2011 Coupled Ocean-Atmosphere Mode in the Tropical Indian Ocean

Iskhaq Iskandar[1,2]*, Wijaya Mardiansyah[1,2], and Dedi Setiabudidaya[1]

[1]Jurusan Fisika, Fakultas MIPA, Universitas Sriwijaya, Inderalaya, Ogan Ilir (OI), 30662, Sumatra Selatan, Indonesia
[2]Also at Pusat Study Geo-hazard dan Perubahan Iklim, Fakultas MIPA, Universitas Sriwijaya, Inderalaya, Ogan Ilir (OI), 30662, Sumatra Selatan, Indonesia

E-mail: iskhaq@mipa.unsri.ac.id

Abstract

A coupled ocean-atmosphere mode in the tropical Indian Ocean, called the Indian Ocean Dipole (IOD), occurred from the boreal summer to the fall of 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, revealing that it was weak and short-lived. It developed in July, peaked in September, decayed in October, and terminated in November. During the peak phase, the maximum negative sea surface temperature anomaly off Sumatra-Java reached -1.2°C. As an 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 Samudera Hindia 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. Dalam studi ini, data observasi satelit, data reanalysis dan data dari hasil pengukuran arus laut digunakan untuk mengevaluasi terjadinya fenomena IOD di tahun 2011. Hasil studi ini 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 Sumatra-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 arus ini menunjukkan bahwa arus zonal bergerak ke arah barat sebagai respon terhadap angin timuran pada fase puncak IOD di tahun 2011.

Key words: equatorial zonal current, Indian Ocean Dipole, RAMA buoy networks, 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 a colder-than-normal sea surface temperature (SST) off Sumatra-Java and a warmer than normal SST over the central and eastern equatorial Indian Ocean off East Africa.

Associated with this SST pattern, anomalous easterly winds dominate the circulation over the equator while enhanced southeasterly winds prevail along the southern coast of Sumatra-Java [3,4,5]. As a consequence, the Indian Ocean warm pool and associated convection activities shift 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) experience extremely high levels of 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 expand IOD influence further outside the Indian Ocean rim [8,9].

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

The paper is organized as follows: Section 2 describes the data and the methods used in the present study. Section 3 presents the ocean-atmosphere evolution associated with the 2011 IOD event and discusses the main findings of this study. Section 4 is reserved for summary.

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 are available for the times span from October 21, 1992 to December 26, 2013, with horizontal resolution of 1° × 1° and temporal resolution of 5 days. Acoustic Doppler Current Profiler (ADCP) moorings as part of the RAMA program [11] have 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 October 27, 2004 to August 17, 2012. Meanwhile, the 90°E mooring provides subsurface current data up to 300 m depth from November 14, 2000 to June 7, 2012.

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

Methods. The IOD was measured using 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 between January 2003 and December 2011, for which all data are available. The anomalies for all variables were then calculated as the deviation from their respective mean climatology. The anomaly fields were then smoothed with a 15-day running mean filter.

3. Results

The DMI from January to December 2011 is presented in Figure 1, together with the time 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 a positive value in late March, the SST remained warm until December 2011.

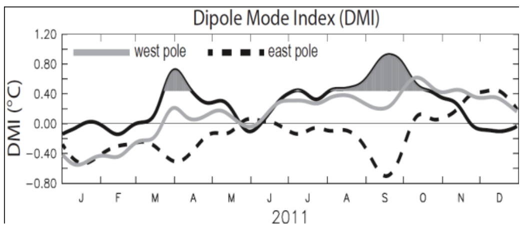

Figure 1. Time series of the Dipole Mode Index (*black line*) together with the averaged SST anomaly in the eastern pole (*dashed line*) and in the western pole (*gray line*).

The positive DMI began to develop in June, in phase with the warming of the western equatorial Indian Ocean as shown by the black and gray lines in Figure 1. However, the DMI remained constant and did not exceed its one standard deviation (0.43°C) until early August. It is shown that the eastern equatorial Indian Ocean remained 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. A previous study demonstrated that a rapid development of positive DMI was associated with incoming upwelling Kelvin waves generated by an easterly wind anomaly as well as the enhancement of coastal upwelling off Sumatra-Java [4]. The DMI reached its peak in September, which was 0.82°C. From 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 facilitate a basin-wide view of the evolution of the 2011 IOD event, SST and surface winds evolution in the tropical Indian Ocean are presented in Figure 2. The surface winds along the southern coast of Sumatra-Java and along the Equator were weak during June 2011. However, the sea surface temperature anomaly (SSTA) data for the area off southern Java already revealed a prominent negative anomaly, while that for the central basin showed a weak negative anomaly (Figure 2a). There was a built-up warmer SST further west off the eastern coast of Africa.

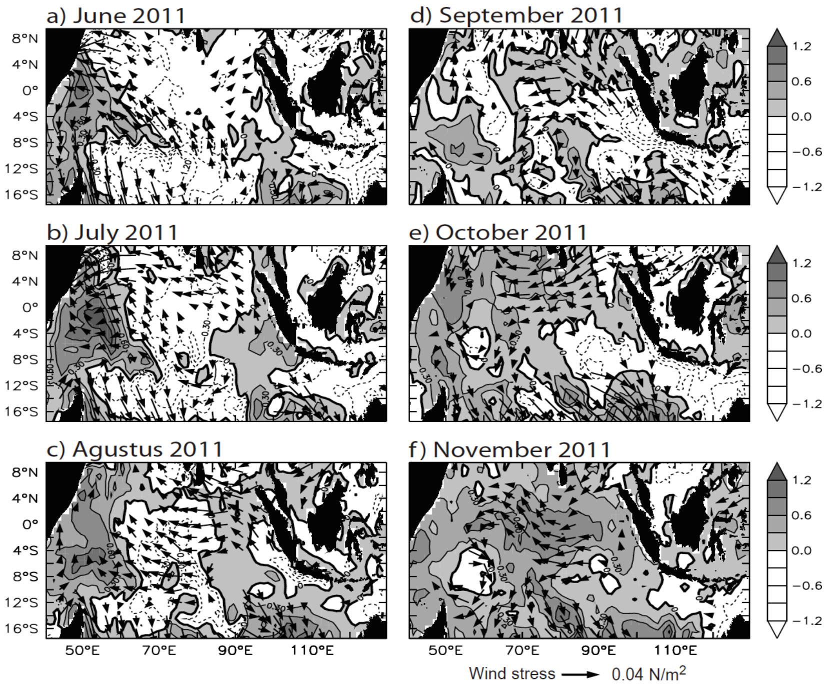

Figure 2. Ocean-atmosphere evolution associated with the 2011 IOD event represented by SSTAs (shaded in °C) and wind stress anomalies (vectors in N/m^2) from (a) June through (f) November 2011. For SSTAs, positive values are shaded and negative values are contoured with interval 0.2 N/m^2. Zero contours are highlighted with thick-black contour. Wind stress data with magnitude less than 0.01 N/m^2 are not plotted.

In July, the southeasterly wind and easterly wind anomalies begin to develop along the southern coast of Sumatra and along the Equator, respectively (Figure 2b). The warming in the western basin was strengthened, while the SSTAs off Sumatra remained positive. The easterly wind anomalies along the Equator were strengthened in August while the SSTAs off Sumatra-Java became negative (Figure 2c). However, the warming in the western basin was weakened. In September, strong negative SSTAs up to -1.2°C was observed off Sumatra-Java associated with strong southeasterly winds (Figure 2d). The SSTAs in the western basin, however, was weakly negative and the SSTA dipole pattern was unclear. A prominent dipole pattern was observed again in October, although the winds had already weakened (Figure 2e). The IOD and its associated SSTA pattern were terminated in November, when most of the basin was covered by positive SSTAs (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.

4. Discussion

Previous studies have shown that ocean dynamics in term of oceanic equatorial waves play significant role on the evolution of the IOD events [1,2,3]. Figure 3 shows time-longitude evolutions of the zonal wind stress, sea surface height and zonal currents along the equator during 2011. Strong intraseasonal winds, which were dominated by westerly winds, were observed throughout the year, except from July to early September, when the IOD began to develop (Figure 3a). These westerly winds forced downwelling Kelvin waves to propagate eastward, as indicated by a positive SSH anomaly. For example, strong westerlies 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 revealed that eastern-boundary reflected upwelling Rossby waves generated by incoming downwelling Kelvin waves could reduce the eastward zonal currents along the Equator [17]. Additionally, the Rossby waves signal can be seen in the westward phase propagation of the zonal current along the Equator (Figure 3c). Also, there were strong westerly winds in June (Figure 3a) that forced strong eastward zonal currents along the Equator (Figure 3c).

The IOD began 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 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 an 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 and co-occurred with the decaying phase of the DMI time series from late September to October (*see* Figure 1). During the termination of the 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 are believed to play an important role in the termination of the IOD event, in agreement with a previous study [18].

The associated subsurface oceanic responses to the anomalous atmospheric circulation that occurred in 2011 can be seen in the evolution of the subsurface zonal currents observed in the central and eastern equatorial Indian Ocean (Figure 4). It is demonstrated 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 a depth of approximately 100 m with maximum velocity of about 65 cm/s. Below the thermocline, strong eastward currents were observed with slight upward phase propagation. These eastward subsurface zonal currents attained maximum speeds of up to 60 cm/s. Just prior to the onset of the 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 brief disturbance of the eastward current in August. Note that the westward currents observed from July-August reached a deeper layer of up to approximately 150m depth.

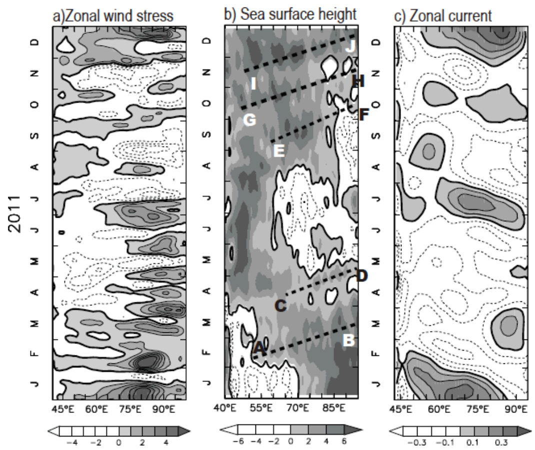

Figure 3. Time-longitude diagram of (a) zonal wind stress anomaly ($\times 10^{-2}$ N/m^2), (b) sea surface height anomaly (cm) and (c) zonal current anomaly (m/s) along the Equator. Positive values are shaded and zero contours are highlighted with thick-black contours.

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 60-140m 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 the 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 speeds of 70 cm/s observed at 60 m depth. These eastward currents were observed from the near surface all the way down to a deeper layer.

The zonal currents in the eastern equatorial Indian Ocean indicated a slight difference from 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 the 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 from 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, strong eastward currents corresponding to the 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 alternating eastward and westward currents within 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 a 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 a depth of approximately 80 m.

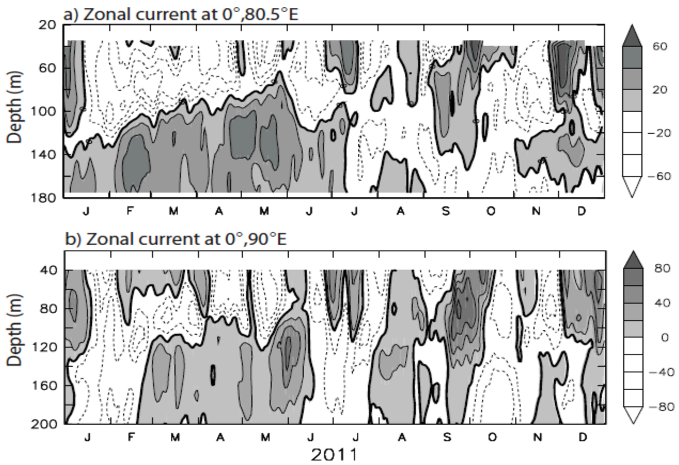

Figure 4. Time-depth section of zonal current anomalies observed in (a) 0°S, 80.5°E, and (b) 0°S, 90°E. Positive values (eastward currents) are shaded, while negative values (westward currents) are contoured. Zero contours are highlighted with thick-blacked contours.

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 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.

5. Summary

Combined data from in-situ oceanic observations, satellite observation, and reanalysis atmospheric datasets revealed an anomalous oceanic-atmospheric condition in the tropical Indian Ocean in 2011. This anomalous condition was associated with a positive IOD event.

The analysis indicates that the 2011 IOD event was a relatively weak and short-lived event. It developed in early summer (July), peaked in late summer (September), decayed in early fall (October), and terminated in late fall (November) (Figure 1).

During the peak phase of IOD in September, the cold SST anomalies in the eastern equatorial Indian Ocean off Sumatra-Java reached a negative value of -1.2°C (Figure 2). These strong negative SST anomalies in the eastern equatorial Indian Ocean account for most of the DMI value observed during September, indicated by larger SST anomalies in the eastern pole compared to those in the western pole (Figure 1).

The evolution of the 2011 IOD event was associated with oceanic equatorial wave dynamics. The initiation of the event co-occurred with the presence of eastward propagating upwelling Kelvin waves (negative SSH anomalies) and westward zonal current anomalies, which were forced by anomalous easterly winds along the Equator (Figures 3–4). The termination of the event in October, on the other hand, was associated with the fall Wyrtki jet (eastward currents) and downwelling Kelvin waves (positive SSH anomalies) enhanced by westerly wind anomalies.

It is evident from this study that the spring Wyrtki jet was absent during 2011 (Figure 4), as also previously shown for the 1994 IOD event [19]. This result, however, necessitates further efforts in order to assess the dynamics and possible impact of an absent/weakened spring Wyrtki jet with regards to the evolution of the IOD event.

Acknowledgments

The University of Sriwijaya is acknowledged for its financial and infrastructure support through a Research Grant No. 198/UN9.3.1/LT/2014. The Ferret program was used for analysis and graphics in this study. This is the Center for Geo-hazard and Climate Change Study's contribution number 1402.

References

[1] Saji, N.H., B.N. Goswami, P.N. Vinayachandran, T. Yamagata. 1999. A dipole mode in the tropical Indian Ocean. Nature, 410, 360–363.
[2] Webster, P.J., A.W. Moore, J.P. Loschnigg, R. R. Leben. 1999. Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997-98. Nature, 410, 359–360.
[3] Murtugudde, R., J.P. McCreary, A.J. Busalacchi.2000. Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997–1998 J. Geophys. Res., 105, 3295–3306.
[4] Horii, T., H. Hase, I. Ueki, Y. Masumoto. 2008. Oceanic precondition and evolution of the 2006 Indian Ocean dipole Geophys. Res. Lett., 35, doi:10.1029/2007 GL032464.
[5] Iskandar, I., M. Irfan, F. Syamsuddin. 2013. Why was the 2008 Indian Ocean Dipole a short-lived event? Ocean Sci. Journal, 48/2, 1–12.
[6] Yamagata, T. S.K. Behera, J.–J. Luo, S. Masson, M. Jury, S. A. Rao. 2004. Earth Climate: The Ocean-Atmosphere Interaction, Geophys. Monogr., No. 147, AGU, 189–212.
[7] Luo, J.-J. 2011. State of the climate in 2010. Bull. Am. Meteor. Soc., 92, S138–S140.
[8] Saji, N. H., T. Yamagata. 2003. Possible impacts of Indian Ocean Dipole mode events on global climate. Clim. Res., 25, 151–169.
[9] Cai, W. A. Sullivan, T. Cowan. 2009. Argo profiles a rare occurrence of three consecutive positive Indian Ocean Dipole events, 2006-2008. Geophys. Res. Lett., 36, doi:10.1029/ 2009GL040163.
[10] Bonjean, F., G.S.E. Lagerloef. 2002. Diagnostic Model and Analysis of the Surface Currents in the Tropical Pacific Ocean. J. Phys. Oceanogr., 32, 2938–2954.
[11] McPhaden, M. J. et. al.. 2009. RAMA: The Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction. Bull. Amer. Meteor. Soc., 90, 459–480.
[12] Ducet, N., P.Y. Le Traon, G. Reverdin. 2012. Global high-resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2. J. Geophys. Res., 105/C8, 19,477–19,498.
[13] Uppala, S.M., et al. 2006. The ERA 40 re-analysis. Quart. J. R. Meteor. Soc., 131, 2961–3012. doi:10.1256/ qj.04.176.
[14] Reynolds, R.W., N.A. Rayner, T.M. Smith, D.C. Stokes, W.Q. Wang. 2002. An improved in situ and satellite SST analysis for climate. J. Climate, 15, 1609–1625.
[15] Stewart, R.H. 2008. Introduction to Physical Oceanography, Texas A&M University Press, USA, p48.
[16] Wyrtki, K. 1973. An equatorial **jet** in the Indian Ocean. Science, 181, 262–264.
[17] Nagura, M., M.J. McPhaden. 2010. Wyrtki Jet dynamics: Seasonal variability.J. Geophys. Res., 115/C11026, doi:10.1029/ 2010 JC006423.
[18] Rao, S.A., T. Yamagata.2004. Abrupt termination of Indian Ocean Dipole events in response to intraseasonal disturbances.Geophys. Res. Lett., 31/L19306, doi:10.1029/2004 GL020842.
[19] Vinayachandran, P.N., H. Saji, T. Yamagata. 1999. Response of the equatorial Indian Ocean to an anomalous wind event during 1994. Geophys. Res. Lett., 26, 1613–1616.