Contrasting the evolution of moderate and extreme positive Indian Ocean Dipole events

A. Hermawanto¹,², Lixin Wu¹, and Mamenun²

¹Physical Oceanography Laboratory/CIMST, Ocean University of China and Qingdao National Laboratory for Marine Science and Technology, Qingdao, China
²Center for Applied Climate, Indonesia Agency for Meteorology Climatology and Geophysics (BMKG), Jakarta, Indonesia.

Abstract A recent study suggested, due to greenhouse warming, the frequency of extreme positive IOD (pIOD) events will increase in the future However, there is no information about the different character between extreme and moderate events During the period of 1979-2014, we identified 3 extreme and 4 moderate events Based on composite analysis of surface wind, sea surface temperature (SST) and temperature of the upper ocean, it is indicated there is a distinction on temporal and spatial evolution of equatorial easterly wind anomaly (EEWA) and the mean depth of 20°C isotherm (thermocline) over the eastern part of the equatorial Indian ocean The EEWA was started around June (October) and retreat in November for extreme (moderate) events The thermocline of extreme (moderate) events also showed an earlier shallowing, started in May (October) and reached the most shallow of depth around November Indicating that, during extreme events, the positive Bjerkness feedback strengthened earlier Using mixed layer heat budget analysis, it is revealed that during moderate events, the ocean dynamic process dominantly influences the cooling process of SST only in the peak phase, while during extreme events, the ocean dynamic process has dominant role in the whole process (from initial until peak phase) The early coupled process of EEWA and thermocline in shaping strong SST cooling gives time for us to monitor the developments of extreme pIOD and prepare mitigation against the impact at the peak phase However, the results presented in this study are based on limited samples from observations, thus requiring further clarification with numerical models and analysis of ensemble long integrations.

Keywords: pIOD, equatorial easterly wind anomaly, SST, thermocline.

1. Introduction

Indian Ocean Dipole is one of the dominant modes of climate over equatorial Indian ocean region, during the positive Indian Ocean Dipole (pIOD), the eastern part of the Indian ocean basin experienced negative anomalous rainfall, while the western experienced positive anomaly (Saji, et al., 1999) Indian Ocean Dipole does not affect Indian ocean basin country only but also gives serious impact on the climate over a region that is located far away from the basin (Saji & Yamagata, 2003; Hong, et al., 2008)

Figure 1 represents the distribution of anomalous rainfall during Sep-Oct-Nov (the peak phase of IOD) in the year of 2006, 1997, 1994 and 1982 We noticed that during 1994, 1997 and 2006, the area of negative rainfall anomaly over eastern equator Indian Ocean extends westward and reached on central equator Indian Ocean, while in 1982, the area of negative rainfall anomaly seems to be restricted in the
eastern part of equatorial Indian ocean. The area expansion of negative anomalous rainfall as one seen in 1997, is a character of rainfall during extreme pIOD (Cai et al., 2014). In a recent study by Cai et al., (2014), it was found that the number of extreme events will increase by threefold in the future as a consequence of greenhouse warming.

In previous studies, the extreme pIOD events examined only as an individual case study (Webster, et al., 1999; Yu & Rienecker, 1999; Ueda, et al., 2000; Murtugudde, et al., 2000; Rao, et al., 2002; Rao, 2009; Vinayachandran, et al., 1999; Vinayachandran, et al., 2007), and some of those are the earliest studies that initiated the intensive research about IOD. Since all of those studies discussed the extreme pIOD as an individual case, none of them explicitly stated the common features of extreme events. Other studies which also examined the character of IOD based on many events, merely focused on the differences between positive and negative IOD (Hong, et al., 2008) or the different of pIOD with and without ENSO (Drbohlav, et al., 2007; Hong, et al., 2008; Yu, et al., 2005) or based on the term of peak time and the duration of IOD (Du, et al., 2013) or based on the strength of dipole mode index (DMI) (Saji, et al., 1999). None of them examined the different character based on the impact on rainfall during its peak phase.

Annamalai et al., (2003) examined the factors that drive the initiation process of IOD, in the study, the events of moderate and extreme were grouped into one category, called strong IOD, thus the different character between moderate and extreme still have not discussed yet. Cai et al., (2014) examined separately the moderate and extreme but did not examine in detail the differences in structure and time evolutions. Therefore, the different character between extreme and moderate pIOD events is still an issue worth to discuss.

**Figure 1** Precipitation anomaly (mm.day$^{-1}$) during peak phase of IOD (Sep-Oct-Nov) in (a) 1982, (b) 1994 (c) 2006 and (d) 1997. The year of 1982, categorized as moderate, while the years of 1994, 1997 and 2006 are categorized as extreme events. Yellow enclosed contour indicates the area whose anomalous precipitation less than -1 mm.day$^{-1}$, to highlight the extension of significant negative rainfall anomaly during extreme events.

Since the extreme criterion in this study is based on the severity of the impact (the enhanced and vast coverage area of negative precipitation anomaly) over the eastern equatorial Indian Ocean, the influence of extreme pIOD over Indonesia as the region which is located just to the eastern equatorial Indian ocean is another point of interest. In order to display the different severity of the events, using Indonesia rainfall stations observation data, the distribution of anomalous rainfall during moderate and extreme events are also demonstrated in this study.
The main purpose of this study is to describe the differences in temporal evolution and structure of the two events based on the composite analysis. We extend previous work by providing a comparison of all extreme and moderate events that ever happened (rather than a single case study) during 1981-2014. Therefore, from the result, we could identify the common features of the two pIOD categories. Data and the composite method we used are described in section 2. In section 3, the distribution of rainfall over Indonesia is presented. Evolution of the structure, analysis of heat budget and thermocline anomaly are presented in the next section. Finally, the summary and discussion are presented in section 5.

2. Data and Methods

The monthly NCEP reanalysis (Kalnay et al., 1996) of wind circulation and NOAA Extended Reconstructed Sea Surface Temperature from 1948-2014 are used in this study. Global Precipitation Climatology Project (GPCP) version 2.3 dataset provided by the NOAA ESRL (http://www.esrl.noaa.gov/psd) used to determine the extreme event through empirical orthogonal function (EOF) analysis. In addition, we also utilized monthly rainfall data from the observed stations were provided by Indonesia Agency for Meteorology, Climatology, and Geophysics (BMKG) to show the evolution of rainfall anomaly distribution over Indonesia. In order to diagnose the ocean process, we used ECMWF Ocean Reanalysis System (ORA-S3) (Balmaseda, et al., 2008) and Simple Ocean Data Assimilation (SODA 2.2.4) product of Carton, J.A and B Giese, (2008)

For anomaly calculation, the climatology is subtracted from the data series. The climatology was obtained by averaging entirely available data time series, except for wind and sea surface temperature, we used the long-term monthly means of 1981-2010 dataset which available on NOAA ERL website. Nevertheless, the result does not varies much when we utilized the 1948-2013 average as the climatology.

In order to define the years of extreme events, we followed the method as used in Cai et al., (2014) by applying EOF analysis to precipitation dataset (GPCP). An extreme pIOD event is defined when the first principal component is greater than 1 s.d and the second principal component is greater than 0.5 s.d. For moderate event, we used Dipole Mode Index-DMI (Saji, et al., 1999). A moderate event was determined when the magnitude of DMI is greater than 0.75 s.d other than the extreme events. From this method, we identified 1994, 1997 and 2006 as the extreme years, while 1982, 1991, 2002 and 2012 as the moderate. We note that the sample size of our study is small as there are only a few extreme IOD during 1979-2013. Thus, we advise using discretion in interpreting the result from this composite analysis.

3. Distribution of anomalous rainfall over Indonesia associated with moderate and extreme events

The purpose of this section is to demonstrate the importance of studying extreme pIOD for practical implication. In the previous study, As-syakur et al., (2014) examined the spatial-temporal relationship of rainfall in Indonesia during ENSO and IOD years using remote sensing dataset. They found, in general (without separating the extreme and moderate) the temporal pattern relationship of rainfall with IOD and ENSO is high response during June-July-August (JJA) and September-October-November (SON). Consistent with As-syakur, A.R., et.al., (2014), as one can see in figure 2, the influence both of extreme and moderate pIOD to Indonesia rainfall during April-May is unclear (indicated with many no significant impact of rainfall) and to have significant impact started in June-July continue until August-September and October-November.

During moderate years, Indonesia started to significantly experience negative anomaly of rainfall in June-July. Meanwhile, for extreme events, it is started in August-September. Both extreme and moderate events are terminated at the same time in November. It means, time for Indonesia to experience negative rainfall anomaly is earlier and longer during moderate rather than in extreme years. However, the magnitude of negative rainfall anomaly during extreme years are more severe than moderate as indicated...
more stations experienced negative anomalous rainfall less than -100 and -200 mm.month$^{-1}$ (illustrated with more dots with brown and red color)

![Figure 2](image-url)

**Figure 2** Composite of bimonthly rainfall anomaly during (left) extreme [1994, 1997, 2006] and (right) moderate [1982, 1991, 2002, 2012] events. Filled (open) circle indicate anomalous precipitation significant (not significant) at 95% The unit is in mm.month$^{-1}$.

Figure 2 gives information that between moderate and extreme years, the distribution of rainfall is different. Firstly, different in time to start experienced significant negative anomaly of rainfall and secondly, different in the magnitude of negative anomaly of rainfall. The occurring of significantly negative rainfall anomaly in August until November gives consequences that Indonesia will experience a longer and more severe dry season than the climatology, while extreme or moderate pIOD occurred.

4. **Contrasting the evolution of extreme and moderate pIOD**

4.1. **Wind and Sea Surface Temperature Anomaly (SSTA) pattern**

In this section, we started to examine the different features of evolution between moderate and extreme pIOD derived from a composite of surface wind and sea surface temperature anomaly (figure 3 and 4). By contrasting the evolution, we identified some different features between the two events.
Strong equatorial easterlies wind anomaly (EEWA) appeared over the central Indian ocean which was started by Jun-Jul and persistently occurred until Oct-Nov during extreme events (figure 3.i) Unlike the extreme, on moderate events, the strong EEWA appeared only in Oct-Nov period (figure 3.h) This means that there was an earlier appearance of strong EEWA during extreme events In addition, the magnitude of EEWA for extreme events are stronger than moderate throughout the events (from initial to peak phase) (figure 3.a,b,c and i), while during moderate, strong EEWA only occurred during the peak phase (figure 3.d,e,f,g, and h) The coverage area of EEWA also showed something different, the EEWA extent crossing 70 °E during extreme events (figure 4.h), while during moderate, the EEWA was restricted to central of Indian ocean only (figure 4.d).

In line with wind circulation, the spatial evolution of SSTA also showed something different During extreme years, cooling sea surface temperature over the eastern pole of Indian ocean started to active from June-July (preceded by basin-wide cooling during April-May), then continued to strengthened and extended westward along the coast of Sumatera during August-September, together with the strengthening of EEWA This cooling of SSTA reached its maximum in October-November (figure 4.h) However, during moderate events, the evolution of cooling SSTA in June-July and August-September (development phase) over eastern equatorial Indian ocean, looks there are no significant changes and then started to strengthen in October-November (peak phase)

In the other side, the basin warming over central and west of Indian ocean during moderate events looks more dominant and covered up a larger area than extreme Meanwhile during extreme events, weak warming occurred in central and west of Indian ocean It may be caused by the absence of unusual strong cold zonal advection in the initial phase (Sun, et al., 2014)
Figure 4 Composite map of bimonthly average (June-July; August-September; October-November) SSTA (shading; unit: °C) and surface winds anomaly (arrow; unit: ms⁻¹) during moderate events Years of moderate pIOD are 1982, 1991, 2002, 2012 Years of extreme events are 1994, 1997 and 2006 Only the wind anomalies significant at 95% are plotted.

4.2. The ocean dynamics process of cooling SSTA over IOD-E

Since the extreme events likely more controlled by the appearance of cooling SSTA in the east pole of equatorial Indian ocean, further in this section we examined the role of the advection and surface heat fluxes for the formation of SSTA over IOD-E For this reason, a mixed layer heat budget analysis on the top 50 m depth over IOD-E was carried out The mixed layer heat balance of IOD-E can be expressed as:

$$\frac{dT_a}{dt} = - \left[ (u^a \frac{dT_a}{dx} + \bar{u} \frac{dT_a}{dx}) + (v^a \frac{dT_a}{dy} + \bar{v} \frac{dT_a}{dy}) + (w^a \frac{dT_a}{dz} + \bar{w} \frac{dT_a}{dz}) \right] + Q_{SW} + Q_{LW} + Q_{SH} + R$$ (1)

The variables \( T, u, v \) and \( w \) are potential temperature, the zonal, meridional and vertical ocean current velocities, respectively, averaged over the top 50 m of the ocean Differential operators \( x, y, z \) and \( t \), are along the zonal, meridional, vertical directions and time, respectively The temperature tendency \( \frac{dT_a}{dt} \) was calculated using a centered-difference approximation Superscript ‘a’ and overbar denote anomalous and long-term averaged quantities, respectively \( Q_{SW}, Q_{LW}, Q_{SH} \) and \( R \) represent the net downward shortwave radiation flux at the ocean surface, net upward longwave radiation flux, surface...
latent heat flux and sensible heat fluxes, and the sum of the fluxes will be called as heat flux $R$ is the residual term representing either the model errors or a process other than heat fluxes and temperature advection.

During moderate years, as indicated in figure 5, total advection and heat flux process, both gave significant role in the form of temperature tendency during the initial and developing phase, but during the peak phase, total advection process acted as a dominant factor. Different from moderate, during extreme events, the total advection process acted as a dominant factor throughout all the phases, from initial to peak phase. Furthermore, we decipher the total advection into zonal and meridional advection components. By decomposing the total advection, one can find out how each of the advection components shaping the temperature tendencies.

In figure 6.b, around April and May, we noticed there was an anomalous zonal advection of anomalous ocean temperature during extreme years which is stronger than moderate. This can be thought that there was a strong transport of anomalous heat by the anomalous ocean current. Since there were no significant wind anomalies in April and May (figure 4.e), we consider the anomalous zonal advection was driven by ocean dynamic process and was not driven by anomalous wind-driven current. This matter will be discussed in the next section.

Furthermore, we gave attention to peak phase in figure 6.a, one can see the magnitude of zonal advection for moderate years (illustrated in black dashed line and magenta full line), showing strong magnitude as it does in the extreme years (red, green, and blue full line). But, something different was seen in meridional advection (figure 6.d), the meridional advection looks stronger than moderate, especially on the mean meridional advection of the anomalous ocean temperature component (figure 6.f).

The conditions above bring information to us that, in the development process of extreme cooling SST, which is noted as the character of extreme pIOD, it is needed not only strong zonal advection but also a combination between strong zonal and strong meridional advection. If there is strong zonal (without strong meridional) advection, the pIOD only reached the moderate, but if there is strong zonal combined with strong meridional advection, the pIOD will be favor into extreme condition. This situation is consistent with Weller & Cai (2014) who said that in combination with the zonal structure of temperature gradient, an anomalous meridional cross-equatorial temperature gradient in the east Indian ocean, controls the declining rainfall over the eastern equatorial Indian Ocean region.
Figure 6 Evolution of zonal (left) and meridional (right) temperature advection of top 50 m depth over IOD-E (90°-110°E, 10°S-equator) during the years of pIOD events Green, red, blue and magenta denotes year of 1994, 1997, 2006 and 1982, respectively Black dashed line indicates the other pIOD moderate events Give attention to the different ordinate scale between zonal and meridional.

4.3 The thermocline (20°C isotherm depth) anomaly over IOD-E

In the previous section, we noticed that during extreme years the total advection component dominates in controlling the temperature tendency over IOD-E throughout the phases, from initial until peak Here we contrasted the condition of ocean subsurface over IOD-E during the events.

Composite of 20°C isotherm depth from extreme and moderate events in figure 7 illustrates the depth of thermocline during extreme and moderate years During moderate years, the mean of thermocline depth appears to shallow (negative anomaly) in peak phase only, while during extreme years, the mean of thermocline depth started to shallow from April (initial phase) then continued and reached the maximum in November (peak phase) and finally went back to normal condition in February This situation is consistent with the evolution of wind and SSTA for extreme and moderate years (figure 4) in the previous section.

If one gives attention to March, the anomalous thermocline depth during extreme and moderate events is relatively not different (in neutral position), but then in April-May, the depth of thermocline shows different progress, the thermocline going to shallow during extreme events, but it does not for moderate This situation is consistent with the appearance of basin-wide cooling of SST over east equatorial Indian ocean in April-May as indicated in figure 4.e The shallow thermocline in initial phase as indicated in figure 7, also mentioned by a previous study (Horii, et al., 2008) The study found that during May 2006, by using mooring buoy dataset, there was an appearance of negative temperature anomaly at the thermocline depth accompanied with strong westward current anomalies.
Figure 7 Mean of longitude-averaged (80°E-100°E) of 20°C isotherm depth anomaly over equator during moderate and extreme pIOD events. Shading indicates the standard deviation.

5. Summary and Discussion
Motivated by Cai, et al., (2014), who stated the frequency of extreme pIOD events will increase in the future, through this study we examined and compared the spatial and temporal evolution of the structure of pIOD between extreme and moderate events. The response of rainfall in Indonesia, as the region located in the Indian Ocean equator that experienced negative anomalous rainfall, also examined.

For the anomalous rainfall over Indonesia, the influence of extreme and moderate pIOD during April-May is unclear. Furthermore, during moderate pIOD, Indonesia experienced deficit rainfall earlier (June-July) than extreme events (Augustus-September). However, if we look at the severity level, rainfall during moderate events are less severe than extreme years.

For the wind circulation, based on composite analysis, it indicates that there is an earlier strengthening of EEWA during the development phase of extreme pIOD. This EEWA persistently occurs until peak phase, this condition is not seen during moderate events. The depth of thermocline also showed earlier shallowing during the initial phase of extreme events.

The early appearance of strong EEWA and shallowing of thermocline, made the Bjerkness positive feedback strengthened earlier as well, and in the end facilitated the stronger positive feedback during the next phase (peak). We expected that these are the reason why SST cooling in equatorial eastern Indian Ocean becomes stronger in extreme events than moderate.

The results presented in this study are based on limited samples from observations, due to the least number of extreme and moderate pIOD events that occurred during satellite era (1979-present), thus we realized still requiring further clarification with numerical models and analysis of ensemble long integrations.

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