Biogeosciences Discuss., 5, 3905–3918, 2008
www.biogeosciences-discuss.net/5/3905/2008/

Biogeosciences Discussions

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Phytoplankton blooms induced/sustained by cyclonic eddies during the Indian Ocean Dipole event of 1997 along the southern coasts of Java and Sumatra

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Received: 18 August 2008 – Accepted: 21 August 2008 – Published: 26 September 2008

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The Indonesian archipelago is the gateway in the tropics connecting two oceans (Pacific and the Indian Ocean) and two continents (Asia and Australia). During the Indian Ocean Dipole 1997, record anomalous and unanticipated upwelling had occurred along the southern coasts of Java and Sumatra causing massive phytoplankton blooms. But the method/mode/process for such anomalous upwelling was not known. Using monthly SeaWifs chlorophyll-*a* anomalies, TOPEX Sea Surface Height (SSH) anomalies, Sea Surface Temperatures (SST) and currents from a state-of-the-art OGCM, we report the presence of a series of cyclonic eddies along southern coasts of Sumatra and Java during November, December 1997 and January 1998. Upwelling caused by these cyclonic eddies, as also supported by the SSH and SST anomalies, has been responsible for the phytoplankton blooms to persist and dissipate during the 3 months (November, December 1997 and January 1998).

1 Introduction

The majority of the ocean's productivity occurs within the tropics along the equatorial band of 10° N to 10° S (Longhurst, 1993). The Indonesian seas are the center of biological diversity exhibiting high variability in ocean color (Veron, 1995; Yoder and Kennely, 2003). The variation of seasonal solar heating over the continents of Asia and Australia drives the monsoons, which change wind direction twice a year (Tomascik et al., 1997; Webster et al., 1998). During the southeast monsoon (April to October), southeasterly wind from Australia generates upwelling, bringing cooler waters and increased nutrients to the surface along the southern coasts of Java and Sumatra. Conditions are reversed during the northwest monsoon, the northwest monsoon, which develops between December and March, is forced by high atmospheric pressure over Asia and low pressure over Australia. Coastally trapped Kelvin waves, generated along the equatorial Indian Ocean during the monsoon transitions (April and October),

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also affect upwelling and downwelling processes (Arief and Murray, 1996; Clarke et al., 1993; Sprintall et al., 2000). ENSO (El Niño-Southern Oscillation) and monsoons create the largest sea surface temperature variability and sea surface height anomaly along the southern coasts of Java and Sumatra (Susanto et al., 2001a, b). In addition to ENSO and monsoons, other forcings that influence chlorophyll-*a* concentrations in the Indonesian seas are tides (Ffield and Gordon, 1996; Susanto et al., 2000), Madden-Julian Oscillation (MJO), Kelvin and Rossby waves (Arief and Murray, 1996; Clarke et al., 1993; Sprintall et al., 2000) and the Indian Ocean Dipole (IOD) (Saji et al., 1999; Webster et al., 1999). In November 1997, Indian Ocean Dipole coinciding with El Niño created a very strong upwelling event covering a large area from south Java to the equator around mid of west Sumatra (where no upwelling exists in this region during non IOD/El Niño years). Using monthly anomalies of November, December 1997 and January 1998, we investigate the variability of the chlorophyll-*a* concentrations, SSH and SST. Further we also use currents from the sate-of-the-art ECCO (Estimating the Circulation and Climate of the Ocean) model to understand the impact of circulations in terms of cyclonic eddies on the phytoplankton variability observed along the Sumatra and Java coasts during the IOD year 1997.

2 Data

The domain considered for the study is 1° N–14° S; 85°–115° E. Monthly chlorophyll-*a* anomalies from SeaWifs for November, December 1997 and January 1998 were computed as departures from the 1997–2007 climatological mean for that month. It is now recognized that for several reasons, SeaWifs is able to observe aspects of chlorophyll-*a* variability that were not apparent in the CZCS (Coastal Zone Color Scanner) data. SeaWifs with its global coverage as well as improved cloud screening is able to track the transient features (Murthugudde et al., 1999). To understand and analyze the observed variability of the chlorophyll-*a* concentrations, the surface currents (10-day mean) from a state-of-the art ECCO (Estimating the Circulation and Climate of the

Ocean) MIT OGCM (Massachusetts Institute of Technology Ocean General Circulation Model) are used; this model is configured to best resolve the upper ocean circulation of the tropics (Rahul et al., 2004). The model domain covers the globe (80° S to 80° N) with a 1-deg zonal and meridional resolution, telescoping to a 1/3-degree latitudinal resolution within 20-deg of the equator. The model/data product is obtained by assimilating a comprehensive set of observations (altimetry from TOPEX/POSEIDON, XBTs (Expendable Bathythermograph), current meter measurements, drifters, floats, CTDs (Conductivity, Temperature, Depth sensors), satellite sea surface temperature, tide gauges, bottom pressure measurements, and NCEP air-sea flux estimates) into the MIT Ocean General Circulation Model (OGCM). Monthly Sea Surface Height (SSH) anomalies (calculated as departures from the 1993–1999 climatological mean for that month) are generated from the TOPEX data while the NCEP monthly SST variability is investigated from the ECCO model output.

3 Results

Monthly chlorophyll-*a* anomaly plots during November, December 1997 and January 1998 are shown in Figs. 1a, 2a and 3a, these plots were computed as departures from 1997–2007 mean for that month. Monthly chlorophyll-*a* concentrations for Nov, December 1997 and January 1998 are shown in Figs. 1b, 2b and 3b and the circulation vector plots from the OGCM are shown in Figs. 1c, 2c and 3c. Figure 4a, c and e represent the TOPEX SSH anomalies from 1993–1999 climatological mean during November, December 1997 and January 1998, while Fig. 4b, d and f show the SST variability from the OGCM for November, December 1997 and January 1998.

Figure 1a shows a positive chlorophyll-*a* anomaly along the southern coasts of Java and Sumatra during November 1997. The positive anomalies of the chlorophyll-*a* concentrations spread like a 'spray' with very strong positive anomalies (~1 mg/m^3) along the south of Java and weakening in magnitude but with wider spatial coverage as we move north-westwards (till 85° E longitudinally and over 10 S–2 N, latitudi-

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nally). The variability of the positive anomaly is between +1 along the southern coast of Java to +0.1 along the East Indian Ocean (85°–90° E; 8° S–2° N). The variability in the chlorophyll-*a* anomalies during the December 1997 is shown in Fig. 2a, from the figure it is clear that the "chlorophyll spray" like structure with positive anomalies have weakened along the south of Java, but have intensified along the Sumatra coast and have spread into the eastern Bay of Bengal. Figure 3a shows the variability of the positive chlorophyll-*a* anomalies during January 1998, it is observed that the positive chlorophyll-*a* anomaly has weakened substantially along the south of Java but for a patch of positive anomalies along the coast of Java, however high positive anomalies are found along the coast of Sumatra. Also the spatial extent of the positive anomalies into the East Indian Ocean has reduced and so have the magnitudes (+0.1 to +0.2 mg/m^3). The monthly plots (Figs. 1b, 2b and 3b) of the chlorophyll-*a* variability during November, December 1997 and January 1998 is similar to monthly anomaly plots (Figs. 1a, 2a and 3a). By March 1998, the chlorophyll-*a* concentrations come to the climatological levels (figure not shown).

The physical processes that inject nutrients into the euphotic zone from below are of prime importance. To investigate the possible processes that might have lead to the phytoplankton bloom, the oceanic response has been investigated with a state-of-the-art MIT-OGCM. Although this model does not simulate the biological response, it is exceptional in resolving circulations; especially the meso-scale eddies, in the tropical Indian Ocean (Rahul et al., 2004). The velocity vector plots (10-day means) from ECCO model during 2nd of November, December 1997 and January 1998 at 35-m depths are analyzed in Figs. 1c, 2c and 3c. Figure 1c shows the velocity vectors during November 1997, the plot reveal a series of 4 cyclonic gyres C1, C2, C3 and C4 as indicated in the figure. C1 is over 9°–12° S; 104°–114° E (along Java coast), C2 over 6°–10° S; 100°–105° E, C3 over 1°–7° S; 92°–100° E (along southern Sumatra coast) and C4 is over the domain 2°–4° S; 85°–90° E (along the East Indian Ocean.). The velocity vectors during December 1997 are plotted in Fig. 2c, the circulations during this month also show a cyclonic pattern, but the number of cyclonic eddies is reduced to two i.e., C5 and C6.

C5 is observed along the Java coast over 9°–13° S; 105°–113° E) while C6 is a massive cyclonic eddy covering large area (1°–11° S; 88°–103° E) along the Sumatra coast and the East Indian Ocean. C7 and C8 are the cyclonic eddies observed during January 1998 as shown in the Fig. 3c. C7 (2–13 S; 88–102 E) and C8 (8–11 S; 104–112 E) are weakly formed cyclonic eddies; though the magnitude of the currents is strong the cyclonic structure is weaker than C1–C6.

The variability in TOPEX sea surface height anomaly during November 1997, December 1997 and January 1998 is plotted in Fig. 4a, c and e. The SSH anomaly plots clearly bring out globules of strong negative SSH anomalies along the coasts of Java and Sumatra, the magnitude of the negative SSH anomaly is maximum during November 1997 (Fig. 4a) and then gradually weakens by January 1998 (Fig. 4c, e). The SST variability during the same time is shown in Fig. 4b, d, and f and patterns of SST variability are similar to the SSH plots.

4 Discussion

Although SSTs in the central-western tropical Indian Ocean were anomalously warm during 1997, the eastern sector was unusually cool. These cool SSTs were the result of recently discovered coupled ocean-atmosphere dynamics (Saji et al., 1999; Webster et al., 1999), termed the Indian Ocean Dipole (IOD). During the 1997 IOD, enhanced southeasterly trade winds drove strong upwelling along the southwest coast of Sumatra, causing SSTs to drop by around 4°C. The chlorophyll-*a* bloom occurs as a result of the upwelling that pumps the nutrients of the deep rich water to the euphotic zone through various mechanisms. New pumping mechanisms have been proposed to account for unexplained phytoplankton blooms incorporating the role of mesoscale eddies and Rossby waves (Uz et al., 2001; Villareal et al., 1999). In the Atlantic Ocean, the similar implications of cyclonic circulation of an eddy in enhancing the phytoplankton bloom have also been reported (McGillicuddy et al., 1997, 1998; Oschlies and Garcon, 1998; Falkowski et al., 1991; Dadou et al., 1996). In the present case though it was reported that the observed chlorophyll-*a* concentrations was due to upwelling (Susanto et al., 2001a, b), the process by which this upwelling takes place has not been reported. The novelty of this study as stated above comes from the fact we have tried to relate the biological response and the physical response through eddies, i.e., the upwelling caused such high positive chlorophyll-*a* anomalies through the cyclonic eddies (C1–C8). The cyclonic circulation associated with the cold-core eddy is capable of pumping up nutrient-rich waters into the euphotic zone leading to 8–10 times enhanced chlorophyll-*a* concentrations compared to the non-eddy regions (Prasanna Kumar et al., 2004). These cyclonic eddies occurred as a result of the interference between the eastward propagating coastal Kelvin waves and the westward propagating Rossby waves. Upon carefully examining the Figs. 1a, c, 2a, c and 3a, c it is interesting to note that the pattern of the enhanced chlorophyll-*a* patches along the Java and Sumatra coasts coincide with the presence of the cyclonic eddies. Further evidence of the impact of these cyclonic eddies comes from comparing the TOPEX SSH anomalies, the globules of negative SSH anomalies (indicating decrease) coincide with the cyclonic eddies (Figs. 1a, 2a and 3a) (indicating upwelling). This study also advances the previous studies by investigating the chlorophyll-*a* variability in January 1998 (earlier studies were confined to the November and December 1997). This investigation shows that the positive chlorophyll-*a* anomalies did exist even in January 1998 and the presence of weak cyclonic eddies supports this observation. The model simulations of the circulations have been carefully checked for the other years (1997, 1998, 2000) during the same time period and over the same region, no such cyclonic eddies are simulated by the model, confirming that the eddies were in fact a result of the anomalous conditions that prevailed during the Indian Ocean Dipole year 1997.

5 Conclusions

Ocean productivity in the Indonesian region is generally proportional to the strength of upwelling (Kinkade et al., 1997) and severity of the 1997 IOD event on the phytoplank-

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ton along the Java and Sumatra coasts has been a consequence of such unprecedented upwelling. The effect of eddies in inducing the phytoplankton blooms have investigated in the Atlantic (McGillicuddy et al., 1997, 1998; Oschlies and Garcon, 1998; Falkowski et al., 1991; Dadou et al., 1996) and recently the role of a super cyclone in inducing higher chlorophyll-*a* concentrations along its path (in the Bay of Bengal) by enhancing upwelling through a cyclonic eddy has also been reported (Rahul et al., 2008). The results from this study add a new dimension of the ocean's response along the southern coasts of Java and Sumatra during the IOD 1997 by identifying the series of cyclonic eddies. The occurrence of the high chlorophyll-*a* concentrations during January 1998 is also a new insight (earlier studies considered the variability during the peak IOD months of November and December). The presence of the cyclonic eddies has been supported by the TOPEX SSH and the model derived SSTs.

Acknowledgements. I am thankful for the contribution of the Consortium for Estimating the Circulation and Climate of the Ocean (ECCO) funded by the National Oceanographic Partnership Program for providing the circulations. I am also thankful to the constructive comments from the anonymous reviewers, which have honed this paper. This work has been funded under the SATCORE program through INCOIS. Thanks to the Director, IITM for encouragement.

References

Arief, D. and Murray, S. P.: Low-frequency fluctuations in the Indonesian through flow through Lombok Strait, J. Geophys. Res., 101, 12 455–12 464, 1996.

Clarke, A. J. and Liu, X.: Observations and dynamics of semiannual and annual sea levels near the eastern Indian Ocean boundary, J. Phys. Oceanogr., 23, 386–399, 1993.

Dadou, I., Garcon, V., Andersen, V., Flierl, G. R., and Davis, C. S.: Impact of the North Equatorial Current meandering on a pelagic ecosystem: a modeling approach, J. Mar. Res., 54, 311–342, 1996.

Falkowski, P. G., Ziemann, D., Kolber, Z., and Bienfang, P. K.: Role of eddy pumping in enhancing primary production in the ocean, Nature, 352, 55–58, 1991.

Ffield, A. and Gordon, A. L.: Tidal mixing signatures in the Indonesian Seas, J. Phys. Oceanogr., 26, 1924–1937, 1996.

Kinkade, C., Marra, J., Langdon, C., Knudson, C., and Ilahude, A. D.: Monsoonal differences in phytoplankton biomass and production in the Indonesian Seas: tracing vertical mixing using temperature, Deep-Sea Res. I, 44, 581–592, 1997.

Longhurst, A.: Seasonal cooling and blooming in tropical oceans, Deep-Sea Res. I, 40, 2145–2165, 1993.

Murtugudde, R., Signorini, S., Christian, J., Busalacchi, A., McClain, C., and Picaut, J.: Ocean color variability of the tropical Indo-Pacific observed by SeaWifs during 1997–1998, J. Geophys. Res., 104, 18 351–18 366, 1999.

McGillicuddy, D. J. and Robinson, A. R.: Eddy-induced nutrient supply and new production in the Sargasso Sea, Deep-Sea Res. I, 44, 1427–1450, 1997.

McGillicuddy, D. J., Robinson, A. R., Siegal, D. A., Jannasch, H. W., Robinson, R., Dickey, T. D., McNeil, J., Michaels, A. F., and Knap, A. H.: Influence of mesoscale eddies on new production in the Sargasso Sea, Nature, 394, 263–265, 1998.

Oschlies, A. and Garcon, V.: Eddy-induced enhancement of primary production in a model of the North Atlantic Ocean, Nature, 394, 266–268, 1998.

Prasanna Kumar, S., Nuncio, M., and Narvekar, J.: Are eddies nature's trigger to enhance biological productivity in the Bay of Bengal?, Geophys. Res. Lett., 31, L07309, doi:10.1029/2003GL019274, 2004.

Rahul Chand Reddy, P., Salvekar, P. S., Deo, A. A., and Ganer, D. W.: Westward propagating Twin Gyres in the Equatorial Indian Ocean, Geophys. Res. Lett., 31, L01304, doi:10.1029/2003GL018615, 2004.

Rahul Chand Reddy, P., Salvekar, P. S., and Nayak, S.: Super cyclone induces a meso-scale phytoplankton bloom in the Bay of Bengal, IEEE Geosci. Remote S., GRSL-00030, accepted, 2008.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N., and Yamagata, T. A: Dipole mode in the tropical Indian Ocean, Nature, 401, 360–363, 1999.

Sprintall, J., Gordon, A. L., Murtugudde, R., and Susanto, R. D.: A semi-annual Indian Ocean forced Kelvin waves observed in the Indonesian Seas, May 1997, J. Geophys. Res., 105, 17 217–17 230, 2000.

Susanto, R. D., Gordon, A. L., and Zheng, Q.: Upwelling along the coasts of Java and Sumatra and its relation to ENSO, Geophys. Res. Lett., 28, 1559–1602, 2001a.

Susanto, R. D., Gordon, A. L., and Zheng, Q.: Upwelling within the Indonesian Seas and its relation to Monsoon and ENSO, The Fifth IOC/WESTPAC International Scientific Symposium, Seoul, Republic of Korea, 27–31 August 2001, 2001b.

Susanto, R. D., Gordon, A. L., Sprintall, J., and Herunadi, B.: Intraseasonal variability and tides in Makassar Strait, Geophys. Res. Lett., 27, 1499–1502, 2000.

Tomascik, T., Mah, A. J., Nontji, A., and Moosa, M. K.: The Ecology of the Indonesian Seas Part I, Periplus Editions (HK) Ltd., Singapore, 94–100, 1997.

Uz, B. M., Yoder, J. A., and Osychny, V.: Pumping of nutrients to ocean surface waters by the action of propagating planetary waves, Nature, 409, 597–600, 2001.

Veron, J. E. N.: Corals in Space and Time: Biography and Evolution of the *Scleractinia*, Cornell University Press, Ithaca, NY, USA, 321 pp. , 1995.

Villareal, T. A. C., Pilskain, M. B., Brezezinski, M., Lipschuiltz, F., Dennerr, M., and Gardner, G. B.: Upward transport of oceanic nitrate by migrating diatom mats, Nature, 397, 423–425, 1999.

Webster, P. J., Magana, V. O., Palmer, T. N., Shukla, J., Thomas, R. A., Yanai, M., and Yasunari, T.: Monsoon: processes, predictability, and the prospects for prediction, J. Geophys. Res., 103, 14 451–14 510, 1998.

Webster, P. J., Moore, A. M., Loschnigg, J. P., and Leben, R. R.: Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997–98, Nature, 401, 356–360, 1999.

Yoder, J. A. and Kennelly, M. A.: Seasonal and ENSO variability in global ocean phytoplankton chlorophyll derived from 4 years of SeaWiFS measurements. Global Biogeochem. Cy., 7, 1112, doi:10.1029/2002GB001942, 2003.

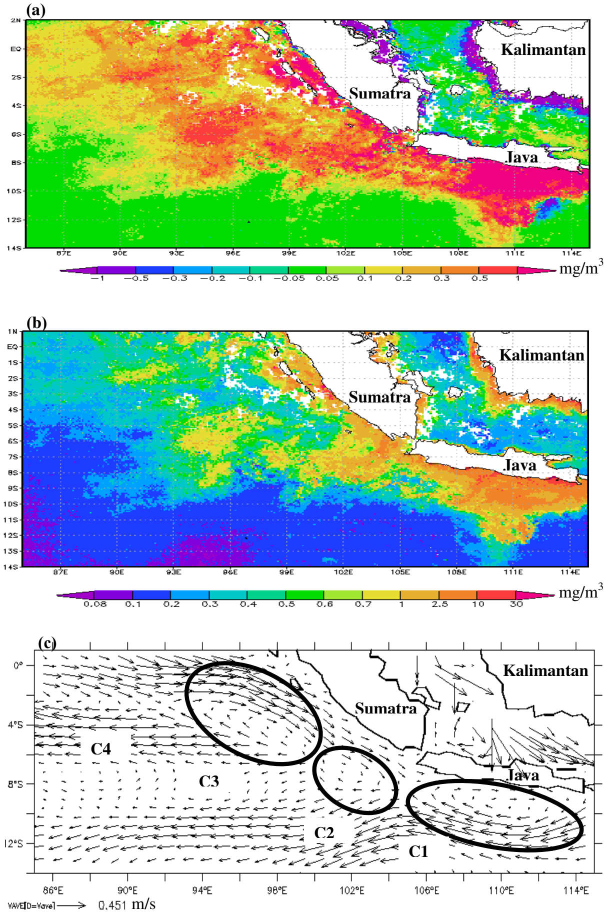

Fig. 1. (a) chlorophyll-*a* anomaly (mg/m^3) plot for November 1997, **(b)** Monthly chlorophyll-*a* (mg/m^3) concentrations for Nov 1997, **(c)**. Currents (m/s) at 35-m depth from the OGCM during November 1997. C1–C8 are marked on the figures to represent the cyclonic eddies.

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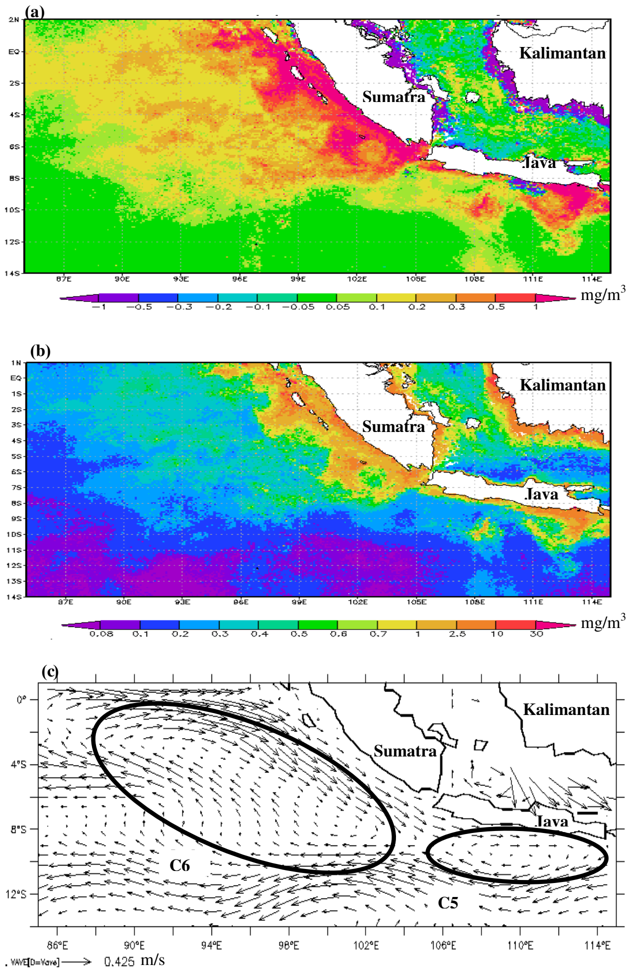

Fig. 2. Same as Fig. 1 but for December 1998.

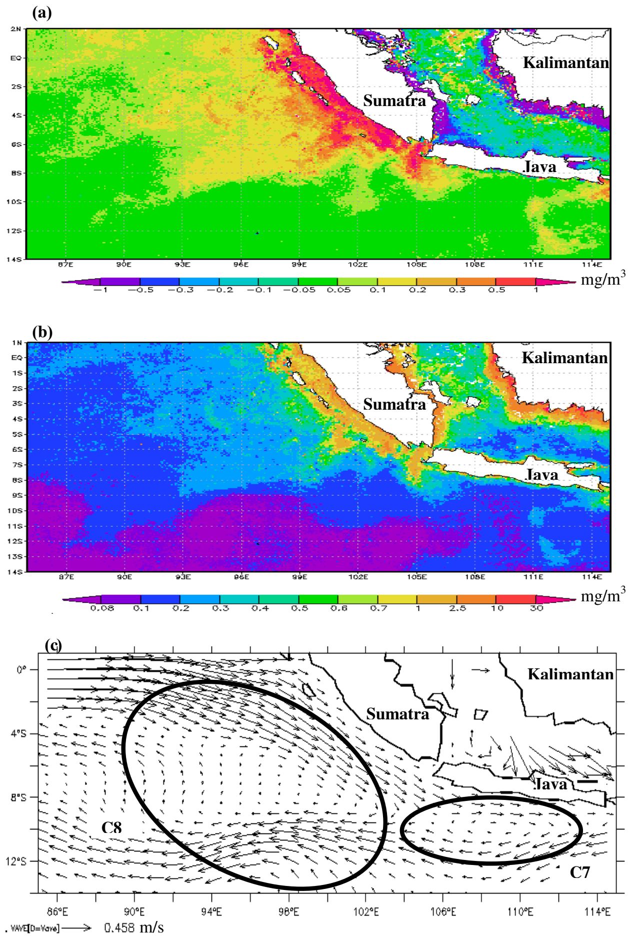

Fig. 3. Same as Fig. 1 but for January 1998.

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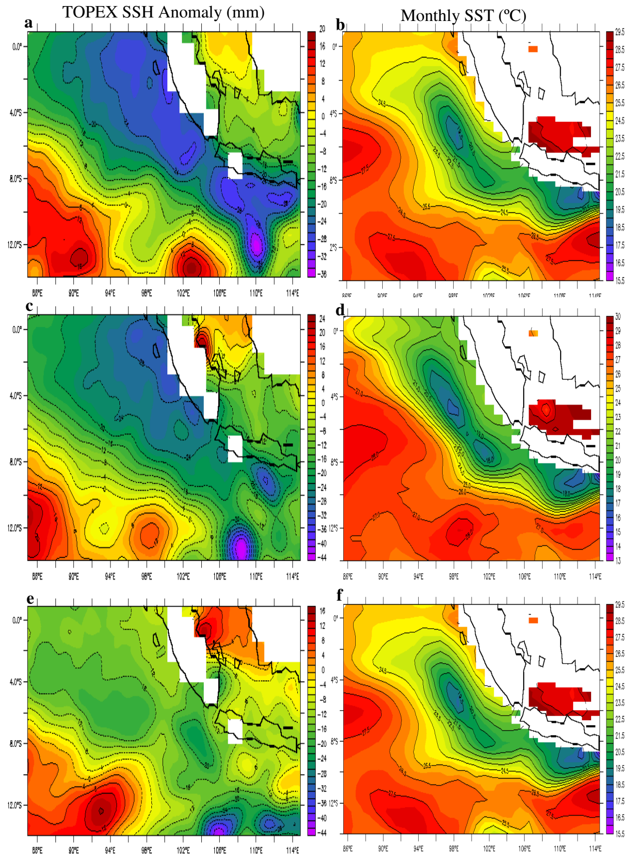

Fig. 4. **(a)**, **(c)** and **(e)** TOPEX SSH anomaly (mm) plots for November, December 1997 and January 1998, respectively, while **(b)**, **(d)** and **(f)** represent the SST (˚C) variability for November, December 1997 and January 1998, respectively.