ANOMALOUS OCEANIC CONDITIONS IN THE TROPICAL INDIAN OCEAN DURING 2006 AS REVEALED BY MULTI-SATELLITE SENSORS

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ABSTRACT

A positive Indian Ocean Dipole (IOD) took place in the tropical Indian Ocean during 2006. The evolution of this event started in July 2006 and intensified during August 2006. It was indicated by negative sea surface temperature anomalies, lower than normal sea level and suppressed convection in the southeastern equatorial Indian Ocean in contrast to western counterpart. Peak negative SST anomalies exceeding 1°C were observed in the eastern basin during September–November coinciding with anomalous easterly winds along the equator and strong southeasterly winds along the coast of Sumatra and Java. The expression of this positive IOD was also seen in other physical variables: negative sea surface height anomalies of about 30 cm and negative rainfall anomalies exceeding 8 mm/day were observed in the eastern basin. The event was terminated in December 2006 mainly due to warming of the eastern pole. The magnitude of this event determined by the east-west temperature gradient across the tropical Indian Ocean was the third largest in the last 30 years, after 1997 and 1994 events.

Keywords: Indian Ocean Dipole, Dipole Mode Index, equatorial upwelling, Kelvin waves.

INTRODUCTION

The Indian Ocean is unique compare to the Pacific and Atlantic Oceans in a way that it is blocked at the northern boundary by the Asian land mass. Consequently, the contrast of heating between the land and the ocean results in dramatic seasonal wind reversals over the Indian Ocean. During the boreal winter (December–March) the winds blow from the northeast (northeast monsoon), while during boreal summer (June–September) the winds are characterized by southwesterlies (southwest monsoon). Over the equator, strong westerly winds blow during the transition period between two monsoons in April–May and October–November.

The tropical Indian Ocean also experiences interannual variability in response to remote and internal coupled ocean-atmosphere phenomena. The remote forcing comes from the Pacific Ocean associated with the ENSO [Yamagata *et al.*, 2004], while the inherent mode is associated with the Indian Ocean Dipole (IOD) [Saji *et al.*, 1999; Webster *et al.*, 1999]. In particular, the IOD event is inherent coupled ocean-atmosphere phenomenon in the tropical Indian Ocean that develops via feedbacks between zonal wind stress, sea surface temperature (SST) and thermocline depth anomalies. The positive IOD event is characterized by cold (shallow) SST (thermocline) anomalies in the southeastern tropical basin, accompanied by warm (deep) SST (thermocline) anomalies in the western tropical basin [Saji *et al.*, 1999; Webster *et al.*, 1999]. Changes in SST are closely associated with changes in surface winds: the equatorial winds reverse direction from westerlies to easterlies during the peak phase of the positive IOD event. The situation reverses for the negative IOD events.

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Since the seminal work by Saji *et al.* [1999], several aspects of the IOD event have been investigated using observational and numerical data. For example, Rao *et al.* [2002] have shown the existence of subsurface dipole pattern. They showed that anomalous easterly winds during the peak phase of the positive IOD events uplift thermocline in the eastern basin and deepen thermocline in the central and western basin.

Moreover, the IOD affects the climate variability in the Indo-Pacific region, such as drought in the Indonesian region [Behera *et al.*, 1999; Saji *et al.*, 1999; Webster *et al.*, 1999], rainfall variability in the Indian continent [Behera *et al.*, 1999; Ashok *et al.*, 2001] and the African rainfall [Black *et al.*, 2003; Behera *et al.*, 2005]. The IOD also influences the word climate through the atmospheric teleconnection [Saji and Yamagata, 2003]. More recently, Iskandar *et al.* [2008] have shown that the IOD also influence instraseasonal zonal currents and instraseasonal Kelvin waves along the equatorial Indian Ocean.

In this study, we present evidences of the occurrence of positive IOD event during 2006 using data from multi-satellite sensors. The remainder of this paper is organized as follows. In section 2, we briefly describe the data used in this study. Section 3 presents the results. Emphasis is on the evolution of the positive IOD during 2006 and its impact on the rainfall over the maritime continent. Finally, the last section is reserved for summary.

DATA

The monthly wind field data used in this study were obtained from QSCAT scatterometer for the period of August 1997–December 2006. The SST and rainfall data were derived from the monthly Tropical Rainfall Measuring Mission (TRMM) Microwave Imager data for period of January 1998–December 2006. The wind fields, SST and rainfall data have a spatial resolution of 0.25° and they are available at http://www.ssmi.com.

The merged sea surface height (SSH) data were derived from multiple satellite altimeters for the period of January 1998–December 2006. The SSH data have a spatial resolution of 1/3° and they are available at http://www.aviso. oceanobs.com. The monthly outgoing long-wave radiation (OLR) data were obtained from NCEP-NCAR reanalysis data for period of January 1998–December 2006.

Mean climatologies of SST, rainfall, SSH and OLR were calculated from time series over the period January 1998–December 2006, while those for wind fields were calculated over the period January 2000–December 2006. Then, anomaly fields for all variables were constructed on the basis of the deviations from their mean climatologies.

RESULTS AND DISCUSSION

Evolution of the positive Indian Ocean Dipole of 2006

The intensity of the IOD events was determined by Dipole Mode Index (DMI), which indicated the east-west temperature gradient across the tropical Indian Ocean [Saji *et al.*, 1999]. Positive DMI refers to positive IOD event, while negative IOD event is represented by negative DMI. Time series of DMI during 2006 showed that the tropical Indian Ocean was on the normal condition during January – July. The value of DMI was within its one standard deviation ± 0.53 (Fig. 1a). Similarly, the SSH anomaly shows small variations during this period (Fig. 1b). The zonal wind averaged along the equatorial Indian Ocean, on the other hand, reveals intraseasonal variability, in particular during May – July (Fig. 1c).

The DMI increased in early August, exceeded its one standard deviation by the end of August and it remained positive (>1°C) until November (Fig. 1a). The SSH anomaly in the eastern (western) Indian Ocean also decreased (increased) in early August and remained negative (positive) through the end of IOD event (Fig. 1b). The initiation of the IOD was associated with the change in equatorial winds, which showed prevailing easterlies from the end of July, except for short-term variability associated with intraseasonal variations, which had large amplitude during July - August (Fig. 1c). The easterly winds were strengthened in September and remained strong until early November.

From mid-November, the easterly winds along the equator were weakened and the DMI rapidly decreased and reached its normal condition in December (Fig. 1a and 1c). Horii *et al.* [2008] have shown that the termination of the IOD event in 2006 is mainly due to rapid warming of the eastern equatorial Indian Ocean (see also dashed-curve in *Figure 1a*). Considering the magnitude of the DMI, the IOD event in 2006 was the third largest event in the last 30 years, after the 1997 and 1994 events. Note that the SSH anomaly in the eastern Indian Ocean remained negative though the IOD was terminated (Fig. 1b). This may indicate that the ocean dynamics play a minor role on the termination of the IOD event in 2006.

In order to show the basin-wide evolution of the IOD event in 2006, time evolution of SST, wind and SSH anomalies are plotted in Figures 2, 3 and 4, respectively. Negative SST anomalies exceeding 0.5°C appeared off South Java in June, and spread westward along 10°S (Fig. 2b). Associated with the changes in SST, southeasterly-wind anomalies were intensified along the coast of Sumatra and Java (Fig. 3b). These anomalous winds generated upwelling along the coast of Sumatra and Java leading to negative SSH anomalies (Fig. 4b).

By July - August, cold SST anomalies of about 0.5 – 1°C spread northward along the coast toward the equator (Figs. 2c-d). As a result, southeasterly winds were further intensified along the coast and easterly wind anomalies were observed along the

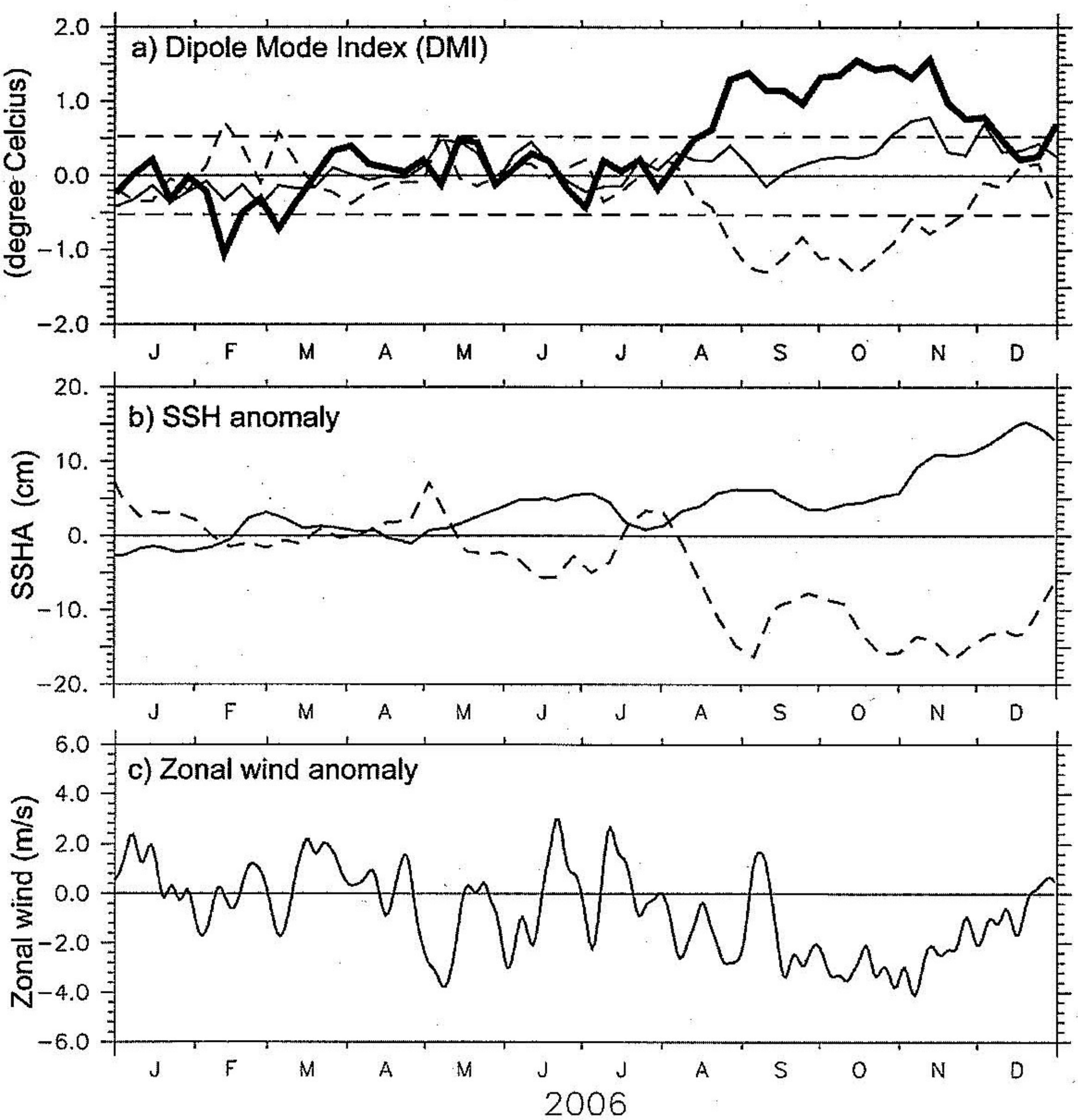

Figure 1. a) Time series of Dipole Mode Index (*thick line*) during January – December 2006. DMI is defined as the SSTA difference between the western equatorial Indian Ocean (50°E - 70°E, 10°S - 10°N, *thin line*) and the eastern equatorial Indian Ocean (90°E - 110°E, 10°S – equator, *thin-dashed line*) [Saji *et al.*, 1999]. Two horizontal-dashed lines indicate one standard deviation (± 0.53). b) Same as in (a) but for SSH anomaly averaged over the western (*solid line*) and over the eastern (*dashed line*) equatorial Indian Ocean. c) Zonal wind anomaly averaged along the equatorial Indian Ocean (50°E - 100°E).

equator (Figs. 3c–d). These easterly wind anomalies generated upwelling Kelvin waves along the equator, which were clearly observed in the SSH anomaly patterns (Fig. 4d). Moreover, these negative SSH anomalies of about 15 cm propagate poleward along the coast once they reached the eastern boundary (Fig. 4d). In the off-equatorial region, downwelling Rossby waves indicated by warm SST and positive SSH anomalies (Fig. 2d and 4d) were observed in response to the easterly winds along the equator (Fig. 3d).

The easterly winds along the equator were intensified in September (Fig. 3e) when cold SST anomalies exceeding 1°C occupied the eastern equatorial Indian Ocean (Fig. 2e). Typical positive IOD patterns were well established in October indicated by cold SST anomalies in the east and warm SST anomalies in the central and western basin (Fig. 2f) associated with strong easterly anomalies along the equator (Fig. 3f). The cold SST anomalies exceeding 1.5°C were located off Sumatra, while warm SST anomalies of about 0.5°C covered most parts of the central and western basin. The expression of positive IOD event was also seen in the SSH patterns. Negative SSH anomalies of about 30 cm were observed in the eastern basin, while positive SSH anomalies less than 5 cm were appeared in the central and western basin (Fig. 4e–f). These anomalous conditions continued until November (Fig. 2g, 3g and 4g). In addition, there was a strong positive SSH signal off-equator between 5°S - 12°S, which propagated westward and persisted during August–December (Figs. 4d–h). Previous studies [Rao *et al.*, 2002; Rao and Behera, 2005] have shown that these downwelling Rossby waves play an important role in the termination of the positive IOD event, through the reflection of downwelling Kelvin waves upon reached the western boundary. Moreover, Luo *et al.* [2008] suggested that a better simulation of these Rossby waves could lead to a better prediction of the IOD event.

The IOD event was terminated in December, when warm SST anomalies of about 0.5°C covered the equatorial region and southern coast of Java (Fig. 2h). Corresponding change was observed in the surface winds. Weakening of easterly winds was observed along the equator during December (Fig. 3h). However, the SSH anomalies remained negative in the eastern basin during December (Fig. 4h) and this continued until February 2007 (*not shown*). The difference in evolution of SST and SSH indicates that surface heat exchange play an important role during the termination of the positive IOD event [Behera *et al.*, 1999].

It should be noted that the El Niño event took place in the Pacific Ocean during 2006/2007 [*McPhaden*, 2008]. However, it is still a subject of ongoing debate whether the IOD is forced remotely from the Pacific Ocean by the ENSO or whether the IOD is an independent mode of climate variability in the tropical Indian Ocean [Meyers *et al.*, 2007]. Annamalai *et al.* [2005] have demonstrated that the structure and magnitude of tropical Indian Ocean SST anomalies have important role on the evolution of the ENSO events in the Pacific. As for the 2006, McPhaden [2008] has suggested that anomalous atmospheric-oceanic conditions in the tropical Indian Ocean during 2006 have affected the evolution of the 2006/2007 El Niño event.

IOD impact on rainfall over the maritime continent

Previous studies have demonstrated a dramatic impact of the positive IOD event on rainfall variability over the surrounding continent [Saji *et al.*, 1999; Behera *et al.*, 1999]. Suppressed (increased) convection over the cold (warm) SST anomaly regions lead to large deficit (excess) in rainfall in the eastern (western) regions. To explore the convective activity during 2006, we calculated monthly Outgoing Long-wave Radiation (OLR) anomalies over the tropical Indian Ocean and over the maritime continent for the period of May through December 2006 (Figs. 5a-h). Note that negative OLR anomalies typically indicated areas that had above-average cloudiness and convection in that region. Meanwhile, the positive OLR anomalies typically indicated regions that had drier conditions (clear sky and high pressure) and less convection.

It was seen from Fig. 5a that the mean May OLR anomalies were positive over the tropical Indian Ocean while they were negative over the maritime continent. Over the central-south Indian Ocean, they reach 35 W/m^2. Corresponding spatial patterns of rainfall anomalies were shown in Figure 6a. The rainfall anomalies were mainly negative over the Indian Ocean (over positive OLR anomalies), while they were mostly positive over the maritime continent (over negative OLR anomalies). In June, the OLR anomalies were negative over the tropical Indian Ocean and maritime continent except over the eastern Indian Ocean near the Sumatra (Fig. 5b). As a result, positive rainfall anomalies covered most of region from the western Indian Ocean to the western Pacific Ocean (Fig. 6b).

In July, positive OLR anomalies prevailed over the eastern Indian Ocean and over the maritime continent, while negative anomalies were observed over the western Indian Ocean (Fig. 5c). The dipole-like pattern in the OLR anomalies with positive anomalies over the eastern basin and negative anomalies over the western basin, were strengthened in August (Fig. 5d). Peak positive anomalies exceeding 40 W/m^2 were observed over the eastern Indian Ocean and maritime continent in September-November. In contrast, peak convection associated with negative OLR anomalies of about 30 W/m^2 were observed over the western part of the basin (Fig. 5e–g). The patterns of rainfall anomalies were consistent with the OLR distributions. Excess rainfalls of about 8 mm/day were observed over the peak convection region in the western basin (Fig. 6d–g). Over the eastern Indian Ocean and maritime continent, on the other hand, deficit rainfalls of about -8 mm/day were collocated with positive OLR anomalies (Fig. 6d–g).

In December when the IOD was terminated, warm SST anomalies along the equatorial Indian

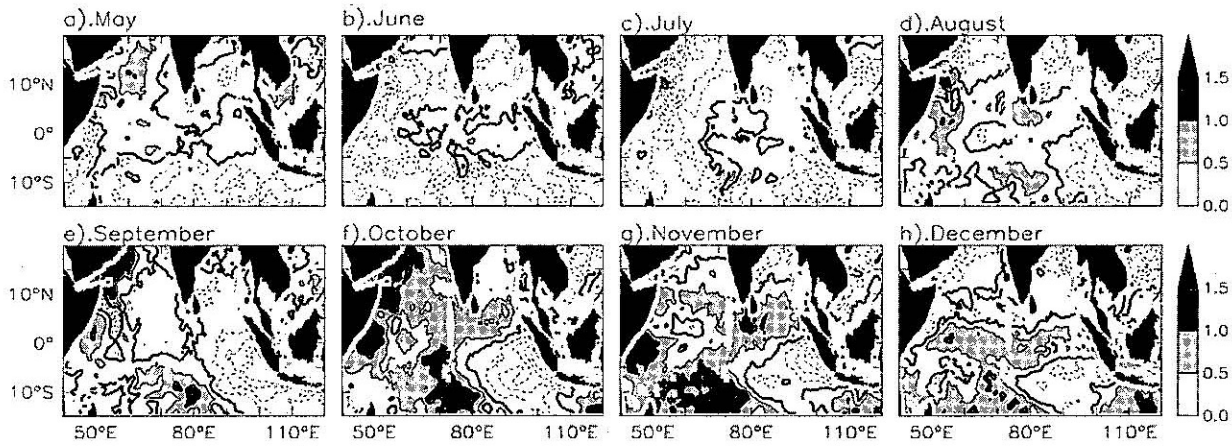

Figure 2. Monthly anomaly of TRMM sea surface temperature (°C) for (a) May, (b) June, (c) July, (d) August, (e) September, (f) October, (g) November and (h) December 2006. Positive values are shaded, while negative values are contoured with an interval of 0.5°C. Zero contours are highlighted with bold-lines.

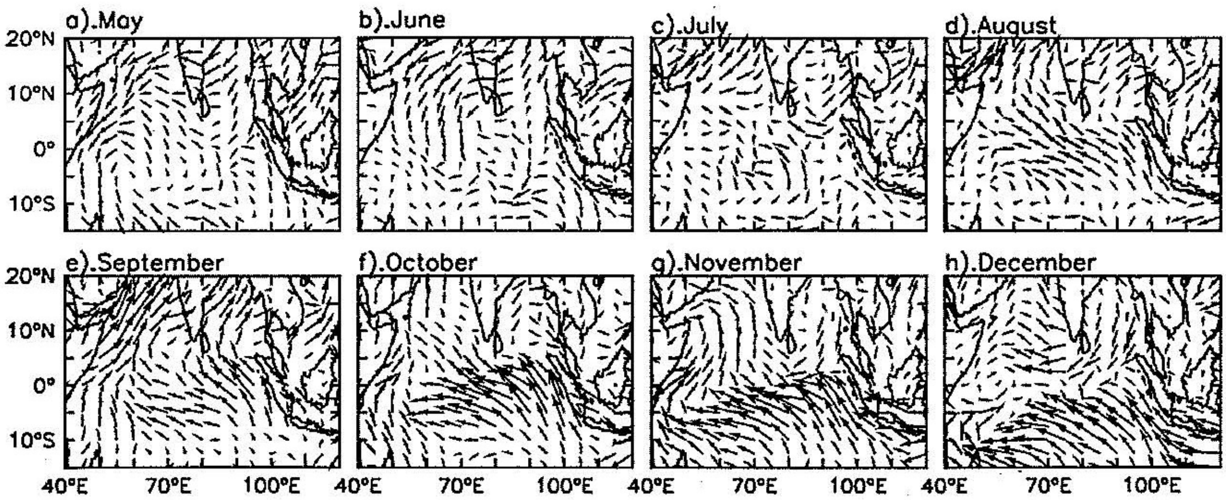

Figure 3. Monthly anomaly of QuikSCAT winds (m/s) for (a) May, (b) June, (c) July, (d) August, (e) September, (f) October, (g) November and (h) December 2006.

Ocean (*see* Fig. 2h) enhanced convection over the equatorial Indian Ocean (Fig. 5h). These deep convections were associated with the positive rainfall anomalies (Fig. 6h). Over the central and eastern maritime continent, however, positive OLR anomalies leading to suppressed convection (negative rainfall), were still observed during December 2006.

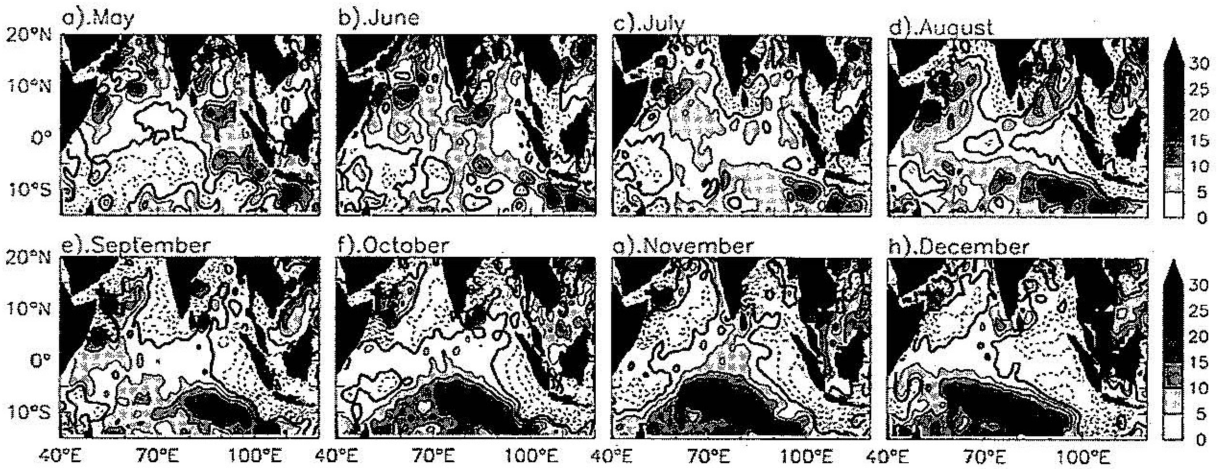

Figure 4. As in Figure 2 except for SSH anomaly. Contour interval is 5 cm.

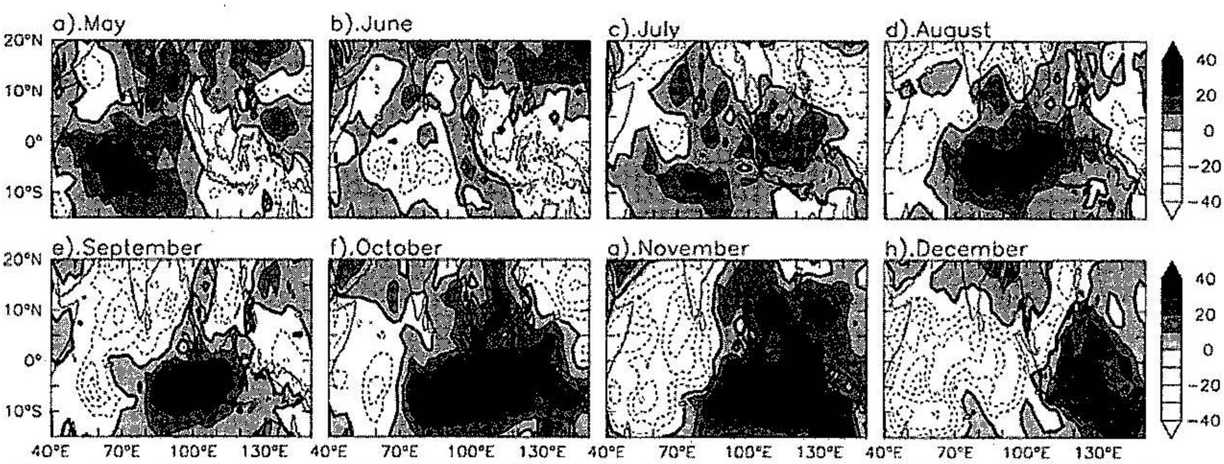

Figure 5. As in Figure 2 except for NCEP-NCAR outgoing long-wave radiation (OLR) anomaly (W/m^2). Contour interval is 10 W/m^2.

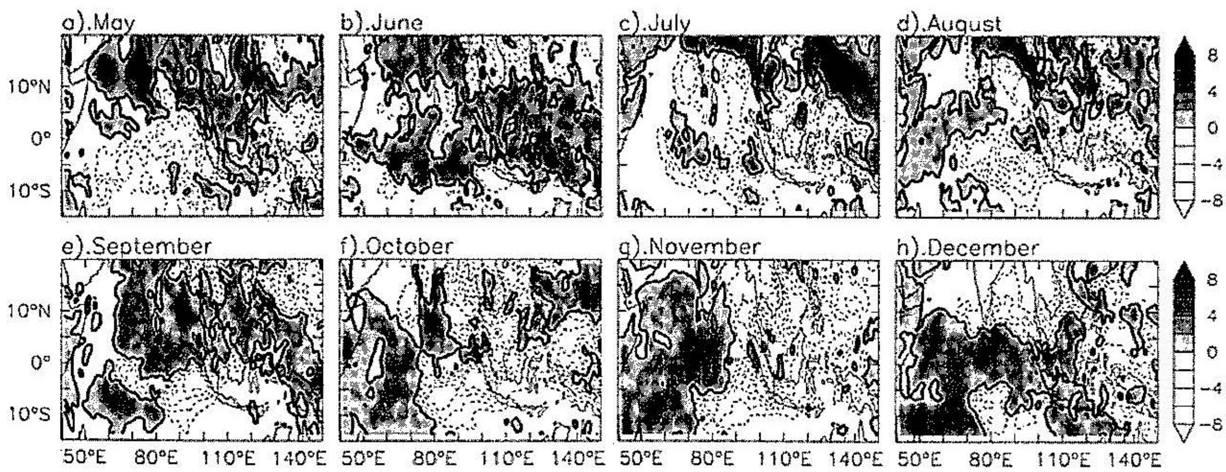

Figure 6. As in Figure 2 except for TRMM rainfall anomaly (mm/day). Contour interval is 2 mm/day.

SUMMARY

The characteristics of positive IOD event were observed by multi-satellite sensors during 2006. Cold SST anomalies were observed in the eastern Indian Ocean off Sumatra and Java, while warm SST anomalies covered most of the central and western Indian Ocean. Associated with cold SST anomalies, anomalously strong southeasterly winds along the coast of Sumatra and Java and easterly winds along the equator were observed during the peak phase of the event in September – November. The easterly winds triggered upwelling Kelvin waves. The waves propagated across the basin and bifurcated poleward upon reaching the western coast of Sumatra. Associated with the upwelling Kelvin waves, negative SSH anomalies were observed along the equator and along the eastern boundary of the Indian Ocean.

The expressions of the positive IOD event in 2006 were also seen in the OLR and rainfall patterns. During the peak phase of the event, suppressed convection indicated by positive OLR anomalies were observed over the eastern tropical Indian Ocean and maritime continent. On the other hand, enhanced convection (negative OLR anomalies) covered most of the central and western tropical Indian Ocean. This dipole pattern in OLR anomalies was associated with rainfall anomalies: deficit rainfall was observed over the eastern tropical Indian Ocean and maritime continent, while the central and western tropical Indian Ocean experienced excess rainfall anomalies.

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