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Two modes of dipole events in tropical Indian Ocean

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By analyzing the distributions of subsurface temperature and the surface wind stress anomalies in the tropical Pacific and Indian Oceans during the Indian Ocean Dipole (IOD) events, two major modes of the IOD and their formation mechanisms are revealed. (1) The subsurface temperature anomaly (STA) in the tropical Indian Ocean during the IOD events can be described as a “<” -shaped and west-east-oriented dipole pattern; in the east side of the “<” pattern, a notable tongue-like STA extends westward along the equator in the tropical eastern Indian Ocean; while in the west side of the “<” pattern, the STA has opposite sign with two centers (the southern one is stronger than the northern one in intensity) being of rough symmetry about the equator in the tropical mid-western Indian Ocean. (2) The IOD events are composed of two modes, which have similar spatial pattern but different temporal variabilities due to the large scale air-sea interactions within two independent systems. The first mode of the IOD event originates from the air-sea interaction on a scale of the tropical Pacific-Indian Ocean and coexists with ENSO. The second mode originates from the air-sea interaction on a scale of the tropical Indian Ocean and is closely associated with changes in the position and intensity of the Mascarene high pressure. The strong IOD event occurs when the two modes are in phase, and the IOD event weakens or disappears when the two modes are out of phase. Besides, the IOD events are normally strong when either of the two modes is strong. (3) The IOD event is caused by the abnormal wind stress forcing over the tropical Indian Ocean, which results in vertical transports, leading to the upwelling and pileup of seawater. This is the main dynamic processes resulting in the STA. When the anomalous easterly exists over the equatorial Indian Ocean, the cold waters upwell in the tropical eastern Indian Ocean while the warm waters pileup in the tropical western Indian Ocean, hence the thermocline in the tropical Indian Ocean is shallowed in the east and deepened in the west. The off-equator component due to the Coriolis force in the equatorial area causes the upwelling of cold waters and the shallowing of the equatorial India Ocean thermocline. On the other hand, the anomalous anticyclonic circulations and their curl fields located on both sides of the equator, cause the pileup of warm waters in the central area of their curl fields and the deepening of the equatorial Indian Ocean thermocline off the equator. The above three factors lead to the occurrence of positive phase IOD events. When anomalous westerly dominates over the tropical Indian Ocean, the dynamic processes are reversed, and the negative-phase IOD event occurs.

Indian Ocean Dipole modes, subsurface temperature anomaly, sea surface wind stress anomaly, formation mechanism

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The available observations and studies show that there exists the dipole phenomenon caused by seawater temperature anomalies in the India Ocean, which is similar to ENSO in the Pacific Ocean. The Indian Ocean Dipole (IOD) has significant influence on the Asian monsoon, the abnormality of atmospheric circulation and precipitation in monsoon regions. By analyzing sea surface temperature anomaly (SSTA) in the tropical Indian Ocean, Webster et al.[1] and Saji et al.[2] pointed out for the first time the existence of the IOD event in the equatorial Indian Ocean, which played important role in the climate abnormality around the India Ocean. He et al.[3] made a detailed analysis of the variability features of temperature anomaly in the tropical Indian Ocean. In view of the importance of the IOD event, a great amount of researches have been conducted into their spatio-temporal features and formation mechanism. Some researchers[4－8] believed that the IOD event was caused by atmospheric circulation anomaly over the tropical Indian Ocean induced by ENSO. While other researchers[1,2] emphasized that the IOD event, as a coupled ocean-atmosphere-land system being self-maintaining, was the phenomenon independent of ENSO.

The recent numerical simulations[9,10] indicated that the IOD event had occurred even without the existence of the ENSO event. Up to the present, no conclusion about the evolution and formation mechanism of the IOD event has been come to yet.

As a matter of fact, however, SSTA is only the apparent form of the IOD event at the sea surface, and it is greatly influenced by heat flux through the air-sea interface. As shown by the observations, the variation of thermocline depth is an optimum index for studying the IOD. However, due to the lack of the observed ocean data, the analysis of the ocean subsurface layer is still less. With the increase of understanding the thermocline role and the accumulation of ocean data, advances[11, 12] are being achieved in the study of the Indian Ocean thermocline. On the basis of analyzing the interannual variability of the subsurface temperature, the sea surface wind stress and their relationship in the tropical Pacific-Indian Ocean during the IOD event, this paper gains a deeper insight into the evolution of IOD events and discusses their formation mechanism, in order to improve abilities of the IOD event prediction.

1 Data and Methods

Owing to lack of the long term ocean data observed in the study area, the SODA monthly mean data and sea surface wind stress data provided by Carton et al.[13] are employed in this study. The data set covers the area 60°S to 60°N, 0°E to 360°E during January 1950 to December 2000, with a time interval of one month. There are 20 layers of data in the vertical. The available data set includes data of the surface wind stress and the ocean temperature data in the tropical Pacific and Indian Oceans from 30°S to 30°N within 500 m in 14 layers, covering 600 months from January 1951 to December 2000.

Chao et al.[14] used the curved surface formed by the depths of the maximum STA(MSTA) instead of the climate thermocline surface. Recently, Qian et al.[15] pointed out that the MSTA could well describe the thermocline depth variation and be a better factor than SSTA in controlling climate variability, because it could memorize the air-sea interaction variation and store ocean energy in the upper layer. Based on the above results and temperature data, we calculate the climate thermocline surface and the temperature anomaly over it, as an index of thermocline depth anomaly (TCA) to characterize STA. The subsurface temperature increase when the thermocline deepens, and vice versa.

The previous observations and researches indicated that there were remarkable interannual and interdecadal variabilities in the Indian Ocean temperature. Therefore, in order to study the main IOD features of interannual variability, firstly the annual, interdecadal and longer periods of variations should be removed from the above data. To do so, a 1－8 year band pass filter were used to obtain the TCA interannual variability. Then an EOF analysis of it was made. No doubt, the long-term trend was also eliminated after filtering. A similar process was carried out for the surface wind stress anomaly data.

2 Basic features of STA during the IOD event

Figure 1 shows the spatio-temporal distributions of the first two modes of the TCA interannual variability in the tropical Indian Ocean. It can be seen from Figure 1 that the first mode shows a typical dipole distribution which accounts for 29.4% of the total variance. The STA in the tropical Indian Ocean behaves like a “<”-shaped and west-east-oriented dipole pattern with the equator as its axis. The “<” pattern intersects the equator at 70°－75°E, from which it extends southeastward at an angle of

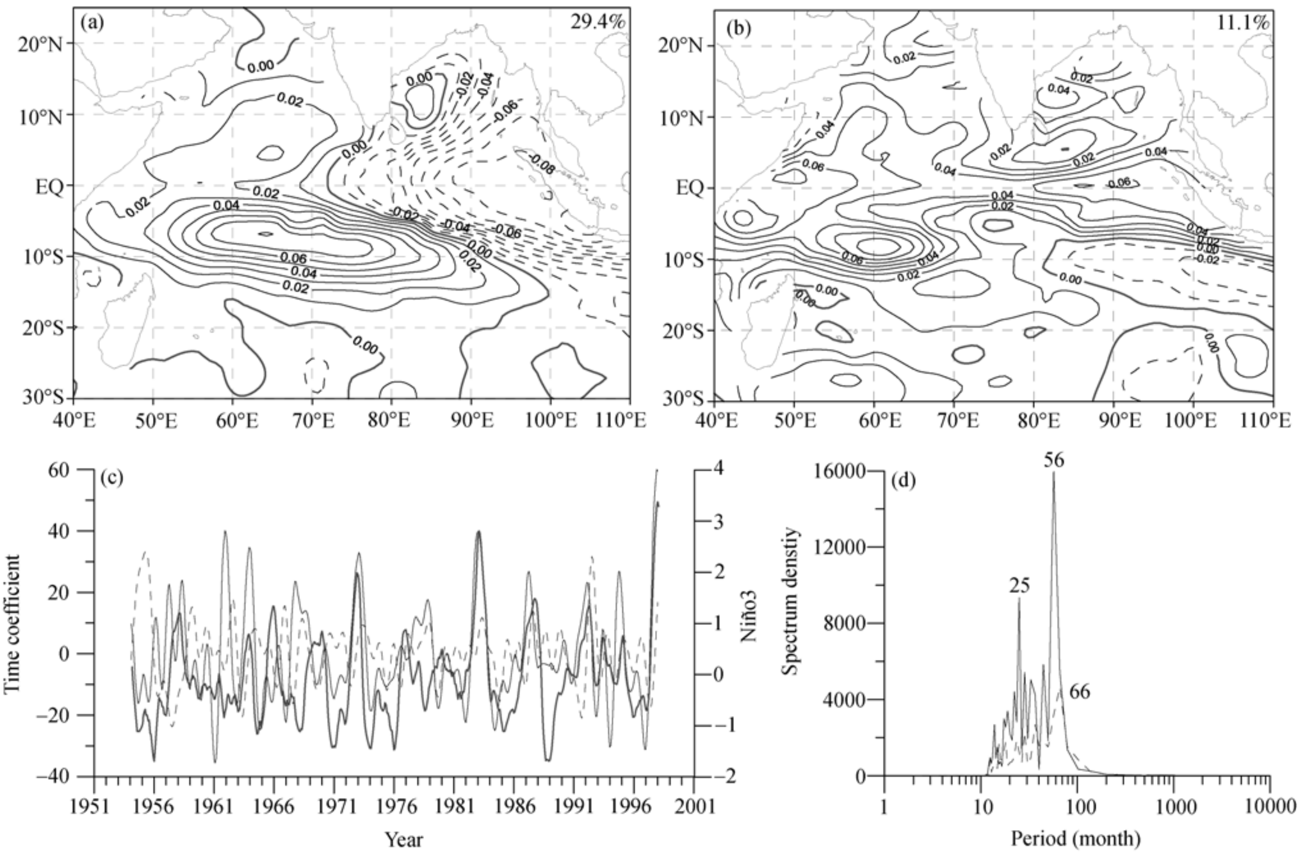

Figure 1 Spatio-Temporal distributions of the first (a) and second (b) modes of the interannual variability of the thermocline depth anomalies in the tropical Indian Ocean (solid and dashed lines denote positive and negative values, respectively, contour interval is 0.01℃), corresponding time coefficients (c) and spectra analysis results (d) (solid and dashed lines denote the first and second modes, respectively; thick solid line in (c) denotes the Niño3 index).

30° and northeastward at an angle of 45°, respectively, until it reaches 15°S and 15°N. In an area east of the “<” pattern in the tropical eastern Indian Ocean, a larger TCA region with its center off the west coast of Indonesia shows a tongue-like extension going westward along the equator, while in the tropical mid-western Indian Ocean west of the “<” pattern, there are two TCA centers which have large magnitude and opposite signs to those east of the “<” pattern and are rough symmetrical with respect to the equator. The large TCA center south to the equator is larger than that north to the equator in both region and magnitude, and the latter crosses the Indian Peninsula and extends northeastward in the Bay of Bengal. Generally, the IOD event in the tropical Indian Ocean shows the east-west difference of the STA; however, in reality, it implies the difference of STA between the tropical eastern Indian Ocean and the tropical southwestern Indian Ocean. The STA is slightly larger in order of magnitude in the tropical eastern Indian Ocean than that in the tropical western Indian Ocean. And, their time coefficients which have the ENSO period of 56 months and the quasi-biennial period 25 months, which are relatively well correlated with the Niño3 index (r=0.57). A detailed analysis of the time coefficients of the first eigenvector field and the Niño3 curve reveals that in some years both of them are in phase or nearly in phase, for example, in 1963, 1972/1973, 1982/1983, 1986/1987, 1991/1992, 1994 and 1997/1998, the El Niño event occurred, and in 1964, 1970, 1973/1974, 1984/1985 and 1995/1996, the La Niña event occurred, and in some other years they were out of phase, such as in 1965, 1968/1969 and 1978/1979. In some years, such as in 1960, 1961 and 1967, only the strong IOD events happened. The above relationship indicates that the IOD event has, to some extent, correlation to ENSO but keeps its own behavior. The second eigenvector field accounts for 11.1% of the total variance, which is much smaller than the contribution of the IOD event. Its spatial distribution is featured by the fact that its eigenvalues are of the same sign over the entire area (except for the area in the southeast of the tropical Indian Ocean) with the equator as its symmetrical axis. Its time coefficients have a long-term variation of 66 months, and it was well correlated to the IOD (r=0.41%) with a lag of six month, especially since the 1980s. This eigenvector field has no significant simultaneous correlation with Niño 3 index, but has a correlation of −0.34 with the 5-month lag Niño 3. Thus it can be seen that there indeed exists an obvious IOD type STA distribution in the tropical Indian Ocean, which not only was a result of the influence of ENSO, but might also be related to some local air-sea coupled system in the Indian Ocean.

According to the definition of Saji et al.[2], the DMI index, which is the difference of SSTA between the tropical western Indian Ocean (10°S—10°N, 50°—70°E) and the tropical eastern Indian Ocean (10°S—0°, 90°—110°E), can be used to represent the interannual variability of the IOD event. By comparison, the variability of the DMI is basically in agreement with that of the first mode of the TCA in the present study. Taking the positive phase IOD events in 1961/1962, 1963/1964, 1967/1968, 1972/1973, 1982/1983, 1986/1987, 1991/1992, 1994 and 1997/1998, and the negative phase IOD events in 1960/1961, 1964, 1984, 1991/1992 and 1996/1997 for example, both of them appeared at the same or nearly the same times. A correlation analysis shows that the zero-lag correlation coefficient between the DMI index and the first mode of TCA is 0.62 and the two-month lag correlation coefficient is 0.69, which is the largest, implying that the evolution of the IOD event in the surface and subsurface is basically simultaneous, with its evolution in the surface leading that in the subsurface by two months.

3 Two modes of IOD

The available observations show that most of the IOD events are accompanied by the ENSO events. Obviously, they are under the same large scale air-sea coupled system. Therefore, an EOF analysis of the TCA index was made in the tropical Pacific-Indian Oceans. The results showed that the first eigenvector field of the TCA in the tropical Pacific-Indian Oceans (Figure 2(a)) had the following features. In the tropical Pacific, the spatial distribution of the TCA was the typical ENSO one, which showed a dipole-type distribution in the east-west direction with 160°W as its meridional axis. In the tropical Indian Ocean, the spatial distribution of the TCA was the typical IOD one, i.e., one pole located at the east of the "<" pattern in the tropical eastern Indian Ocean and the other at the west of the "<" pattern in the tropical mid-western Indian Ocean. Compared with the typical dipole distribution (Figure 1(a)), both of them are generally in agreement except that the STA in the north of the tropical mid-western Indian Ocean are slightly smaller. The time coefficients reflect the evolution of the ENSO events, and there is a one-to-one correspondence between the IOD events and nearly all the ENSO events that occurred during the past over forty years (Figure 2(c)). The EI Niño events in 1963, 1965, 1968/1969, 1972/1973, 1976, 1982/1983, 1986/1987, 1991/1992, 1993, 1994/1995 and 1997/1998 and the La Niña events in 1964, 1967/1968, 1970/1971, 1973/1974, 1975/1976, 1984/1985, 1988/1989, 1995/1996 and 1998 are all displayed by in the time coefficients of the eigenvector field. This mode is generally called the ENSO mode, which has two significant periods: 56 and 44 months (Figure 2(d)). The Indian Ocean part of the mode is named the first mode or the ENSO mode of the IOD event; the Pacific Ocean part of the mode is named the first mode of ENSO. The main eigenvectors of the second mode of the TCA in the tropical Pacific-Indian Oceans appear in the tropical Pacific Ocean, while those of the third mode appear in the Indian Ocean (Figures omitted). This indicates clearly that the local air-sea coupled system makes a major contribution to the secondary TCA. For this reason we removed the effect of the first mode from the TCA in the tropical Pacific-Indian Oceans, i. e., removed the contribution of the ENSO event from the TCA, and then made an EOF analysis of the TCA in the tropical Pacific Ocean and the tropical Indian Ocean, respectively. The results showed that after removal of the ENSO event signal, the first mode in the tropical Pacific Ocean showed a north-south seesaw-like distribution with its horizontal axis at 6°—8°N (see the area of the tropical Pacific Ocean in Figure 2(b)). Its time coefficients were best correlated with the first mode when there was an eight to nine month delay (r=0.78) and it had two significant periods: 56 and 44 months (Figure 2(d)), which is so called the second mode of ENSO. A research[16] pointed out that it was a combination of these two modes of the ENSO event that constituted an EI Niño/La Niña cycle. After removal of the ENSO signal, the spatial distribution of the first mode in the tropical Indian Ocean (see the area of the tropical Indian Ocean in Figure 2(b)) is extremely similar to that of a typical dipole (Figure 1(a)), with its spa-

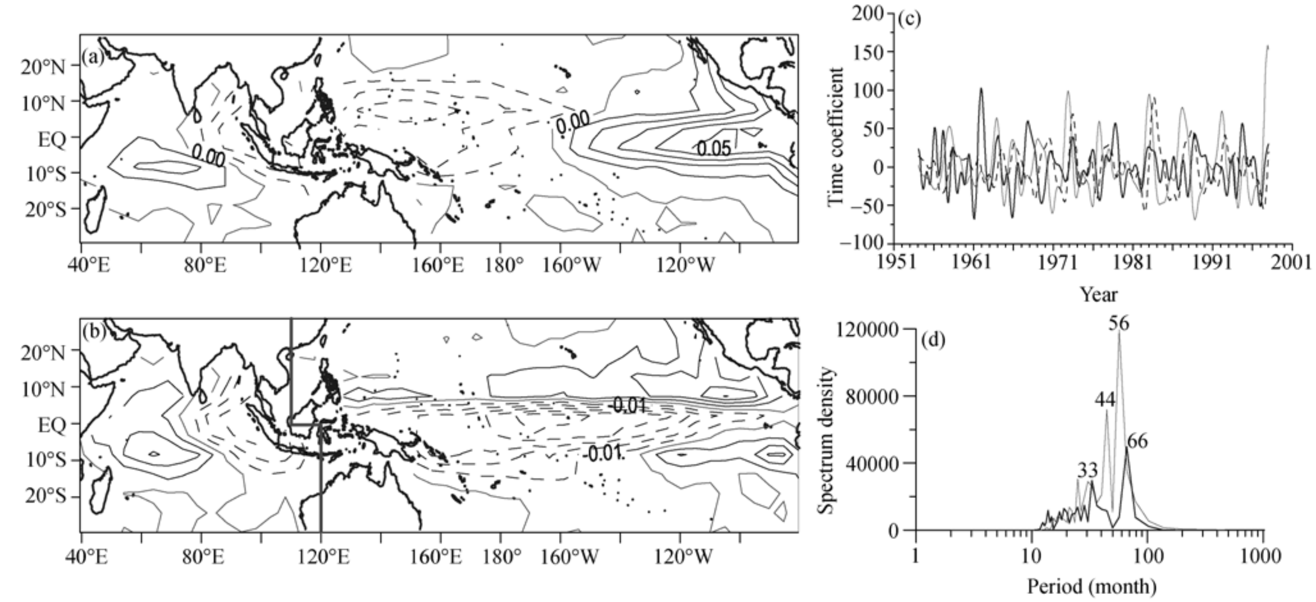

Figure 2 Spatio-temporal distributions of the first mode with ENSO (a) and the second mode without ENSO (b) of the interannual TCA variability in the tropical Indian-Pacific Oceans (solid and dashed lines denote positive and negative values, respectively, contour interval is 0.01℃), their corresponding time coefficients (c) and spectra (d) (thin solid line indicates the first mode, thick solid line, the second mode in the tropical Indian Ocean and dashed line in (c), the second mode in the tropical Pacific Ocean).

tial correlation coefficient being 0.90. Compared with the spatial distribution of the first mode of IOD, the TCA north of the equator is more remarkable in the tropical mid-western Indian Ocean west of the "<" pattern . Its time coefficients have little correlation with the first mode of IOD, indicating that this mode, so called the second mode of the IOD, is completely independent of the large scale tropical Pacific-Indian Ocean air-sea coupled system. A spectral analysis showed that the second mode of the IOD had the following two significant periods: 66 and 33 months, which were remarkably different from the variability of ENSO. From the eigenvector fields and their time coefficients of the two modes of IOD event we calculated their contributions to the total variance, which were found to be 26.2% and 23.6%, i. e. they had the same order of magnitude, with the first mode contributing slightly more. A detailed comparison between the time evolution curves of the IOD event (Figure 1) and its two modes (Figure 2) reveals that, the IOD event is remarkably strong when the temporal variabilities of the two modes are in phase, and it is very weak or disappears when the two are out of phase. When one mode is strong enough and the other is weak, the IOD event only reflects the strong one. Obviously, the occurrence of an IOD event is associated with a combination of the two modes mentioned above. What interests us most is, the occurrence of an ENSO cycle is caused by the combination of two modes in the tropical Pacific STA with different spatial distributions but the same type of temporal variabilities, while that of the IOD event is caused by the combination of two modes in the tropical Indian STA with the same type of spatial distributions but different temporal variability.

From the time coefficients of the second mode of IOD event shown in Figure 2, it can be seen that after removal of the ENSO signal there were 9 stronger IOD modes in the tropical Indian Ocean with positive phases, which occurred in 1961/1962, 1963/1964, 1967/1968, 1972/1973, 1982/1983, 1986/1987, 1992, 1994/1995 and 1997/1998, and 8 stronger IOD modes with negative phases, which occurred in 1960/1961, 1964, 1966/1967, 1981, 1984, 1992/1993, 1993/1994 and 1996/1997. During these periods there occurred 11 El Niño events in 1963, 1965, 1968, 1972/1973, 1976, 1982/1983, 1986/1987, 1991/1992, 1993, 1994/1995 and 1997/1998 and 8 La Niña events in 1964, 1967/1968, 1970/1971, 1973/1974, 1975/1976, 1984/1985, 1988/1989 and 1995/1996, respectively. These El Niño and La Niña events led to the formation of stronger IOD modes with positive or negative phases respectively, in which the two modes constituted the interannual variability of the IOD event in the Indian Ocean. By using the first TCA eigenvector field in the tropical Pacific-Indian Ocean, the first TCA eigenvector field in the tropical Pacific and in the Indian Oceans after removal of the ENSO, and their corresponding time coefficients, the recovery fields of interannual TCA variabilities of IOD events in the tropical Indian Ocean were obtained. Figure 3 shows the TCA evolution processes in the tropical Indian Ocean and tropical Pacific Ocean during the three strong IOD events with positive phases in the tropical Indian Ocean. It can be seen from the Figure 3 that in 1961, a strong IOD event with positive phases started in June, whose early stage was a strong IOD event having negative phases in 1960/1961. In August 1961 there occurred an east-west "<" pattern IOD distribution in the tropical Indian Ocean, with a significant negative TCA anomaly center east of the "<" pattern in the tropical eastern Indian Ocean, which as a cold tongue extended westward along the equator,, and a significant positive TCA anomaly area west of the "<" pattern in the tropical mid-western Indian Ocean, with two positive centers on both sides of the equator, one of which on the south side was stronger, when a typical IOD distribution with positive phase took place in the tropical Indian Ocean. This IOD event reached its peak in November 1961, when the extremes of the positive and negative anomaly centers in the Indian Ocean were +3.0℃ and −3.5℃, respectively. After this, the IOD weakened rapidly and disappeared in June 1962. Meanwhile the tropical Pacific Ocean was in a normal state at this period. This IOD event was mainly determined by the second mode of the IOD in the tropical Indian Ocean. The IOD event in 1994 started in May and ended in March 1995. It reached the strongest in October 1994, with its extreme of −2.0℃ as the negative anomaly center in the tropical eastern Indian Ocean, and its corresponding positive anomaly of +2.0℃ located at the south of the tropical mid-western Indian Ocean. Its spatial distribution was also a typical IOD distribution, accompanied by a very weak EI Niño event in the tropical Pacific Ocean. This IOD event was caused by the combined effects of the local air-sea interaction in the tropical Indian Ocean and the ENSO event. The 1997/1998 IOD event mainly originates from a strong EI Niño event, although a weak IOD of positive phase could also be generated by local air-sea interaction in the tropical Indian Ocean. This event started in April 1997 and ended in July 1998. It reached its peak period in November 1997, when the extremes of the positive and negative anomaly centers were +4.5℃ and −5.0℃, respectively, which were the largest one of all IOD events. At this time, there was a large area of the warm pool in the tropical western Pacific and tropical eastern Indian Ocean which was of significant negative TCA anomalies while there was a large area of significant positive TCA anomalies in the tropical mid-western Indian Ocean (south of the equator in particular) and the tropical eastern Pacific Oceans, which showed the large-scale air-sea interaction in the tropical Pacific-Indian Ocean.

From the above analysis we can draw the following conclusion that the IOD event is essentially composed of two independent modes, one being related to ENSO and the other being closely associated with the Indian Ocean local air-sea system. The two modes share the same spatial distributions but have different interannual variabilties.

4 Surface abnormal wind stress field during the IOD event and its forcing on the thermocline depth anomaly

The above analysis indicates that the IOD is in fact the result of air-sea interaction in the tropical Pacific Ocean and the tropical Indian Ocean. In virtue of this, we regarded the ocean and the atmosphere as a coupled system and carries out a joint EOF analysis of the TCA and the surface wind stress anomaly (WSA) field in the tropical Indian Ocean, from which the main IOD modes of the air-sea coupled system were obtained. Considering that the first mode of the IOD event is chiefly the oceanic phenomena generated in the air-sea coupled system of the tropical Indian Ocean and tropical Pacific Ocean scales, and the second mode of the IOD event is chiefly the oceanic phenomena generated in the local air-sea coupled system of the tropical Indian Ocean. Therefore, an EOF analysis was made of the TCA and WSA in the tropical Pacific-Indian Ocean, and the TCA after removal of the ENSO signal and the WSA in the tropical Indian Ocean, respectively. Figure 4 shows the distributions of the first modes of the TCA and WSA in the tropical Pacific-Indian Ocean, and the distributions of the first modes of TCA and WSA after removal of the ENSO signal in the tropical Indian Ocean, in which the former accounts for 23.4% of the total variance, and the latter 13.0%. Compared with the two TCA modes shown in Figure 2, they are very much in agreement with their corresponding counterparts in either spatial distribution or temporal variability, which further confirmed that the two modes of the IOD event indeed resulted from air-sea

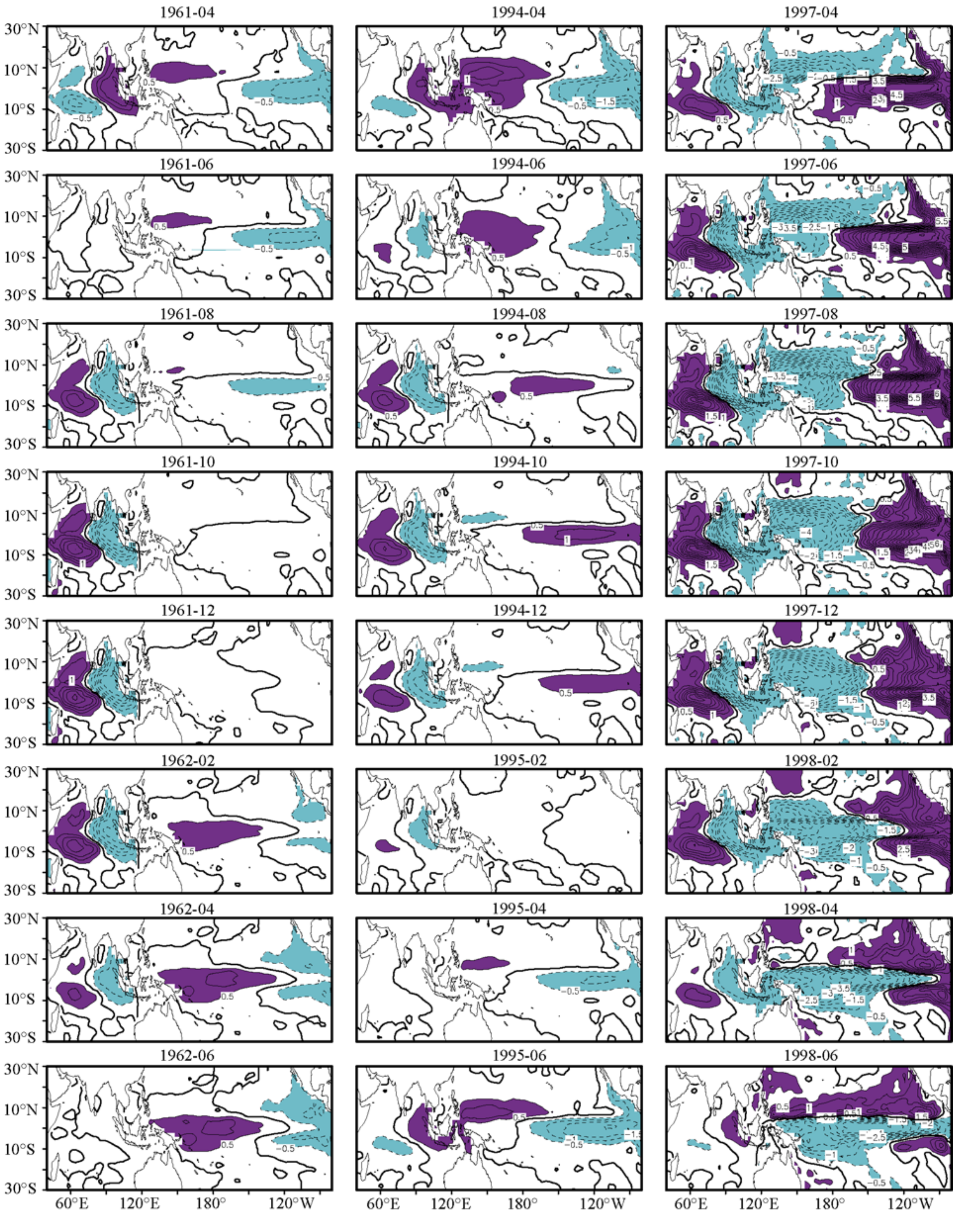

Figure 3 A TCA evolution processes in the tropical Pacific-Indian Ocean during three strong positive phase IOD events (Left: in 1961, middle: in 1994, right: in 1997, solid and dashed lines show positive and negative values, respectively, contour interval is 0.5℃, purplish red shaded areas denote their temperature of ≥+0.5℃, and blue shaded areas, those of ≤−0.5℃).

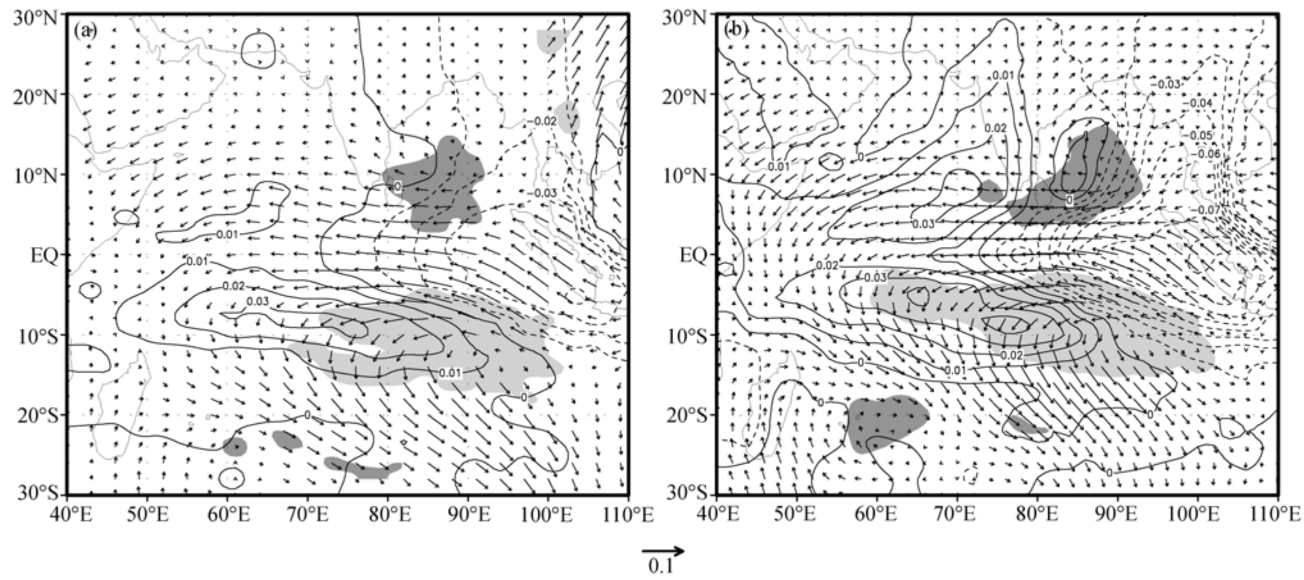

Figure 4 Distributions of TCA and corresponding WSA of the two modes of the tropical IOD event (solid and dashed lines denote the positive and negative values, respectively, the contour interval is 0.01℃) and corresponding surface wind stress anomalies (vectors mark abnormal wind stresses, (10^{-1} N/m^2 in the unit); the shading denotes abnormal wind stress curls; in the southern hemisphere light shading ($\geqslant 0.1\times10^{-8}$ N/m^3) indicates abnormal anticyclonic curls, and dark shading ($\leqslant -0.1\times10^{-8}$ N/m^3), abnormal cyclonic curls. The opposite is true for the northern hemisphere of two modes (Left: the first mode; right: the second mode).

interactions of the tropical Indian-Pacific Ocean scale and of the Indian Ocean local scale, respectively. A detailed comparison between the spatial distribution types of the eigenvector fields of the first and second modes of WSA in the tropical Indian Ocean reveals that the two are much the same with only minor differences. As far as positive phase IOD events are concerned, the two modes have the following common features: there are abnormal southeast trade winds in the tropical southeastern Indian Ocean, the strong abnormal easterly in the equatorial eastern Indian Ocean and tropical midwestern Indian Ocean, relatively strong and noticeable abnormal anticyclonic circulation and a corresponding curl center south of the equator in the tropical Indian Ocean, and a relatively weak abnormal anticyclone and corresponding curl center north of the equator in the Bay of Bengal. Their differences are as follows, compared to the WSAs of the first mode, its second mode is more northward, thus the abnormal easterly north of the equator are stronger, and the abnormal anticyclone north of the equator in the Bay of Bengal is more noticeable, making the second mode more symmetrical with respect to the equator than that of the first mode. The abnormality of the surface wind stress fields is completely reversed for the negative phase IOD events. Hence it can be seen that the surface abnormal wind stress fields over the Indian Ocean were basically the same, whether the IOD event resulted from air-sea coupled systems of the tropical Indian -Pacific Ocean scale or of only the tropical Indian Ocean scale. And this is the dynamic cause that the tropical Indian Ocean STA resulted from two independent air-sea systems, have the same spatial pattern.

In order to further understand the features of surface abnormal wind stress during IOD events and its forced action on the TCA, the TCA and WSA distributions are given here for the peak periods of strong IOD events resulted from air-sea coupled systems in the tropical Indian Ocean and the tropical Pacific-Indian Ocean, respectively. In 1960/1961 the IOD event was strong with negative phase, and in 1961/1962 it was strong with positive phase. However, no ENSO occurred in the tropical Pacific Ocean during the two IOD events, which were mainly determined by the second IOD mode (upper panel in Figure 5). Fisher at al.[9] pointed out that it was closely associated with the trade wind anomaly induced by the variations in position and intensity of the Mascarene high Pressure in the southern Indian Ocean. In 1995/1996, a La Niña event occurred in the tropical Pacific Ocean, and a negative phase IOD event in the tropical Indian Ocean; in 1997/1998 a strong EI Niño event occurred in the tropical Pacific Ocean and a strong positive phase IOD event in the tropical Indian Ocean. During the same period the IOD event was mainly determined by the first IOD mode (lower panel in Figure 5) when the second IOD mode occurred locally in the Indian Ocean was relatively weak. The previous studies[4−8] showed that this was closely related to the zonal wind anomaly of the Indian Ocean caused by ENSO. The 1960/1961 negative phase IOD event started in June 1960 and ended in June 1961, reaching its peak in December 1960, when a positive STA anomaly center of +2.5℃ occurred in the tropical eastern Indian Ocean, extending westward along the equator as a tongue-like distribution and the negative STA regions were −1.0℃ located on both sides off the equator in the tropical mid-western Indian Ocean, and the STA region south of the equator was much larger than that in the north. At the same time the surface wind stress anomaly field had the following features, i.e., the abnormal westerly appeared in the equatorial Indian Ocean and the abnormal cyclonic circulation and its corresponding cyclonic curl fields took place on both sides of the equator in the tropical Indian Ocean. The south and north curl centers off the equator were located in the tropical mid-eastern Indian Ocean and in the Bay of Bengal respectively, but the latter was weaker. The positive phase IOD event in 1961/1962 started in June 1961 and ended in June 1962, reaching its peak in November 1961, when there was a negative STA center (−3.0℃) in the tropical eastern In-

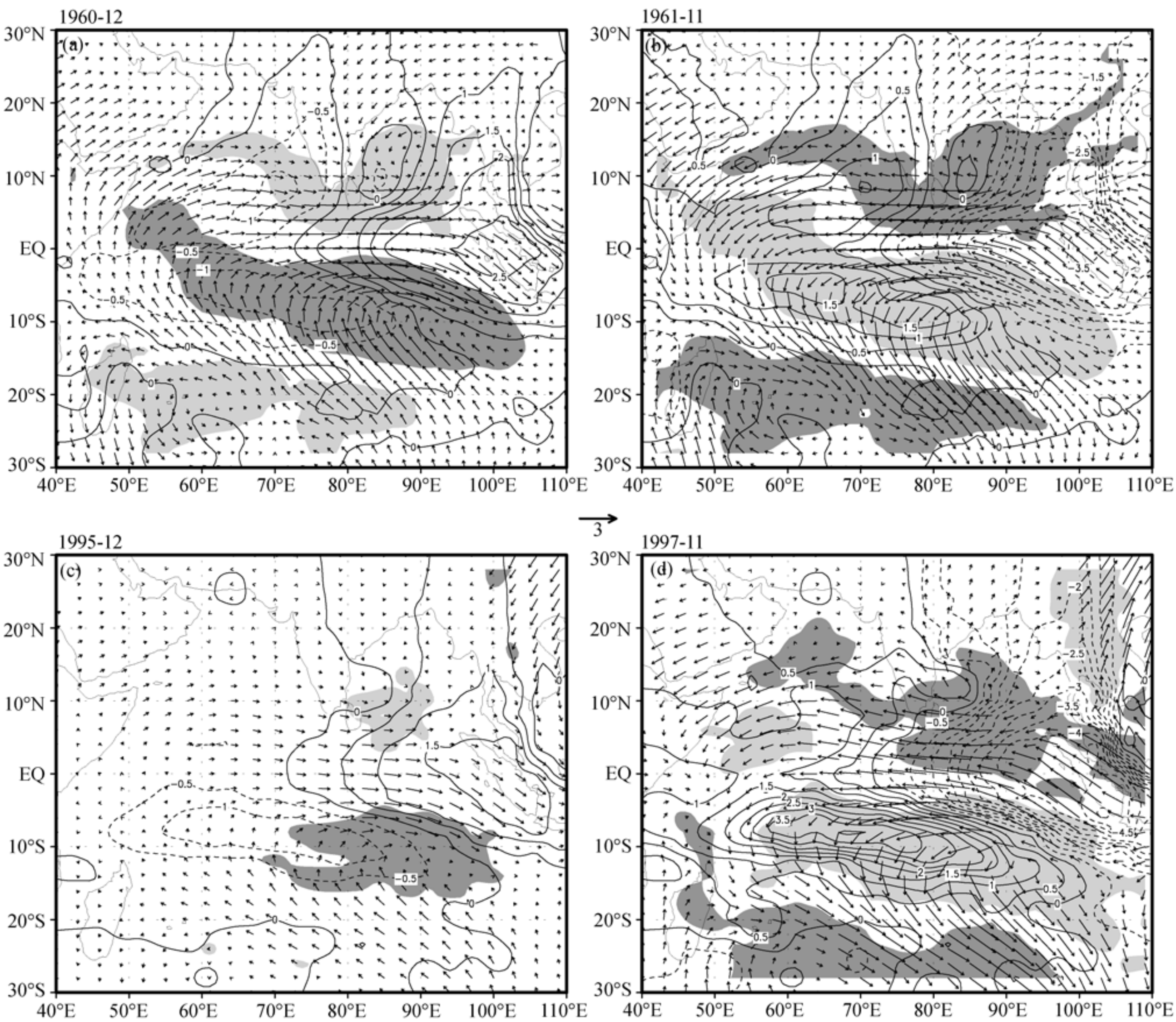

Figure 5 Distributions of the TCA and the WSA in the tropical Indian Ocean during the peak periods of the strong positive and negative phase IOD events (isolines indicate the STA, solid and dashed lines denote positive and negative values, respectively, contour interval is 0.5℃ and vectors mark abnormal surface stresses (unit: 10^{-1} N/m^2), shading shows the abnormal wind stress curls; in the southern hemisphere light shading (⩾10.0×10^{-8} N/m^3) shows abnormal anticyclonic curls and dark shading (⩽-10.0×10^{-8} N/m^3), the abnormal cyclonic curls. The opposite is true for the northern hemisphere.

dian Ocean extending westward along the equator as a tongue-like distribution, and there were several regions of positive STA in the tropical mid-western Indian Ocean with positive centers on both sides of the equator, in which the south one had large range of greater than +1.5℃; the north one had larger range of +1.0℃; and the other one reaching +0.5℃ in the Bay of Bengal. The surface wind stress anomaly field at this period was exactly opposite to that in December 1960. By comparing the two negative phase IOD events occurred in December 1995 and in December 1960, it can be seen that their STA were similar, i.e. both of them had significant positive STA centers in the tropical eastern Indian Ocean, and negative one centers with the equator as the rough symmetrical axis in the tropical mid-western Indian Ocean, except that in December 1995 the negative center north of the equator in the tropical mid-western Indian Ocean was weaker than that of the south. Both of the surface wind stress anomaly fields were very similar their abnormal westerly in the equatorial Indian Ocean, their abnormal cyclonic circulations and corresponding curl centers south of the equator in the tropical mid-eastern Indian Ocean and north of the equator in the Bay of Bengal, except that in December 1995 the abnormal cyclonic circulation in the Bay of Bengal was slightly weaker. In 1997/1998 an extremely strong El Niño event occurred, which triggered off a strong positive phase IOD event in the Indian Ocean, and reached its peak in November 1997, when the negative STA in the tropical eastern Indian Ocean reached –4.5℃ and the positive one south of the equator in the tropical mid-western Indian Ocean reached +3.5℃. Compared with the positive phase IOD event in December 1961, in the 1997 event, its intensity was stronger, also the positive STA center north of the equator in the tropical mid-western Indian Ocean in November 1997 was weaker in intensity, more to the west in location, and less symmetrical with respect to the equator, and the abnormal anticyclonic circulation north of the equator in the Bay of Bengal at this time was relatively weak and so was the Indian Southwestern Monsoon.

Concerning the formation mechanism of IOD events, so far, most of the present researches are on the basis of wave theories. Fischer et al.[9] suggested that abnormal easterly over the equator should trigger the cold Kelvin waves propagating eastward along the equator, that rapidly should reach the Sumatra coast and extend northward and southward as a coastal Kelvin wave, reducing the depth of thermocline and decreasing SSTs on the equator and the eastern boundary and propagating westward into interior as a Rossby wave, the reduction of SSTs should further inhibit convection and precipitation in the tropical southeastern Indian Ocean, the latter might bring about the dynamical Matsuno-Gill atmospheric response with a westward displaced abnormal anticyclones including an easterly equatorial component over the Indian Ocean, which eventually could develop into a positive phase IOD event. Xie et al.[17], Qian et al.[18] and Li et al.[19] proposed that the positive STA in the tropical western Indian Ocean was caused by the westward propagation of the positive STA (a signal of thermocline deepening) in the eastern Indian Ocean, which was induced by Rossby waves excited by the equatorial easterly. Differing from above opinions, Wang el al.[20] argued that the anomalies of heat contents in the tropical eastern Indian Ocean had been proved as advection from the tropical western Pacific through the Indonesian Throughflow during the 1997/1998 El Niño event. Viewing from the facts revealed by this study, however, it is found that the IOD is more like an east-west seesaw oscillation phenomenon of the STA induced by surface abnormal wind stress forcing. Recently Li et al.[21] made a numerical study of the occurrence and evolution of the IOD and pointed out that the main dynamic cause of the generation and development of the IOD was the abnormal circulation structure induced by surface abnormal easterly in the equatorial Indian Ocean, that the main dynamic cause of its evanescence was the change of abnormal easterly into abnormal westerly, and that the main physical mechanism of the IOD mode generation and evolution was its vertical transport effect. According to the distributions of surface abnormal wind stress fields, there are abnormal easterly (westerly) and abnormal anticyclonic (cyclonic) circulations in the tropical Indian Ocean off the equator in the range of 60° to 105°E during the positive (negative) phase IOD events, in which the STA intensity to the south is significantly larger than that to the north. The above surface abnormal wind stress in the tropical Indian Ocean and the Indian Ocean Basin topography show that, when there exist abnormal easterly over the equator, the off-coast winds in the tropical eastern Indian Ocean will cause the cold water upwelling, the thermocline ascent and the subsurface temperature decrease, meanwhile the shoreward winds in the tropical western Indian Ocean will cause warm water pileup, the thermocline descent and the subsurface temperature increase, leading to the thermocline deeper in the west and shallower in the east in the tropical Indian Ocean. Due to the action of the Coriolis force, the off-equator flow induced by abnormal easterly along the equator causes the cold water upwelling in the equatorial area, the thermocline ascent and the subsurface temperature decrease, leading to shallow the thermocline in the equatorial Indian Ocean; at the same time, the abnormal anticyclonic circulations and its corresponding curl fields on both sides of the equator in the tropical Indian Ocean will cause the warm water pileup in the central areas of the abnormal curl fields, the thermocline descent and the subsurface temperature increase, leading to deepening the thermocline in the tropical off-equator area, especially in the tropical mid-eastern Indian Ocean. Under the combined action of the above three factors, a “<” pattern of STA will take place in the tropical Indian Ocean, which is negative in the east and positive in the west. Because the surface abnormal wind stress is stronger in the south of the equator than that in the north of it, the STA in the tropical mid-western Indian Ocean appears to be of rough symmetrical distribution, in which it is stronger in the south than that in the north. Therefore, the basic pattern of the IOD is determined by the thermocline deeper in the west and shallower in the east in the tropical Indian Ocean, the shallowing of the thermocline in the equatorial area will cause the negative STA as a tongue-like distribution extending westward in the tropical eastern Indian Ocean and the positive STA should be weaker along the equatorial area and stronger in the off-equator area, furthermore, the deepening of the thermocline in the tropical Indian Ocean off the equator will be the main cause for the “<” pattern of STA in the tropical Indian Ocean, and the abnormal surface wind stress on both sides of the equator, which is stronger in the south and weaker in the north, and should lead to the rough symmetry with respect to the equator of the STA in the tropical mid-western Indian Ocean. During the negative phase IOD events, the action of the three factors are exactly opposite, and their combined actions will lead to the STA distribution in the tropical Indian Ocean being opposite to the above discussed. Figure 6 presents a block diagram showing the formation mechanism of the IOD event in the Indian Ocean, illustrating the dynamic processes of their generation. From Figure 6 it can be seen that the IOD event in the Indian Ocean are, in fact, the result of the forcing of surface abnormal wind stress in the tropical Indian Ocean, leading to a “<” seesaw

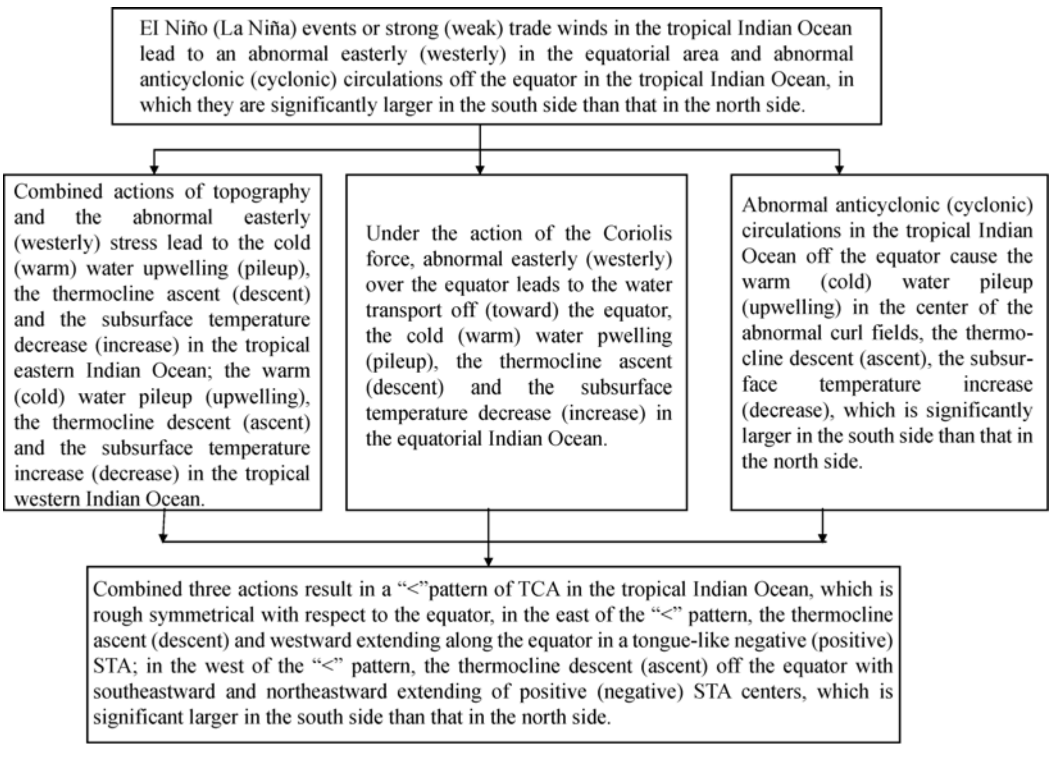

Figure 6 Dynamic processes of the formation of IOD events in the tropical Indian Ocean.

pattern of STA in an area between the tropical eastern Indian Ocean and the tropical mid-western Indian Ocean, and the phase change (from positive to negative and vice versa) being controlled by the interannual variability of the surface abnormal wind stress.

5 Discussion and conclusions

Since the discovery of the IOD event, many ideas of its generation have been proposed. Some of them suggested that IOD events be due to air-sea interactions in the Indian Ocean, and others hold the opinion that IOD events are caused by the ENSO event in the tropical Pacific Ocean. The recent numerical studies however, showed that, there were two mechanisms of triggering the IOD event formation. One is that the IOD event can be caused by the Walker circulation induced by ENSO, the other is that it can be caused by the trade wind anomaly in the tropical Indian Ocean, which is induced by the Mascarene high anomaly in the southern Indian Ocean. This indicates that the IOD event should be generated by the interaction of two independent air-sea systems, one having a scale of the tropical Pacific-Indian Ocean, and the other, that of the tropical Indian Ocean. The former is closely related to ENSO, while the latter is associated with the Mascarene high anomaly, each of which can bring about the IOD mode in the tropical Indian Ocean, which has the same spatial distributions but different temporal variabilities and whose combined effects should give rise to the IOD event. It explains why the IOD events happened in most of the ENSO years, also, no the IOD event happened in some other ENSO years and the IOD events appeared in some no ENSO years.

A detailed analysis reveals that the surface abnormal wind stress fields corresponding to the two IOD modes are different, especially in the Indian subcontinent and in the region of the Bay of Bengal. The intensity of the abnormal cyclonic or anticyclonic circulation in this region is significantly stronger in the second mode than the first mode in the tropical Indian Ocean. Although both modes lead to the IOD event, their influence on the climate in the South Asia area may be different. As the IOD event is composed of two IOD modes independent of each other, both the ENSO event and the trade wind anomaly in the Indian Ocean should be taken into consideration in making the IOD event prediction. In fact, the above factors cause some difficulties in predicting the IOD events and their influence on the climate.

To summarize, the following preliminary conclusions can be arrived at, based on the present study.

(1) The STA in the tropical Indian Ocean during the IOD event can be described as a “<”-shaped and west-east-oriented dipole pattern.

(2) The IOD event is composed of two modes, which have similar spatial patterns but different temporal variabilities due to the large scale air-sea interactions within two independent systems.

(3) The IOD event can be caused by the abnormal wind stress forcing over the tropical Indian Ocean surface, which results in vertical transports, leading to the pileup and upwelling of seawater. When the anomalous easterly exists over the equatorial Indian Ocean, the cold waters upwell in the tropical eastern Indian Ocean while the warm waters pileup in the tropical western Indian Ocean, hence the thermocline in the tropical Indian Ocean is shallowed in the east and deepened in the west. The off-equator component due to the Coriolis force in the equatorial area causes the upwelling of cold waters and the shallowing of the equatorial India Ocean thermocline. On the other hand, the anomalous anticyclonic circulations and their curl fields located on both sides of equator can cause the pileup of warm water in central area of the curl field and the deepening of the equatorial Indian Ocean thermocline off the equator. The combination of the three factors mentioned above leads to the occurrence of positive phase IOD event. When anomalous westerly dominates over the tropical Indian Ocean, the dynamic processes should be reversed, and the negative-phase IOD event can occur.

The conclusions drawn from this study are preliminary. The further dynamic analyses and numerical simulations are needed in order to better understand the formation mechanism of IOD events and the detailed physical processes of air-sea interaction in the tropical Indian Ocean during their evolution.

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