Equatorial Monsoon System as Regulation for a Dipole Mode in the Indian Ocean

by

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Abstract

In this paper, we studied the equatorial monsoon systems and its association with the dipole mode in the Indian Ocean using NCEP/NCAR reanalysis data, outgoing long-wave radiation (OLR) and sea-surface temperature (SST) data.

The western Indian Ocean is characterized by a prominent semi-annual cycle, in contrast, the eastern Indian Ocean is dominated by an annual cycle. Because of the above phase difference in the tropical Indian Ocean between its western and eastern regions, the east-west (colder-warmer) SST contrast is usually enhanced in autumn. The inter-annual dipole mode, usually seen in autumn, can be understood as a result of the enforced climatological SST contrast. The termination of the dipole mode is closely connected with the appearance of the climatological suppressed convection during February–March over the entire tropical Indian Ocean.

The influence of the reversed Walker Circulation on the Indian Ocean, in response to the ENSO event, exhibits a distinct seasonal difference. If a divergent wind appears in summer over the Indian Ocean, the resultant SST becomes warmer (colder) in the western (eastern) Indian Ocean through air-sea interaction.

Thus, the seasonal differences of the coupling process between the monsoon and the ENSO may be a significant factor for understanding the phase-locking feature of the dipole mode.

1. Introduction

The east-west dipole structure in the tropical Indian Ocean – an interannual anomalies of low (high) sea-surface temperature and suppressed (enhanced) convection in the eastern (western) Indian Ocean – has been thought to be independent of external forcing such as the El Niño/Southern Oscillation (Webster *et al.*, 1999 ; Saji *et al.*, 1999). However, quite recently, Ueda and Matsumoto (2000) showed that its triggering process was closely associated with the warm episode of the 1997–98 El Niño through different air-sea interactions between the western and eastern Indian Ocean.

An important issue is why the dipole event

usually terminates in boreal winter. The previous study suggested that the life cycle of the dipole is modulated by the strong monsoon seasonality, but the detailed structure has yet to be revealed. Furthermore, the seasonality of El Niño (Mitchell and Wallace, 1996) and its coupling with the annual cycle of the monsoon may have a significant role in inducing the dipole structure in the Indian Ocean.

Therefore, we highlight the seasonal evolution process in the equatorial Indian Ocean, which may explain the phase locking-feature of the dipole event. In the rest of this paper, data sources will be reviewed in Section 2. Sections 3 describes the seasonal change of sea-surface temperature, surface wind and convective activity. The anomalous Walker Circulation during the warm episode of El Niño and its possible influence on the climatological

wind over the tropical Indian Ocean is given in Section 4. Section 5 attempts to postulate how the inter-annual SST anomalies are induced as a result of the modulated Walker circulation during different seasons. A concluding summary of the results is found in Section 6.

2. Data

In order to manifest the physical process responsible for an inter-annual SST anomaly and its linkage with the El Niño/Southern Oscillation (ENSO), we used weekly mean SST data. These data are a combined set of satellite and in situ observations, using an optimum interpolation method for a 1° grid between 1982 and 1999 (Reynolds and Smith, 1994). We also utilized daily NCEP/NCAR reanalysis data from 1972 through 1999 (Kalnay et al., 1996). Also used are daily outgoing longwave radiation (OLR) data with a resolution of $2.5^\circ \times 2.5^\circ$ derived from the NOAA satellite for the same period as the SST data. The OLR data is considered to be a proxy of convective activities over the tropical regions (Liebmann and Smith, 1996).

3. Monsoon seasonality

The climatological features of the seasonal evolution process in the equatorial Indian Ocean exhibit a distinct phase difference between the western and eastern regions and contrast greatly with the climatological features of the tropical Pacific Ocean (Fig. 1). In a general sense, a semi-annual cycle is evident in the western Indian Ocean for the SST and OLR fields. In contrast, the eastern Indian Ocean appears to undergo an annual cycle. The seasonal progress of sea-surface temperature (SST) is principally regulated by the surface wind speed through the heat exchange between the ocean and atmosphere (Fig. 1a-b). The strong westerly (easterly) wind over the western Indian ocean is usually accompanied by a strong southerly (northerly) wind component. However, the reverse is true for the eastern Indian ocean (not shown). Looking at these figures, it can be seen that the seasonal march of SST lags behind the annual cycle of the surface wind by about two months.

Because of the phase difference seen in SST between the western and eastern Indian Ocean, its east-west gradient (subtracting east from west) exhibits two peaks during spring and autumn (Fig. 1c). The first peak is caused by notable SST warming in the western Indian Ocean due to weaker

wind corresponding to the transition period from winter to summer monsoon. The second peak is attributed to both the warmer SST in the western Indian Ocean and SST minimum in the eastern Indian Ocean. In this way, the zonal gradient of the annual anomaly of SST is usually enhanced during autumn in the climatological annual march.

The annual cycle of OLR in the tropical Indian Ocean is plotted in Fig. 1d. The out-going longwave radiation (OLR) indicates a proxy of rainfall. During May-December, a phase difference between the western and eastern Indian Ocean enhances the east-west contrast in June and at the end of December (Fig. 1e). In Fig. 1d, the convection is usually greatly suppressed over the entire region of the tropical Indian Ocean from mid-February through April. In the typical dipole event, the convection over the western Indian Ocean is usually enhanced from October through January. This active convection strengthens the surface easterly wind over the equatorial Indian Ocean, which enhances the dipole structure through a positive feedback process. The climatological suppression of convection breaks the positive feedback loop, which may explain why the anomalous convective anomaly over the western Indian Ocean associated with the dipole usually disappears in February. In other words, the strongly suppressed convection acts as a barrier restricting the growth of the dipole structure. Thus, the phase-locking features of the dipole can be explained by the strong monsoon seasonality.

4. Influence of Reversed Walker Circulation

In order to examine the influence of ENSO, we made a longitude-height section of the climatological circulation fields along 5°S - 5°N during June to August (Fig. 2a). In this figure, there appears to be a baroclinic structure over the Indian and Pacific Oceans - an opposite zonal wind direction between the lower and upper troposphere called "Walker circulation". To examine the synchronized case between the dipole and El Niño (Saji et al., 1999), we plotted the composite anomalies of divergent flows for the years 1972 and 1997 from June to August (Fig. 2b). The reversed Walker circulation is clearly seen due to the strong El Niño event. For the Indian Ocean, there exists an easterly (westerly) wind anomaly in the lower (upper) troposphere that indicates weaker monsoon circulation.

If the above divergent wind anomaly is superimposed on the climatological wind during the summer season (see Fig. 1b), westerly (easterly) wind becomes weakened (enhanced) and the resultant

Figure. 1 Time-longitude sections of the climatological seasonal evolution in the tropical Indian Ocean (5°S-5°N). Panel a, the zonal wind at the surface. Panel b, sea surface temperature (SST). Panel d, outgoing longwave radiation (OLR). The annual mean has been removed for SST and OLR. Panel c, east-west contrast (subtracting 45°-55° E minus 85°-95°E) of SST. Panel e, OLR in the equatorial Indian Ocean.

Figure 2. Longitude-height sections of the divergent winds averaged for 5°S–5°N from June to August. Panel (a) is for the climatological state, and (b) for composite anomalies of the warm episode for the 1972 and 97 El Niño.

SST anomaly is above (below) normal over the western (eastern) Indian Ocean. In contrast, the similar dipole event did not occur during the year of 1982–83 despite the large El Niño event. This was because a divergent wind anomaly over the Indian Ocean due to the warm episode appeared in autumn not the summer season, which may have resulted in a seasonally different air–sea interaction. This will be discussed in the following section.

5. Discussion

A possible coupling process between the dipole and the ENSO is shown in Fig. 3a–d. The top panel denotes the reversed Walker circulation in response to a warm episode of the El Niño. If the anomalous divergent wind appears in a different season, the climatological wind will be modulated by a different process (upper panel). Since the wind direction changes in the annual cycle, the pattern of inter-annual SST anomaly will be different (second panel). The third panel shows the seasonal component of SST from its annual mean value. It is interesting to note that the anomaly pattern of Fig. 3b is the same between the inter-annual SST anomaly (second panel) and the seasonal variation of

SST. Because of the strong monsoon seasonality, the coupling between the seasonal cycle and the inter-annual mode is quite an important factor for the dipole structure. Furthermore, positive feedback through the air–sea interaction plays a crucial role in strengthening the dipole mode. In a typical year of the dipole, a positive (negative) SST anomaly and active (suppressed) convection are found over the western (eastern) Indian Ocean and are accompanied by easterly surface wind during autumn. This east–west asymmetric structure of the SST and convective activity are enhanced by the oceanic waves induced by the easterly wind (Ueda and Matsumoto, 2000). Thus, the nonlinear enhancing process between the annual and inter-annual modes should be considered for understanding the mature phase of the dipole. In the bottom panel, we can see four different SST anomaly patterns despite the same external forcing of the low-level divergent wind as the climatological field of SST and wind have strong seasonality. The largest east–west SST contrast appears when the reversed Walker circulation begins summer. However, no remarkable SST contrast can be found except for the summer case that may associated with the warming in the entire Indian Ocean (Chambers et al., 1999).

A recent study revealed that the 1997–98 dipole event was induced through the process of Fig. 3b (Ueda and Matsumoto, 2000). However, one may question why the dipole event did not take place during other El Niño years. In this paper, we studied the detailed structure of the 1982–83 El Niño event. Figure 4 shows a longitude–time section of SST and surface wind anomaly along 5°S–5°N. SST warming in excess of 0.5°C began to appear in May 1982, which was almost at the same time as the 1997–98 El Niño. However, westerly wind anomalies over the Pacific Ocean were delayed by about two months compared with 1997. In other words, the formation of reversed Walker circulation lagged behind that of 1997 about two months. Over the eastern Indian Ocean, the easterly anomaly was not recognizable from July to September 1982. Figure 1 suggests that the climatological easterly winds over the eastern Indian Ocean during August and September play an important role in the cooling of SST in the succeeding October and November. During this period of 1982, the reversed Walker circulation was not recognizable over the equatorial eastern Indian Ocean. Therefore, the colder SST anomaly over the eastern Indian Ocean was not enhanced.

From October to December 1982, the easterly anomaly was seen over the eastern Indian Ocean,

Figure 3. Possible monsoon-ENSO coupling for producing SST anomaly in the tropical Indian Ocean. The top panel shows anomalous divergent winds during the El Niño. The first row of panels shows the climatological winds at the surface and the expected wind modulation by the divergent wind anomaly (in *italics*). The second row of panels represents the SST anomaly during the succeeding season through the air-sea interaction. The third row of panels displays the climatological SST fields. Note that the plotted values deviate from the annual mean state. The bottom panels presents the actual SST anomaly (sum of interannual SST anomaly and seasonal component). The coupling starts in spring (a), summer (b), autumn (c) and winter (d).

Figure 4. Longitude-time sections of weekly SST and surface wind anomalies from climatological mean value (1982-97) averaged between 5°S and 5°N during 1982. Wind vectors are drawn at every 5° in the longitudinal direction. Contour interval is 1.0°C. Negative contours are dashed. Light (heavy) shading denotes SST anomalies greater (less) than 0.5°C (-0.5°C). A unit vector of 4 ms⁻¹ is plotted in the upper right of this figure.

Figure 5. Longitude-time sections of weekly OLR anomalies from climatological mean value and actual surface wind averaged between 5°S and 5°N during 1982. Contours of -40, -20, +20 (Wm⁻²) are drawn. Full (dashed) lines correspond to plus (minus) contours. Light (heavy) shading denotes OLR anomalies greater (less) than 20Wm⁻² (-20Wm⁻²). A reference vector of 5 ms⁻¹ is plotted in the upper right of this figure.

Figure 6. Time series of u-component wind anomalies averaged over the equatorial Indian Ocean (5S-5°N, 50°E-90°E) for (a) coupled cases between the dipole mode and ENSO event, and (b) the decoupled cases.

while the actual wind speeds were relatively low and enhanced convective activities appeared over the eastern Indian Ocean (Fig. 5). This was because the easterly wind anomalies were canceled by the climatological westerly wind usually seen around November (Wyrtki, 1973). In 1997, the easterly wind anomalies were much stronger over the equatorial Indian Ocean and the actual wind still remained easterly in spite of climatological westerly winds (Ueda and Matsumoto, 2000). Therefore, it is considered that the colder SST anomalies over the eastern Indian Ocean were not enhanced despite the large 1982-83 El Niño event.

Finally, we show the seasonal evolution of u-component wind anomaly over the equatorial Indian Ocean for the other El Niño cases in Fig. 6. Saji et al. (1999) revealed that the dipole event occurred during the 1972-73 El Niño. However, the dipole was not observed despite the El Niño in 1976, 82 and 87. Figure 6a (b) displays coupled (decoupled) cases

between the dipole and the El Niño event. In the coupled cases, the u-component wind anomaly is easterly from summer through winter, corresponding to the process of Fig. 3b. In contrast, the decoupled cases do not display a distinct easterly wind anomaly during the summer season.

The above scenario requires further clarification using an atmosphere-ocean coupled model and reliable observation data collected a longer period.

6. Conclusion

The results presented above indicate that the seasonal evolution process in the tropical Indian Ocean exhibits a phase difference between its western and eastern regions that produces a remarkable dipole-type SST gradient in the annual cycle. The divergent wind anomaly in response to the El Niño has a sufficient potential for modulating monsoon circulation that may change the SST condition. If

the external forcing appears at a time other than the summer season, the anomalous SST anomaly like the 1997-98 dipole would not be generated. Thus, the seasonal coupling between monsoon flow and the ENSO is a crucial factor for the Indian Ocean dipole. Also, the phase-locking feature of the dipole in the annual cycle, especially its termination, can be explained by the strong monsoon seasonality, which is fundamentally different from the El Niño process in the Pacific Ocean.

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インド洋での双極子モードを規定する赤道モンスーンシステム

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1982年から1999年までのNCEP/NCAR再解析データ、外向き長波放射量(OLR)および海面水温(SST)データを用いて、赤道でのモンスーンによる季節サイクルとインド洋での双極子モードとの関係を調べた。

赤道インド洋の西側では半年周期が卓越するが、東インド洋では年周期が顕著であり、この位相差のため季節サイクルの中で秋に西高東低のSSTコントラストが生み出される。年々変動偏差としてみられる双極子モードは、このSSTコントラストがさらに強化されたものとして理解出来る。また、双極子モードの終焉は気候学的に赤道インド洋全域で2月から3月にかけて対流活動が抑制される事と関係している。

ENSOに伴う反転したウォーカー循環のインド洋への影響は季節によって異なり、夏に出現する場合に効果的に気候学的な西(東)インド洋での西風を弱(強)め、大気海洋相互作用を通して引き続く秋に西高東低のSSTコントラストが形成されるものと考えられる。

このように双極子モードの季節位相固定性の理解においては、モンスーンとENSOの季節による結合過程の違いが重要である。