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A Review about Indian Ocean Basin Mode and Its Impacts on East Asian Summer Climate

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Abstract: In recent years, more and more studies have paid attention to the impacts of Indian Ocean on global climate. This review provides a synopsis of the climatological characteristics over the Indian Ocean, Indian Ocean basin mode and its impacts on East Asian summer climate.**DOI:** [（英）DOI]

Keywords: Indian Ocean; East Asian summer climate; Indian Ocean basin mode

1 Introduction

The influence of the tropical Indian Ocean on the East Asian summer climate has long being studied in China and some mechanisms have been proposed. Compared with the ocean-atmosphere coupling mode ENSO (El Niño–Southern Oscillation) in Pacific, the sea temperature variability in the tropical Indian Ocean is relatively small and has not been paid much attention to by climatologists (Annamalai and Murtugudde, 2004).

In 1997, significant climate anomalies occurred around the Indian Ocean. In the west bank of the Indian Ocean, serious flooding in North Africa caused thousands of deaths and serious economic losses, while severe droughts in the east coast caused many forest fires. Some investigators have shown that this event was caused by the Indian Ocean Dipole (Saji et al., 1999; Webster et al., 1999). So the change of the sea surface temperature (SST) in the Indian Ocean and its impact on the global climate have become the focus of international climate research in recent years (Schott et al., 2009).

Using the empirical orthogonal function to analyze the changes of SST in the Indian Ocean, it is found that the first leading mode is the Indian Ocean basin mode, showing the uniform warming or cooling in Indian Ocean to its peak March to May. Earlier studies showed that the ENSO could cause the anomalous surface heat fluxes, especially the latent heat fluxes and shortwave radiation fluxes, which play an important role in maintaining the Indian Ocean basin mode (Klein et al., 1999). Recent studies have shown that the Indian Ocean basin mode is not simply a passive response to ENSO forcing, but involves complex ocean-atmosphere interactions and ocean dynamic processes in tropical Indian Ocean, and has a significant effect on the East Asian summer climate. Therefore, it is necessary to systematically summarize and review the mechanism of the Indian Ocean basin mode and its influences on the East Asian climate.

At present, there are some retrospective articles on the Indian Ocean circulation and its influence on the global climate. For example, Annamalai and Murtugudde (2004) reviewed the passive and active relationships between the Indian Ocean SST and the global climate; Schott et al. (2009) reviewed the variation of SST in the Indian Ocean and its impact on the global climate. Chinese scientists have long studied the influence of the Indian Ocean basin mode on China and the East Asian summer climate, but these studies have not been summarized in these references. In addition, great progress has been made in the study of the Indian Ocean basin mode and its influence on the East Asian summer climate in recent years, but these studies are not included in the previous reviews. Therefore, it is necessary to comprehensively summarize the mechanism of the tropical Indian Ocean basin mode change and its influence on the East Asian summer climate.

In this paper, the tropical Indian Ocean basin mode and its influence on the East Asian summer climate are reviewed, including the past research of Indian Ocean in

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China. In order to systematically review these researches, the following sections are arranged in this paper: Section 2 is the Indian Ocean SST climatology characteristics and long-term variation; Section 3 shows the variability of the basin mode; Section 4 summarizes the influence of the Indian Ocean basin mode on the summer climate in East Asia; and Section 5 is the summary and discussion. The article is written at the time of the first anniversary of the death of Academician Ye Duzheng to express our grief and in memory of his outstanding contributions to the East Asian monsoon research.

2 Climatological characteristics and long-term variation of Indian Ocean SST

In the global ocean, the Indian Ocean has its unique variation characteristics. On one hand, it has a relatively unique area, with the Himalayas to its north, the African plateau to its west, the Sunda Islands and the Australian continent to its east. The eastern boundary consists of many islands, connecting the tropical western Pacific warm pool by the Indonesian Throughflow. The Indian Ocean is mainly distributed south of 20°N in the northern hemisphere and extends to Antarctica in the southern hemisphere. On the other hand, its thermodynamic structure is also different from that of other oceans. The annual mean wind field over the equatorial Indian Ocean is westerly, significantly different from the climatic characteristics of the prevailing easterlies over the equatorial Pacific and Atlantic, which makes the thermocline of the tropical Indian Ocean thick in the east and thin in the west. At the same time, the SST of the tropical Indian Ocean is relatively high. In terms of the annual mean temperature, the tropical Indian Ocean SST is above 28 °C over the east of 60°E and between 10°S and 10°N, and is connected with the western Pacific warm pool as a whole (Zhou et al., 2001).

The seasonal cycle of the Indian Ocean SST is affected by the solar radiation and the monsoon circulation. The SST in the southern Indian Ocean is mainly affected by the solar radiation, but the SST in the northern Indian Ocean is greatly affected by the seasonal evolution of the monsoon circulation. In spring, the SST of the northern Indian Ocean increases gradually due to the enhancement of the solar radiation. However, during the Asian summer monsoon onset, the upwelling along the Somali coast makes the SST cold, and the evaporation causes the SST in the northern hemisphere to be low in summer. In the equatorial Indian Ocean, the monsoon circulation affected area is mainly in the western Indian Ocean, while seasonal variation of the SST in the eastern equatorial Indian Ocean is not obvious, always above 28 °C (Levitus et al., 2005).

Since the 1950s, the SST of the Indian Ocean has obviously increased. Using the sea temperature data from COADS (the Comprehensive Ocean-Atmosphere Data Set) and WOA94 (the 1994 World Ocean Atlas), Levitus et al. (2005) studied the global SST trends over recent decades. Their results show the temperature increase over most of the tropical oceans, of which the Indian Ocean temperature increase is the most significant. Using the data from GISST (Global Sea-Ice and Sea Surface Temperature), Zhou et al. (2001) further confirmed that the Indian Ocean has been warming since the mid-1950s, with the equatorial Indian Ocean warming about 0.6 °C. In addition to the continuous warming of SST in recent decades, there is a long-term change trend in the deep layer of the Indian Ocean (Alory et al., 2007; Alory and Meyers, 2009). On the south side of the subtropical return current of the Indian Ocean, between 40°S–50°S, the sea temperature increases 1–2 °C over the last 40 years from the surface to the deep layer; the temperature also increases from the surface to 250 m on the north side of the subtropical return current (around 25°S); between 5°N–15°S, the temperature increases above the 20 °C isothermal surface and decreases in the subsurface (100–200 m); and there is a significant increase trend of the temperature from the surface to 250 m north of 10°N.

So, what is the reason causing different long-term temperature change trends in different areas and depths of the Indian Ocean? Alory et al. (2007) have shown that the sea temperature changes, on the north side of the Indian Ocean Antarctic Circumpolar Current (AAC) and on the south side of the subtropical return current, is caused by the 0.5° southward shift of the southern Indian Ocean subtropical return current. Human activities may have caused changes in the Southern Annular Mode and Antarctic sea ice over recent decades, which in turn caused the southward shift of the subtropical return current, affecting SST anomalies in the southern Indian Ocean (Gille 2002; Aoki et al., 2003; Cai et al., 2005). The subsurface seawater cooling and the thermocline shallowing in the tropical Indian Ocean may be due to the weakening of the easterly trade winds in the tropical Pacific in recent decades. The weakening of the easterly trade winds makes the western Pacific warm pool thermocline shallow, resulting in the shallow thermocline in the tropical Indian Ocean through the Indonesian Throughflow, and the shallower oceanic mixing layer and the subsurface seawater cooling (Alory and Meyers, 2009).

3 Indian Ocean basin mode

3.1 Development of the Indian Ocean basin mode

The tropical Indian Ocean is often gradually warming accompanied by the El Niño event and peaks three months after the mature of the El Niño event. There are two processes that will lead to the development of the Indian Ocean basin mode. One is the atmospheric bridge process (Lau et al., 1997): in El Niño year, the convection over the

Indian Ocean is suppressed so that the sea surface receives more solar shortwave radiation, and the decrease of the lower level wind speed weakens the latent heat release; the increase of shortwave radiation and the decrease of the latent heat release lead to the warming in most of the Indian Ocean (Klein et al., 1999).

The other one is the ocean dynamic and the regional ocean-atmosphere process. The low-level subtropical anticyclone circulation prevails over the southwestern Indian Ocean, so the thermocline depth is relatively shallow, with an annual average of only about 50 m (Xie et al., 2002; Lau and Nath, 2003). During the El Niño mature period, the anticyclone anomaly was generated in the lower level over the subtropical southeastern Indian Ocean, stimulating the descending Rossby fluctuation propagating westward. The fluctuation propagated to the southwestern Indian Ocean after three months, affecting the regional temperature anomaly in the southwestern Indian Ocean with shallow thermocline, and resulting in the anomalous sea temperature in the subtropical southwestern Indian Ocean (Huang and Kinter, 2002; Xie et al., 2002). In spring, the anomalous sea temperature in the subtropical southwestern Indian Ocean resulted in the anomalous precipitation, leading to the anomalous antisymmetric circulations in the southern and northern hemispheres over the equatorial Indian Ocean. When the subtropical southwestern Indian Ocean temperature was warmer, the northern Indian Ocean had anomalous easterly wind. After the early summer, the Indian monsoon and the East Asia southwest monsoon broke out. The anomalous easterly could weaken the climatological wind field, reduce the release of the latent heat from the ocean to the atmosphere, and warm the northern Indian Ocean. This ocean-atmosphere process allows the Indian Ocean basin mode to be maintained for a longer period of time (Du et al., 2009).

There is an interdecadal variation in the duration of the tropical Indian Ocean basin scale warming mode. The basin scale warming mode decays rapidly and cannot maintain to the summer before the late 1970s, but it can last until the summer after that (Huang et al., 2010; Xie et al., 2010). The maintenance of the basin scale warming mode in the Indian Ocean may be related to the antisymmetric mode of the Indian Ocean in spring. Using the observational data after 1979, Wu and Kirtman (2005) pointed out that there are antisymmetric modes of sea temperature, precipitation and wind of Indian Ocean in spring, which is closely related to the previous winter sea temperature anomalies in the eastern equatorial Pacific. Du et al. (2009) further pointed out that this antisymmetric mode may be triggered by the tropical southwestern Indian Ocean. The ocean fluctuations have led to the warming in the southwestern Indian Ocean and resulted in the anomalous convection over the southwestern Indian Ocean, leading to the formation of a low-level antisymmetric cross-equatorial flow field over the tropical Indian Ocean. This antisymmetric cross-equatorial flow field can maintain from the spring to the early summer and is opposite to the climatological wind field in the early summer, weakening the low-level wind field over the Indian Ocean. The weakening of the wind field reduces the release of the sea surface latent heat, so the sea temperature anomalies in the tropical Indian Ocean, especially in the northern Indian Ocean, could maintain to summer. However, before the late 1970s, the antisymmetric mode of the spring wind field was not closely related to the sea temperature in the central and eastern equatorial Pacific of the previous winter, leading to a rapid decay of the basin scale mode, so it cannot maintain until summer (Huang et al., 2010).

3.2 Changes of Indian Ocean basin mode under global warming

Under the global warming, a new type of El Niño events began to increase from 1990s. Unlike the typical El Niño event, which corresponds to the warm SST anomaly in the central and eastern Pacific, these new type of El Niño events are characterized by warm SST anomalies in the central Pacific and cold SST anomalies in the eastern Pacific. This type of El Niño is commonly called as the Central Pacific El Niño event (Ashok et al., 2007). Tao et al. (2015) studied different effects of these two types of El Niño events on the Indian Ocean SST (Fig. 1). During the typical El Niño event, the Indian Ocean exhibited uniform warming across the basin (Fig. 1). While during the Central Pacific El Niño event, the Indian Ocean temperature did not change significantly. This is because during the El Niño event, the Matsuno-Gill circulation response to the anomalous precipitation in equatorial eastern Pacific affects the Indian Ocean through the propagation of atmospheric Kelvin fluctuations. The El Niño event in the central Pacific is characterized by the excessive precipitation in the central Pacific and reduced precipitation in the eastern Pacific. This opposite zonal precipitation anomalies cannot cause significant atmospheric Kelvin fluctuation, having little effect on the Indian Ocean. In addition, the Central Pacific El Niño strength is weaker than the typical El Niño strength, more susceptible to other atmospheric or oceanic signals, and thus has less impact on the tropical Indian Ocean.

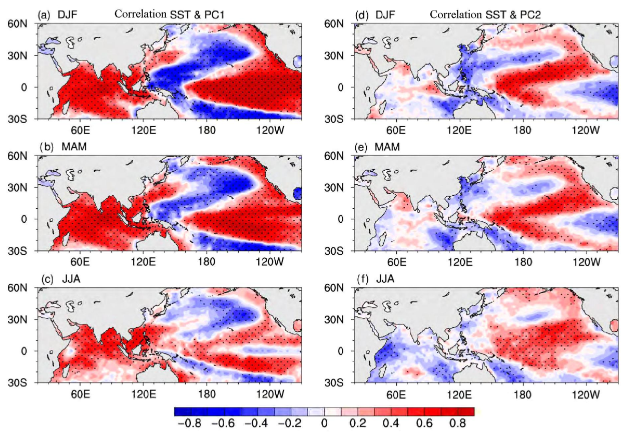

Fig. 1 The correlations of seasonal TIO (the Indian Ocean) SST with the tropical Pacific Niño-3.4 index (right panels) and Modoki El Niño index (left panels), respectively. (a, d) Seasonal mean from December to February; (b, e) seasonal mean from March to May; (c, f) seasonal mean from June to August [From Tao et al. (2014)]

Using the GFDL-CM2.1 model, Zheng et al. (2011) studied the response of the Indian Ocean basin mode to the global warming. Although the strength of the model-simulated ENSO is weakened in the future and the duration is shortened, the Indian Ocean basin mode and the capacitor effect are enhanced. This is mainly due to the fact that the duration of the ENSO is shortened under the global warming and the corresponding SST anomalies in the Pacific Ocean recede faster, resulting in the increase of the SST gradients between the Indian Ocean and Pacific, and enhancing the anomalous easterly in the south branch of the northwestern Pacific anticyclone. This anomalous easterly can extend into the northern Indian Ocean, weakening the climatological wind field over the Indian Ocean, and reducing the evaporation of the Indian Ocean according to the evaporation-wind-sea temperature mechanism, in favor of the strengthening and long-lasting of the sea temperature anomalies in Indian Ocean. Using a single model can make the conclusions model-dependent. The Coupled Model Intercomparison Project (CMIP), promoted by the World Climate Research Program (WCRP), particularly the latest implementation of the Fifth Coupled Model Intercomparison Project (CMIP5), provides a good opportunity for us to use multi-model approaches to study the climate change. More recently, Tao et al. (2015) and Hu et al. (2014) used multiple CMIP5 ocean-atmosphere coupled models to predict changes of the Indian Ocean basin mode under global warming. They found that the Indian Ocean warming has been strengthened under the global warming and this is related to the corresponding increase of the water vapor response. The relationship between the saturated vapor pressure and the temperature is non-linear. With the increase of the temperature, the same temperature anomaly could cause more saturated vapor pressure anomaly. Therefore, under the global warming, the El Niño event of the same strength can cause larger water vapor anomalies in the lower troposphere in the central and eastern Pacific. In the tropics, the tropospheric temperature profile often follows the wet convection adjustment. When the low-level water vapor increases, the troposphere temperature also increases, resulting in the enhanced tropospheric temperature response to the El Niño SST anomalies under the global warming. The tropospheric temperature propagates to the Indian Ocean by the atmospheric Kelvin fluctuation, making the temperature warmer over the Indian Ocean (the tropospheric temperature, simplified as TT, mechanism). The increase of the anomalous ocean-atmosphere temperature difference leads to the increase of the downward latent heat flux and the decrease of the upward latent heat flux, increasing the warm anomaly of the Indian Ocean. In addition, the sea temperature anomalies in the Indian Ocean and the circulation anomalies in the northwestern Pacific also have feedback effects: the warm sea temperature anomalies in the Indian Ocean can cause low-level anticyclone anomaly in the northwestern Pacific, while the westward propagation of its south branch easterly anomaly causes the tropical northern Indian Ocean warmer. Under the global warming, these two kinds of feedbacks strengthen, so the Indian Ocean warm SST anomaly can maintain longer and stronger during the El Niño decaying period, and therefore the Indian Ocean basin mode and the ENSO become more closely linked as shown in Fig. 2.

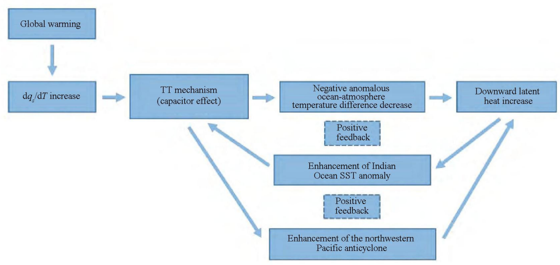

Fig. 2 The mechanism for strengthening of TIO basin mode under global warming, and dq_s/dT represents the deviation of saturated specific humidity to air temperature

4 Effect of the Indian Ocean basin mode on the East Asian summer climate

In this section, we first review the earlier work of Chinese scientists on the influence of the Indian Ocean SST on the East Asian summer climate, and then review the influence of the Indian Ocean basin mode on the East Asian summer climate.

4.1 Earlier work of Chinese scientists on the impact of the Indian Ocean on the East Asian climate

Luo et al. (1985) analyzed the relationship between the Indian Ocean and the rainy season precipitation in eastern

China. It is pointed out that the sea temperature in the Bay of Bengal and the Arabian Sea in previous year winter and the Mei-yu rainfall in the middle and lower reaches of the Yangtze River have a good relationship: the warmer over these ocean areas, the more the precipitation in the Yangtze River valley, and vice versa. Jin and Luo (1986) pointed out that when the Mei-yu rainfall in the Yangtze River valley is more, there are positive SST anomalies from the Bay of Bengal to the South China Sea and the western Pacific, while the SST anomaly along the Somali coast is negative. Chen (1991) proposed a model of the Indian Ocean effect on the East Asian summer monsoon. It is pointed out that during the period when the east is warm and the west is cold from the Arabian Sea to the South China Sea, the air ascends over the warm area in the South China Sea and descends over the cold water area along the Somali coast, so the South Asian easterly is formed in the upper level and the thermal circulation of the southwest monsoon in the lower level, accompanied by the anomalous distribution of SST in the equatorial Pacific, with the cold SST in the east and warm SST in the west, leading to the enhancement of the Walker circulation in the Pacific and the Indian Ocean and forming the strong tropical convergence zone around the warm water area in the South China Sea. The ascending air in the convergence zone moves northward and descends below the upper-level strong easterly jet, which enhances the development of the Hadley circulation on the north side of the convergence zone, and results in the southwestward extension of the west ridge of the subtropical high. When the SST is cold in the east and warm in the west from the Arabian Sea to the South China Sea, the Walker circulation weakens, and the whole central and western equatorial Pacific is occupied by the anti-clockwise Walker circulation. The descending air strengthens in the western Pacific, weakening the Hadley circulation on the north side of the convergence zone, and causing the western Pacific subtropical high ridge to be weak and northward.

Wu et al. (2000) pointed out that the relationship between the SST anomalies in the central and eastern equatorial Pacific and the climate in China is only a superficial phenomenon, but the SST anomaly in the Indian Ocean has a direct causal relationship with the climate in China. The warm SST anomaly in Indian Ocean increases the evaporation of water vapor and the ocean-atmosphere temperature differences, resulting in an anomalous increase of the sensible heating and a cyclonic circulation near the surface. The anomalous development of the southerly wind in the east transports large amounts of water vapor northward to produce anomalous precipitation which extends northeastward and is accompanied by the deep convective latent heating. The heating increases with the height in the middle and lower troposphere, the south wind develops, and the subtropical high strengthens to the east of the heating zone. The heating decreases with height in the upper troposphere, the northerly wind develops, and the subtropical high strengthens to the west of the heating zone. Therefore, when the positive SST anomalies occur in the northern Indian Ocean, the western Pacific subtropical high will develop anomalously at 500 hPa and below, and the South Asian high will also develop anomalously at 200 hPa.

4.2 Influence of the Indian Ocean basin mode on the East Asian Climate

Previous studies have shown that the uniform warming of the Indian Ocean basin can trigger the northwestern Pacific anticyclonic anomaly in summer. Xie et al. (2009) proposed the mechanism that the anticyclone over the northwestern Pacific is triggered by the Indian Ocean as shown in Fig. 3. The warming of the tropical Indian Ocean in summer stimulates the upper-level warm Kelvin fluctuation, and the low pressure trough extending to the western Pacific can cause the winds to flow towards the Equator in the low-level northwestern Pacific, resulting in the Ekman divergence in the northwestern Pacific boundary layer. The low-level divergence can suppress the convection and trigger the anticyclonic anomaly in the northwest, which further suppresses the convection development and strengthens the low-level anticyclone development. Thus, the interaction between the local convection stimulated by the Indian Ocean-triggered Kelvin fluctuation and the large-scale circulation, leads to the formation and maintenance of the low-level anticyclone anomalies in the northwestern Pacific. Moreover, the anticyclone anomaly in the northwestern Pacific can propagate westward to the northern Indian Ocean, warming the Indian Ocean (Kosaka et al., 2013). In this process, the Indian Ocean serves as a signal store that stores the winter ENSO signals and influences the East Asian summer climate, so it is called the Indian Ocean capacitor effect (Yang et al., 2007; Xie et al. 2009). This capacitor effect has also been confirmed by other studies (Wu et al., 2009; Wu et al., 2010). Huang and Hu (2008) pointed out that the SST in the northern Indian Ocean plays a major role in the above process, while the south Indian Ocean has little effect on the anomalous anticyclone over the northwestern Pacific. The Indian Ocean capacitor effect has an important influence on the distribution of the summer air temperature and extreme high temperature disaster in China. When the Indian Ocean is warmer, the summer temperature in southern China is higher, the temperature in northeastern China is lower, the precipitation in the Yangtze River basin higher (Hu et al., 2011), and the Jiangnan area is prone to extreme high temperature disasters in late summer (Hu et al. 2013). In addition to the summer, some studies have shown that the anomalous SST of the Indian Ocean basin mode during the winter can also cause the anomalous anticyclone in the subtropical northwestern Pacific (Watanabe and Jin, 2003).

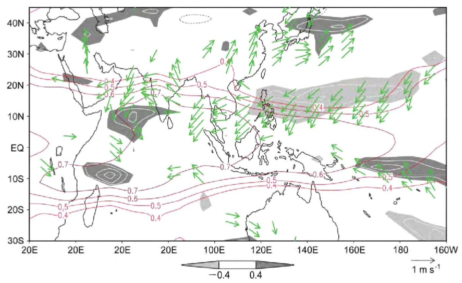

Fig. 3 Correlation of summer rainfall (shade, interval at 0.1), 850-hPa winds (vectors) and tropospheric temperature (contours, vertical average from 850 hPa to 200 hPa) with the previous winter Nino-3.4 index (seasonal mean from December to February). [From Xie et al. (2009)]

In addition, Yang et al. (2007) and Huang et al. (2011) pointed out that the Indian Ocean can also affect the variation of the South Asian high. The warmer tropical Indian Ocean can trigger the Matsuno-Gill response, resulting in the anomalous geopotential height in the upper troposphere, and then making South Asian high stronger and more southerly (Fig. 4). Furthermore, it is found that the Indian Ocean can affect the position and strength of the subtropical high-level jet in East Asia. In the warmer year of the Indian Ocean, the South Asian high is strengthened and the pressure gradient increases on the north side of the South Asian high, resulting in the strengthened jet. On the other hand, the Indian Ocean suppresses the convection activity in the tropical northwestern Pacific, resulting the teleconnection wave train anomaly along East Asia–Pacific/Pacific–Japan (EAP/PJ), and making jet stronger and more southerly jet (Qu and Huang, 2012b). The changes of the South Asian high and the East Asia westerly jet can cause the adjustment of the mid-troposphere westerly zone and the temperature advection, leading to the change of the ascending, and ultimately affecting the East Asia summer precipitation anomaly (Kosaka et al., 2011).

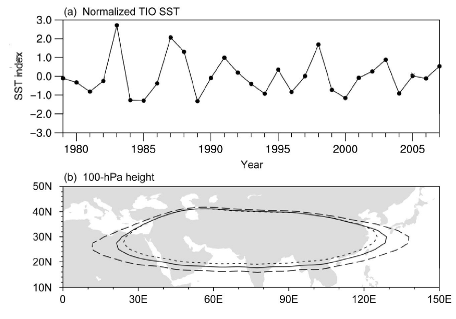

Fig. 4 (a) Normalized TIO (20°S–20°N, 40°–100°E) SST in June–August (JJA) from 1979–2007. (b) Contour lines for 100-hPa 16 720 gpm geopotential height when TIO SST is warm (dashed line), cold (dotted line) and climatological (solid line) in JJA. [From Huang et al. (2011)].

The interdecadal variability of the Indian Ocean basin mode influence on the East Asian summer climate is also significant. Huang et al. (2010) pointed out that the effect of the SST anomalies in the tropical Indian Ocean basin on the northwestern Pacific anticyclone has been intensified in recent decades (Fig. 5). Before 1976/77, the Indian Ocean basin mode could not maintain to the summer, so it had little effect on the anticyclone in the northwestern Pacific. Compared with the previous period, the tropical Indian Ocean basin mode maintained longer after 1976/77, resulting in greater summer tropical Indian Ocean SST anomalies. Further studies indicate that the Kelvin fluctuation excitation over the Indian Ocean is related to the magnitude of the SST anomaly, and the higher the SST anomaly, the stronger the Kelvin fluctuation. The SST anomalies in the summer tropical Indian Ocean are more likely to trigger the Kelvin fluctuation after 1976/77, causing the anomaly of the northwestern Pacific–East Asia summer climate. Before 1976/77, the ocean basin mode decayed rapidly, and the summer SST anomaly was very weak, so the effect of the Kelvin fluctuation on the summer climate of the East Asia–northwestern Pacific was also weak. The interdecadal variability is related to the Indian Ocean SST conditions. After 1976/77, the thermocline of the subtropical southwestern Indian Ocean became shallower, and the descending oceanic Rossby fluctuation triggered by El Niño in the subtropical south Indian Ocean increased the SST in the subtropical southwestern Indian Ocean, so that the Indian Ocean basin mode can maintain a longer time.

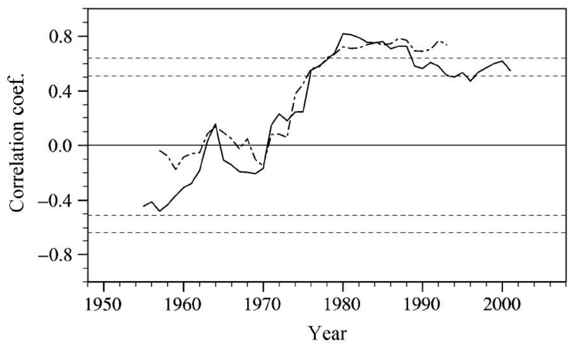

Fig. 5 The 15-year sliding correlations between the NWP (northwestern Pacific) anticyclone and JJA TIO SST indices of observation (solid line), and the 15-year sliding correlations of the NWP anticyclone index between observations and the ensemble-mean simulation (dash line). Horizontal black dash lines denote 95% and 99% confidence levels. [From Huang et al.(2010)].

Qu and Huang (2012a) found that the effect of the Indian Ocean basin mode on the South Asian high also has significant interdecadal variability. The influence of the Indian Ocean on South Asian high has been increasing in recent decades. On the one hand, this is related to the warmer SST and its enhanced variation in Indian Ocean, which enables the Indian Ocean to trigger stronger local tropospheric temperature anomalies, then affecting the strength and location of the South Asian high. On the other hand, this interdecadal variability is adjusted by the western Pacific SST and the precipitation over India during the Indian Ocean basin mode (Qu and Huang, 2015). In the summer of the Indian Ocean warming year, if the western Pacific is warmer, the Indian Ocean basin mode is closely related to the South Asian high; similarly, if the precipitation over India is weak, the link between the Indian Ocean basin mode and the South Asian high is weak.

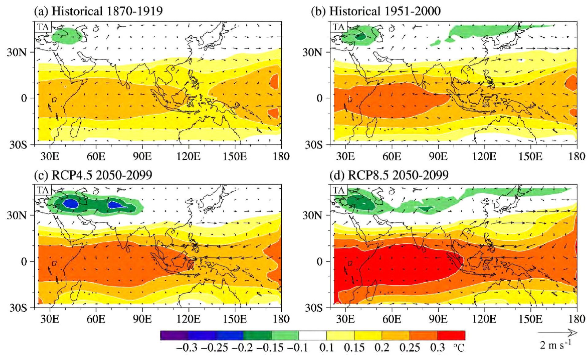

Fig. 6 The MME (Multiple Model Ensemble) mean of MJJ (May–June–July) tropospheric temperature anomalies (units: °C; colors; vertical average from 850 to 200 hPa) and 850-hPa winds anomalies (vectors; m s^{-1}) obtained by regression on the normalized DJF (December–January–February) Niño-3.4 SST index during (a) 1870–1919 in the historical run, (b) 1951–2000 in the historical run, (c) 2050–2099 in the RCP4.5 run, and (d) 2050–2099 in the RCP8.5 run. [From Hu et al. (2014)].

The influence of the Indian Ocean basin mode on the East Asian summer climate is also affected by the climate warming. Our study has shown that this influence may become stronger under the global warming (Hu et al., 2014). Using 19 CMIP5 ocean-atmosphere coupled models, we studied the effects of ENSO on the summer climate in East Asia and northwestern Pacific. In the historical climate simulations, the interdecadal change characteristics of the effect can be simulated by 8 models. During the high-impact period, the ENSO can affect the East Asian–northwestern Pacific summer climate by affecting the Indian Ocean SST and the resulted capacitor effect. During the low-impact time period, this process is not obvious. The simulated results are consistent with the observations. In addition, we used RCP4.5 (Representative Concentration Pathway 4.5) and RCP8.5 to study the ENSO influence on the summer climate in East Asia–northwestern Pacific. The results show that this effect is enhanced with the increase of the greenhouse gas concentration and the strengthening of the ENSO-induced Indian Ocean capacitor effect. The enhancement mechanism is that the response of the saturated water vapor to temperature is non-linear, and the same temperature anomaly can cause greater water vapor anomaly under global warming. In the tropical troposphere, the temperature is controlled by the SST and the low-level absolute humidity, so the same SST anomaly can cause greater tropospheric temperature anomaly, resulting in a stronger Indian Ocean capacitor effect in the El Niño decaying year, and leading to greater anomalies of the East Asian summer climate (Fig. 6).

5 Summary and prospect

Chinese scientists have long concerned about the Indian Ocean impact on the East Asian summer climate, and proposed a number of possible impact mechanisms. With the abundant observational data available over the past 10 years in Indian Ocean, the research of Indian Ocean has been more and more in-depth. This paper systematically reviews the results of these studies, to commemorate the outstanding contributions of Mr. Ye Duzheng to the East Asian monsoon research.

Although the present study analyzes the development processes of the Indian Ocean basin mode and its influence on the East Asian climate from different aspects, there are still some shortcomings in the current research.

Firstly, the current study shows that the tropical Indian Ocean basin mode can affect the East Asian summer climate through a number of pathways. Some studies have shown that the tropical Indian Ocean basin mode can cause the anticyclone anomaly in the subtropical northwestern Pacific by triggering the Kelvin fluctuation, resulting in the climate anomaly in East Asia. Other studies have also shown that the tropical Indian Ocean basin mode has caused the East Asian summer climate anomaly by affecting the South Asian high and the East Asian high-level jet. The link between these influence pathways is unclear. In order to better understand the impact of the Indian Ocean basin mode on the summer disastrous climate in East Asia, it is necessary to comprehensively study the mutual cancelling or enhancement of these pathways in future.

Secondly, the occurrence of the Indian Ocean basin mode is often accompanied by SST anomalies in other regional seas, such as SST anomalies in the equatorial Pacific, South China Sea and the Atlantic. These SST anomalies may interfere with the effect of the Indian Ocean on the East Asian climate, thus affecting the stability of the relationship between the Indian Ocean basin mode and the East Asian climate anomaly. We need to analyze the synergistic or cancelling effects of SST anomalies in different regions on the East Asian climate in the future.

Finally, the current study shows the interdecadal variation in the maintenance time of the Indian Ocean basin mode, which may be related to the global warming, or related to the interdecadal variation of the subsurface ocean thermodynamic conditions in the Indian Ocean. In order to better analyze the future climate anomalies in East Asia, we need to predict the changes of the Indian Ocean basin mode over the next few decades.

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When the article was written, it was the first anniversary of the death of Academician Ye Duzheng. Everything is still vivid when looking back, as if he has never left. We use this article to express our grief and memories, also to systematically sum up the recent work of his students, looking forward to a greater breakthrough. Once again thanks to Mr. Ye for his many years' guidance, and his kindness will be remembered forever.

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[尾注]