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Influence of the Indian Ocean Dipole on the Indian Ocean Meridional Heat Transport

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ABSTRACT

Influence of the Indian Ocean Dipole (IOD) on the Indian Ocean Meridional Heat Transport (MHT) is studied using 60-yr SODA data. Results show that there is anomalous heat transport from the equatorial region to higher latitudes in both hemispheres during IOD events, and the anomalous poleward MHT occurs mainly in the western Indian Ocean. IOD has strong influence on the MHT during late summer and fall, which is consistent with the seasonal phase-locking characteristics of IOD itself. The MHT anomaly caused by anomalous meridional velocity, which is induced by wind, is the major contributor of the total MHT anomalies. EOF analysis shows that the IOD is a key factor for interannual variability of the MHT in the Indian Ocean. These findings are very useful for understanding the Indian Ocean heat balance and climatic implications of IOD.

1. Introduction

The Meridional Heat Transport (MHT) is one of the most important manifestations of the ocean's role in global climate. Estimates of the time–mean MHT show that ocean carries the same order of magnitude of energy away from the tropics toward the poles as the atmosphere does (reviewed by Jayne and Marotzke, 2001). Since the Indian Ocean is strongly influenced by monsoon activities, there exists a unique cross equatorial heat transport in the Indian Ocean. The net effect of this cross equatorial heat transport is that the heat is transferred from the summer hemisphere to the winter hemisphere. This has been shown to be the primary process of the modulation of the northern Indian Ocean (NIO) heat balance (Loschnigg and Webster, 2000). Since the sea surface temperature (SST) of NIO is critically important for the annual cycle and interannual variability of Asian monsoon (Harzallah and Sadourny, 1997; Meehl, 1987, 1997), studying the mechanism and variability of the Indian Ocean MHT would be very helpful for understanding the SST variations in the Indian Ocean, thus improving the predictability of the monsoon activities.

Although the annual mean and seasonal variations of the Indian Ocean MHT has already been well studied, the characteristics and mechanisms of the interannual variability are still poorly understood. Loschnigg and Webster (2000) analyzed the cross equatorial heat transport anomalies during 1984–1990 and found that the increased heat transport in 1988 is consistent with strengthened meridional overturning circulation driven by strong south Asia summer monsoon, while the reduced heat transport in 1987 is coherent with weak south Asia summer monsoon. Similar results were found by some Chirokova and Webster (2006) using 41-yr model results. But correlation analysis shows no linear correlation between the cross equatorial heat transport anomalies and monsoon index. The correlation between the cross equatorial heat transport and El Nino is neither significant. Some studies suggest that there is a biannual tendency of the MHT variability (Chirokova and Webster, 2006; Loschnigg et al., 2003), and the cross-equatorial heat transport can contribute to biennial nature of the ENSO monsoon system by affecting the heat content of the Indian Ocean and resulting SST anomalies over multiple season (Loschnigg et al., 2003). Hu et al. (2005) show that the meridional overturning circulation, which could lead to MHT, has a period of 4 years. Although the findings of the above studies are not fully consistent, they all agree that the interannual variability of Indian Ocean MHT is mainly determined by the Ekman transport variations induced by wind stress (see also, Jayne and Marotzke, 2001). Overall, the understandings of the Indian Ocean MHT interannual variability is currently quite limited, the governing mechanisms of the Indian Ocean heat transport still needs to be further studied.

Indian Ocean Dipole (IOD) is one of the dominant modes of the Indian Ocean interannual variability (review by Schott et al., 2009). IOD could influence the meridional heat transport by its corresponding wind stress and temperature anomalies. The wind stress anomalies could influence the strength of meridional overturning circulation, causing mass transport changes, and the temperature anomalies could change the quantity of heat carried by ocean circulation. Hu et al. (2005) suggest that the IOD may influence the spatial pattern of the Indian Ocean MHT.

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Most of the previous studies about the Indian Ocean MHT interannual variability only consider relative shorter period or certain anomalous cases, and the effect of IOD has not been paid much attention to. The present study is aimed to reveal the influence of IOD on Indian Ocean MHT based on the diagnosis of 60-yr SODA data. The rest of this paper is organized as follows. In Section 2, we examine the characteristics of MHT anomalies associated with IOD. Then we decompose the heat transport anomalies into various components in Section 3 to evaluate the contributions of different physical processes. In Section 4 we investigate to what extent the interannual variability of the Indian Ocean MHT can be explained by IOD. Finally, the conclusion and discussion are given in the last section.

2. Characteristics of MHT anomalies associated with IODs

The spatial distribution and temporal evolution of the MHT anomalies associated with IOD are studied in this section. The SODA Version 2.0.0-4 (1958–2007, horizontal resolution 0.5° × 0.5°) product (Carton and Giese, 2008) is used in this study. Since the Indian Ocean has been warming significantly during the past decades and our focus is the interannual variation, a 7-year high-pass filter is first applied to the SODA data to remove decadal signals and trend. Fig. 1a shows the climatology seasonal cycle of MHT (integrated to the bottom of the Indian Ocean) calculated using SODA data. The distribution of MHT shows similar characteristics with previous studies: A large southward transport between spring and fall and a northward transport during the rest of the year. The maximum MHT exists on the south side of the equator between 10° and 15°S (Chirokova and Webster, 2006). The maximum southward MHT could reach 2.5 PW, which is larger than the results shown in Chirokova and Webster (2006). The interannual variations of MHT based on SODA data are shown in Fig. 1b. The MHT anomalies show significant biannual tendency which has been found in previous studies (Chirokova and Webster, 2006; Loschnigg et al., 2003). The magnitude of the interannual variations is also comparable to the result in Chirokova and Webster (2006). These results indicate that the SODA data can capture the major processes that determine MHT seasonal and interannual variations.

We then calculate the Dipole Mode Index (DMI), which is defined as the difference between the mean SST anomalies of west pole (50°E–70°E, 10°S–10°N) and east pole (90°E–110°E, 10°S–0°) (Saji et al., 1999), and find that there are 7 significant IODs exceeding 1.5 standard deviation of the DMI in 1958–2007. These IODs are 1961, 1963, 1967, 1972, 1982, 1994 and 1997 events. The following composite analyses are based on these 7 IOD events.

According to Loschnigg and Webster (2000), the MHT can be calculated as follows:

$$Q_v(t) = \rho C_p \iint vTdxdz \tag{1}$$

where $v(x,z,t)$ and $T(x,z,t)$ are the meridional velocity and temperature, respectively; ρ is the density of water; C_p denotes the specific heat of water, longitude and depth are denoted by x and z, respectively. Since 50 m is commonly used as a typical mixed layer depth in studies about Indian Ocean (e.g. Baquero-Bernal et al., 2002; Behera and Yamagata, 2001; Vinayachandran et al., 2007), z is also defined as 50 m in our calculation to represent the heat transport in the upper mixed layer.

Since IOD is seasonal phase-locking and usually reach its peak in October (Saji et al., 1999), the spatial distribution of MHT anomalies in October of IOD years is first studied. Fig. 2a shows the MHT anomalies across different latitudes of the Indian Ocean in October of IOD years, and the thick black line is the mean (or composite) of the 7 IOD events. The MHT anomalies in Fig. 2a are calculated according to the climatology

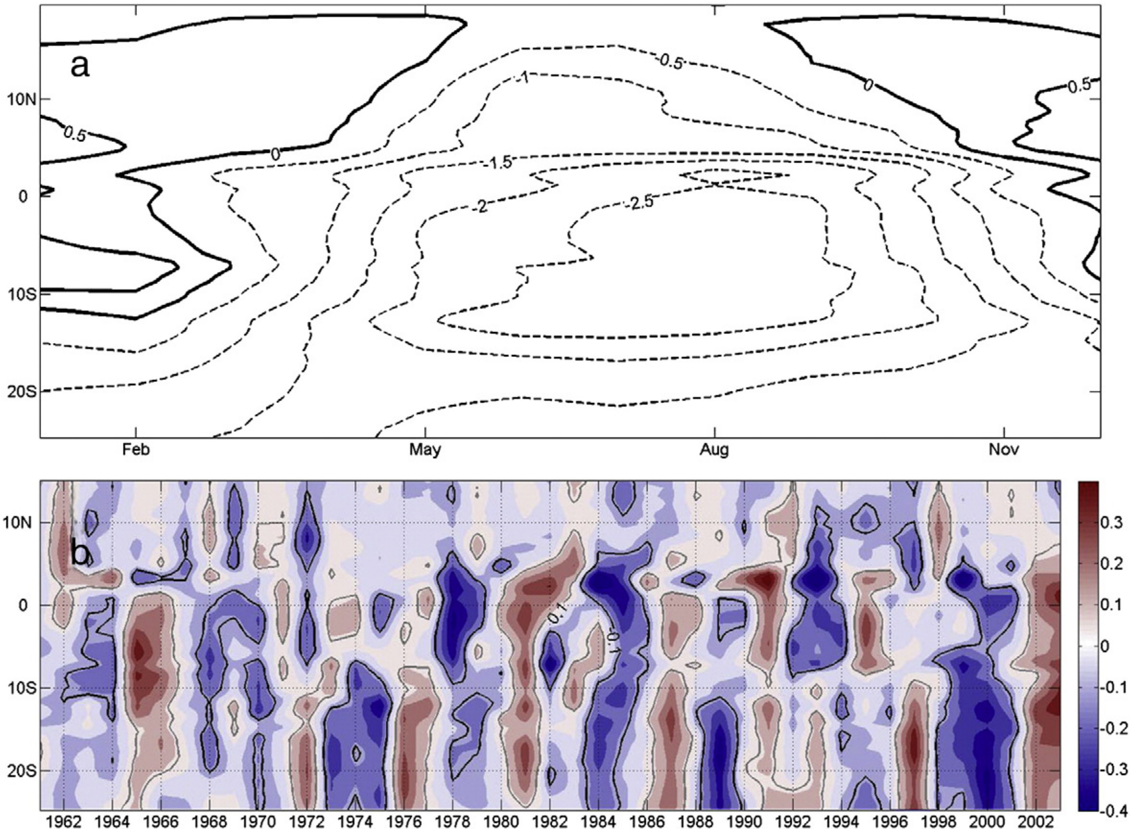

Fig. 1. (a) Seasonal cycle of the meridional heat transport in the Indian Ocean based on SODA data. (b) Space-time distribution of the annually averaged anomalies of the meridional heat transport (seasonal cycle removed). (Units: PW).