Influence of the Indian Ocean Dipole (IOD) on Convectively Coupled Kelvin and Mixed Rossby-Gravity Waves

Fadhlil R Muhammad1*, Sandro W. Lubis2, Inka Tiarni1, and Sonni Setiawan1

1Department of Geophysics and Meteorology, Bogor Agricultural University (IPB), Indonesia
2Department of the Geophysical Sciences, University of Chicago, Chicago, USA

E-mail: fadhlil_muhammad@apps.ipb.ac.id

Abstract. Indian Ocean Dipole (IOD) is a mode of natural climate variability that arises from a zonal-dipole structure in interannual variations of the tropical Indian Ocean. Understanding the influence of IOD on atmospheric circulation is important in order to improve weather forecasts and climate predictions in the Tropics and the extratropics on time scales beyond a few days. This study investigates the role of IOD on convectively coupled equatorial wave (CCEW) activity, including Kelvin and MRG waves and examines the potential links between them. The results show that positive IOD event leads to enhance Kelvin wave and MRG wave activities over the eastern Africa and southern Indian Ocean. On the other hand, it suppresses Kelvin and MRG wave activities over the eastern Indian Ocean and the Maritime continent. It is also shown that IOD’s influence on Kelvin and MRG waves activity is non-dependent to ENSO activity. These results highlight the importance of IOD in generating Kelvin and MRG waves in the tropics.

1. Introduction

Indian ocean dipole (IOD) is the primary inter-annual variability in Indian Ocean. IOD characterized by zonally dipole sea surface temperature anomaly pattern [1]. This SST anomaly is cool over the eastern Indian Ocean and warm over western Indian Ocean with easterly wind during positive IOD and the opposite during negative IOD [1]. This warm/cool SST anomaly contributes to enhanced/suppressed convection over this region. This suggests that IOD may play an important role in triggering convectively coupled equatorial planetary waves (CCEWs) in this region.

Equatorial Planetary waves [2] are planetary scale disturbance generated by large-scale convective processes and propagate through the tropics [3-4]. This disturbance, generated by convection, commonly referred to as convectively coupled equatorial waves (CCEWs) can control the intensity and timing of precipitation over the tropics [5-6]. Furthermore, CCEWs contributes up to 16-20% of the total intraseasonal precipitation in the tropics [7]. Huang and Huang [8] found a significant negative (positive) correlation of CCEWs activity with the IOD index over southeastern Indian Ocean (Central-eastern pacific). Despite this evidence, the relationship between IOD and CCEWs is not well understood.

This study seeks to understand the relationship between IOD and CCEWs. The main concern of this study is to elucidate how IOD influence CCEWs. We examine the variations of MRG and Kelvin wave...
activities during positive and negative IOD events that occur between August and November, owing to the seasonality of IOD [9-10]. Furthermore, relationship between CCEW modulation of tropical deep convection (MRG and Kelvin waves) and IOD events in relation to ENSO is also explored.

2. Data and Methods

2.1 Data
The data used for representing the dynamical fields are daily zonal wind, meridional wind at 850 hPa with periods of 1981-2013 obtained from NCEP/NCAR Reanalysis I with resolution of 2.5° x 2.5°. We also used sea surface temperature (SST) data obtained from NOAA Optimal Interpolated v2 SST and interpolated outgoing longwave radiation (OLR) obtained from NCEP/NCAR Reanalysis with the same periods and resolution as dynamical fields. Positive and Negative IOD event is defined by Dipole Mode Index (DMI). In particular, positive (negative) DMI value higher (lower) than one standard deviation is classified as positive (negative) IOD event. DMI data are obtained from NOAA website (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/DMI).

2.2 Methods
First, the raw data are processed to get the monthly anomalies of each variables. We used composite analysis by calculating the mean value of each respective IOD events. This is done to see the pattern on each IOD events. We examine the influence of IOD on the convectivity related to CCEW by using correlation and cross-correlation. We isolate the waves in OLR using space-time filter as discussed in [7]. The filter is a modified space-time filter, an improvement from the earlier filter used by Straub and Kiladis [11] and Wheeler and Kiladis [5].

Figure 1. Correlation of DMI with NINO 3.4 SST index for all month (left) and ASON only (right).

The correlation analysis is used to examine the influence of IOD on CCEW. We calculate the correlation coefficient between DMI and OLR filtered monthly variance anomalies. This method is already done to examine the influence of IOD to MJO [12] and CCEW activity [8]. Despite Webster et al. [13] and Saji et al. [1] found a relatively weak correlation between DMI and NINO SST 3.4 index (r<0.35), the dependency of IOD on ENSO is still a controversial issue. Figure 1 shows the correlation between DMI and NINO SST 3.4 Index. A relatively weak correlation (r~0.21) is found during all months but improved significantly during ASON months only (r~0.51). Wilson et al. [12] examine the correlation between DMI and NINO SST 3.4 index during ASON months and found relatively high correlation between the two (r~0.6). To deal with this issue, apart from simple correlation, we also used partial correlation as described in Saji and Yamagata [14], Kug et al. [15], and Wilson et al. [12] to
control the influences of ENSO on IOD. We also used cross-correlation to examines the evolution of IOD influences on CCEW.

3. Results and Discussion

3.1 The Characteristics of IOD

First, we examine the characteristics of IOD during positive and negative event. Figure 2 shows composite of non-filtered OLR and SST anomalies during both of IOD events. The composites show unique features of IOD. During positive IOD event, positive (negative) anomalies of SST (OLR) and negative (positive) anomalies of OLR (SST) are found in western Indian Ocean (Southeast Indian Ocean and Indonesia). This pattern is also found in Saji et al. [1]. During negative IOD, we found similar patterns with opposite signs. The anomalies are stronger in Southeast Indian Ocean than Western Indian Ocean during both events.

This pattern shows that during positive IOD event, an increase of SST in western Indian Ocean provides the moisture for convection in the region. An increase of SST gives more strength to lower-level easterlies and a decrease of sea level pressure in positive IOD thus, induces convection in western Indian Ocean. Negative IOD event has similar pattern but with opposite signs. There is an observed anomalous high-pressure anticyclone (low-pressure cyclone) in southeastern Indian Ocean slightly west of anomalous SLP and a weaker anomalous low-pressure cyclone (high-pressure anticyclone) to the north during positive IOD (negative IOD) events [12,16].

3.2 Influence of IOD on Large-Scale Convection

To better understand the influence of IOD on large-scale convection, we first analyze the composite lifecycle of SST anomalies during IOD events, as shown in Figure 3. We can see that a negative correlation in southeast Indian Ocean start from lag 0 until at least lag +3. After IOD event occur (after lag 0) there is a significant correlation between DMI and SST. For examples, during positive IOD event, DMI is increasing thus, gives decreasing (increasing) SST in southeastern Indian Ocean (western Indian Ocean). We expect an increase of convection and wave activity in the areas that have significant correlation. In
the pre-conditioning of IOD (before lag 0), western Indian Ocean SST is somewhat influences the DMI in longer period than southeastern Indian Ocean SST.

Next, we observe the influence of IOD to OLR anomalies. Figure 4 shows the cross-correlation between DMI and OLR anomalies. There is a positive correlation around southeastern Indian Ocean from lag -4 throughout lag +2. This positive correlation means that an increase (decrease) in DMI is linked to an increase (decrease) of OLR anomalies in southeastern Indian Ocean. An anomalous increase in southeastern Indian Ocean SST as proxied by the decrease of DMI will give more moisture to convection process and further increase the convection thus a decrease in OLR anomalies. This increase in convection emanates CCEW that will propagate through the tropics. From figure 4 we can deduce that OLR and DMI gives influence to each other.

We will consider a positive IOD event which is associated with a decrease of convection around southeastern Indian Ocean (figure 2). Before the event, there is an expected increase of DMI. From Figure 4, we can assume that this increase is related to the decrease of convection around southeastern Indian Ocean four months before the expected increase of DMI. Following the theory of Indian Ocean Dipole [9][17], this increase of DMI is induced by anomalous easterly surface wind which drove the cold water below southeastern Indian Ocean to the surface. This decrease in SST will drove anomalous positive SLP over southeastern Indian Ocean, creating a high-pressure anti-cyclonic center. This then will induce convection over western Indian Ocean and suppress convection over southeastern Indian

![Figure 3. Cross-correlation between DMI and SST. Contours plotted at 95% confidence level are shaded.](image)
Ocean. Before lag 0, a stronger convection over western Indian Ocean will result into negative cloud-SST feedback and decrease SST over the area (DMI tends to decrease) from lag -2 until lag -1, hence hampers the development of positive IOD. When DMI takes lead after lag 0 (which we consider that a positive IOD event has already occurred), an increase of DMI (Positive IOD) will result in a decrease of OLR anomalies over the western Indian Ocean until lag +3, hence an increase in convection and a sign of development of positive IOD. This relationship suggests that to maintain the influence, IOD has to maintain the balance between positive and negative feedback of air-sea relationship. This corroborates the finding of [9] that IOD is a weakly damped oscillator in the absence of external forcing. However,
increase in convection and a positive variance anomaly means an increase in convection too, hence the opposite sign.

Figure 5 shows that before the expected increase of DMI (negative lags), total disturbances in the southeastern Indian Ocean and western Indian Ocean play a role in SST gradient over Indian Ocean. Decrease (increase) of total disturbances over southeastern Indian Ocean correlated with the increase (decrease) of DMI and increase (decrease) of total disturbances over western Indian Ocean correlated with the increase (decrease) of DMI. This suggests that during expected positive IOD event (DMI tends to increase), increase of total disturbances over southeastern Indian Ocean (western Indian Ocean) will hamper (aid) the pre-conditioning of IOD. The opposite is true for negative IOD event.

After IOD event (after lag 0), we observe a negative (positive) correlation in southeastern Indian Ocean (western Indian Ocean). During positive IOD (negative IOD), there will be enhanced total disturbances in convection for at least 3 months after the event occurred in western Indian ocean (southeastern Indian Ocean). By these results, these two locations will become sources for CCEW.

3.3 Influence of IOD on Kelvin Waves

In this section, we examine the influence on IOD forcing on Kelvin waves. Figure 6 shows correlation between DMI and OLR variance anomalies filtered by space-time filter [7]. The linear correlation shows
a negative correlation on southeastern Indian Ocean extending to the east of Australia and positive correlation in the Pacific (figure 4a). This negative correlation means an increase (decrease) of convection associated with Kelvin waves in southeast Indian Ocean when DMI increase (decrease).

Figure 6. Correlation between DMI and variance of Kelvin wave-filtered OLR anomalies (hereafter refer to Kelvin wave activity) (a), (b) Partial correlation between DMI and Kelvin wave activity while controlling the effect of ENSO. (c) Partial correlation between DMI and Kelvin wave activity while controlling for the effect of IOD. Correlation coefficients are significant at 95% confidence level. Positive correlation is found in western Indian Ocean extending to north of Sumatera. This positive correlation means an increase of DMI is associated with an increase in convection associated with Kelvin waves. The increase (decrease) of DMI means an increase (decrease) of southeast Indian Ocean SST. The pattern in figure 6a is also found by Huang and Huang [8]. This pattern also resembles IOD features.

To control ENSO’s influence on the correlation, partial correlation described in section 2 is used. Figure 6b shows a partial correlation after removing the ENSO’s influence. After removing ENSO’s influence, partial correlation shows similar pattern to the simple linear correlation (figure 6a). This means correlation found in Figure 6a is not dependent on ENSO. To further elucidate the effect of ENSO, we also using partial correlation between NINO 3.4 SST index and Kelvin OLR variance. Figure
4c shows the partial correlation between ENSO and convection associated to Kelvin wave activity, controlling IOD’s influence. Figure 6c shows a very different pattern than those in Figure 6a and 6b. Relatively high positive correlation is found in the Pacific, owing to the ENSO’s influence on Pacific Ocean. We decided to leave this finding to future studies as this study only focus on IOD.

IOD has measurable controls of convection associated with Kelvin wave activity over southeastern Indian Ocean and western Indian Ocean while the influence over northern Australia seems to be influenced by ENSO. These patterns are also observed by Huang and Huang [8]. The results show that IOD has direct control over convection associated with Kelvin wave activity in Indian Ocean, even without ENSO’s influence.

![Figure 7](image_url)

**Figure 7.** Same as in Figure 3, except between DMI and variance of Kelvin wave-filtered OLR anomalies.

Figure 7 shows a cross-correlation between DMI and OLR associated with Kelvin wave activity. The influence starts at lag -4 at 80-90E, 15-20S and 0-10N. Positive correlation is observed during lag -4 at 0-10N and persists until lag 0 while extending to 50E at lag -3. Negative correlation is observed at 80-90E and extending to 130E and moving eastward until vanished at lag +1. To make the explanation easier, we defined the negative correlation as “ION” or Indian Ocean negative and positive correlation as “IOP” or Indian Ocean positive. These two resemble the dipole mode, which is an important feature of IOD. During positive IOD event, IOP will experience an increase of convection associated with Kelvin waves and ION will experience a decrease of convection and vice versa for negative IOD event.

ION is first observed at lag -4, which means an increase of OLR is leading the decrease of DMI four months earlier. In southeast Indian Ocean (northwest Indian Ocean), a decrease of DMI means an
increase (decrease) of SST. This leading relationship means that an increase of DMI happened after the decrease of convection associated with kelvin waves. IOP is first observed during lag -6 (not shown) at 60-120E and 5-10N. The increase of SST in northwest Indian Ocean contributes positively in the convection in this location. IOP extends to east of Africa during lag -2 and moving westward until it completely disappeared at lag +4 (not shown).

Convection associated with Kelvin wave activity enhanced the SST gradient between southeast Indian ocean and northwest Indian ocean via Bjerknes feedback [18] with a lead time of 4 and 6 months. As proposed by Fischer et al. [17], during positive (negative) IOD event, easterly (westerly) wind induces upwelling in southeast (western) Indian Ocean, decreasing SST in the area and increasing the SST gradient. By this explanation, we propose that Kelvin wave activity may contributes to the growth of IOD event by increasing the convection in western Indian ocean (southeast Indian ocean) during positive (negative) IOD event and propagating eastward, causing negative cloud-SST feedback [9] east of the area and weaken the feedback over the area, notice that this waves activity is not only generated from IOD activity.

Kelvin wave activity increased after positive IOD (negative IOD) events in western Indian Ocean (southeastern Indian Ocean). This increase of activity in western Indian Ocean persists until at least 3

**Figure 8.** Same as in Figure 6, except for variance of MRG wave-filtered OLR anomalies.
months and 2 months in southeastern Indian Ocean. It must be noticed that the influence in southwestern Indian Ocean is more related to ENSO than IOD.

3.4 IOD Influence on MRG Waves

Next, we examine the influence of IOD on MRG wave activity. Figure 8 shows the correlation between DMI and OLR variance anomalies associated with MRG wave activity. Figure 5a shows a negative correlation in southeast Indian Ocean extending to Southern Indonesia and positive correlation in northwest Indian Ocean. This finding shows the similar pattern with Huang and Huang [8]. After controlling the ENSO’s influence (figure 8b), the pattern persists. This suggests a relatively independent influence of IOD on convection associated with MRG waves. By controlling the IOD effect as in section 3.3, we can conclude the controls of IOD with regards of ENSO. Figure 8c shows a correlation of NINO 3.4 SST index with OLR associated with MRG wave activity. Figure 8c shows no significant correlation in southeast Indian Ocean. This discovery suggests that IOD has measurable control over convectivity associated with MRG waves in southeast Indian Ocean and northwest Indian Ocean.

![Figure 9](image-url)

**Figure 9.** Same as in Figure 7, except for MRG wave activity.

Figure 9 is the cross-correlation between DMI and convection associated with MRG wave activity. We observe ION in lag -3 at 70-80E and 10-15S then it extends to Java Sea during lag -1 until it disappeared in lag +3. We also observe IOP in lag -2 at 70-80E and 10-15N then it extends to east Africa and disappeared at lag +3 (notice that it vanished during lag +1 but appears again during lag +2). MRG
waves may also play a role in before expected IOD event as discussed in section 3.3. While the pattern is similar, the correlation pattern shows some differences between MRG waves and Kelvin waves. In figure 7, IOP is observed in the most part of western Indian Ocean but in Figure 9, IOP is only observed in the northern part of western Indian Ocean. This suggests that MRG waves may play a weaker role before IOD event than Kelvin waves. MRG waves also have shorter influence than Kelvin waves as discussed above. MRG wave activity may propagate the convection westward, causing negative cloud-SST feedback in the west of IOP and ION.

After IOD event, there is significant correlation for at least 3 months. This suggests that IOD may enhance the convection associated with MRG wave activity during both events. During positive IOD (negative IOD) events, MRG waves activity is enhanced in western Indian Ocean (southeastern Indian Ocean). This increasing/decreasing activity is similar to Kelvin waves.

4. Conclusion

This study demonstrated that the large-scale convective system associated with IOD significantly influences Kelvin and MRG waves over the Indian Ocean and the Maritime Continent. Increased DMI towards positive values is linked to enhanced (suppressed) CCEW activity around the western Indian Ocean (southeast Indian Ocean). In particular, a positive IOD event leads to enhanced Kelvin wave activity over the eastern Africa and southern Indian Ocean. On the other hand, it suppresses Kelvin and MRG wave activities over the eastern Indian Ocean and the Maritime continent. Such effects are non-dependent to ENSO (as demonstrated by the results of partial correlation between DMI, NINO 3.4 SST index, and variance of wave-filtered OLR) and can last up to 3 months. This study suggests that the IOD even can indeed provide the latent-heat source for generating Kelvin and MRG waves in the tropics, with or without the influence of ENSO.

References

[1] Saji N H, Goswami B N, Vinayachandran P N and Yamagata T 1999 A dipole mode in the tropical Indian ocean Nature 401 360–3
[2] Lindzen R D 1967 Planetary waves on beta-planes Mon. Weather Rev. 95 441–51
[3] Lindzen R S 2003 The Interaction of Waves and Convection in the Tropics J. Atmos. Sci. 60 3009–20
[4] Masunaga H 2009 A 9-season TRMM Observation of the Austral Summer MJO and Low-frequency Equatorial Waves J. Meteorol. Soc. Japan 87 295–315
[5] Wheeler, Matthew C. Kiladis G N 1999 Convectively Coupled Equatorial Waves: Analysis of Clouds and Temperature in the Wavenumber–Frequency Domain J. Atmos. Sci. 56 374–99
[6] Takayabu Y N 1994 Large-Scale Part Cloud Disturbances Features Associated of the with Cloud Equatorial Disturbances Waves . I: Spectral of the Cloud Disturbances J. Meteorol. Soc. Japan 72 433–49
[7] Lubis S W and Jacobi C 2015 The modulating influence of convectively coupled equatorial waves (CCEWs) on the variability of tropical precipitation Int. J. Climatol. 35 1465–83
[8] Huang P and Huang R 2011 Climatology and interannual variability of convectively coupled equatorial waves activity J. Clim. 24 4451–65
[9] Li T, Wang B, Chang C-P and Zhang Y 2003 A Theory for the Indian Ocean Dipole–Zonal Mode* J. Atmos. Sci. 60 2119–35
[10] Hiroaki Ueda; Jun Matsumoto 2000 A Possible Triggering Process of East-West Asymmetric Anomalies over the Indian Ocean in Relation to 1997/98 El Niño J. Meteorol. Soc. Japan 78 803–18
[11] Straub K H and Kiladis G N 2002 Observations of a Convectively Coupled Kelvin Wave in the Eastern Pacific ITCZ J. Atmos. Sci. 59 30–53
[12] Wilson E A, Gordon A L and Kim D 2013 Observations of the madden julian oscillation during Indian ocean dipole events J. Geophys. Res. Atmos. 118 2588–99
[13] Webster P J, Moore A M, Loschnigg J P and Leben R R 1999 Coupled ocean-atmosphere
dynamics in the Indian Ocean during 1997-98 Nature 401 356–60
[14] Saji N H and Yamagata T 2003 Possible impacts of Indian Ocean Dipole mode events on global climate Clim. Res. 25 151–69
[15] Kug J S, Jin F F and An S Il 2009 Two types of El Niño events: Cold tongue El Niño and warm pool El Niño J. Clim. 22 1499–515
[16] Shinoda T and Han W 2005 Influence of the Indian Ocean Dipole on the Southern Oscillation. J. Meteorol. Soc. Japan 18 3891–909
[17] Fischer A S, Terray P, Guilyardi E, Gualdi S and Delecluse P 2005 Two Independent Triggers for the Indian Ocean Dipole/Zonal Mode in a Coupled GCM J. Clim. 18 3428–99
[18] Bjerknes J 1969 Monthly Weather Review Atmospheric Teleconnections From the Mon. Weather Rev. 97 163–72