monthly means from six years (January 1998–December 2003) of wind data. Residual wind data are calculated by subtracting the monthly climatological mean from the monthly data for January 1997 to December 2003.

3. Seasonal Variability and Harmonic Analysis

[15] Because the Indonesian Seas lie between Australia and Asia, they are strongly affected by the Asia-Australia monsoon system. Hence we expect that ocean color and SST variability will follow the seasonal reversal of the monsoon winds. The equatorial pressure trough moves according to the position of the sun, crossing the equator twice each year. In the northern hemisphere summer, a low pressure develops over Asia, while in the northern hemisphere winter, a high pressure forms over Asia. Between the high and low-pressure systems, the monsoons develop. *Wyrtki* [1961] described the transition months between monsoons as March–April–May; and September–October–November. The peaks of the southeast monsoon are June–July August while the northwest monsoon peaks in December–January–February. Though in general, the wind patterns follow *Wyrtki*'s [1961] scheme, our current observational data indicate that the duration of the monsoon transition is shorter. The northwest monsoon occurs during the months of November to March, while southeast monsoon develops in the month of May, and continues through September. April and October are transition months.

[16] To investigate the effect of the AA monsoon, we apply harmonic analysis to extract the annual signal in each grid point of winds, SST, and ocean color time series. We use the method of minimizing the least squares error to fit the annual signal on each grid point time series. After calculating the mean of the annual signal, we remove the mean and present the annual harmonic variability.

3.1. Ocean Color

[17] The monthly climatological mean of ocean color from January 1998 to December 2003 is shown in Figure 2. First, we note that there are areas in the Indonesian Seas that seem to exhibit little if any month-to-month variability in ocean color. These are deep-water areas: in the western Pacific, the Indian Ocean, the Sulawesi Sea, the Halmahera Sea, and the Flores Sea (north of the Nusa Tenggara Island chain). (The Nusa Tenggara Island chain is defined as all islands east of Bali, which includes the islands of Lombok, Sumbawa, Flores, Sumba, and Timor.) Throughout the year, the highest ocean color concentrations are observed in the Malacca Strait, around the coast of Kalimantan/Borneo, Arafuru and Aru Seas and the eastern Banda Sea. During the southeast monsoon (July through October), high ocean color concentrations are observed in the area south of the Jawa-Nusa Tenggara Island chain, the Jawa Sea and the Karimata Strait.

[18] Along the coasts south of the Jawa-Nusa Tenggara Island chain, the maximum in ocean color

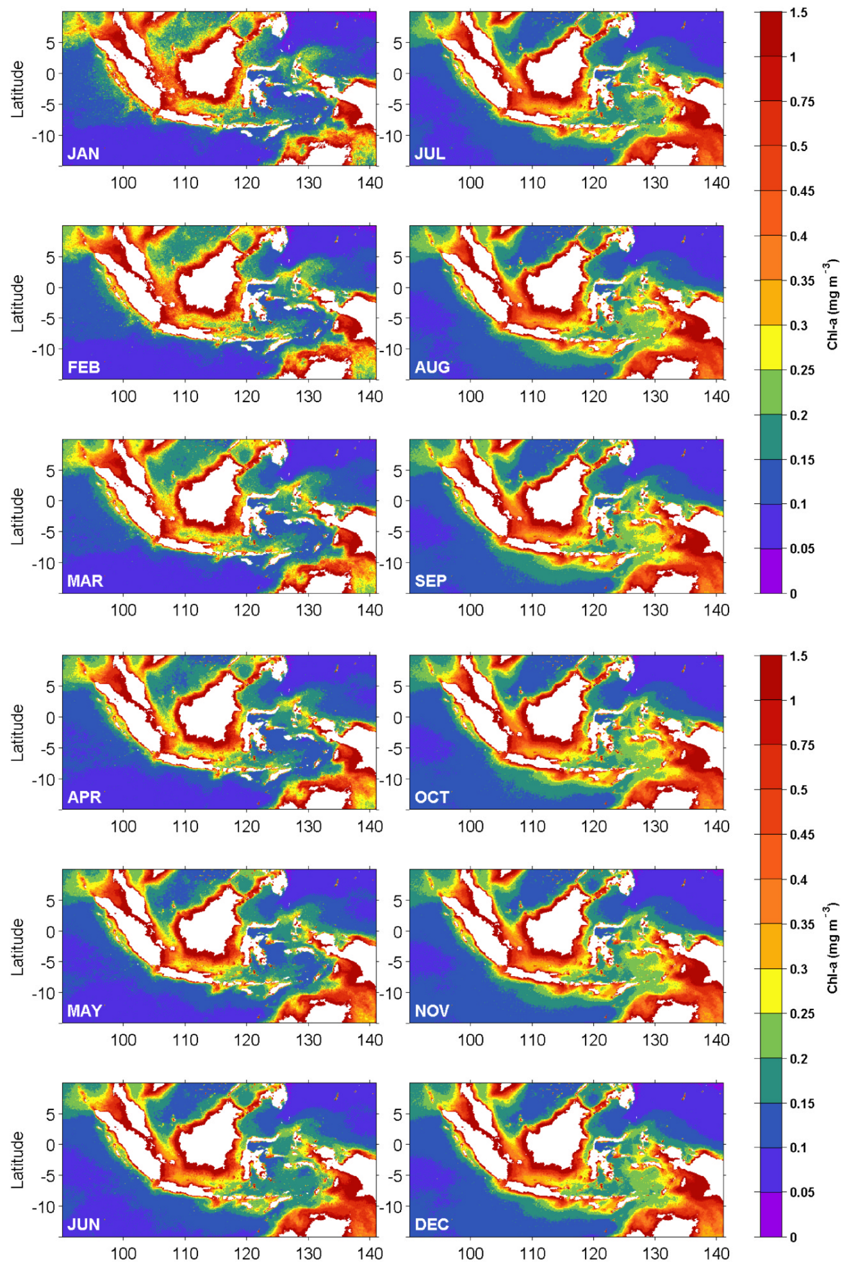

Figure 2. Monthly climatological mean of chlorophyll-a concentration derived from the SeaWiFS sensor on board the Seastar satellite based on 8-day composites from January 1998 to December 2003. In general, within the internal Indonesian seas, higher chlorophyll concentrations are observed during the southeast monsoon (northern hemisphere summer) in comparison to those during the northwest monsoon.

appears to move to the west over the period of the southeast monsoon. This is consistent with westward movement of the upwelling center due to an alongshore wind shift and latitudinal changes in the Coriolis parameter [*Susanto et al.*, 2001a]. The eastern Banda Sea shows an increase in ocean color during southeast monsoon [see *Moore et al.*, 2003] associated with upwelling induced by the wind divergence during the southeast monsoon [*Gordon and Susanto*, 2001]. In the eastern Banda Sea and south of the Jawa-Nusa Tenggara Island chain, ocean color declines during the northwest monsoon.

[19] The results of the harmonic analysis described above are summarized in Figure 3. The annual harmonic range is about 1.5 mg m^{-3} with the largest

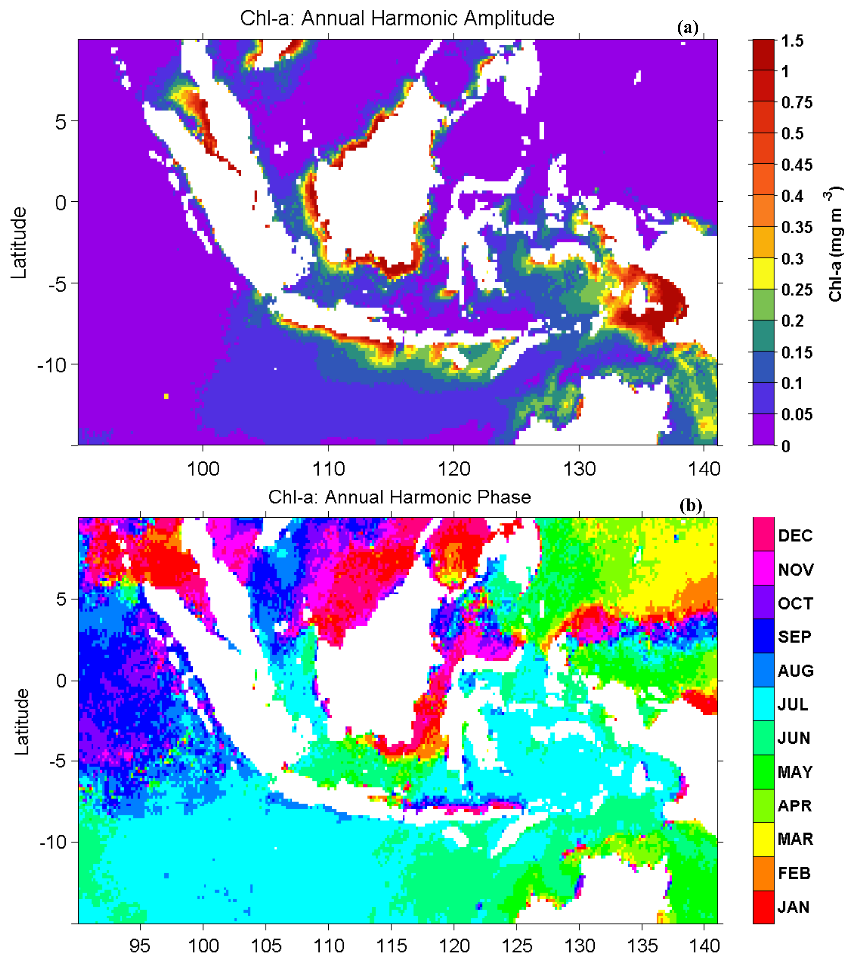

Figure 3. Annual harmonic analysis of the monthly mean chlorophyll-a concentration derived from the SeaWiFS sensor on board the Seastar satellite from January 1997 to December 2003: (a) the annual harmonic amplitude and (b) its associated phase (the month in which the maximum occurred). The maximum chlorophyll concentration within the Indonesian seas occurs during the southeast monsoon (north hemisphere summer), except along the northern part of the Nusa Tenggara Island chain, the Makassar Strait, the Sulawesi Sea, and the Malacca Strait.

variability occurring in the region off the west coast of Irian Jaya (Papua New Guinea), the southern Jawa-Nusa Tenggara coast and along the south and west coasts of Kalimantan, and Malacca Strait. The mean annual amplitude varies from very low values to 1.5 mg m^{-3}. Excluding south of Jawa-Nusa Tenggara Island chain and eastern Banda Sea, the seasonal change in ocean color occurs in proximity to land. Thus water depth and river runoff, in addition to the monsoons, become strong drivers for variability in ocean color. Unfortunately, there are no river runoff data available in the region to quantify its effect on the ocean color variability.

[20] The harmonic amplitudes show strong signals for those deep water areas affected by the monsoons, such as south of Jawa and in the eastern Banda Sea. The phase of the harmonic has a roughly north-south aspect, where areas south of the equator are associated with the months of the southeast monsoon, while those areas north of the equator are associated with the months of the northwest monsoon. The exceptions are the Makassar Strait and Flores Sea north of the Nusa Tenggara Islands, which indicate a maximum during the northwest monsoon. However, their seasonal amplitudes are small (less than 0.1 mg m^{-3}).

[21] During the months of the northwest monsoon, there are somewhat higher values of satellite chlorophyll-a in the Malacca Strait and more so off northern Kalimantan, eastern Kalimantan, and in the Makassar Strait (Figure 2). The effect of the northwest monsoon, however, appears to elicit a weaker biological response overall. The Makassar Strait shows increases in chlorophyll-a during

November–December in the north and January–February in the south, and agrees with the in situ data collected during the *Arlindo* cruises in 1993–94 [*Kinkade et al.*, 1997]. The eastern Indian Ocean, in contrast, becomes more oligotrophic. Interestingly, the area to the north of Lombok Strait, in the Flores Sea, does not show an increase in ocean color during the southeast monsoon. During the southeast monsoon, the winds induce upwelling along the southern coasts of Nusa Tenggara Islands, while on the northern coasts, the winds induce downwelling. During the northwest monsoon, there are increases in chlorophyll-a concentration north of the Nusa Tenggara Islands. In May and June, with the advent of the southeast monsoon, the annual cycle begins again.

[22] There are also interesting smaller scale features in the monthly climatology. There is a localized minimum of ocean color concentration in the Indian Ocean side of the exit passages of Indonesian throughflow along the Nusa Tenggara Islands (Lombok and Ombai Straits). The minimum in ocean color occurs in almost every month, but the contrast with surrounding waters is greatest during the southeast monsoon when upwelling drives an increase in chlorophyll south of Jawa and Nusa Tenggara Islands. The minimum in ocean color concentration indicates an advective affect of the Indonesian throughflow. The throughflow has a maximum during the southeast monsoon [*Hautala et al.*, 2001]. *Moore and Marra* [2002] suggested that the occurrence and strength of SeaWiFS observed blooms in the Ombai Strait are related to thermocline depth modulated by both ENSO and the monsoons.

3.2. Ocean Sea Surface Winds

[23] In order to investigate the wind variability, we processed and analyzed various wind parameters (wind speed and stress, zonal and meridional wind speed/stress, wind divergence and curl). We choose to show the zonal wind stress, which indicates the wind strength and direction. The monthly climatological mean of zonal wind stress derived from ERS1/2, NSCAT, and QSCAT scatterometers based on monthly data from January 1998 to December 2003 is shown in Figure 4. The AA monsoon is characterized by seasonal changes in wind speed/stress directions. During the southeast monsoon (May–September), easterly winds blow from Australia and veer such that winds become southwesterly to the north of the equator. Similarly, during the northwest monsoon, winds to the north of the equator are northeasterly and become northwesterly in the southern hemisphere. April shows the lowest overall wind speeds/stress and is clearly the month of transition between the northwest and southeast monsoon. The southeast monsoon begins in May, with winds in the Arafuru Sea and the eastern Indian Ocean indicating first. The zone of maximum wind moves northwest in the Indian Ocean along the Nusa Tenggara Island chain from Jawa to Sumatra. Easterly winds spread and intensify through June reaching their maximum in July and August, after which they begin to subside. A band of very low wind speed brackets a zone slightly north of the equator.

[24] October is a monsoon transition month, where low winds occur within the internal Indonesian Seas, although, high zonal winds still exist in the Indian Ocean (10°S/90°E). In December, the winds have turned, and increase north of the 5°N latitudinal band and reach a maximum in January–February. The maximum northwesterly winds both north and south of the Jawa-Nusa Tenggara Island chain (5°S) occur in February. The northwest monsoon is less consistent than the southeast monsoon, and also of much shorter duration. Thus the largest wind event of the year is the southeast monsoon from May through August.

[25] Annual harmonic analysis (Figure 5) indicates that the amplitude of monsoon winds is asymmetric between southeast and northwest monsoon. The annual range is about 0.125 N m^{-2} with the South China Sea region exhibiting the largest variability. The mean of annual harmonic varies from -0.09 to 0.04 N m^{-2}. As expected, low zonal wind speeds, associated with the intertropical convergence zone, are observed along the equatorial band. The maximum annual cycle of winds occurs during the southeast monsoon north of the 5°N latitudinal band (off Andaman Sea and South China Seas). During the northwest monsoon, the maximum zonal wind occurs in the southern part of the Indonesian archipelago, with the highest variability in the Arafuru Sea (north Australia) and southern tip of the Sunda Strait. The maximum zonal wind during the southeast monsoon is higher than during the northwest monsoon. Figure 5b clearly shows the separation of the zonal wind due to the AA monsoon between southern and northern hemispheres.

3.3. Sea Surface Temperature

[26] The monthly climatological mean of NOAA-AVHRR derived SST, based on monthly data from

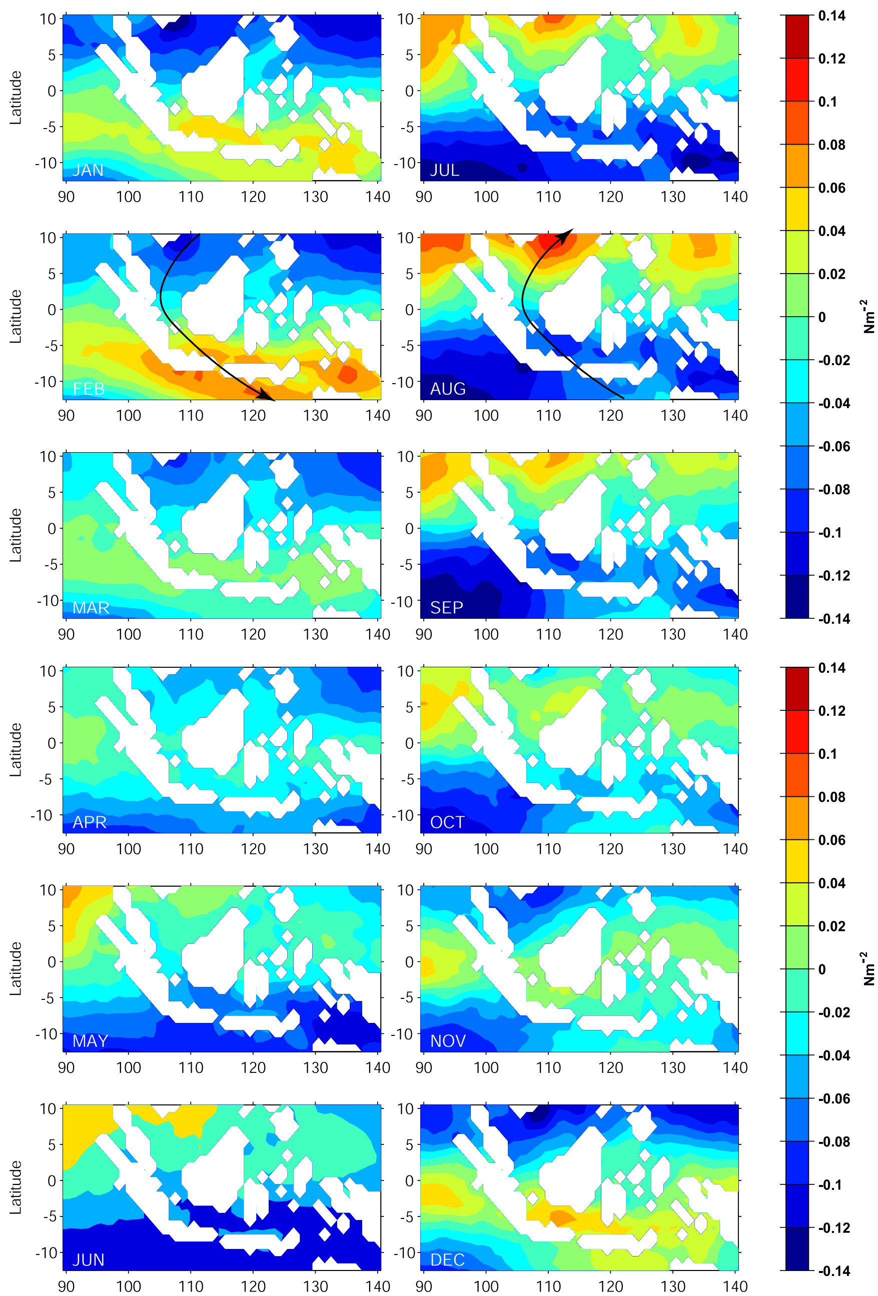

Figure 4. Monthly climatological mean of zonal wind stress derived from ERS1/2, NSCAT, and QSCAT scatterometers based on monthly mean data from January 1998 to December 2003. Seasonal monsoon winds are clearly seen. Stronger eastward zonal winds from the Australian continent affect the southern part of Indonesia during the southeast monsoon (April–October). Conditions are reversed during the northwest monsoon (October–April). Solid arrows in the months of February and August represent the general pattern of wind directions during the northwest monsoon and southeast monsoon, respectively.

January 1998 to December 2003, is shown in Figure 6. Similar to the ocean color variability, the climatological mean SST patterns over the Indonesian region clearly demonstrate the effect of the monsoon cycle. Colder temperatures are found in the boreal winter months (December to March) in the South China Sea due to the northwest monsoon, and in June to August in the south of the equator due to the southeast monsoon. During the peaks of southeast monsoon, from June–September, colder temperatures are observed in the Arafuru Sea, Banda Sea and off the southern part of the Jawa-Nusa Tenggara Island chain. Strong southeasterly winds induce divergence

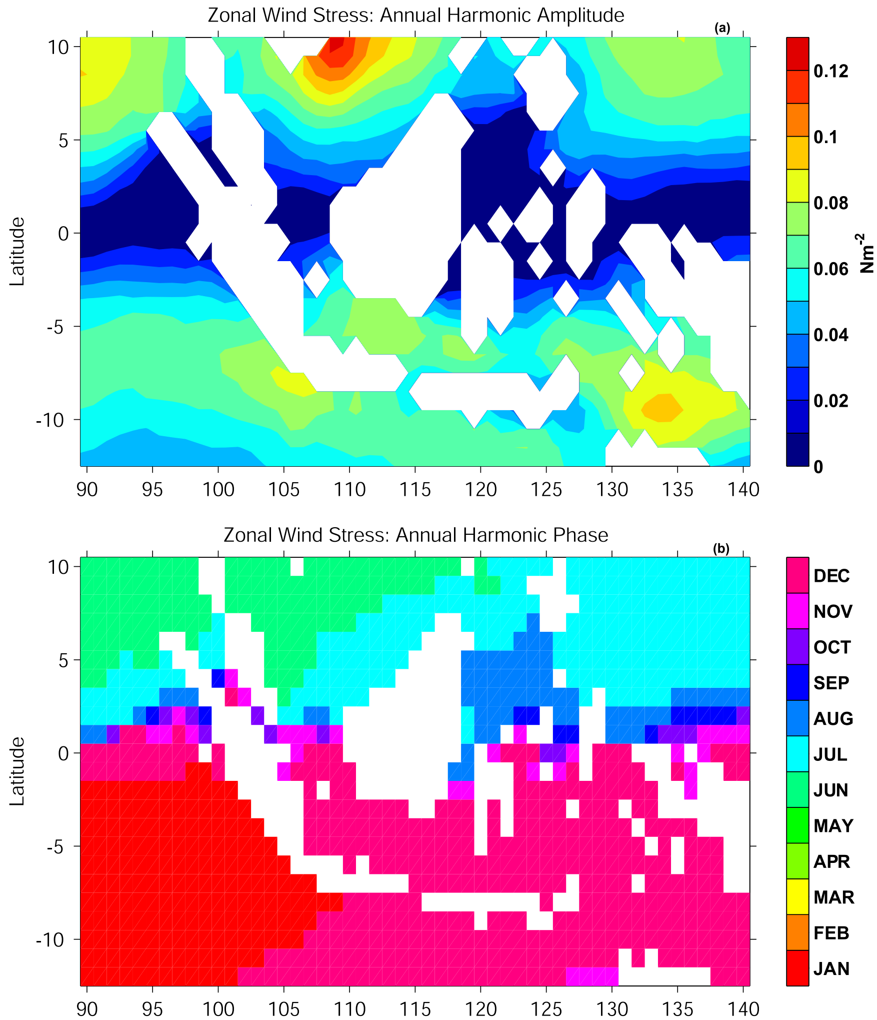

Figure 5. Annual harmonic analysis of the monthly mean of zonal wind stress derived from ERS1/2, NSCAT, and QSCAT scatterometers from January 1998 to December 2003: (a) the maximum amplitude zonal wind and (b) its associated phase (the month in which the maximum occurred). The seasonality of the monsoon is clearly seen from the phase of the wind stress. Maximum wind stress occurs in the South China Sea and Bay of Bengal during the northern hemisphere summer.

along the coasts of the Jawa-Nusa Tenggara Island chain and within the Banda Sea, and generate upwelling, reducing the SST. In addition, strong winds enhance vertical mixing, also reducing the SST.

[27] It is not clear how much of the change in SST during the southeast monsoon is caused by evaporative cooling [see *Kinkade et al.*, 1997], mechanical mixing, or coastal upwelling [*Feng and Meyers*, 2003; *Moore et al.*, 2003; *Susanto et al.*, 2001a, 2001b]. Within the internal Indonesian Seas, warmer temperatures are clearly observed. Although the Timor Sea shows some cooling, it lasts only a month, leaving it a warm zone bracketed by the colder Arafuru Sea and Jawa Current region. Cooling during the southeast monsoon is not uniform over the southern areas. The Timor Sea is anomalously warmer than areas to the west or east, a condition that persists throughout the year. Conditions are reversed during the northwest monsoon with colder temperatures observed in the South China Sea.

[28] The annual harmonic analysis of SST and its associated phase is shown in Figure 7. Unlike the ocean color and winds where we are interested in "how large" and "where and when" the maximum values occurred, for SST we are interested in the minima, as they often relate to injections of nutrients into the euphotic zone. The annual range for SST is about 3.5°C with regions close to Australia (Arafuru Sea, Indian Ocean between Jawa/Nusa Tenggara and Australia) and the South

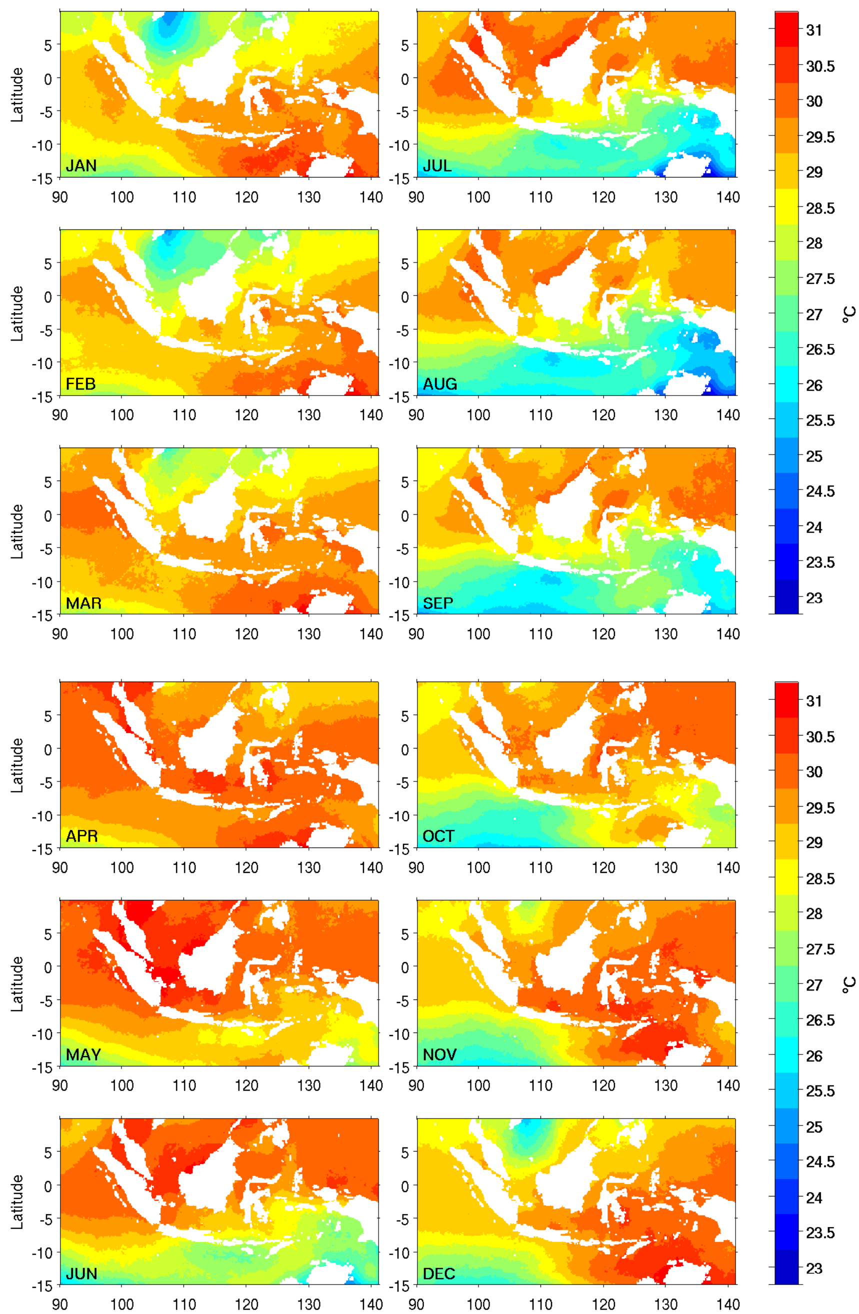

Figure 6. Monthly climatological mean of sea surface temperature derived from NOAA-AVHRR based on monthly mean data from January 1998 to December 2003. Seasonal variability due to the Asia-Australia monsoon system is clearly present. During the peak of the southeast monsoon from July to September, cooler temperatures are observed in the Banda Sea, Arafura Sea, and south of Java-Nusa Tenggara Island chain. Conditions are reversed during the peak of the northwest monsoon.

China Sea exhibiting the largest variability. The mean of the annual harmonic varies from 26.8 to 29.9°C. The SST shows smaller amplitude variability within a 5° latitude band north and south of the equator, with clear intrusions of colder (warmer) water occurring in the South China Sea during the northwest (southeast) monsoon and in the Arafuru-Banda Seas during the southeast (northwest) monsoon.

[29] A warm temperature feature (especially around the monsoon transition in March and

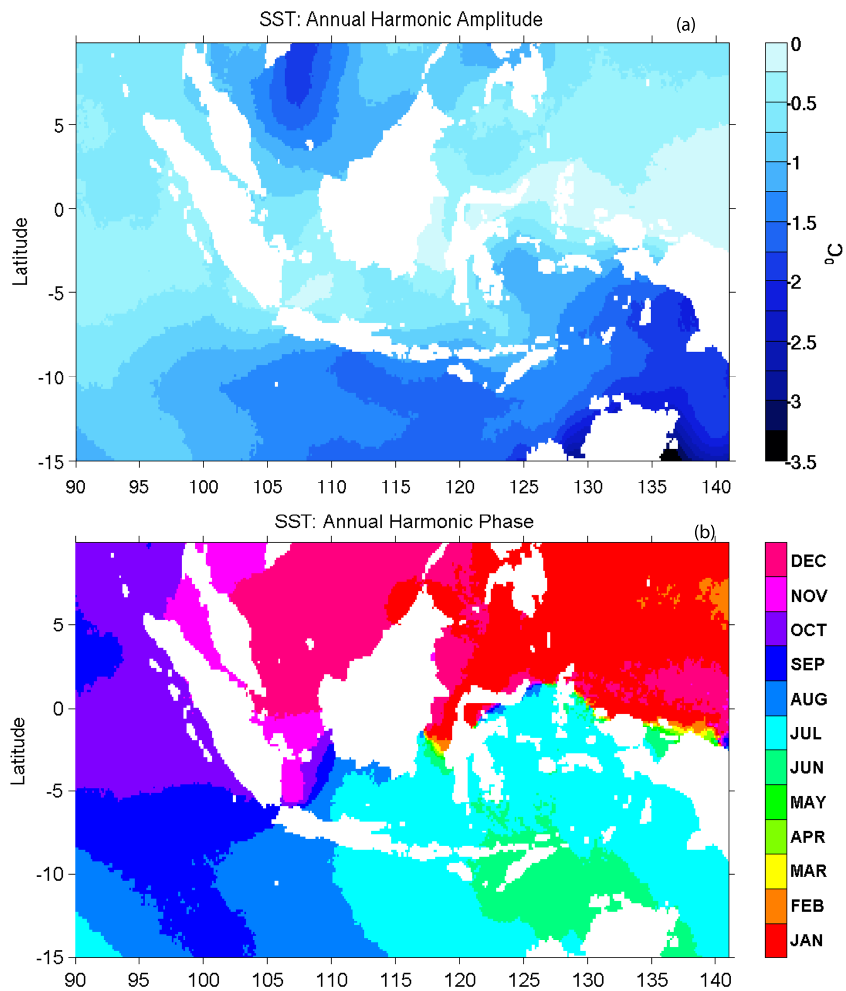

Figure 7. Annual harmonic analysis of the monthly mean sea surface temperature derived from NOAA-AVHRR, January 1998 to December 2003: (a) the minimum SST amplitude at a given location and (b) its associated phase (the month in which the minimum occurred). From the annual phase, Indonesian Seas are clearly affected by the Asia-Australia monsoon system.

April; Figure 6) is clearly seen extending from the Pacific through to the Indian Ocean indicating the link through the Indonesian Seas. Along the ITF pathways, SST tends to be higher. Both oceans affect SST variability within the Indonesian Seas. The opposing action of the ITF and southeast monsoon is clearly seen in the Flores Sea, the western part of Banda Sea and the Timor passages. In these regions the increases in temperature due to the ITF are compensated with cooling caused by the southeast monsoon.

4. Effect of the 1997 El Niño on Ocean Color

[30] It is well known that the Indonesian region is adversely affected by climate swings associated with ENSO, the La Niña and El Niño. The very strong El Niño that occurred in 1997/98 and the La Niña period that followed had devastating effects on the landmasses in Indonesia [*Gutman et al.*, 2000; *Page et al.*, 2002]. Because our data (ocean color, SST and winds) spans the years of a major El Niño/La Niña (1997/1998) transition, it is expected to be a major source of interannual variability in ocean color, SST, and winds. The impacts of 1997 El Niño to the ocean-atmosphere in the Indonesian Seas are stronger than those of 1998 La Niña. For Indonesia, the peak of ENSO effects occurs in the second half of Year 0 (the year when ENSO started). The El Niño and La Niña year definition follows the list given by the National Center for Environmental Prediction (see http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears).

[31] Unlike the eastern tropical Pacific, ocean productivity in the Indonesian Seas increases during the El Niño phase. The impact of the El Niño on the ocean color climatology is generalized over the entire region, but the strongest effect is confined to those areas that exhibit upwelling as a response to the monsoon. The 1997/98 El Niño coincided with Indian Ocean Dipole (IOD) events, anomalous easterly wind stress along the southern part of the Indonesian Seas generated strong upwelling along the coast of Jawa and Sumatra and in the Banda Sea [*Moore et al.*, 2003; *Saji et al.*, 1999; *Susanto et al.*, 2001a, 2001b; *Webster et al.*, 1999]. Upwelling brings nutrient-rich water near the surface, enhancing productivity and increasing ocean color. In terms of magnitude, the greatest effect is in response to the southeast monsoon [*Moore et al.*, 2003; *Moore and Marra*, 2002; *Susanto et al.*, 2001a, 2001b]. There was also an ENSO related extension of the monsoon effect through November in regions throughout the archipelago.

[32] As expected, monsoon winds, SST, and ocean color do not always follow the annual harmonic. Interannual forcings not only generate interannual variability but also may influence the strength and timing of the annual cycle. *Susanto et al.* [2001a, 2001b] show that the largest standard deviation in SST variability in the Indonesian Seas from 1981 to 1999 occurs in the region south of the Jawa-Sumatra during the 1997 southeast monsoon, coinciding with the 1997/98 El Niño. They show that the upwelling center south of the Jawa-Sumatra Islands extends northwestward along the west Sumatra coast and persists through November 1997. Entrainment cooling is a prominent cause and zonal and meridional advection also contributes significantly: the cold SST anomaly is observed first in the southeast off Jawa and then subsequently advected northwestward along the coast. Strong cooling was evident southwest of Jawa-Sumatra by September 1997 and continued into January 1998. As a consequence of this cooling, there was an equatorial SST gradient from east to west in the Indian Ocean, a reversal of the climatological condition. In the upwelling region, there were anomalously strong easterlies during the fall, replacing the climatological westerlies, which strengthened alongshore winds off Sumatra and further reduced the SST [*Murtugudde et al.*, 2000].

[33] To determine the effect of interannual variability associated with the 1997/1998 El Niño/La Niña (which coincided with IOD event) on the distribution and magnitude of ocean color (chlorophyll-a), we make a comparison between the month of November 1997 (El Niño phase) and November 1998 (La Niña). We also compare November 1997 to the mean of the six November means for 1998 to 2003. Figure 8a shows the difference in ocean color between the monthly mean for November 1997 (El Niño) and the average of the six November means. These results indicate that 1997/98 El Niño has strong effect on the ocean color variability in the southern coast of Java, western coast of Sumatra, Kalimantan and Irian Jaya. These interannual phenomena not only increase the ocean color concentration in these upwelling regions (south coast of Jawa and southwest coast of Irian Jaya), but also prolong the increases for up to three months. During the normal year, by the end of October the northwest monsoon should have been developed which induces downwelling (instead of upwelling) in the western coast of Sumatra and southern coasts of Java and Nusa Tenggara Island chain. During this strong 1997/98 El Nino and IOD event, anomalously early winds induced a stronger upwelling in along these coasts. In addition, the region of high ocean color concentration was extended toward the west coast of Sumatra, which usually shows a low seasonal variability of ocean color (Figure 3a). These results support previous finding that the center of upwelling along the coast of Jawa-Sumatra moves northwestward and extends further north off the western coast of Sumatra [*Susanto et al.*, 2001a]. The distributions of ocean color spread further westward off the Sumatra coast to follow the upwelling center and anomalous wind stress. In the same time, Rossby waves developed and propagated westward in this region enhancing the westward spreading of ocean color distribution [*Murtugudde et al.*, 2000; *Webster et al.*, 1999].

[34] Another area affected by the ENSO cycle is the region to the southwest of Irian Jaya, but clouds obscure this region during the El Niño year. Figure 8b shows the difference between ocean color for November 1998 (La Niña) and the 6-year November mean. The largest differences occur off the southwest coast of Irian Jaya and surrounding Kalimantan. Some small differences are also observed along the coast of the Jawa-Nusa Tenggara Island chain, Banda Sea, Malacca Strait, and off the coast of northern Australia. We cannot be sure if the ocean color around the coastline of Kalimantan is from chlorophyll-a alone, since this region is shallow and subject to significant river runoff. Shallow waters with high sediment load in the proximity

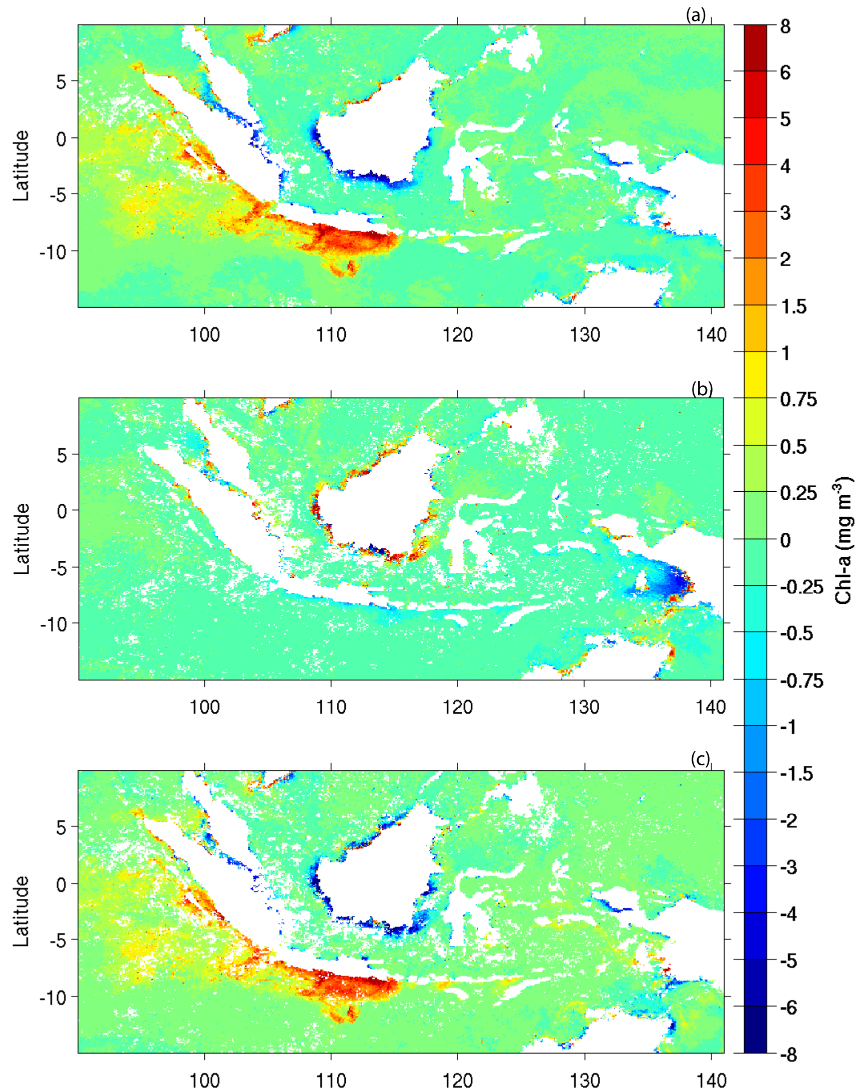

Figure 8. SeaWiFS derived chlorophyll-a: (a) the difference between the month of November 1997 (during the peak of 1997/98 El Niño) and the 6-year monthly mean; (b) the difference between the month of November 1998 (during the peak 1998 La Nina) and the 6-year monthly mean; and (c) the difference between November 1997 and November 1998.

of river outflows have been the source of problems with the interpretation of SeaWiFS imagery [*Eplee et al.*, 2001; *Hu et al.*, 2000; *Li*, 2003]. River runoff data for this region are not available. As seen in Figures 8a and 8b, the ocean color around the coastline of Kalimantan probably represents the effect of river runoff. During the strong 1997/98 El Niño a drought occurred over Kalimantan and low ocean color values are observed (Figure 8a). On the other hand, there are higher ocean color values (Figure 8b) during La Nina when much more rainfall is expected. However, in the southwest coast of Irian Jaya, previous field data indicated that indeed there was high chlorophyll-a concentrations in this region [*Ilahude et al.*, 1990, 2004].

[35] The 1997/98 El Niño enhances satellite estimates of chlorophyll-a concentration in comparison to the 6-year mean, while during the La Niña phase, chlorophyll-a in the same region is slightly lower (Figure 8b). In that way, the effect of each phase of the ENSO cycle is asymmetric. These results agree with a previous assessment that El Niño has a much larger effect on the marine ecosystems of Indonesia than does La Niña (JM, unpublished data). Figure 8c shows the difference between monthly mean ocean color for November

1997 (El Niño) and November 1998 (La Niña), which reinforces what is shown by their respective differences from the climatology.

5. Discussion

5.1. Variability in Ocean Color

[36] Prior to SeaWiFS, there are data available from the Coastal Zone Color Scanner (CZCS), which observed many parts of the ocean from 1978–1986. Monthly composites for the Indonesian Seas, Southeast Asia and Australia are available from http://seawifs.gsfc.nasa.gov/SEAWIFS/CZCS_DATA/australia.html. The CZCS images are consistent with the variability in SeaWiFS; however, CZCS coverage is very limited. For example, images for Indonesia from 1982, an El Niño year, are available for only one or two months and only over restricted areas.

[37] From shipboard-based surveys of chlorophyll-a undertaken for the Indonesian Seas as part of the *Arlindo* Program of 1993–1994, *Kinkade et al.* [1997] concluded that the higher chlorophyll-a concentrations were observed during the southeast monsoon and there was an east-west gradient in the chlorophyll variability. The SeaWiFS data agree with that overall assessment, but at much higher spatial and temporal resolution, and show that the dominant mode of annual variability in the Indonesian Seas is the monsoons. During the southeast monsoon, strong southeasterly winds induce upwelling in the eastern Banda Sea and along the south coast of the Jawa-Nusa Tenggara Island chain, enhancing ocean color in these regions. In turn, the effect of the monsoon is modulated by large-scale ocean-atmosphere phenomena such as ENSO and the Indian Ocean Dipole. The southeast monsoon is the stronger in terms of its effect on ocean properties observed from space. Its effects are seen in both SST and ocean color. By comparison, the northwest monsoon is more short-lived. Perhaps because of geography, the northwest monsoon elicits less of a biological response.

[38] Nevertheless, we can link the variability in ocean color and SST to variations in the wind. As southeasterly winds increase in May and June, surface waters become cooler, beginning in the east (Arafuru and Timor Seas). The cooler waters spread westward as the monsoon progresses, followed by increases in chlorophyll-a concentration (as indicated by ocean color). The actual driving mechanism for the cooler water is not clear. *Kinkade et al.* [1997] argued that convective processes could explain much of the cooling, as dry air from the Australian desert passes over the water. *Moore et al.* [2003] however, show that the pigment distributions in the Banda Sea in September 1998 were the result of wind-driven upwelling [*Gordon and Susanto*, 2001; *Waworuntu et al.*, 2000], an idea first promulgated by *Wyrtki* [1961]. The monthly composites of ocean color favor wind-driven upwelling as an explanation for the variability seen in the Banda Sea since the initial appearance of a change in ocean color occurs in the eastern part of the Banda Sea, where wind-driven upwelling would be expected.

[39] The change in ocean color with the onset of the southeast monsoon seems to move westward as the season progresses. The shift to the west in the color maximum in the Jawa Current region follows the temperature minimum. The relationship between color and SST is maintained over the area from the Arafuru Sea to the Jawa Current region, and notably, where ocean color has a minimum in the Timor Sea across this zonal region, SST is higher as well. The SST relationship to ocean color that is apparent for the southeast monsoon in eastern Indonesia and in the eastern Indian Ocean does not occur for the northwest monsoon. The South China Sea cools during the northwest monsoon, but this is not accompanied by any strong increase in ocean color.

5.2. Anomalies

[40] We now turn to instances where the variability does not follow the general pattern of the monsoon. First, we can ask the question as to why there are higher apparent chlorophyll-a concentrations in the coastal zone of Kalimantan but not off Sulawesi Island. The answer is likely a combination of river runoff, coastal environments, and water depths. Kalimantan has larger rivers flowing into the coastal zone, coastal mangrove communities, and shallower coastal waters compared to Sulawesi (Figure 1), which has a higher proportion of coral reefs [*Liu et al.*, 2006]. Thus the waters around Kalimantan have constituents aside from chlorophyll-a that also contribute to ocean color, such as CDOM, and particulate matter associated with river input or mangrove communities. The coral reefs of Sulawesi occur in clearer waters. Water depth, coastal ecosystem characteristics, and river runoff are important ingredients to the climatology of ocean color in the western part of Indonesia.

Although we cannot ascribe the variability around Kalimantan to the effects of runoff, the differences in coastal ecosystem structure remain, and are the probable cause of the difference.

[41] Second, why does the area north of the Nusa Tenggara Island chain, in the Flores Sea, always exhibit low values of ocean color? This area shows low values even during the southeast monsoon. SSTs are slightly warmer here, which may result from wind-induced downwelling. However, a tongue of cooler water enters from the Banda Sea in August (Figure 6), and still the area is anomalously low in pigment biomass. The distribution of surface winds, however, seems to hold the answer. During the initiation of the southeast monsoon, the Flores Sea appears to be in a wind shadow, and the low winds combined with downwelling produces an area low in chlorophyll-a.

[42] Third, we question why the Karimata Strait seems anomalously low compared to the Jawa Sea. Both seas are part of an extensive continental shelf region, and have similar topographic characteristics and riverine inputs [*Liu et al.*, 2006]. They seem to be subject to similar wind-forcing (Figure 4). One possibility is the nature of the riverine input to the coastal zone, or alternatively the interaction of physiographic effects, winds, and currents in the region that produce greater vertical mixing in the Jawa Sea compared to the Karimata Strait.

5.3. Interannual Variability

[43] The 1997 El Niño was a very significant event in Indonesia [e.g., *Page et al.*, 2002] as well as the Indian Ocean [*Murtugudde et al.*, 1999, 2000]. It perturbed the climatology to some extent due to the role El Niño conditions played in enhancing the bloom of phytoplankton that occurs south of Jawa, with chlorophyll-a concentrations reaching 2–3 mg m^{-3} (Figures 5 and 6). The northwest monsoon was also enhanced [*Murtugudde et al.*, 1999], although the biological response was weaker. Interestingly, the effect of the El Niño was centered on the area to the immediate south of eastern Jawa (Figure 6a), and this is true for the symmetrical difference in November 1998 (Figure 6c). This suggests that the interannual variation of ocean color is modulated by both the ENSO and the internal dynamics of the Indian Ocean. *Yoder and Kennelly* [2003] showed that the region south of Jawa has a strong negative amplitude for mode-1 of their global EOF. *Murtugudde et al.* [2000] and *Annamalai et al.* [2003] suggest, on the basis of model results, that the upwelling off Jawa and Sumatra in November 1997 was forced by local and remote processes about equally, while *Saji et al.* [1999] and *Webster et al.* [1999] argue that coupled ocean-atmosphere dynamics internal to the Indian Ocean force the anomalies.

[44] ENSO is the main driver of interannual variability in SST, wind, and ocean color for the Indonesian region. During the 1997/98 El Niño event, anomalously easterly winds enhanced the upwelling along the coast of Jawa-Sumatra reducing the sea surface temperature, which increased the pressure gradient between Jawa-Sumatra and western Indian Ocean. Hence it further enhanced the easterly wind. Anomalously easterly winds associated with the El Niño/IOD generated an anomalous upwelling [*Susanto et al.*, 2001a; *Feng and Meyers*, 2003].

[45] In conclusion, the variability of satellite-derived chlorophyll-a concentration and SST within the Indonesian Seas is strongly affected by the AA monsoon and larger scale coupled ocean-atmosphere phenomena associated with ENSO and IOD. In general, chlorophyll-a concentration is higher during the southeast monsoon compared to that of northwest monsoon. The 1997/1998 El Niño, which coincided with IOD intensified the upwelling associated with the southeast monsoon. Hence the 1997 El Niño further enhanced the high chlorophyll-a concentration along the south coast of the Sumatra-Jawa-Nusa Tenggara Island chain and in the Banda Sea.

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