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Citation: [AIP Conference Proceedings](#) **1617**, 48 (2014); doi: 10.1063/1.4897101

View online: <http://dx.doi.org/10.1063/1.4897101>

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Surface and Subsurface Oceanic Variability Observed in the Eastern Equatorial Indian Ocean during Three Consecutive Indian Ocean Dipole Events: 2006 – 2008

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Abstract. 8-year and 4-year long velocity time series records from the equatorial Indian Ocean successfully captured, for the first time, complete evolution of subsurface currents associated with three consecutive Indian Ocean Dipole (IOD) events in 2006 – 2008. It is found that strong eastward subsurface zonal currents in the layer between about 90 m and 150 m were observed, which were opposite to the normal conditions. Vertical structure of the zonal currents resembles that of the typical zonal currents in the equatorial Pacific with an eastward subsurface current lies beneath the surface westward currents. This vertical structure of the zonal currents was associated with anomalous easterly winds along the equatorial Indian Ocean during the maturing phase of the IOD events. In addition, subsurface temperature structures obtained from RAMA buoy network show negative temperature anomalies preceded the surface temperature evolution associated with the IOD events. The negative subsurface temperature anomaly lasted for several months before it changes into positive anomaly as the IOD terminated. The surface temperature structure indicated by the Dipole Mode Index (DMI) revealed that the 2006 IOD was a strong event, while the 2007 and 2008 events were weaker and short-lived events. The evolution of the IOD events were linked to the dynamics of oceanic equatorial wave. It is found that upwelling equatorial Kelvin waves forced by anomalous easterly wind stress play an important role in generating cooling tendency during the development and maturing phase of the IOD events. The demise of the IOD events, on the other hand, was linked to eastern-boundary-reflected Rossby waves that terminated the cooling tendency in the eastern Indian Ocean induced by the wind-forced Kelvin waves. Weakening of the zonal heat advection, then, provided a favor condition for the surface heat flux to warm the sea surface temperature in the eastern equatorial Indian Ocean.

Keywords: Indian Ocean Dipole, Kelvin wave, RAMA buoy, Rossby wave, zonal current.

PACS: 29.70.Aa.

INTRODUCTION

The Indian Ocean Dipole (IOD) refers to a couple ocean-atmosphere mode in the tropical Indian Ocean, which is characterized by an anomalous cooling of the sea surface temperature (SST) in the southeastern region off the Sumatra and Java coast and anomalous warming in the western and central equatorial region [1,2,3]. This typical SST pattern is associated with a suppressed atmospheric convection over the eastern Indian Ocean warm pool. On the other hand, the atmospheric convection off East Africa and central Indian Ocean is enhanced. These conditions lead to a severe drought over the Indonesian and Australia region and excess rainfall over the east Africa, India, and some parts of South Asia [4].

Early study [1] has suggested that the IOD event has a quasi-biennial variation, in which the SST gradient and the zonal wind anomalies change the sign

from one year to the following year. However, a consecutive positive IOD (pIOD) event may occur as previously observed. Previously [5] has shown that observational records revealed a consecutive triple pIOD event in 1944 – 1946. Moreover, using subsurface temperature profiles observed by the Argo combined with data from multi-satellite sensors, [6] have shown the occurrence of three consecutive pIOD events in 2006 – 2008. They suggested that the western-boundary-reflected upwelling equatorial Kelvin enhanced seasonal upwelling and thus generated the SST gradient during the positive events of 2006 and 2008. In contrast, during the pIOD of 2007 event, the eastern-boundary-reflected upwelling Rossby waves play an important role in generating the west-east SST gradient.

The objective of this study is to present the evolution of the three consecutive pIOD events in 2006 – 2008 using available observational data. In

addition, using a wind-driven, linear, continuously stratified long-wave ocean model, we examined quantitatively the role of equatorial waves during the evolution of the events.

DATA AND METHOD

Daily time series of temperature and salinity recorded by the TRITON buoy in the eastern equatorial Indian Ocean (1.5°S , 90°E) were used in this study. This buoy is part of the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) program [7,8,9,10]. The data are available from 23 October 2001 to 9 March 2011. ADCP moorings at (0° , 90°E) and (0° , 80.5°E) as part of RAMA program provided subsurface current data from 14 November 2000 to 19 March 2009 and from 27 October 2004 to 17 October 2008, respectively.

The merged satellite sea surface height (SSH) data from Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) were used in this study. The data covers a period of 14 October 1992 to 22 July 2009, with temporal and horizontal resolutions of 7 days and 0.25° , respectively. The surface winds were obtained from the QSCAT daily winds, which are available from 19 July 1999 to 29 October 2009 on $0.25^{\circ}\times 0.25^{\circ}$ grid. Sea surface temperature (SST) data were derived from the Tropical Rain Measuring Mission (TRMM) data with weekly resolution on $0.25^{\circ}\times 0.25^{\circ}$ grid from January 1998 to December 2009. Meanwhile, the air-sea flux data were obtained from TropFlux analysis on $1^{\circ}\times 1^{\circ}$ horizontal resolution [7]. The data are available in daily resolution from January 1989 through December 2009.

Note that mean climatologies of all variables were calculated from time series over the period of January 2002 to December 2008, except for the subsurface current at 0° , 80.5°E which were derived from time series over the period of January 2004 – December 2007. The anomaly fields for all variables, then, were defined on the basis of deviations from their mean climatology. Finally, a 15-day running mean filter was used for smoothing the anomaly fields.

RESULTS

Figure 1 shows the time series of Dipole Mode Index (DMI) during 2006 – 2008 indicating the magnitude of the event. Following [1], we defined DMI is defined as the difference in SST anomaly between western region ($50^{\circ}\text{E}-70^{\circ}\text{E}$, $10^{\circ}\text{S}-10^{\circ}\text{N}$) and eastern region ($90^{\circ}\text{E}-110^{\circ}\text{E}$, $10^{\circ}\text{S}-\text{Equator}$). It is clearly shown that the 2006 pIOD was followed by

two consecutive pIOD events in 2007 and 2008. In addition, the DMI also indicates that the 2006 pIOD was a typical IOD event, which developed in boreal summer 2006, reached a matured phase in fall 2006 and decayed in winter 2006. The strong 2006 pIOD event was followed by two other pIOD events: a weaker and short-lived pIOD event in 2007, and an early matured and abruptly terminated pIOD event in 2008 [11].

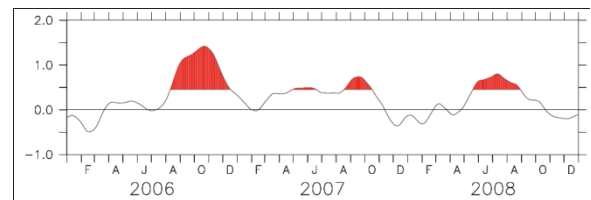


FIGURE 1. Time series of Dipole Mode Index (DMI) from January 2006 to December 2008. The DMI is defined as the difference in SST anomaly between western region ($50^{\circ}\text{E}-70^{\circ}\text{E}$, $10^{\circ}\text{S}-10^{\circ}\text{N}$) and eastern region ($90^{\circ}\text{E}-110^{\circ}\text{E}$, $10^{\circ}\text{S}-\text{Equator}$).

Surface Oceanic Evolution

Figure 2 shows time-longitude diagrams of the surface zonal wind and the sea surface height (SSH) along the equator together with the depth of 20°C isotherm (D20) at 1.5°S , 90°E from January 2006 to December 2008. During January – May 2006, there was an alternate change between westerly and easterly winds along the equator (Fig. 2a) that forced downwelling (positive SSH anomaly) and upwelling (negative SSH anomaly) along the equatorial Indian Ocean (Fig. 2b). At the same time, we also observed upward and downward motion of D20 in the eastern Indian Ocean (Fig. 2c). During the maturing phase of the pIOD event from October through December, the winds were dominated by easterly wind anomalies (Fig. 2a). In response to these easterly wind anomalies, the SSH anomalies indicated a typical dipole pattern with negative anomalies observed in the eastern region and positive anomalies were loading in the western region (Figure 2c).

As expected from the Figure 1, the 2006 IOD event uplifted the D20 in the eastern equatorial Indian Ocean into the shallowest depth compared to the other IOD events in 2007 and 2008 (Fig. 2c). It is also shown in Figure 2 that the shallowest D20 in August 2006 was co-occurring with strong upwelling Kelvin wave signals (Fig. 2b) forced by strong easterly winds along the equator (Fig. 2a).

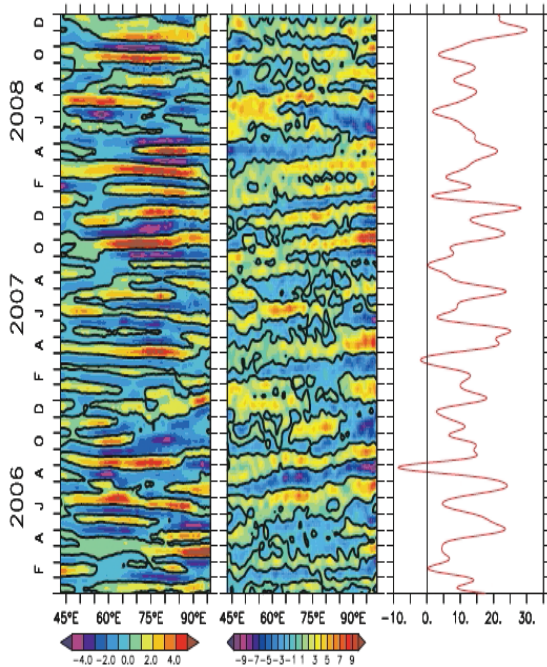


FIGURE 2. Time-longitude diagrams of (a) surface zonal winds, (b) sea surface height, and (c) depth of 20°C isotherm from January 2006 to December 2008. The data have been smoothed with a 31-day running-mean filter.

Subsurface Oceanic Variations

Time-depth sections of the observed zonal currents along the equatorial Indian Ocean are presented in Figure 3. It is shown that during the 2006 and 2007 IOD events, the eastward flowing Wyrtki jets that occur during monsoon transition period in October/November were absent during the fall of 2006 and 2007 (Figs. 3a-b). The absent of fall Wyrtki jets in 2006 and 2007 were associated with strong easterly wind anomalies observed along the equator (Fig. 2a). On the other hand, during 2008 IOD event, the spring Wyrtki jet was absent in April/May. The observed zonal currents indicated anomalous westward currents in April/May, which were opposite to the climatological conditions. This anomalous westward current was associated with the easterly wind anomalies observed along the equator from late March to mid-May (Fig. 2a).

We also noted that during the peak phase of the strong IOD event in September – November 2006 and in June – July 2008, strong eastward undercurrent in the layer between about 90 m and 150 m, were observed, which were opposite to the normal condition (Fig. 3a-b). This typical structure was absent for the 2007 IOD event.

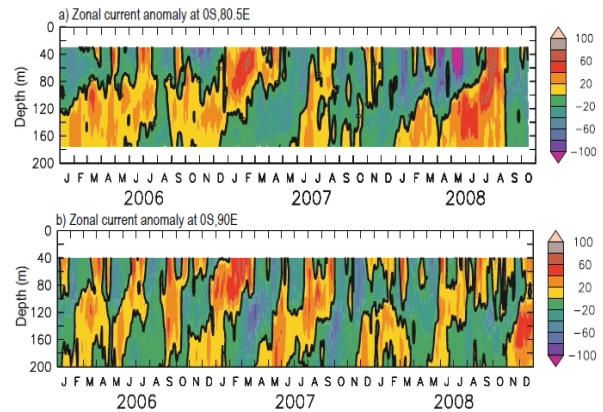


FIGURE 3. Time-depth sections of the zonal current anomaly observed at (a) 0°, 80.5°E, and (b) 0°, 90°E. The fields were smoothed with a 15-day running-mean filter.

There was subsurface signal for the evolution of the IOD event. We found negative subsurface temperature anomalies in May, three months before the onset of the 2006 IOD event and continued for several months after the termination of the IOD event (fig. 4). Similarly, during 2007 IOD event, we also observed negative subsurface temperature though with a weaker amplitude. In contrast, during 2008 IOD event, the initiation of negative temperature anomalies in the thermocline was observed in late April 2008 co-occurred with the development of the DMI (Fig. 1). The negative anomaly lasted only about 4 months until August before it gradually changed to positive anomaly in September. Maximum negative anomaly of about -4°C occurred during the peak phase of the IOD in June – July, during which a spreading of the subsurface isotherm occurred.

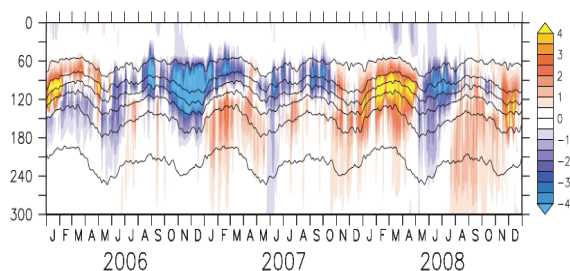


FIGURE 4. Time-depth section of the observed subsurface temperature anomaly from RAMA buoy at 1.5°S, 90°E. The field has been smoothed with 15-day running mean filter.

CONCLUSION

Surface and subsurface oceanic observations in the equatorial Indian Ocean show clearly the evolution of three consecutive IOD events in 2006 through 2008. The development of the events were associated with the dynamics of oceanic equatorial waves, namely the upwelling Kelvin waves along the equator and the downwelling Rossby waves in the off-equatorial regions. These waves were forced by the easterly winds along the equator. The change in wind directions was followed by the change in the near-surface zonal current along the equator. These easterly winds forced westward zonal currents. The surface signatures of the IOD events were indicated by the Dipole Mode Index (DMI). Interestingly, the IOD events can also be inferred from the subsurface temperature observed in the eastern equatorial Indian Ocean. The subsurface temperature indicated negative anomaly during the evolution of the IOD events. Moreover, the subsurface signals were preceded the surface signals. This suggests that the subsurface oceanic observation is a key for a better identification of the IOD events.

ACKNOWLEDGMENTS

This study was supported by the Directorate General for Higher Education through an International Collaboration and Publication Research Grant 2013. The authors thank to the member of Tropical Climate Variability Research Program, JAMSTEC, Japan for helpful discussion and for the RAMA buoy data. This is CGCCS contribution number 1302.

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