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Warming in the Northwestern Indian Ocean Associated with the El Niño Event

YUAN Yuan*[1,3] (袁 媛), ZHOU Wen[2] (周 文), YANG Hui[1] (杨 辉), and LI Chongyin[1] (李崇银)

[1] *State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[2] *Department of Physics and Materials Science, City University of Hong Kong, Hong Kong*

[3] *Graduate University of Chinese Academy of Sciences, Beijing* 100049

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ABSTRACT

This paper investigates possible warming effects of an El Niño event on the sea surface temperature anomaly (SSTA) in the northwestern Indian Ocean. Most pure positive Indian Ocean dipole (IOD) events (without an El Niño event co-occurring) have a maximum positive SSTA mainly in the central Indian Ocean south of the equator, while most co-occurrences with an El Niño event exhibit a northwest-southeast typical dipole mode. It is therefore inferred that warming in the northwestern Indian Ocean is closely related to the El Niño event. Based on the atmospheric bridge theory, warming in the northwestern Indian Ocean during co-occurring cases may be primarily caused by relatively less latent heat loss from the ocean due to reduced wind speed. The deepened thermocline also contributes to the warming along the east coast of Africa through the suppressed upwelling of the cold water. Therefore, the El Niño event is suggested to have a modulating effect on the structure of the dipole mode in the tropical Indian Ocean.

Key words: positive Indian Ocean dipole, El Niño, latent heat flux, thermocline

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1. Introduction

Large-scale air-sea interactions play a crucial role in generating interannual variability in the Tropics. Much attention has been paid to the strongest coupled system of the El Niño/Southern Oscillation (ENSO), which exerts prominent impacts on the global climate (Philander et al., 1990). Recently, the Indian Ocean Dipole (IOD) phenomenon is also presented as another important tropical air-sea interaction (Saji et al., 1999; Webster et al., 1999), characterized by sea surface temperature (SST) anomalies (SSTA) of opposing signs in the western and southeastern Indian Ocean. Since then, many research works have furnished evidence of its great impacts on the climate in neighboring regions (Ashok et al., 2001, 2004; Black et al., 2003; Clark et al., 2003), and also in East Asian, Australian and American countries (Li and Mu, 2001; Guan and Yamagata, 2003; Saji and Yamagata, 2003a).

Recently, an interesting issue concerning the dependence/independence of the IOD and ENSO phenomena has been raised (Allan et al., 2001). In contrast to some studies claiming that IOD is an inherent mode of the tropical Indian Ocean (Yamagata et al., 2002; Ashok et al., 2003; Saji and Yamagata, 2003b), others suggested that it is a part of ENSO evolution, being affected by the modulation of the Walker circulation based on the atmospheric bridge theory (Klein et al., 1999; Baquero-Bernal et al., 2002; Li et al., 2002; Shinoda et al., 2004). This mechanism entails the forcing of the remote atmospheric circulation by SSTA in the tropical Pacific, and the ensuing response of the remote Indian Ocean to such atmospheric changes (Venzke et al., 2000; Lau and Nath, 2003).

It is observed that some positive IOD events cooccur with an El Niño event, while others happen either in the absence of El Niño or sometimes even with a La Niña event (called pure positive IOD). The objec-

*Corresponding author: YUAN Yuan, yuanyuan@mail.iap.ac.cn

tive of this paper is therefore to investigate some differences between the co-occurring cases and pure positive IOD events, and further examine ENSO effects on the SSTA variation in the northwestern Indian Ocean.

Data and methodology are described in section 2. By comparing the SSTA development of pure positive IOD cases and co-occurrences of positive IOD and El Niño in section 3, section 4 reveals the close relationship between the warming in the northwestern Indian Ocean and the El Niño event, and further investigates possible mechanisms. A summary and discussion is given in section 5.

2. Data and methodology

The data used in this study are mainly from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis, including the monthly mean 850-hPa wind and latent heat flux during the period 1960–2003 (Kistler et al., 2001). The monthly mean SST data with $1^\circ \times 1^\circ$ resolution (1960–2003) are derived from the Hadley Centre of UK Meteorological Office (Rayner et al., 2003). The 20°C isotherm depth (Z20) provided by the Simple Ocean Data Assimilation (SODA) dataset of 1960–2001 (Carton et al., 2000) is also used to represent the variations of the thermocline in the subsurface ocean.

For studying the interannual variability, monthly anomalies are obtained by removing the climatology mean. Niño-3 index is defined as the monthly SSTA averaged over the eastern Pacific (5°S–5°N, 150°–90°W), and IOD index is the SSTA difference between the western (10°S–10°N, 50°–70°E) and the eastern (10°S–0°, 90°–110°E) Indian Ocean (Saji et al., 1999).

According to the categories divided by Saji and Yamagata (2003b), composite analyses are performed respectively on pure positive IOD events (1961, 1967, 1977, 1983 and 1994) and co-occurrences of positive IOD and El Niño (1963, 1972, 1982 and 1997), with the significance of the composites tested using the classical Student's t-test (Chervin and Schneider, 1976). The significance of the correlation results is also tested by the t-test with $(N-2)$ degrees of freedom:

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}} ,$$

where r is the correlation coefficient, and N the total number of the time series.

3. SSTA development

It is well-known that an IOD event usually occurs

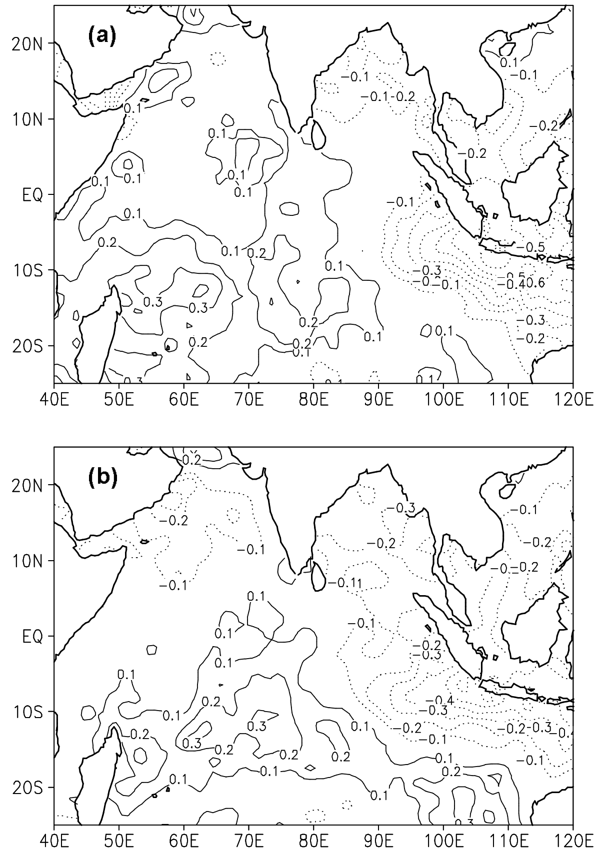

Fig. 1. SSTA structure composite for pure positive IOD events (1961, 1967, 1977, 1983 and 1994) in the boreal (a) summer (JJA) and (b) autumn (SON), with solid lines (dots) for positive (negative) anomalies and the 0°C isotherm omitted. Contour interval is 0.1°C.

in the boreal summer, peaks in autumn, and then decays rapidly in winter (e.g., Saji et al., 1999; Li and Mu, 2001). But the composite SSTA for pure positive IOD and co-occurrence of positive IOD and El Niño show dissimilar evolutions. In summer (June–July–August; JJA), pure positive IOD begins to develop in the southern Indian Ocean with an above-normal SSTA centering the east of Madagascar and a below-normal SSTA in the southeastern Indian Ocean near the Sumatra coast (Fig. 1a). In autumn (September-October-November; SON), positive anomalies are intensified to the maxima in the central Indian Ocean around (10°S, 70°E). With the largest negative SSTA near Sumatra, it forms a west-east zonal dipole mode (Fig. 1b). For the co-occurrence of a positive IOD and an El Niño event, negative SSTA in the southeastern Indian Ocean is very similar to the condition of pure positive IOD, but positive anomalies in the western pole first appear in the northwestern Indian Ocean along the east coast of Africa in summer (Fig. 2a), and then extend southeastward to the central

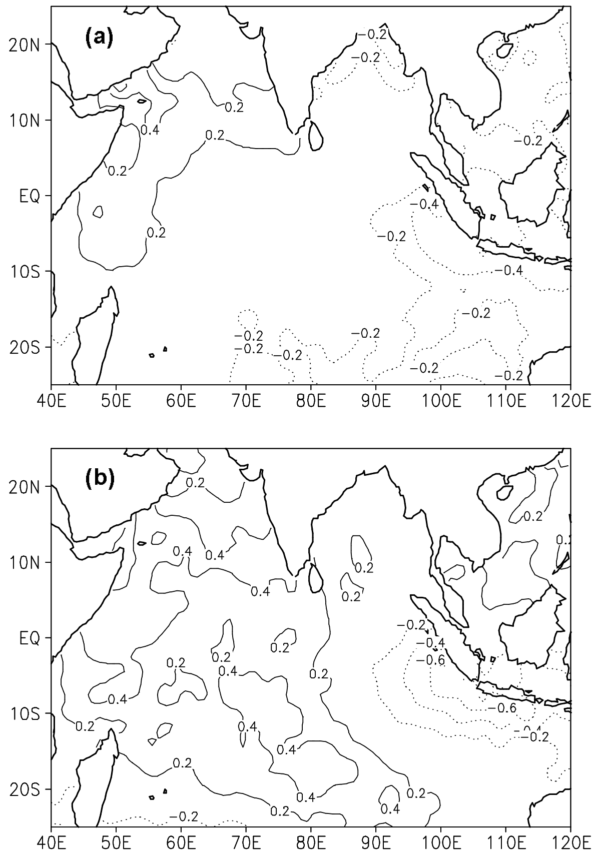

Fig. 2. Same as Fig. 1, but for the co-occurrence of a positive IOD and an El Niño event (1963, 1972, 1982 and 1997) and the contour interval is 0.2°C.

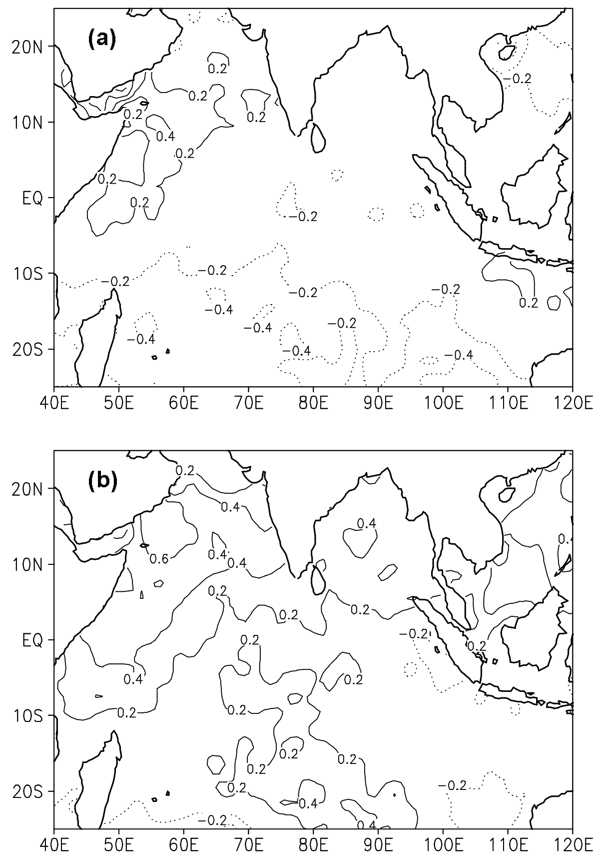

Fig. 3. Same as Fig. 1, but for the SST differences between the co-occurrence and pure positive IOD, and contour interval is 0.2°C.

Indian Ocean with increased intensity in autumn, thus forming a northwest-southeast dipole mode (Fig. 2b).

According to Saji et al. (1999), the typical IOD mode should have the largest positive SSTA mostly located in the western Indian Ocean (10°S–10°N, 50°E–70°E). The co-occurrence in Fig. 2 shows much the same structure. But pure positive IOD cases exhibit a somewhat different pattern, with negative anomalies dominating the western pole north of the equator, and positive anomalies confined to the central ocean south of the equator (Fig. 1).

The differences between co-occurrences and pure IOD events show a highest SST increase in the northwestern Indian Ocean from summer till autumn (Fig. 3), along with another minor increase in the southern Indian Ocean during the autumn season (Fig. 3b). Some conclusions can be inferred from these figures: (1) The IOD mode in co-occurrences is intensified to some extent because of the El Niño-induced signal, consistent with Saji and Yamagata (2003b); (2) The ENSO has different impacts on the western and eastern Indian Ocean. SSTA in the western pole of the

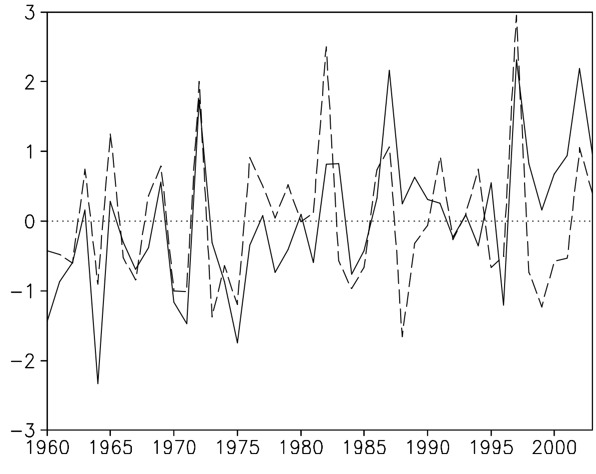

Fig. 4. Normalized seasonal mean NWIO (SON; solid curve) and Niño-3 (October-November-December, OND; long-dashed curve) indices. The NWIO index is defined as SSTA averaged in the northwestern Indian Ocean (5°–15°N, 50°–70°E), and the Niño-3 index is defined as SSTA averaged in the Niño-3 region (5°S–5°N, 150°–90°W).

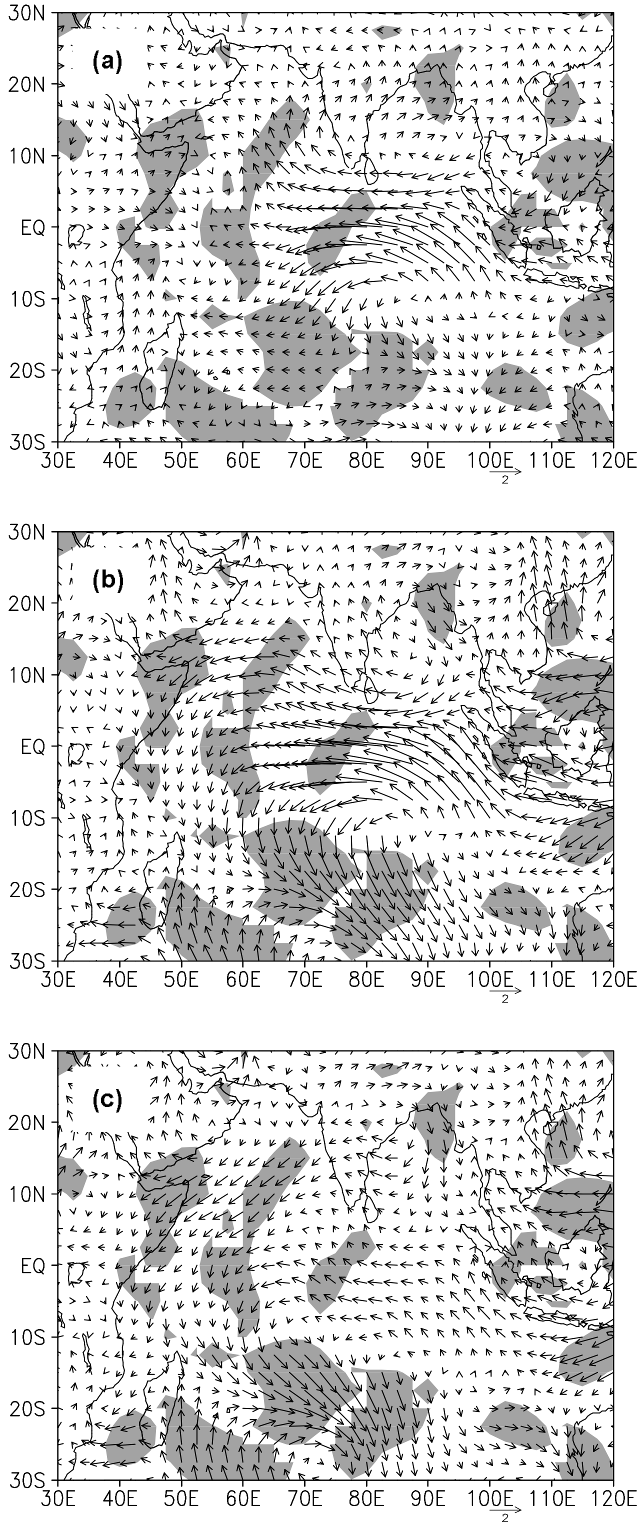

Fig. 5. 850-hPa anomalous winds in autumn (SON) composite for (a) pure positive IOD, (b) co-occurrence with an El Niño event, and (c) differences between the co-occurrence and pure positive IOD. Shaded areas indicate that either zonal or meridional wind is significant above the 95% confidence level.

dipole mode may be more related to the remote ENSO-forcing in eastern Pacific, whereas in the eastern pole SSTA may be more determined by internal thermodynamics in the Indian Ocean itself or some other external forcing; (3) The ENSO event could modulate the structure of the dipole mode in the tropical Indian Ocean. In the following section, we first reveal the close relationship between SSTA in the northwestern Indian Ocean and that in the eastern Pacific, and then investigate physical dynamics for the ENSO impacts on the warming in the northwestern Indian Ocean.

4. Warming in the northwestern Indian Ocean associated with an El Niño event

The key region (5°–15°N, 50°–70°E) is isolated, where the area-averaged SSTA is defined as a new northwest Indian Ocean (NWIO) index.

The normalized time series of the seasonal mean Niño-3 (October-November-December; OND) and NWIO (SON) indices apparently show an in-phase variation, despite their different intensity in some years (Fig. 4). Their significant correlation coefficient of 0.598 greatly exceeds the 95% confidence level, suggesting a close relationship between SSTA in the eastern Pacific and that in the northwestern Indian Ocean: an El Niño event would favor warming in the northwestern Indian Ocean, while a La Niña event may induce cooling in that region.

SST variations in the Indian Ocean have been suggested to be influenced by ENSO through changed surface heat flux, mixing in the upper ocean, or vertical advection (Venzke et al., 2000). In a similar way, we will examine ENSO impacts on the low-level wind anomalies, thermocline variations as well as latent heat flux change in the northwestern Indian Ocean.

The low-level wind anomalies in autumn (SON) for pure positive IOD and co-occurrence of positive IOD and El Niño looks much the same, both characterized by strong southeasterly trades along the west coast of Sumatra and easterly anomalies along the equatorial Indian Ocean (Figs. 5a and 5b). The winds in the co-occurrence appear a little stronger than those in the pure cases, with significant different winds (shadings) observed in the northwestern Indian Ocean and the central ocean south of the equator. For pure positive IOD, anomalous southeasterlies dominate the Arabian Sea, and weak southerly winds occupy the east coast of Africa (Fig. 5a). But in the co-occurrence, northerly anomalies along the eastern African coast are followed by enhanced easterly winds in the northwestern Indian Ocean (Fig. 5b), which lead to significant northeasterly winds there in the difference diagram between the two conditions (Fig. 5c).

In the subsurface ocean, little difference of the 20°C isotherm depth in the northwestern Indian Ocean can be identified between the co-occurrence and pure positive IOD (Fig. 6a), except a narrow strip along the east coast of Africa that has a significant deepened thermocline in the co-occurrence. This indicates that a suppressed upwelling of cold water caused by the anomalous northerly winds (see Figs. 5b and 5c) would help warm the sea surface along the coast. However, a shallower thermocline in the central Indian Ocean is not quite consistent with the increased SSTA there in the co-occurrence (Fig. 2c), suggesting that SST warming in this region cannot be explained by vertical advection.

For the latent heat flux data, positive (negative) value means downward (upward) heat flux into (from)

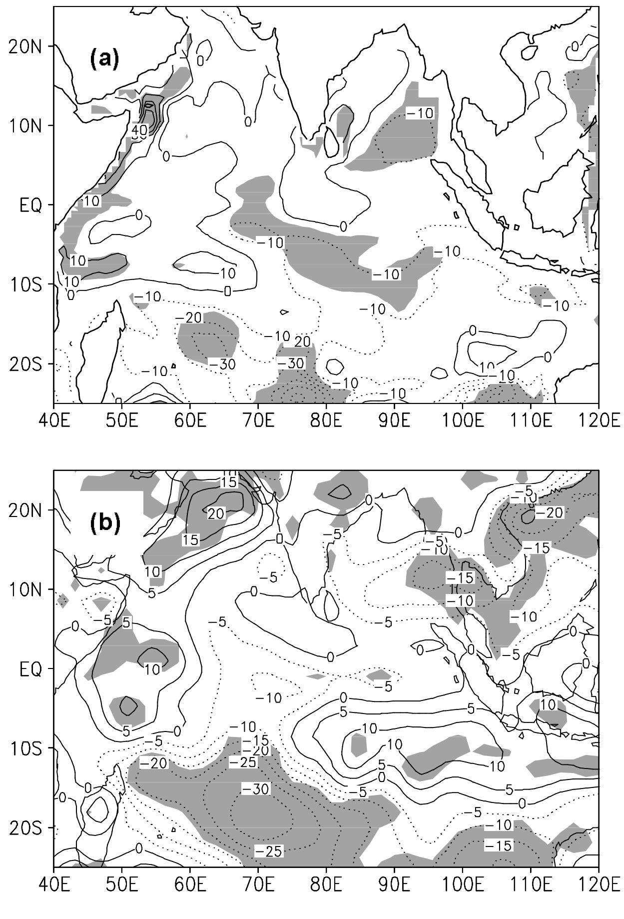

Fig. 6. Differences of (a) the 20°C isotherm depth in the subsurface ocean and (b) latent heat flux into the ocean between the co-occurrence and pure positive IOD. Shaded areas indicate their differences are significant above the 95% confidence level. The contour interval for the 20°C isotherm depth is 10 m, and for the latent heat flux is 5 W m^{-2}.

the ocean. In the difference diagram between the co-occurrence and pure positive IOD (Fig. 6b), significant positive anomalies over the northwestern Indian Ocean suggest that more latent heat flux downward into the northwestern Indian Ocean (i.e., less heat flux released from the ocean) in the co-occurrence has a warming effect on the sea surface, consistent with the positive anomalies of SST there (see Fig. 3b). However, in the central part of the southern Indian Ocean, the cooling effect with less heat flux (negative anomalies) still does not explain the increased SSTA in the co-occurrence (see Fig. 3b).

In summary, considering the different diagrams of SSTA (Fig. 3b) and low-level wind anomalies (Fig. 5c) between the co-occurrence and pure positive IOD, warming in the northwestern Indian Ocean could be primarily caused by relatively less latent heat loss from the ocean due to the reduced low-level wind speed associated with a warm ENSO event in the eastern Pacific. In addition, the vertical advection might also contribute to the warming along the east coast of Africa, as anomalous northerly wind in the co-occurrence would suppress the upwelling to favor a deepen thermocline there.

5. Summary and discussion

This paper investigates possible effects of a warm ENSO event on the warming in the northwestern Indian Ocean. By comparing the SSTA evolution between pure positive IOD events and the co-occurrences of a positive IOD and an El Niño event during the period 1960–2003, it is found that SSTA in the northwestern Indian Ocean has a close relationship with the NINO3 index. We further examine the differences of the low-level winds, the depth of the 20°C isotherm, and the latent heat flux into the ocean between the co-occurrence and pure positive IOD. Our results suggest that warming in the northwestern Indian Ocean during co-occurring years may be primarily caused by relatively less latent heat loss from the ocean due to reduced wind speed associated with the El Niño event. In addition, the deepened thermocline might also contribute to the warming along the east coast of Africa. However, in the central part of the southern Indian Ocean, the increased SSTA in the co-occurrence is neither consistent with the shallower thermocline nor with less latent heat flux into the local ocean. Venzke et al. (2000) suggested that anomalous winds could affect the SSTs in this region by changing the vertical mixing in the subsurface ocean and exciting Rossby waves.

As we mainly focus on the northwestern Indian Ocean, the data reliability in this region is very important. Therefore, only the datasets after the beginning of the satellite era (after 1960) are considered in this paper. According to the categories divided by Saji and Yamagata (2003b), pure positive IOD events after 1960 are 1961, 1967, 1977, 1983, and 1994, and co-occurrences of a positive IOD and a warm ENSO event are 1963, 1972, 1982, and 1997. Limited numbers of samples for composite analyses might be the reason why only a small region in the northwestern Indian Ocean exceeds the 95% confidence level. Additional data investigations or numerical simulations are therefore required to consolidate our results.

Further, pure positive IOD exhibits a west-east zonal mode, which seems not to be the typical pattern as introduced by Saji et al. (1999). By comparison, the typical dipole mode in the co-occurrence has the maximum positive SSTA in the northwestern Indian Ocean, associated with an El Niño event in the eastern Pacific. Their differences suggest a possible modulation effect by ENSO on the structure of the dipole mode in the tropical Indian Ocean. More analyses of the pure negative IOD and co-occurrence with a La Niña event would be the focus of future work.

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