The Influence of the Indian Ocean Dipole on Atmospheric Circulation and Climate①

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ABSTRACT

The SST variation in the equatorial Indian Ocean is studied with special interest in analyzing its dipole oscillation feature. The dipole oscillation appears to be stronger in September–November and weaker in January–April with higher SST in the west region and lower SST in the east region as the positive phase and higher SST in the east region and lower SST in the west region as the negative phase. Generally, the amplitude of the positive phase is larger than the negative phase. The interannual variation (4–5 year period) and the interdecadal variation (25–30 year period) also exist in the dipole. The analyses also showed the significant impact of the Indian Ocean dipole on the Asian monsoon activity, because the lower tropospheric wind fields over the Southern Asia, the Tibetan high in the upper troposphere and the subtropical high over the northwestern Pacific are all related to the Indian Ocean dipole. On the other, the Indian Ocean dipole still has significant impact on atmospheric circulation and climate in North America and the southern Indian Ocean region (including Australia and South Africa).

Key words: Indian Ocean dipole, Sea surface temperature anomaly (SSTA), Asian summer monsoon, Climate impact

1. Introduction

A strong El Niño event occurred in the early summer 1997 (McPhaden, 1999), it caused serious climate disasters in the world wide, such as the drought and forest fire in Indonesia, the flood in the northern region of South America. The previous studies in observation data (Rasmusson and Carpenter, 1983; Ropeleweski and Halpert, 1987) showed that Asian summer monsoon should be weaker with drought in Indian Peninsula in the El Niño year. But it was exactly reverse in 1997 as the mean summer precipitation in India was normal with even more rainfall in the partial region (Bell and Halpert, 1998), and there was also more precipitation in East Africa (Birkett et al., 1999). To investigate the abnormal situations, some analyses have shown that large SSTA in the equatorial Indian Ocean during the 1997–98 El Niño event, the maximum SSTA was over 2°C, can be identified as the origin. Thus, more attentions have been paid to studying the anomalies of SST in the equatorial Indian Ocean and its impacts.

Dipole oscillation of SSTA in the equatorial Indian Ocean has been studied (Saji et al., 1999). Their study shows that mean SST in (10°S–10°N, 50°–70°E) region represents reverse variation feature with one in (10°S–EQ, 90°–110°E) region, the dipole is just 12% in the

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total variability of the Indian Ocean SST and it is not always related to the ENSO. Webster et al. (1999) also suggested that the Indian Ocean dipole in 1997–1998 was independent of the ENSO and caused by strong atmosphere–land–sea interaction. At same time, the study (Anderson, 1999) indicated that the dipole is not only shown in the variation of SST, but also in the variation of subsurface ocean temperature (SOT) of the Indian Ocean.

In fact, the important effect of SSTA in the Indian Ocean on summer rainfall in the middle and lower reaches of the Yangtze River have been indicated earlier by Chinese scientists (Chen et al., 1991; Luo et al., 1985). For better understanding the influence of the Indian Ocean SSTA on the weather and climate, the dipole pattern of the Indian Ocean SSTA need to be studied further, particularly the influence of the dipole on atmospheric circulation and climate.

2. Data

The data used for this study are the monthly $5^\circ \times 5^\circ$ SST data (1900–1997) provided by the Hadley center in UK. The quality of the data set is approvable within meteorological research (Parker et al., 1994; Smith et al., 1998). Beside, the NCEP–NCAR reanalysis data and other data are also used to the statistical analysis in the present study.

3. Spatial–temporal features of Indian Ocean dipole

According to the observation data, the SST variation in northwestern region is opposite to that in southeastern region in the equatorial Indian Ocean. In order to identify this dipole oscillation, a dipole index is defined, which is the difference between the averaged SSTA in the (5°S–10°N, 50°–65°E) region and the (10°S–5°N, 85°–100°E) region. In our definition, differ from that in Saji's study (Saji et al., 1999), some Islands and the Laut Jawa sea have been ruled out the domain. The temporal variation of dipole index in 1900–1997 and its power spectrum are shown in Fig. 1. It is very clear that the dipole index appears interannual variation (4–5 year period) and interdecadal variation (25–30 year period). Another interesting character of interdecadal variability in Fig. 1 is that the dipole index was mainly larger negative value before 1961, but it was mainly positive value since 1961.

In order to reveal the feature of Indian Ocean dipole, the composite analyses are completed, respectively taking 4 years (1961, 1972, 1994 and 1997) with larger positive index and 5 years (1958, 1959, 1960, 1970 and 1996) with larger negative index to engage in. The horizontal distributions of the composite SSTA in the (30°S–50°N, 30°E–80°W) region for the positive and negative phases of the Indian Ocean dipole are respectively shown in Fig. 2. Figures 2a and 2b (Figs. 2c and 2d) display the patterns of dipole for positive phase (negative phase) in July and in December, respectively. The basic feature of Indian Ocean dipole can be clearly seen in Fig. 2, the SSTA is positive (negative) in the equatorial western Indian Ocean and negative (positive) in the equatorial eastern Indian Ocean for the positive (negative) phase. The dipole patterns shown in Figs. 2a and 2b are stronger than that shown in Figs. 2c and 2d, because the dipole index in positive phase is larger than that in negative phase.

Comparing Fig. 2a and Fig. 2b, or Fig. 2c and Fig. 2d, it can be seen that the intensity of Indian Ocean dipole is different in various months. An analysis of seasonal variations

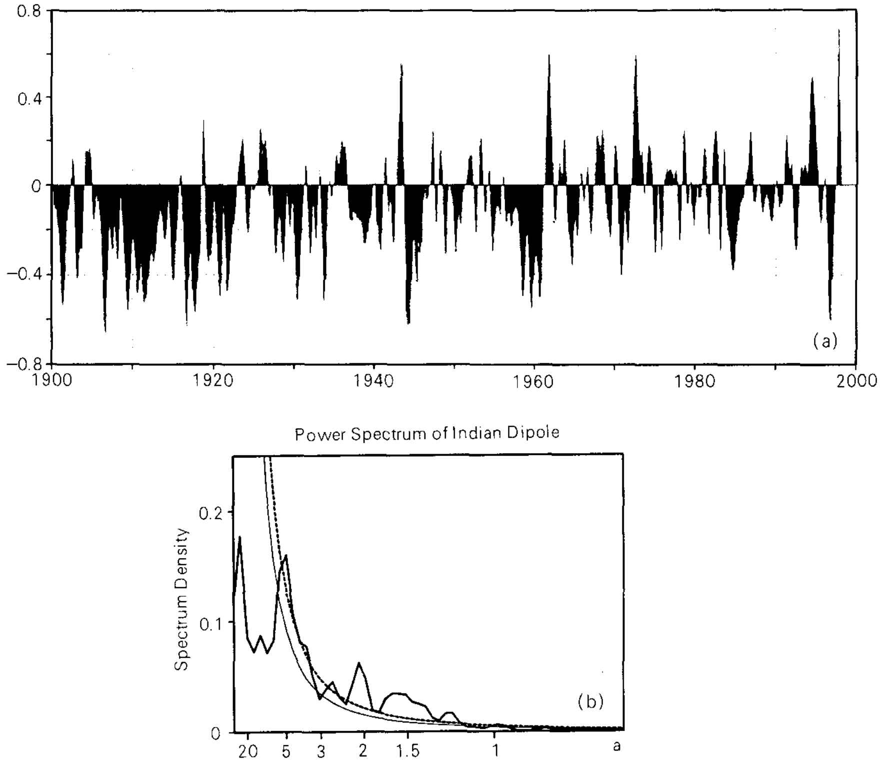


Fig. 1. Temporal variation of monthly Indian Ocean dipole index (a) and its power spectrum (b). The solid and dashed lines represent significance level of 95% and 99% respectively.

of the dipole intensity shows that the seasonal variation of the dipole intensity is very clear, the Indian Ocean dipole is stronger during the July–December and weaker during January–May with the strongest in October and the weakest in February (figure omitted).

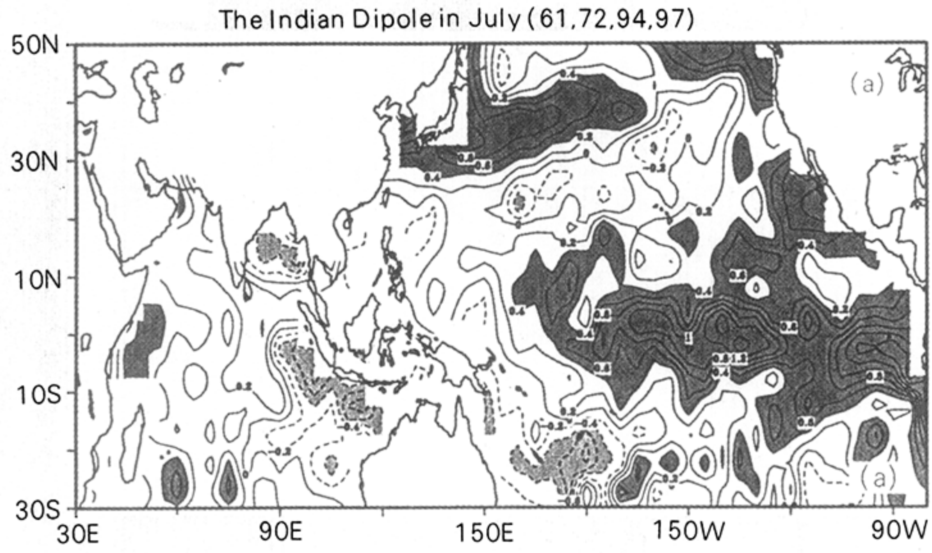
The distribution of SSTA in the tropical Pacific is also shown in Fig. 2. The comparison of the SSTA distributions in the equatorial Indian Ocean and in the equatorial Pacific shows that when the Indian Ocean dipole is in the positive phase, the SSTA will be positive in the equatorial eastern Pacific and negative in the equatorial western Pacific. When the Indian Ocean dipole is in the negative phase, the SSTA will be positive in the equatorial western Pacific and negative in the equatorial eastern Pacific. How about the connection between the Indian Ocean dipole and the SSTA in the equatorial Pacific will be discussed in another paper.

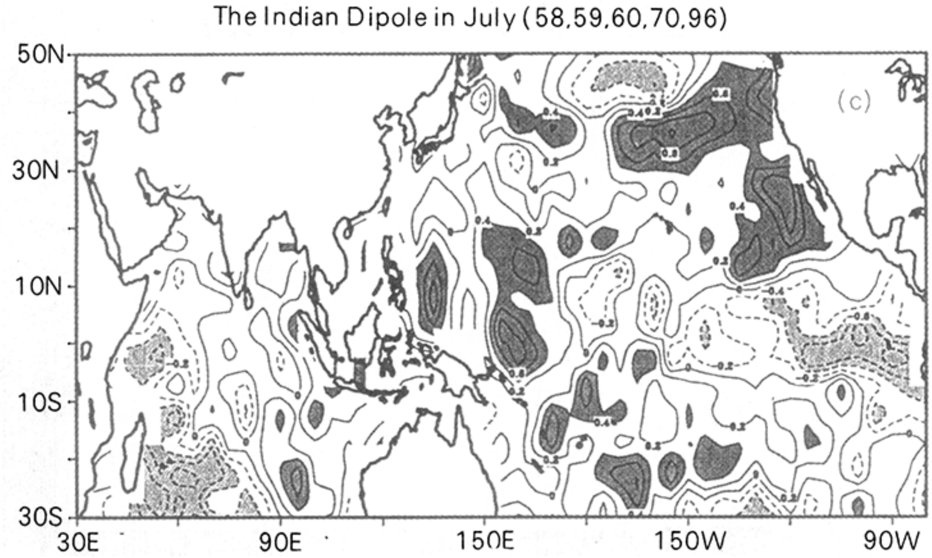
4. Influences of the Indian Ocean dipole on atmospheric circulation and climate

The ENSO has been regarded as important signal and factor of interannual climate variation (Namias and Cayan, 1981; Rasmusson and Wallace, 1983; Li, 1995) and it may be related to the Indian Ocean dipole (Li and Mu, 2001). In the following analyses, some important impacts of the Indian Ocean dipole on the atmospheric circulation and climate will be revealed without the consideration of ENSO.

4.1 *The influences on Asian summer monsoon*

Since the Asian monsoon, particularly Asian summer monsoon has important impact on the life and economy in this area, our attention will focus on the influence of Indian Ocean dipole on the Asian monsoon system first. The anomalous circulation patterns at 850 hPa in summer (June–August) for the positive phase and negative phase of the Indian Ocean dipole





(Fig. 3) showed the difference of the Asian monsoon activity in different phase of the dipole. Corresponding to the positive phase of the Indian Ocean dipole, there are southeasterly wind anomalies over the equatorial Indian Ocean, anomalous westerly wind over Indian Peninsula and anomalous westerly wind over the region from the Bay of Bengal to the South China Sea. This means that the summer monsoon over the South China Sea and Indian Peninsula are stronger in the positive phase of the Indian Ocean dipole. Corresponding to the negative phase, the summer monsoon is weaker over the South China Sea but stronger over the southern India. Because there are weaker southerly wind anomalies over the equatorial western Indian Ocean, weaker northwesterly wind anomalies over the equatorial eastern Indian Ocean, westerly wind anomalies over the southern Indian Peninsula and easterly wind anomalies over the region from the South China Sea to the Bay of Bengal. Therefore, from the synoptic point of view, the Asian summer monsoon will be directly related to the Indian Ocean dipole.

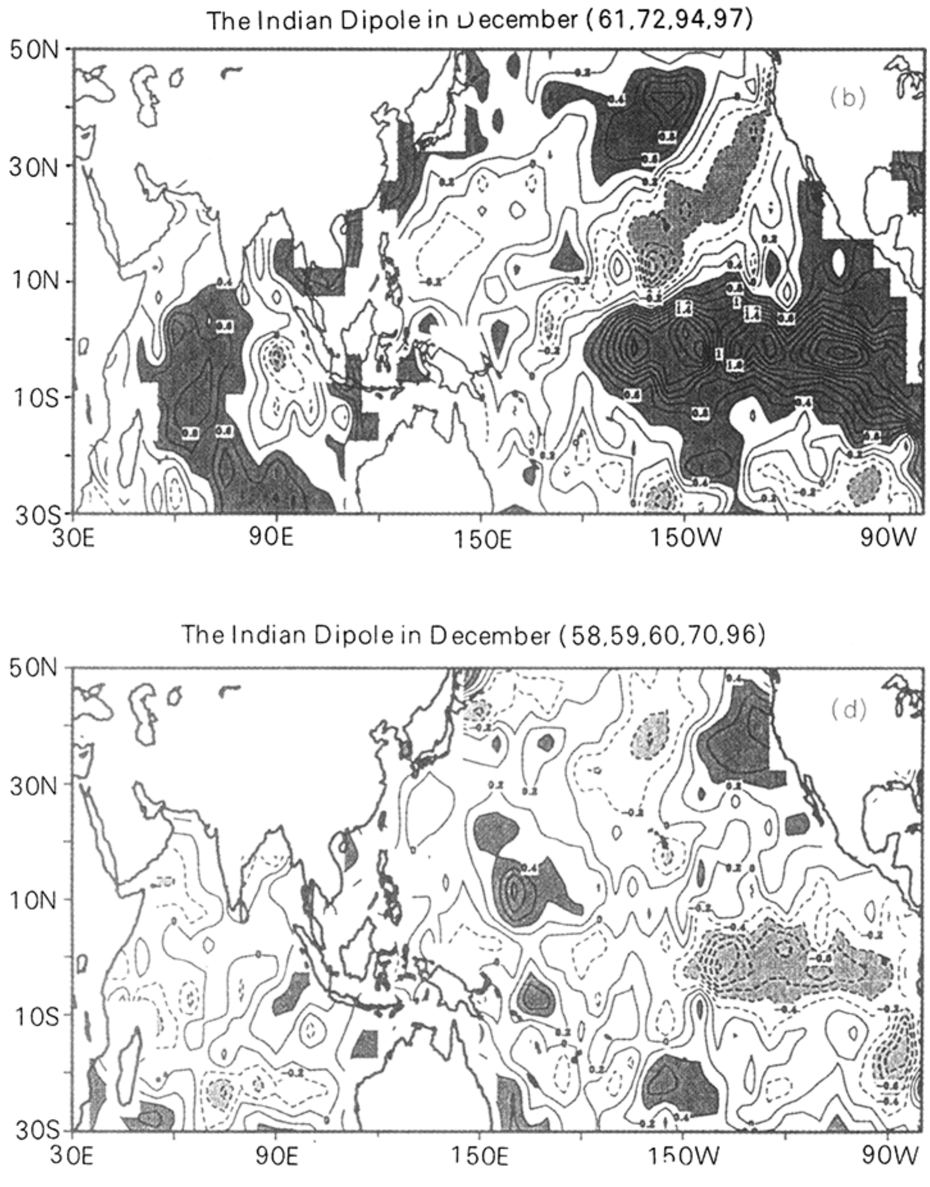


Fig. 2. Composite patterns of SSTA for positive phase (1961, 1972, 1994 and 1997) and negative phase (1958, 1959, 1960, 1970 and 1996) of Indian Ocean dipole. (a) July positive phase, (b) December positive phase, (c) July negative phase, (d) December negative phase.

It is known that the anticyclone in upper troposphere over the Qinghai–Xizang Plateau (called Tibetan high or South Asia high) is an important component of the Asian summer monsoon system, the intensity of South Asia high can partly represent the activity of the Asian summer monsoon. In order to show further the influence of the Indian Ocean dipole on the Asian summer monsoon, the correlation coefficients of the Indian Ocean dipole index with the geopotential height at 200 hPa calculated by using the NCEP reanalysis data (1958–1997) are given in Fig. 4. It shows clearly that the dipole index has negative correlation with the intensity of the South Asia high and a strong negative correlation center is over the Tibetan Plateau. In other words, the South Asian high is weaker (stronger) in the positive

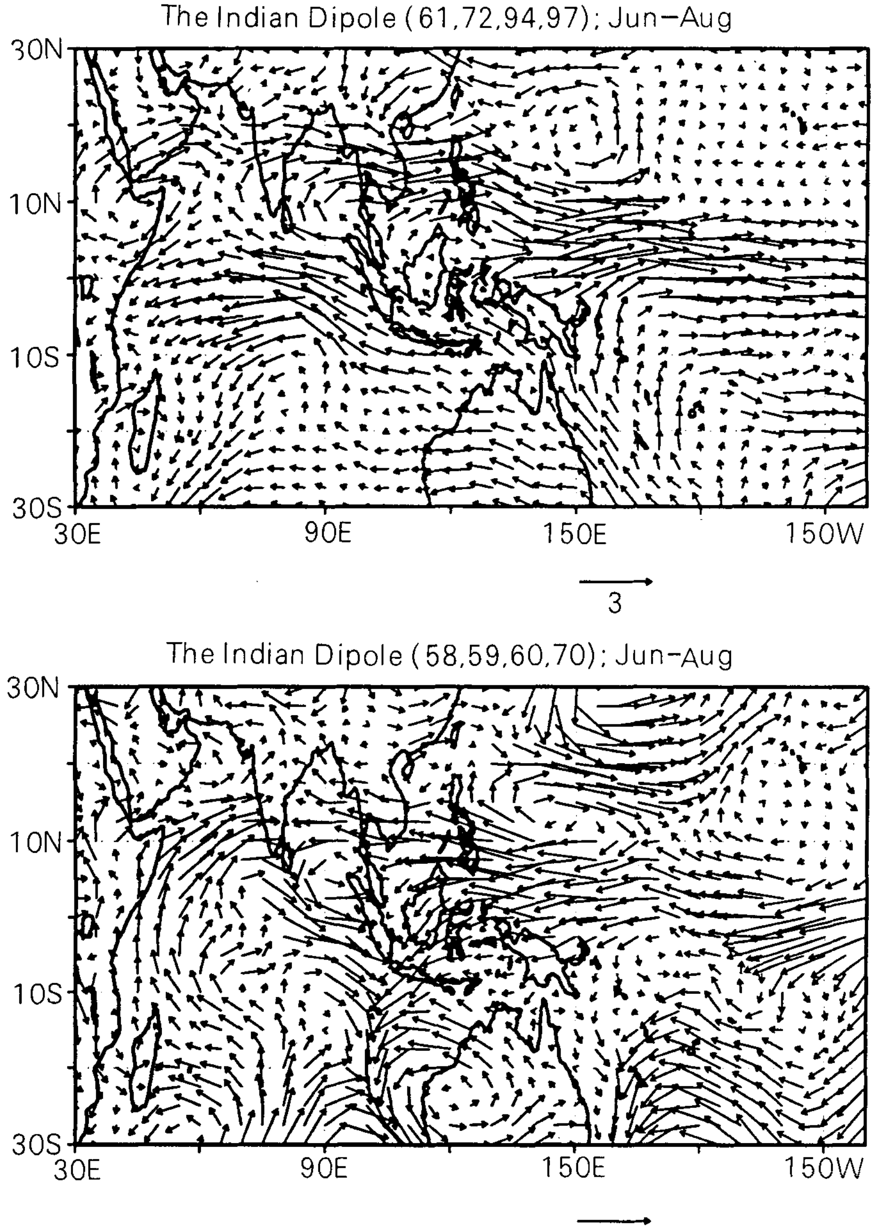


Fig. 3. The circulation patterns at 850 hPa in summer (June–August) over South Asia in the positive phase (a) and negative phase (b) of the Indian Ocean dipole, respectively.

(negative) phase of the Indian Ocean dipole. The influences of South Asia high on the Asian summer monsoon, especially the East Asian summer monsoon, have been investigated in some studies (Tao and Zhu, 1964; Luo et al., 1982). Therefore, the influence of the Indian Ocean dipole on the Asian summer monsoon is in the affirmative, especially on the East Asian summer monsoon.

The subtropical high over the northwestern Pacific is also an important component of the East–Asian summer monsoon system, and it is an important climate system to cause climate anomalies in East Asia (Huang and Yu, 1972; Tao et al., 1998). It is also clearly shown

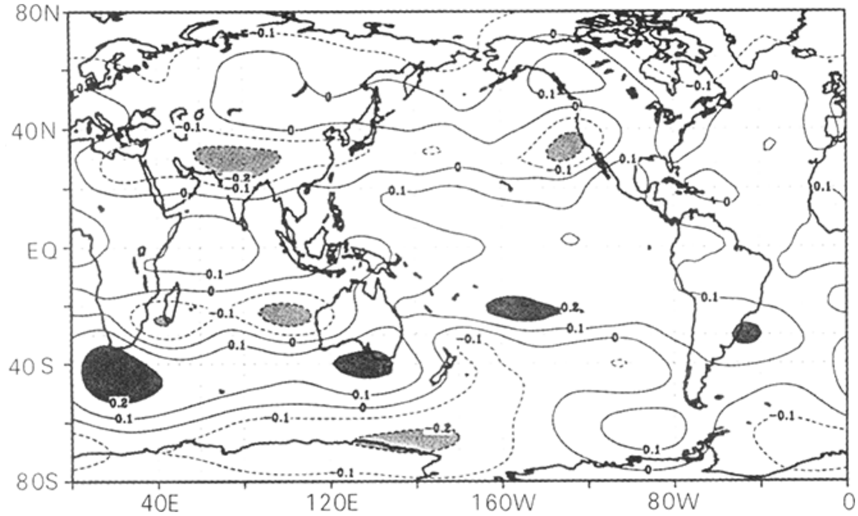


Fig. 4. Distribution of correlation coefficient of the Indian Ocean dipole index with the geopotential height at 200 hPa over the globe. The shadow represents the area, in which the correlation coefficient is more than statistical significance test.

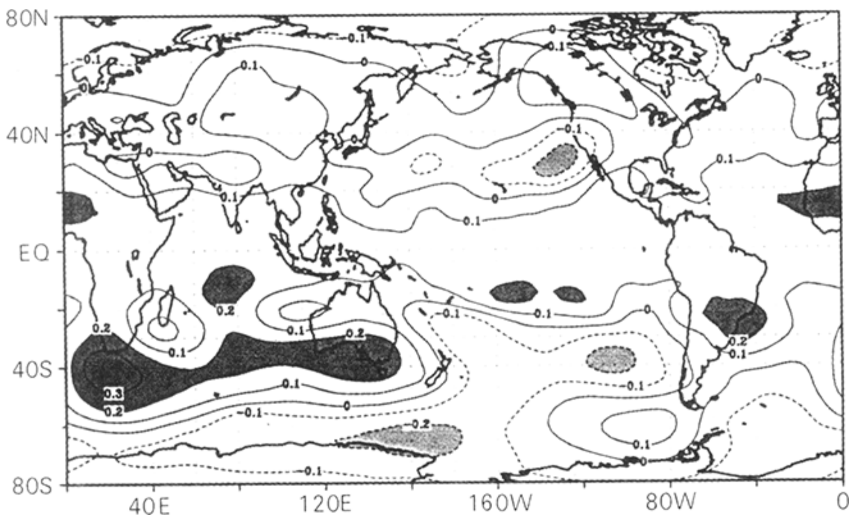


Fig. 5. Same as Fig. 4, but for the geopotential height at 500 hPa.

in Fig. 5 that the subtropical high over the North western Pacific is related to the Indian Ocean dipole, in which the distribution of correlation coefficient of the Indian Ocean dipole index with the geopotential height at 500 hPa over the globe is given. There is a stronger negative correlation zone in 25°–40°N latitudes over the North Pacific and means that the subtropical high is weaker (stronger) in the positive (negative) phase of the Indian Ocean dipole. Over the East Asian continent, the positive correlation is also shown in Fig. 5 and means that there exists an anomalous ridge (trough) at 500 hPa over the East Asian continent corresponding to the positive (negative) phase of the Indian Ocean dipole.

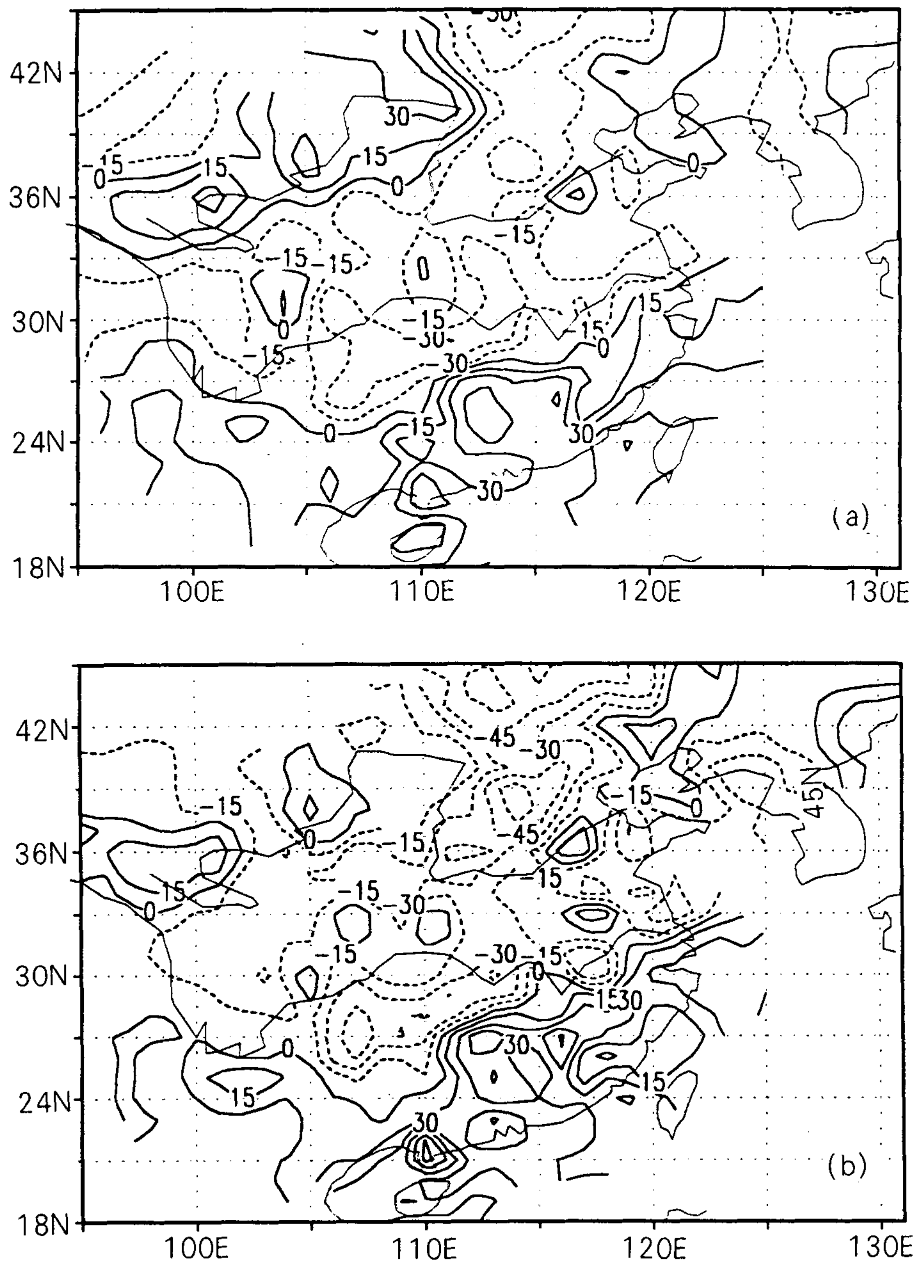


Fig. 6. Summer precipitation anomalies in China corresponding to the positive phase of the Indian Ocean dipole (a) and the differences of summer precipitation anomalies between the positive phase and negative phase of the Indian Ocean dipole (b).

The precipitation anomalies in Eastern China during summer can also reveal the influence of the Indian Ocean dipole on Asian summer monsoon, particularly on the East Asian summer monsoon. The composite precipitation anomalies during summer (June – August) in China corresponding to 4 strong positive phase years and their difference from 5 strong negative phase years are shown in Fig. 6, respectively. Although the Indian Ocean dipole is weaker in summer as we indicated, the figure still showed that the positive (negative) phase of the Indian Ocean dipole is advantageous (not advantageous) to the summer rainfall in southeastern China, southern China, Yunnan and Qinghai regions but not advantageous (advantageous) to the summer rainfall in the other regions of China.

4.2 *The influences on atmospheric circulation and climate in other regions*

Strong correlation zone in 40°–50°S latitudes over the southern Indian Ocean and in the western coast of North America can be also shown in Fig. 4 and Fig. 5. This means that the variations of atmospheric circulation and climate in those regions are related to the Indian Ocean dipole.

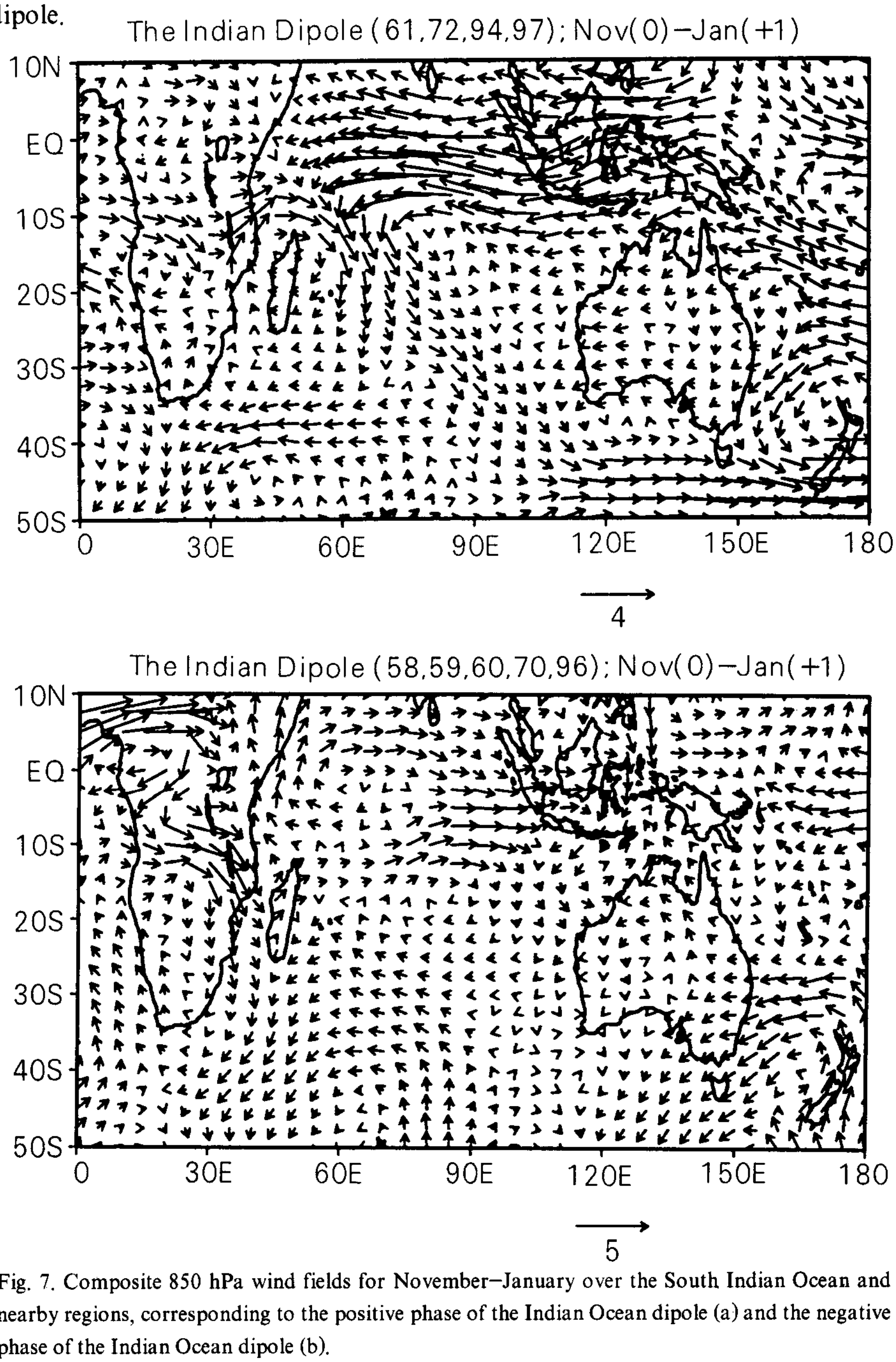


Fig. 7. Composite 850 hPa wind fields for November–January over the South Indian Ocean and nearby regions, corresponding to the positive phase of the Indian Ocean dipole (a) and the negative phase of the Indian Ocean dipole (b).

The correlation coefficients between the Indian Ocean dipole index and the geopotential heights at 200 hPa and at 500 hPa all have a strong negative center over the northeastern Pacific / western coast of North America region. Therefore, there is an anomalous trough (ridge) at upper troposphere over the western coast region of North America corresponding to the positive (negative) phase of the Indian Ocean dipole. Thus, the weather and climate in the USA, particularly in the western region, will be impacted prominently.

Figure 7 shows the composite wind field at 850 hPa in November–January corresponding to the positive phase and negative phase of the Indian Ocean dipole, respectively. Obviously, systemic wind anomalies appear in Australia region and South Africa region. During the positive phase of the Indian Ocean dipole, there are easterly wind anomalies over northeastern Australia and the cyclonic circulation over southwestern Australia and western South Africa. During the negative phase of the dipole, there are easterly wind anomalies over southeastern Australia and an anticyclonic circulation over South Africa. These different circulation patterns will lead to different climate variation in the above mentioned regions. Therefore, the Indian Ocean dipole will also impact obviously the atmospheric circulation and climate in the Southern Indian Ocean region including south Africa and Australia.

5. Omen significance of the Indian Ocean dipole

Since the variations of atmospheric circulation and climate in some regions have been shown to lag the variation of the dipole in the present study, the Indian Ocean dipole index can be one of the indicators for coming climate variation in some regions.

Figure 8 shows the distributions of correlation coefficients of the dipole index five months ahead of global geopotential height at 200 hPa and 700 hPa (similar to that at 500 hPa), respectively. It is shown clearly that there is an obvious PNA pattern over the eastern Pacific / the North America region and a negative value center of lag correlation coefficient over the Tibetan Plateau. Therefore, the positive (negative) phase of the Indian Ocean dipole can be regarded as a factor to predict the appearance of inverse (direct) PNA pattern and weak (strong) Tibetan high after 5 months. Although the geopotential height is not the best to use in the tropics, Fig. 8 still indicated that the easterly wind will be enhanced (weakened) in all tropical troposphere after the occurrence of positive (negative) phase of the Indian Ocean dipole for 5 months.

6. Conclusion

Based on above data analyses, some interesting results on the Indian Ocean dipole can be sum up as follows:

(1) A zonal oscillation as the dipole exists in the SST or SSTA in the equatorial Indian Ocean. This Indian Ocean temperature dipole is of interannual variation (4–5 year period) and interdecadal variation (25–30 year period); and its seasonal variation is also clear, stronger in September–November but weaker in January–April.

(2) Two major patterns of the dipole are: higher SST in the west and lower SST in the east of the equatorial Indian Ocean; higher SST in the east and lower SST in the west. The former is defined as the positive phase and the latter the negative phase of the Indian Ocean dipole, respectively. In general, the dipole is stronger in the positive phase than that in the negative phase.

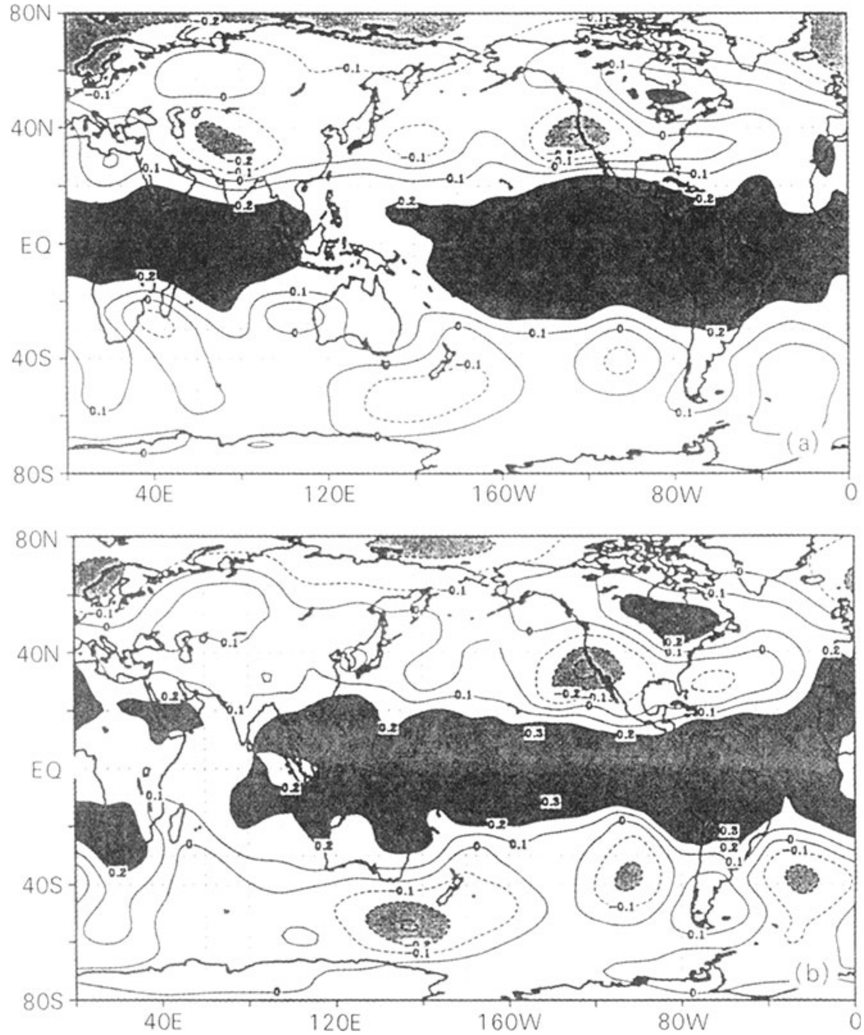


Fig. 8. Global distribution of correlation coefficient between the Indian Ocean dipole index and geopotential height at 200 hPa (a) and 700 hPa (b) with the dipole index five months ahead of the geopotential height.

(3) The Indian Ocean dipole will directly affect the Asian summer monsoon through impacting the lower tropospheric wind field. Corresponding to the positive phase of the Indian Ocean dipole, stronger summer monsoon can be identified over India and South China Sea. But summer monsoon is weaker over the South China Sea and stronger over southern part of Indian Peninsula corresponding to the negative phase of the Indian Ocean dipole.

(4) The Tibetan high as well as subtropical high are getting weaker (stronger) due to the occurrence of the positive (negative) phase of the Indian Ocean dipole. Since the Tibetan high and subtropical high over the northwestern Pacific are important components of the Asian–summer monsoon system, the Indian Ocean dipole can also affect indirectly the Asian–summer monsoon (particularly the East Asian summer monsoon) through affect-

ing the Tibetan high and the subtropical high.

(5) Corresponding to positive (negative) phase of the Indian Ocean dipole, there is an anomalous upper trough (ridge) over the western coast of North America. So the weather and climate will be impacted prominently in the USA, particularly in the western region of USA. The Indian Ocean dipole can also lead to the change of atmospheric circulation and climate in Australia and South Africa regions.

(6) The positive (negative) phase of the Indian Ocean dipole can be regarded as one of the factors used to predict the occurrence of inverse (direct) PNA pattern and the weak (strong) Tibetan high in five months.

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印度洋偶极子对大气环流和气候的影响

李崇银　　穆明权

摘　要

赤道印度洋 SST 的分析研究证实了偶极子型振荡的存在，它在 9–11 月较强而在 1–4 月较弱。若以海温西高东低为偶极子振荡正位相，以海温东高西低为负位相，则一般是正位相时振荡要强于负位相。印度洋偶极子也存在年际(主要周期为 4–5 年)和年代际(主要周期为 25–30 年)变化。分析研究表明，印度洋偶极子对亚洲季风活动有明显影响，因为亚洲地区对流层低层的风场，南亚高压和西太平洋副高强度都与印度洋偶极子有关。另外，印度洋偶极子还对北美和南印度洋(包括澳大利亚和南美)地区的大气环流和气流有影响。

关键词：印度洋偶极子，海温异常(SSTA)，亚洲季风，气候影响