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Coupled Ocean-Atmosphere Mode in the Tropical Indian Ocean during 2011

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Abstract

Coupled ocean-atmosphere mode in the tropical Indian Ocean, so-called the Indian Ocean Dipole (IOD), occurred during boreal summer to fall 2011. In this study, data from satellite observations and atmospheric reanalysis datasets together with data from ocean current mooring were used to evaluate the evolution of the 2011 IOD event. It is shown that the 2011 IOD was a weak and short-lived event. It developed in July, peaked in September, decayed in October and terminated in November. During the peak phase, maximum negative sea surface temperature anomaly off Sumatera-Java reached -1.2 °C. As oceanic response to easterly wind anomalies along the equator, the observed zonal currents in the central and eastern equatorial Indian Ocean also showed prominent westward currents during the peak phase of the 2011 IOD event.

Abstrak

Mode Kopel Laut-Atmosfer di Daerah Tropis Samudera Hindia selama Tahun 2011. Mode kopel laut-atmosfer di kawasan tropis Samudera Hindia yang dikenal sebagai fenomena *Indian Ocean Dipole* (IOD) terjadi pada musim panas hingga musim gugur tahun 2011. Pada studi ini, data observasi satelit, data reanalisis, dan data dari hasil pengukuran arus laut digunakan untuk mengevaluasi terjadinya fenomena IOD di tahun 2011. Hasil studi menunjukkan bahwa fenomena IOD tahun 2011 merupakan jenis IOD yang lemah dan berdurasi pendek. IOD di tahun 2011 mulai terbentuk di bulan Juli, mencapai puncaknya di bulan September, meluruh di bulan Oktober dan menghilang di bulan November. Pada saat fase puncak, anomali suhu permukaan laut di dekat pantai Sumatera-Jawa mencapai -1,2 °C. Data observasi arus di tengah dan di sisi timur ekuator Samudera Hindia menunjukkan adanya respon laut terhadap anomali sirkulasi atmosfer. Hasil pengukuran menunjukkan bahwa arus zona bergerak ke arah barat sebagai respon terhadap angin timuran pada fase puncak IOD tahun 2011.

Keywords: equatorial zonal current, Indian Ocean Dipole, sea surface temperature anomaly

1. Introduction

A natural ocean-atmosphere coupled mode in the tropical Indian Ocean, known as the Indian Ocean Dipole (IOD) or Indian Ocean Zonal Mode (IOZM), was first discovered in 1999 [1,2]. This phenomenon is characterized by colder than normal sea surface temperature (SST) off Sumatera-Java and warmer than normal SST over the central and eastern equatorial Indian Ocean off East Africa.

Associated with this SST pattern, the anomalous easterly winds dominate the circulation over the equator and enhanced southeasterly winds prevail along the southern coast of Sumatera-Java [3-5]. As a consequence, the Indian Ocean warm pool and associated convection activities also shifted westward. The changes in this ocean-atmosphere circulation result in ascending (descending) air motion in the western (eastern) equatorial Indian Ocean leading to severe drought in Indonesia and Australia, while East Africa and South Asia (e.g. India, Bangladesh and Sri Lanka) experienced extremely high precipitation [6,7]. In addition, the anomalous atmospheric circulation over the tropical Indian Ocean associated with the IOD event could also trigger planetary atmospheric waves that bring IOD influence further outside the Indian Ocean rim [8,9].

Considering the important impact of the IOD event on climate, in particular to the Indonesian dry/wet season, the objective of this study was to evaluate the dynamical evolution of the IOD event that took place in 2011.

2. Methods

Data. Near-surface velocity data from the Ocean Surface Current Analysis-Real time (OSCAR) project [10] were used in this study. The data is available from 21 October 1992 to 26 December 2013 with horizontal resolution of 1° × 1° and temporal resolution of 5 d. Acoustic Doppler Current Profiler (ADCP) moorings as part of the RAMA program [11] has been deploying in the central (0°, 80.5°E) and eastern (0°, 90°E) equatorial Indian Ocean. At 80.5°E, the mooring provides daily subsurface current data down to 175 m depth for the period from 27 October 2004 to 17 August 2012. Meanwhile, the 90°E mooring provides subsurface current data up to 300 m depth from 14 November 2000 to 7 June 2012.

Sea surface height (SSH) data from Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) covering a period of 14 October 1992 to 12 December 2012 were used in this study. The data have temporal and horizontal resolutions of 7 d and 0.25°, respectively [12]. Daily 10 meter wind velocity is available from the European Centre for Medium-Range Weather Forecasts (ECMWF) for a period of 1 January 2002 to 31 December 2012 [13]. A blended satellite-in situ Sea surface temperature (SST) product on 1° × 1° grid from December 1981 – December 2012 is used [14].

Methods. The IOD is measured by an index that is the difference between SST anomalies in the western (50°–70°E and 10°S–10°N) and eastern (90°–110°E and 10°–0°S) equatorial Indian Ocean [1]. This index is called the Dipole Mode Index (DMI).

Surface wind stress vectors were calculated using the following bulk formulas [15]:

$$\tau^x = \rho_a C_D U^2, \quad (1)$$

$$\tau^y = \rho_a C_D V^2, \quad (2)$$

where τ^x and τ^y are the zonal and meridional wind stress, respectively. ρ_a is the density of air which is set to be 1.2 kg/m^3. $C_D = 1.2 \times 10^{-3}$ is a non-dimensional drag coefficient. U and V are the zonal and meridional winds (m/s).

Mean climatology for all variables were calculated based on the period of January 2003 to December 2011 when all data are available. The anomalies for all variables are then calculated as the deviation from their respective mean climatology. The anomaly fields are then smoothed with a 15-d running mean filter.

3. Results and Discussion

The DMI during January to December 2011 is presented in Figure 1, together with the times series of the eastern and western poles of the IOD. The SST in the eastern pole was colder than normal from January to mid-May 2011. Meanwhile, the SST in the western pole showed a warming trend toward a positive value from January to March 2011. After reaching the positive value in late March, the SST remained warm until December 2011.

The positive DMI started to develop in June in phase with the warming of the western equatorial Indian Ocean as shown by black and gray lines in Figure 1. However, the DMI remained constant and never exceeded its one standard deviation (0.43 °C) until early August. It is shown that the eastern equatorial Indian Ocean still warm enough until early August (*dashed line in Figure 1*). In late August, the DMI rapidly increased, which co-occurred with a sudden decrease in SST in the eastern basin. Previous study has shown that a rapid development of positive DMI was associated with incoming upwelling Kelvin waves generated by easterly wind anomaly as well as enhancement of coastal upwelling off Sumatera-Java [4]. The DMI reached its peak in September, which was up to 0.82 °C. In late September to October, a rapid decrease in the DMI was observed as the SST in the eastern equatorial Indian Ocean tended to increase. The 2011 IOD event was completely terminated in November 2011.

In order to have a basin-wide view of the evolution of 2011 IOD event, SST and surface winds evolution in the tropical Indian Ocean is presented in Figure 2. The surface winds along the southern coast of Sumatera-Java and along the equator were weak during June 2011.

However, the SSTA off southern Java already showed prominent negative anomaly, while that in the central basin showed a weak negative anomaly (Figure 2a). There was a built up warmer SST further west off eastern coast of Africa.

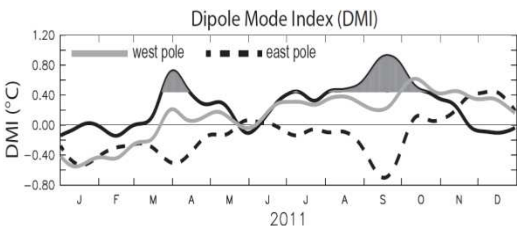

Figure 1. Time Series of the Dipole Mode Index (*Black Line*) together with the Averaged SST Anomaly in the Eastern Pole (*Dashed Line*) and in the Western Pole (*Gray Line*)

In July, the southeasterly wind and easterly wind anomalies start to develop along the southern coast of Sumatera and along the equator, respectively (Figure 2b). The warming in the western basin was strengthened, while the SSTA off Sumatera remained positive. The easterly wind anomalies along the equator were strengthened in August and the SSTA off Sumatera-Java became negative (Figure 2c). However, the warming in the western basin was weakened. In September, strong negative SSTA up to -1.2 °C was observed off Sumatera-Java associated with strong southeasterly winds (Figure 2d). The SSTA in the western basin, however, was weakly negative and that the SSTA dipole pattern was unclear. A prominent dipole pattern was observed again in October though the winds have already weakened (Figure 2e). The IOD and its associated SSTA pattern terminated in November where most of the basin was covered by positive SSTA (Figure 2f). The winds over the equator, however, were still westward, suggesting the importance of surface heat flux in warming the SST in the eastern basin.

The ocean dynamics associated with the evolution of the 2011 IOD event can be explained in term of oceanic equatorial waves (Figure 3). Strong intraseasonal winds, which were dominated by westerly winds, were observed throughout the year, except during July to early September when the IOD started to develop (Figure 3a). These westerly winds forced downwelling Kelvin waves propagating eastward as indicated by positive SSH anomaly. For example, strong westerly in February (Figure 3a) induced strong downwelling Kelvin waves (positive SSH anomaly) indicated by dashed line (A-B) in Figure 3b. Similarly, westerly winds in April also generated downwelling Kelvin waves that propagated eastward (line C-D). However, these westerly winds did not force strong eastward currents along the equator (Figure 3c) [16]. Previous studies have shown that eastern-boundary reflected upwelling Rossby waves generated by incoming downwelling Kelvin waves could reduce the eastward zonal currents along the equator [17]. The Rossby waves signal can be seen in the westward phase propagation of the zonal current along the equator (Figure 3c). There were strong westerly winds in June (Figure 3a) that forced strong eastward zonal currents along the equator (Figure 3c).

The IOD started to develop in July at the time easterly winds prevailed along the equator (Figure 3a). Associated with these easterly winds, upwelling Kelvin waves (negative SSH anomaly) and westward currents were observed (Figures 3b-c). From July until late-September, easterly wind anomalies occupied the equatorial Indian

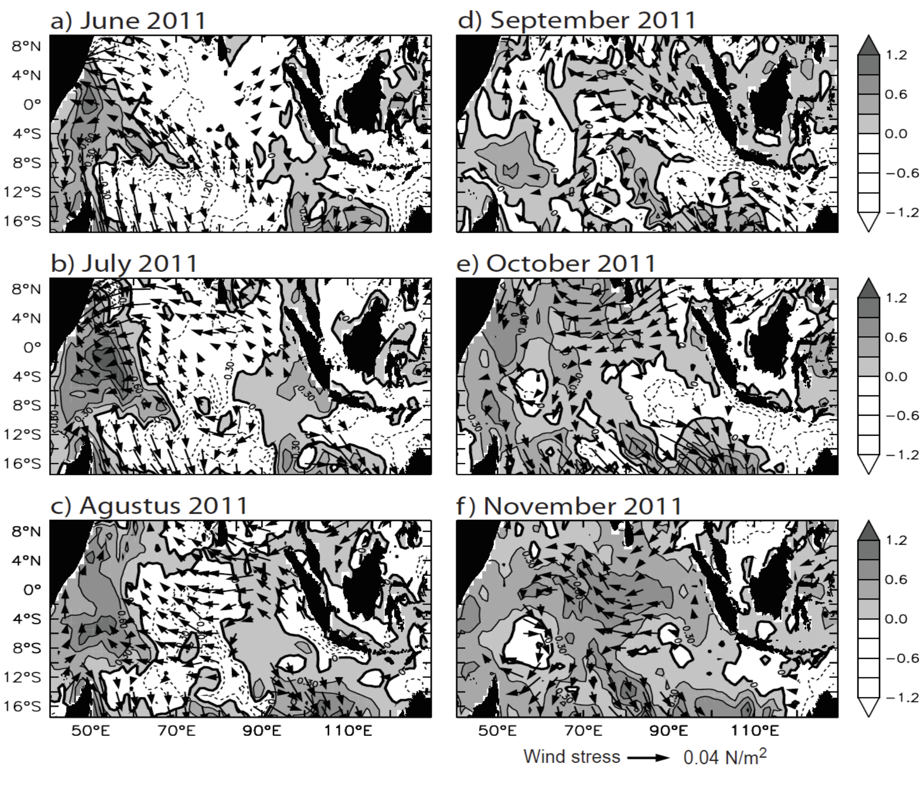

Figure 2. Ocean-Atmosphere Evolution Associated with the 2011 IOD Event Represented by SSTA (shaded in °C) and Wind Stress Anomalies (Vectors in N/m^2) from (a-f) June through November 2011. For SSTA, Positive Values are Shaded and Negative Values are Contoured with Interval 0.2 N/m^2. Zero Contours are Highlighted with Thick-Black Contour. Wind Stress with Magnitude Less than 0.01 N/m^2 are not Plotted

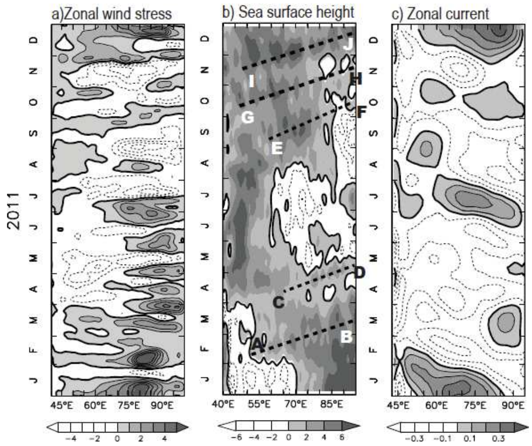

Figure 3. Time-Longitude Diagram of (a) Zonal Wind Stress Anomaly (×10-2 N/m2), (b) Sea Surface Height Anomaly (cm) and (c) Zonal Current Anomaly (m/s) Along the Equator. Positive Values are Shaded and Zero Contours are Highlighted with Thick-Black Contours

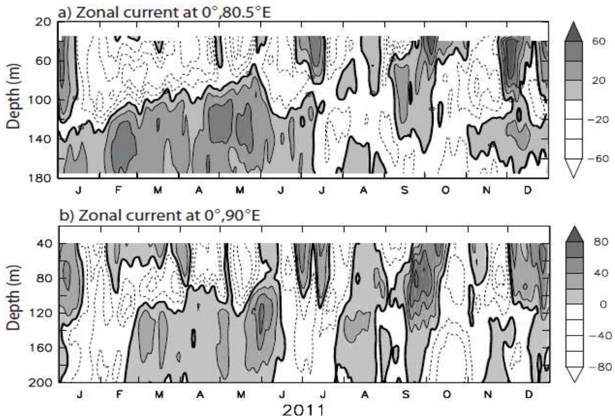

Figure 4. Time-Depth Section of Zonal Current Anomalies Observed in the (a) 0°S, 80.5°E, and (b) 0°S, 90°E. Positive Values (Eastward Currents) are Shaded, while Negative Values (Westward Currents) are Contoured. Zero Contours are Highlighted with Thick-Blacked Contours

Ocean. As a consequence, negative SSH anomalies and westward zonal currents were also observed along the equator. These features are characteristics of the positive IOD event.

During the peak phase of the IOD in September, westerly winds were observed along the equator (Figure 3a). These winds forced downwelling Kelvin waves (line E-F) and eastward zonal current along the equator. It is suggested that these wind-forced downwelling Kelvin waves play an important role during the decaying phase of the IOD event. These downwelling Kelvin waves deepened thermocline in the eastern equatorial Indian Ocean co-occurred with the decaying phase of DMI time series in late September to October (*see* Figure 1). During the termination of IOD event in October and November, there were two episodes of downwelling Kelvin waves observed along the equator (lines G-H and I-J). These downwelling Kelvin waves is believed to play an important role for the termination of the IOD event, in agreement with a previous study [18].

The associated subsurface oceanic responses to the anomalous atmospheric circulation during 2011 can bee seen in the evolution of the subsurface zonal currents observed in the central and eastern equatorial Indian Ocean (Figure 4). It is shown that during early 2011 from late January to June westward current anomalies dominated the zonal current in the central equatorial Indian Ocean (Figure 4a). These westward currents reached the thermocline at depth of about 100 m with maximum velocity of about 65 cm/s. Below the thermo-cline, strong eastward currents were observed with slight upward phase propagation. These eastward subsurface zonal currents had maximum speed up to 60 cm/s. Just before the onset of IOD event in June-July there were strong near-surface eastward currents observed in the central equatorial Indian Ocean (Figure 4a). These eastward currents were forced by strong westerly winds along the equator as shown in Figure 3a. From July to September, westward current anomalies dominated the zonal current variations in the central equatorial Indian Ocean, with a relatively weak and short disturbance of eastward current in August. Note that the westward currents observed in July–August reached a deeper layer up to about 150m depth. However, the westward current in September was confined in the upper layer above 60 m depth with eastward and westward currents observed in the layer between 60–140 m and below 140 m, respectively. Eastward currents associated with the fall Wyrtki jet were evident during October 2011. These eastward currents were generated by the westerly winds as shown in Figure 3a and co-occurred with a decaying phase of the IOD event (*see* Figure 1). After a shorter time reversal into westward currents in November, the eastward currents again appeared from late November with maximum speed of 70 cm/s observed at 60 m depth. These eastward currents were observed from near surface down to a deeper layer.

The zonal currents in the eastern equatorial Indian Ocean indicated a slight difference with those observed in the central equatorial Indian Ocean. In contrast to the observed zonal currents in the central equatorial Indian Ocean, strong westward currents from near surface down to a deeper layer were only observed from mid-January to early February (Figure 4b). Unlike the observed currents in the central Indian Ocean in February to early March, near-surface eastward currents were observed in the eastern equatorial Indian Ocean. Beneath these eastward currents, there existed westward current anomalies in the layer between 60 m and 120 m depth, with slight upward phase propagation. Just below this layer, a strong eastward currents corresponding to Equatorial Undercurrent in the Indian Ocean were observed from February to June.

From April to June, the near surface zonal currents were anomalously westward, indicating an absence of spring Wyrtki jet, similar to those observed in the central equatorial Indian Ocean. After a short variability, showing the alternating eastward and westward currents with a period of less than one month, strong eastward currents were observed in the upper layer above 120 m from late June to early July with maximum speed of 80 cm/s. As the IOD reached its peak, the westward current anomalies dominated the variations in the upper layer from late July to September, although short and weak eastward current anomalies were still observed in August. The decaying phase of the IOD event was associated with the eastward Wyrtki jet in October. This fall Wyrtki jet had a maximum speed of 80 cm/s at depth of about 80 m.

Combining the surface (Figure 3c) and subsurface (Figures 4a-b) observations of the zonal currents in the equatorial Indian Ocean, it may be concluded that the development of the IOD event in July was associated with a strong westward currents in the equatorial Indian Ocean forced by the easterly wind anomalies. On the other hand, the termination of the IOD event in October co-occurred with the presence of the fall Wyrtki jet forced by westerly winds associated with the boreal fall monsoon break.

4. Conclusions

Combined data from in-situ oceanic observations, satellite observation and reanalysis atmospheric datasets showed a relatively weak and short-lived positive IOD event took place during 2011. The development of the event was associated with the oceanic equatorial waves. The development of the event in early summer (July) was associated the upwelling equatorial Kelvin waves, while the termination of the event was associated with the wind-forced downwelling equatorial Kelvin waves in late fall (November).

It is also noted that the maximum negative SST anomaly during the peak of the event in August 2011 was about -1.2 °C. These negative SST anomalies were observed in the eastern equatorial Indian Ocean off Sumatera-Java.

It is evident from this study that the spring Wyrtki jet was absent during 2011 as also previously shown for the 1994 IOD event [19]. This result, however, need further efforts to assess the dynamics and possible impact of absent/weakened spring Wyrtki jet on the evolution of the IOD event.

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