

The Leading Mode of Indian Ocean SST and Its Impacts on Asian Summer Monsoon*

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ABSTRACT

The Indian Ocean (IO) sea surface temperature (SST) was analyzed by using empirical orthogonal function (EOF), and the leading mode of Indian Ocean (LMIO) SST was extracted. The major spatial and temporal characters of LMIO were discussed, and the relationships between LMIO with Indian summer monsoon (ISM) and with China summer rainfalls (CSR) were investigated, then the impacts of LMIO on Asian summer monsoon (ASM) circulation were explored. Some notable results are obtained: The significant evolutionary characters of LMIO are the consistent warming trend of almost the whole IO basin, the distinctive quasi-3- and quasi-11-yr oscillations and remarkably interdecadal warming in 1976/1977 and 1997/1998, respectively. The LMIO impaired the lower level circulation of ISM and was closely related with the climate trend of CSR. It was associated with the weakening of South Asian high, the easterly winds south of the Tibetan Plateau, and the cross-equatorial flows over 10° – 20° N, 40° – 110° E at the upper level; with the strengthening of Somali cross-equatorial jet but the weakening of the circulation of ISM in the sector of India, the strengthening of south wind over the middle and lower reaches of Yangtze River and South China but the weakening of southwesterly winds over North China at lower level and with the increasing of surface pressure over the Asian Continent. Changes in the moisture flux transports integrated vertically over the whole troposphere associated with LMIO are similar to those in the lower level circulation. To sum up, the significant SST increasing trend of IO basin was one of the important causes for weakening of the ASM circulation and the southwards shifting of China summer rainband.

Key words: leading mode of Indian Ocean (LMIO) SST, China summer rainfalls (CSR), Indian summer monsoon (ISM), Asian summer monsoon (ASM), water vapor transport

1. Introduction

Strong evidences indicated that Asian summer monsoon (ASM) showed significant interdecadal variations (Wang, 2001; Yang and Lau, 2004; Joseph and Simon, 2005), and both the Indian summer monsoon (ISM) and East Asian summer monsoon (EASM) showed a consistent decreasing trend during the recent 50 years (Joseph and Simon, 2005; Yang and Lau, 2004). The ISM had significantly decreased in the middle 1960s, end 1970s, and middle 1990s, respectively (Joseph and Simon, 2005). The EASM also weakened after the end 1970s (Wang, 2001). Meanwhile, some researches showed that the inverse rela-

tionship between ISM and ENSO (El Niño/South Oscillation) had broken down in recent decades (Kumar et al., 1999), which triggered the researchers to explore the reasons why the relationship changed and if there were some other factors playing more important role in the variation of ASM under certain climate background. Li and He (2000) elucidated that the key region affecting EASM was not invariable but diverted from one area to another because of the decadal variation of air-sea interaction, and regarded the PDO (Pacific decadal oscillation) as a possible factor inducing the EASM weakened. Some researches (Zhou and Huang, 2003; Yang and Lau, 2004) related the weakening of EASM with “ENSO-like mode” (obvious

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interdecadal SSTA variability appeared in the tropical Pacific).

The relationship of ASM (including ISM and EASM) was changed during recent decades which had been noticed by many researchers as detailed above, and aroused the researchers to find the more important factors in the IO because it is the direct underlying surface of several subsystems of ASM. The impacts of IO SST on ASM and on the regional climate were widely concerned and studied by many researchers. Ashok et al. (2001) believed that the Indian Ocean dipole (IOD) broken the relationship of ENSO apparently because the IOD could influence ISM independently and the anomalous meridional circulation induced by the IOD could weaken or intensify the anomalous circulation induced by ENSO, which depends on the phases and strengths of these two tropical phenomena. Wang et al. (2003) also held this opinion. Gadgil et al. (2004) pointed out that the interplay between ENSO and the IOD mode could lead to different patterns of SST and OLR anomalies over the equatorial IO. As we noted, although the IOD was considered as the second EOF mode of tropical IO SST anomalies (SSTA) and refined to tropical IO region, the phenomenon and its impacts were widely labored on by many researchers since it was brought forward by Saji et al. (1999) and regarded as an important climate factor. But the dominant mode of IO SSTA was gotten much less concerns compared to IOD. In fact, some researchers have noticed the mode, e.g., Tan et al. (2004) indicated that the most significant mode of IO (LMIO) SSTA had the same SSTA sign at basin scale and named it as the monopole mode, and their studies showed that the SSTA in the tropical IO could change from IOD to monopole.

In this paper, the leading mode of IO (LMIO) SSTA was extracted and analyzed. In order to obtain more convincing results, the studying domain is covering the tropical IO and extratropical IO. The relationship between LMIO and ISM is analyzed, and that between LMIO and China summer rainfalls (CSR) is investigated as well; then the impacts of LMIO on ASM are explored.

2. Data and methods

The analyses in this study are based on sev-

eral datasets: the extended reconstructed sea surface temperature (ERSST) monthly dataset provided by the National Oceanic and Atmospheric Administration (NOAA), with a resolution of $2^\circ \times 2^\circ$; the European Centre for Medium-range Weather Forecasts (ECMWF) 40-yr monthly mean reanalysis fields from September 1958 to August 2002, with a resolution of $2.5^\circ \times 2.5^\circ$; the ISMR (Indian summer monsoon rainfalls) data derived from the rain gauge in situ observations offered by the Indian Institute of Tropical Meteorology (IITM) from 1891 to 2003; and Chinese 160-station monthly rainfalls, the derived 74 circulation parameters and Meiyu index from January 1951 to December 2005 provided by Beijing Climate Center (BCC).

The methods used in this investigation include: the empirical orthogonal function (EOF) method and the singular value decomposition (SVD) method (Wei, 1999); the wavelet analysis by using Morlet function (Torrence and Compo, 1998); the low pass filter methods (Ding, 1989); and the correlation analysis and testing method (Wei, 1999).

3. The large-scale variation of IO SST

The IO SSTA from January 1951 to December 2005 are analyzed by using EOF method. The dominant mode (first EOF mode or EOF1) is obtained and named as the leading mode of IO (LMIO) SSTA. The LMIO explains 36.3% of the total variance. Its spatial distribution (Fig.1a) shows that the positive characteristic values are distributed in almost the whole IO basin excluding the sea south of the Cape of Good Hope, and the very significant characteristic values are spread north of 30°S . Its time coefficients (Fig.1c) show a consistent increasing trend. Figures 1b,d show that the LMIO is a long-time scale mode of IO SST with significant 3 yr or longer cycles, especially the cycle longer than 10 yr. There are twice abrupt ascendings in 1976/1977 and 1997/1998, and after each abrupt warming, the time coefficients of LMIO reach and keep a new high level respectively.

The IO SST data are treated with low passed filters of 3 and 10 yr, and then decomposed using EOF respectively. The EOF1 spatial distributions (figure omitted) are just imitated Fig.1a, but both of them

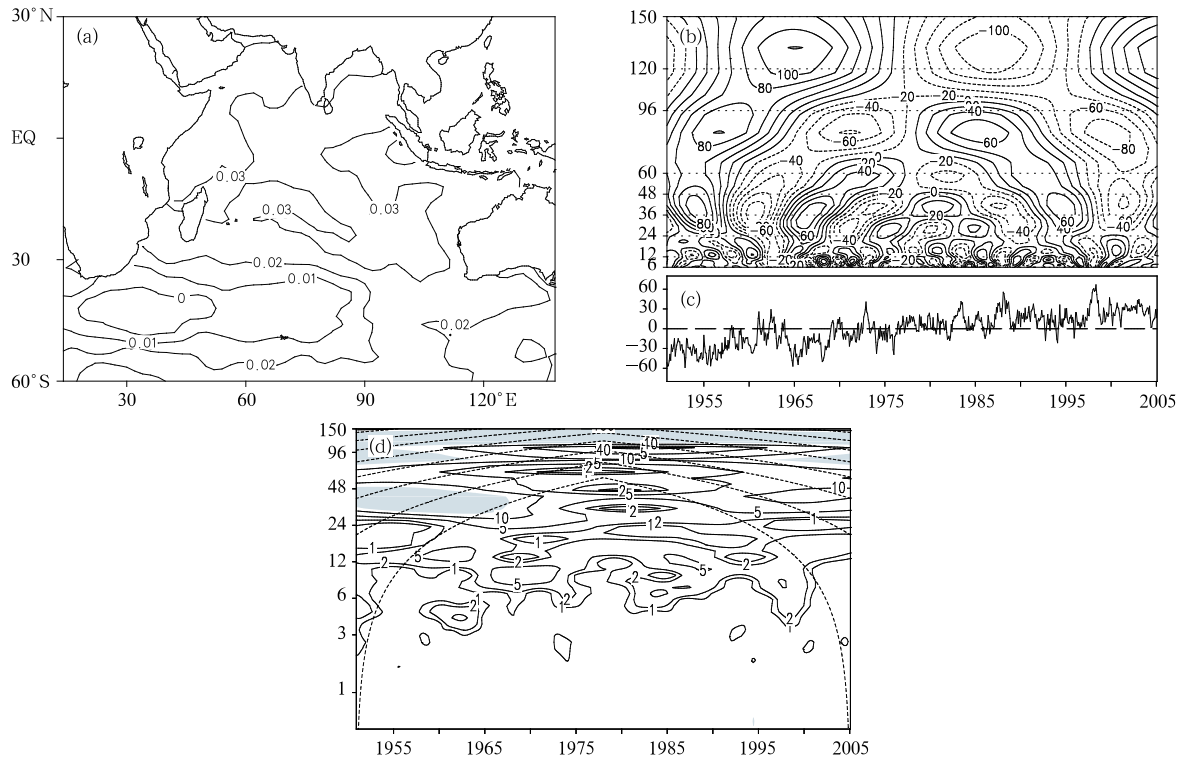


Fig.1. The EOF1 pattern of characteristic value distribution (a) and the time coefficients (c) for IO SSTA; the real part (b) and local power spectrum (d) of wavelet analysis of the time coefficients. The shaded area denotes the significance level passing 0.05 and the dashed contours indicate the “cone of influence” in (d).

account for the total variance above 85%. The analysis denotes that the LMIO is a large-scale and long-time scale mode which represents a remarkable and consistent warming trend of almost the whole IO basin during recent 50 years.

The data are divided into four seasons, and all the distributions of EOF1 for IO SSTA of four seasons (figures omitted) are just taken on the distribution of LMIO of entire sequences. The time coefficients of LMIO in the four seasons (Fig.2) also show twice

abrupt warmings. Their cross correlations of the four-season LMIO (Table 1) show a very close connection.

As an upstream area, the IO is a main source region to transport a great deal of water vapor and energy to ASM region; and as a direct underlying surface of several subsystems of Asian-Australian monsoon, the variation of IO SST, including the significant warming trend should impact the ASM system, the circulation and the rainfalls of ASM region.

Table 1. Cross correlation between LMIO in prior winter and spring, summer, autumn

	Prior winter	Spring	Summer	Autumn
Prior winter	1			
Spring	0.8961	1		
Summer	0.7886	0.9224	1	
Autumn	0.6952	0.8031	0.8917	1

4. The relationship between LMIO and ISM

The ISM represents a large-scale heat source and Goswami et al. (1999) believed that it must be closely

related to Hadley circulation. The meridional velocities averaged over 10°–30°N, 70°–110°E, at 850 hPa (V_{850}) and 200 hPa (V_{200}) have a very close inverse relationship and their correlation coefficient reaches

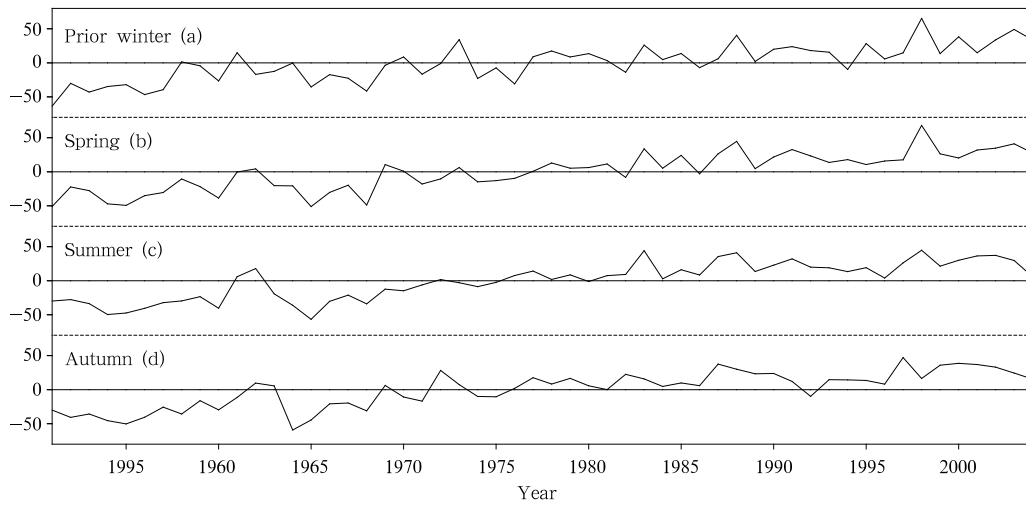


Fig.2. The LMIO of prior winter (a) and spring (b), summer (c) and autumn (d).

−0.7818. The annual cycle of V_{850} and V_{200} (Fig.3) shows that V_{850} turns to south in March but the speed is small; while V_{200} changes to north in June and at the same time the speed of V_{850} increases significantly. Such a phase situation can sustain till September, and after that, it reverses very suddenly and the meridional velocities in lower level change to north while in higher level change to south. According to the linear theory of the atmospheric response proposed by Gill (1980), Goswami (1999) defined a monsoon Hadley index (M_H) to describe the variation of ISM:

$$M_H = V_{850}^* - V_{200}^*,$$

where V_{850}^* and V_{200}^* are the meridional wind anomalies averaged over the season (June–September) and over the extended monsoon region (10° – 30° N, 70° – 110° E) at 850 and 200 hPa, respectively (Fig.4).

The correlations between M_H and LMIO in different seasons are listed in Table 2. Both V_{850}^* and V_{200}^* have inverse relation with LMIO in different seasons, especially V_{200}^* , which indicates that with the warming of almost the whole IO SST, the south meridional winds in lower level are decreased, while the north

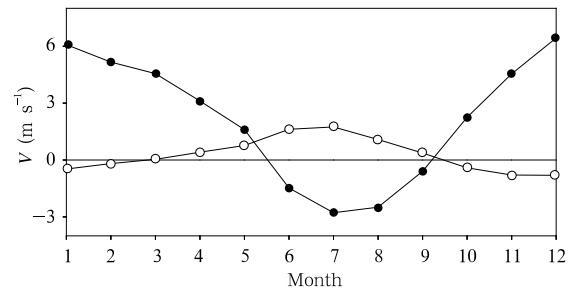


Fig.3. Multi-year mean (1958–2001) annual cycle of V_{850} (open circles) and V_{200} (solid circles).

meridional winds in higher level are increased. But M_H is jointly influenced by V_{850}^* and V_{200}^* and positively related with LMIO. The ISMR has a positive correlation with LMIO. As a matter of fact, the ISMR has a weakly decreasing trend. Therefore the warming trend of the whole IO SST cannot interpret the decreasing trend of ISMR. Joseph and Simon (2005) indicated that the lower level circulation over India has been weakened in recent 50 years and the analysis above suggests that the LMIO may be one of the positive factors for the circulation weakening.

Table 2. The correlations of LMIO in different seasons with V_{850}^* , V_{200}^* , M_H , and ISMR from 1958 to 2001

	V_{850}^*	V_{200}^*	M_H	ISMR
LMIO (prior winter)	−0.0599	−0.4006***	0.3100**	0.2951*
LMIO (spring)	−0.1635	−0.4089***	0.2710*	0.1990
LMIO (summer)	−0.2706*	−0.3353**	0.1615	0.0818

Note: Superscripts “*”, “**”, and “***” after the correlations denote the significance levels passing 0.1, 0.05, and 0.01, respectively.

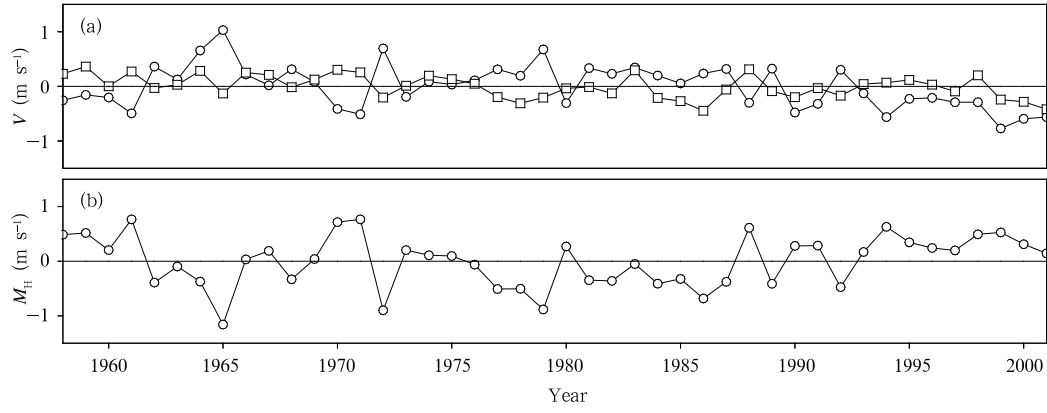


Fig.4. Multi-year (1958–2001) time series of (a) V_{200}^* (open squares) and V_{850}^* (open circles) and (b) M_H .

5. The relationship between LMIO and CSR

The relationships between Chinese 160-station summer rainfalls (right field) and IO SSTA (left field) are analyzed by using SVD method and the heterogeneous correlation patterns for first SVD mode (SVD1)

of left field (Fig.5a) just imitate the EOF1 mode. According to the Haylock-McBride hypothesis (Haylock and McBride, 2001), the predictability for a large-scale domain requires spatial coherence over the domain, and the coherence can be quantified as having large amplitude in the low-order EOFs. The study by

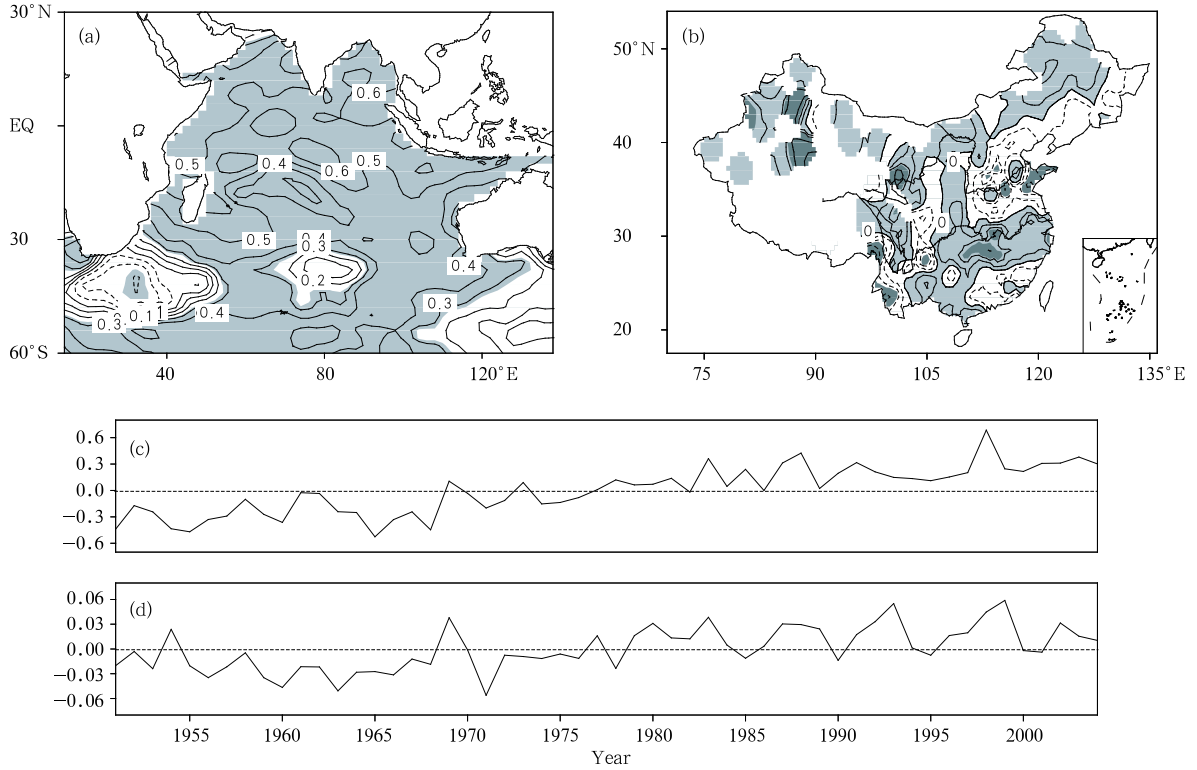


Fig.5. The SVD1 heterogeneous correlation patterns of spring IO SST (left field) (a), 160-station summer rainfalls in China (right field) (b), and temporal coefficients of left (c) and right (d) fields from 1951 to 2004. The shaded area indicates the significance level passing 0.05 in (a); the light shaded area denotes positive correlation region, dashed line denotes negative correlation, dark shaded area denotes the significance level passing 0.05 in (b); and the interval of contours is 10% in (a, b).

Yang et al. (2007) showed that the EOF2 of spring IO SSTA has a distinct dipole mode distribution extending from tropical to extratropical region and named it as SIOD (South Indian Ocean dipole), and the SIOD has significant impacts on IMSR and North China summer rainfalls. In order to keep the continuity of the study, we just detailed the impacts of LMIO in spring below. In fact, the correlations of CSR with other seasons' LMIO are similar to that with spring LMIO (figures omitted).

The SVD1 heterogeneous correlation pattern of CSR (Fig.5b) exhibits that the rainfall correlations over the region east to Hetao area, south of Northeast China, eastern South China, and western Southwest China are negative, while the region of mid-lower reaches of the Yangtze River, north of Northeast China, and Northwest China are positive. Both of the temporal coefficients of left and right fields (Fig.5c,d) show the ascending trend but the former is much more significant than the latter; the relationship between them reaches 0.683 which is above the significance level 0.001. The regression coefficient distribution for 160-station CSR (Fig.6) reflecting the interdecadal linear trend of CSR is similar to the first SVD in Fig.5a, the similarity degree between the two fields reaches 0.7647 which passes the significance level 0.001 and indicates that the interdecadal linear trend of CSR is linked to LMIO.

The Meiyu over the mid-lower reaches of the Yangtze River is one of the most important synoptic and climatic systems in China and the prediction of Meiyu precipitation is vital. The summer rainfalls of the mid-lower reaches of the Yangtze River have positive correlations with LMIO in the SVD analysis above, and we put more efforts to explore the relationship between the Meiyu percentage index and LMIO. By comparing the temporal coefficients of LMIO with Meiyu percentage index (Fig.7), it can be seen that the LMIO is at a very low level phase before the 1960s and has an inverse linkage to Meiyu index, but at a

high level phase after 2000 it has little relationship with Meiyu index; while between these two periods, the LMIO has a positive relationship with Meiyu percentage index. If take the two periods into account, all the correlations of Meiyu percentage index with LMIO in prior winter and spring, summer in the same year are very little; while after removing the two periods, the positive correlations increase largely, especially with spring LMIO (Table 3). The relationship between LMIO and Meiyu is changed and shows an interdecadal variation.

Some studies (Wang et al., 2004; Ren et al., 2005) indicated that the rainfalls over north of Northeast China, southeast of the mid-lower reaches of the Yangtze River, and most regions of western China were increased, while the rainfalls over Northwest China, southeast of Northeast China, and east of Northwest China were decreased, and the SVD analysis above indicates that the trend of CSR during recent 50 years is closely related to the SST warming trend of the whole basin of IO. The impacts of LMIO on the ASM will be analyzed in details to interpret how the southward shifting trend of China summer main rainband is related to LMIO.

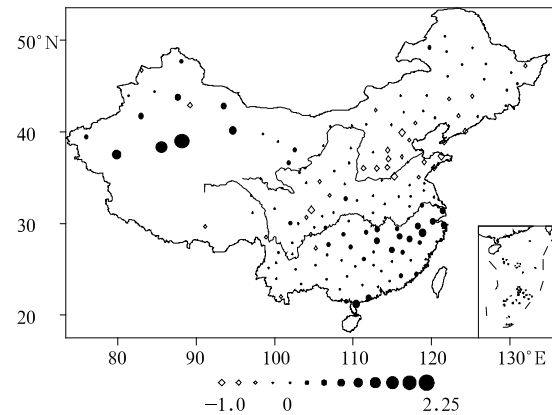


Fig.6. The distribution of regression coefficient b (multiplied by 100) for 160-station summer rainfalls in China from 1951 to 2004 (the mark label interval is 0.25).

Table 3. The correlations of LMIO of prior winter and spring, summer in the same year with Meiyu percentage index before and after eliminating the years before 1957 and after 2000

	LMIO (prior winter)	LMIO (spring)	LMIO (summer)
Meiyu percentage index	0.0467	0.1323	0.0597
Meiyu percentage index (eliminated)	0.2373	0.4112**	0.3195*

Note: Superscripts “*” and “**” denote the significance levels passing 0.05 and 0.01, respectively.

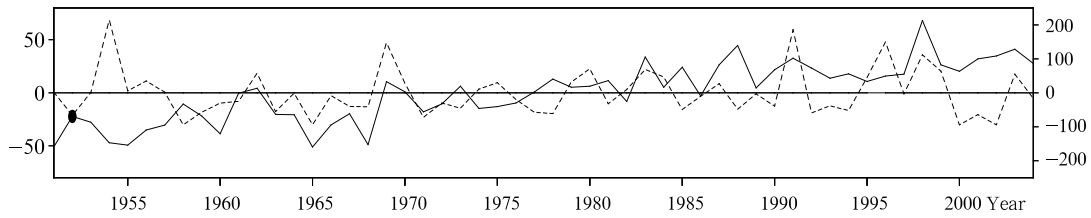


Fig.7. LMIO in spring (solid line, left ordinate) and Meiyu percentage index (dashed line, right ordinate).

6. The impacts of LMIO on ASM circulation

6.1 Surface pressure

The correlation pattern between spring LMIO and summer surface pressure from 1958 to 2002 (Fig.8) shows that the regions of Central and North India, Bay of Bengal, Indochina Peninsula, most areas of East Asia, and Qinghai-Tibetan Plateau are distributed with very significant positive correlations as well as African Continent and Australia; while the regions of IO and western Pacific are distributed with very small positive correlations. The surface pressure over Asian Continent increased significantly after the end of 1970s, which decreased the gradient force between land and sea and weakened the Asian monsoon (Wang, 2001). Therefore, LMIO or the SST warming trend in most part of the IO basin is one of the probable reasons inducing the Asian monsoon tend to weak.

6.2 Lower level circulation

The correlation vector distribution between spring LMIO and lower level flows (Fig.9) shows that the significant southwest correlation vectors distributed off Somali change to northwest vectors around 10°N , 80°E , meet the east vectors coming from India at East Arabian Sea, and then the confluent vectors direct to Sumatra and Java together. The significant northeast vectors above the regions south to the Tibetan Plateau and west of Indochina Peninsula direct and reach India. The region between 125° and 140°E is distributed with significant south correlation vectors, east to the area is the South China Sea which is distributed with the north vectors. The correlation vector distribution above East Asia is characterized by the notable convergence around 27°N , the vectors south of 27°N are directed to northward and those north of it are directed to southward. It can be in-

ferred that although the Somali jets are enhanced due to the warming trend of all basin IO SST, while the

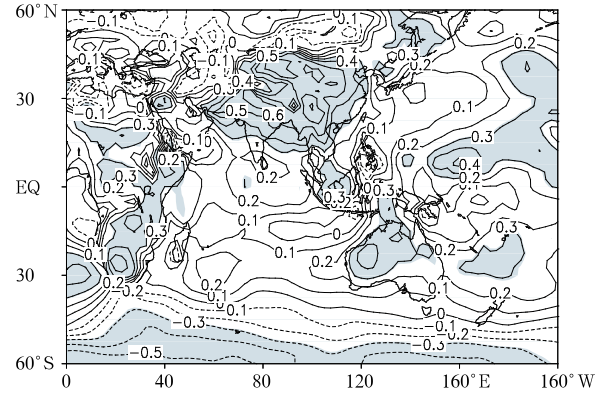


Fig.8. The correlation pattern of surface pressures in summer with spring LMIO from 1958 to 2002. Shaded area denotes the significance level passing 0.05.

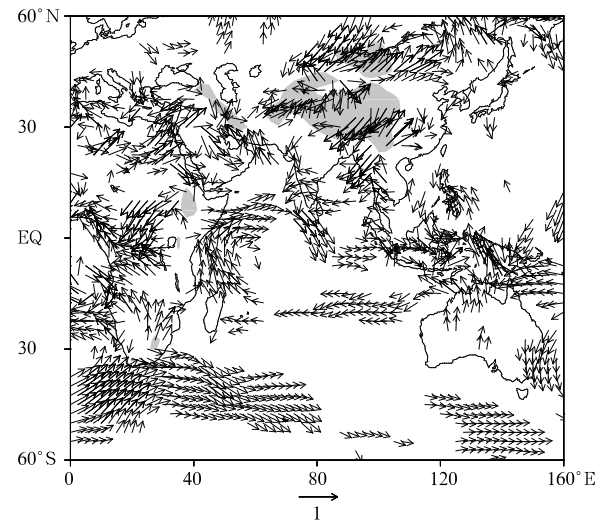


Fig.9. The correlation vector distribution between spring LMIO and summer winds at 850 hPa. Only significance levels of longitudinal or latitudinal correlations passing 0.05 are plotted.

ISM is weakened, which is consistent with the analysis in Section 4; and although the south flows above East Asia are enhanced, while those above North China are impaired significantly.

6.3 Western Pacific subtropical high

The western Pacific subtropical high (WPSH) is one of the most important subsystems of EASM and its variation directly impacts the CSR. The correlation pattern between summer geopotential height field at 500 hPa and spring LMIO (Fig.10) shows that the positive correlations spread from south of 25°N to all the tropical regions and extend to subtropical region of the Southern Hemisphere, and there is a center located to Southwest China. The correlations of LMIO in different seasons with several indices of WPSH (Table 4) reflect that the area and strength of WPSH are closely related to LMIO, especially spring LMIO, but the ridge line and western extending of WPSH are not

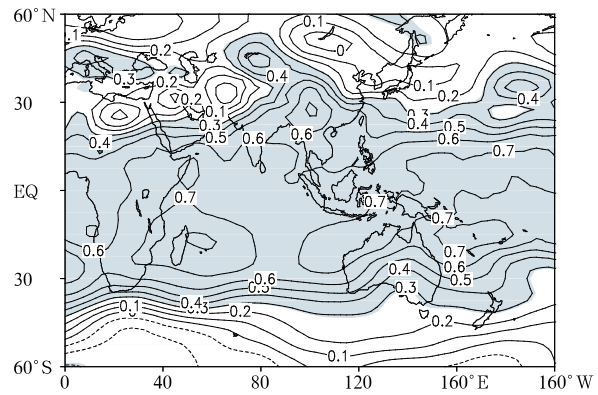


Fig.10. As in Fig.8, but for 500-hPa geopotential height fields.

so close. The analysis denotes that the increasing trend of LMIO during recent 50 years may be closely associated with the variation of WPSH in several aspects: the southward shifting of its ridge line, the enhancing of its strength and the enlarging of its area.

Table 4. The correlations of LMIO in different seasons with several indices of WPSH

	LMIO (prior winter)	LMIO (spring)	LMIO (summer)
Index of area of the WPSH	0.5012**	0.5189**	0.4234*
Index of strength of the WPSH	0.4504*	0.4767**	0.3965*
The ridge line of the WPSH	-0.1050	-0.0893	-0.1314
Index of the northern extending of the WPSH	-0.0738	-0.0625	-0.1379
Index of the western extending of the WPSH	-0.2215	-0.2092	-0.1275

Note: Superscripts “*” and “**” denote the significance levels passing 0.01 and 0.001, respectively.

6.4 Higher level circulation

The South Asian high (SAH) extending from Arab to East Asia with the main body over the Tibetan Plateau can be easily detected in the climate field of summer upper air. The correlation distribution between 200-hPa geopotential height field and spring LMIO (Fig.11) shows that the significant positive correlations spread from south of 30°N and extend to subtropical regions of the Southern Hemisphere and negative correlations spread over East Asia. Such distribution denotes that the LMIO may decrease the geopotential gradient force from north to south and hence impair the strength of SAH. The correlation vector distribution of upper air circulation with spring LMIO (Fig.12) is clear and denotes that the notable south vectors spread from the Arabian Sea, middle and south of India to north of the Bay of Bengal, i.e., the

upper air circulation located over these regions is enhanced; the easterly belt above South Tibetan Plateau is one of the important synoptic symbols of boreal

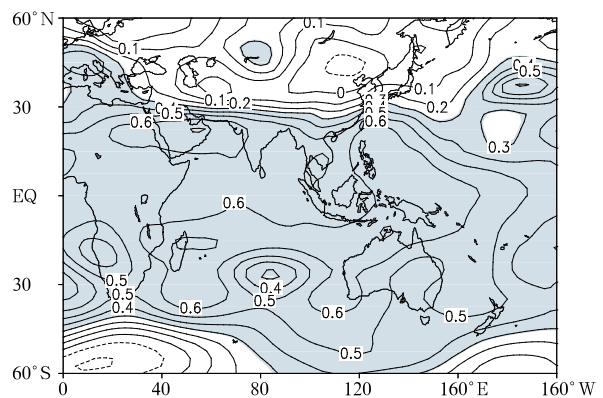


Fig.11. As in Fig.8, but for 200-hPa geopotential height field.

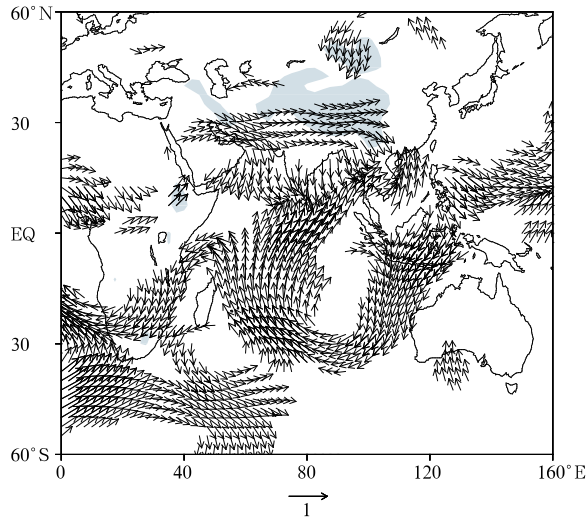


Fig.12. As in Fig.9, but at 200 hPa.

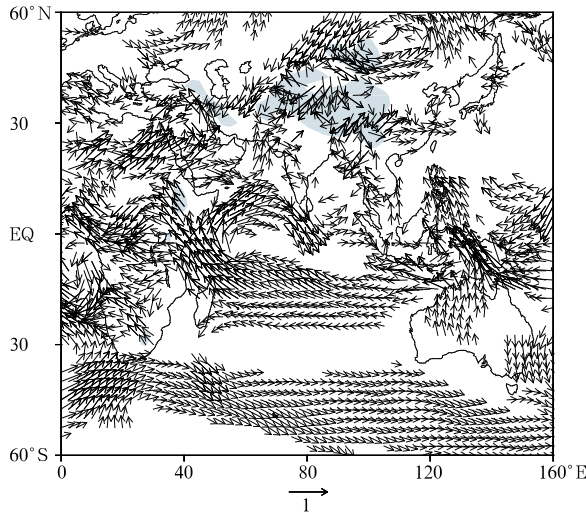


Fig.13. Correlation vector distribution of spring LMIO and vertically integrated water vapor transport fluxes of the entire troposphere in summer. Only significance levels of longitudinal or latitudinal correlations passing 0.05 are plotted.

summer circulation (Ye et al., 1958), while it is impaired due to the increasing trend of LMIO; the upper-air cross-equatorial flows from the South China Sea, Southeast Asia to Southeast IO are also impaired. As a whole, the LMIO with increasing trend impairs the summer monsoon circulation of upper air.

6.5 Water vapor transports

The cross-equatorial water vapor transports through Somali jets are quite important to the ISM;

while the water vapor transports from the IO, South China Sea, and West Pacific are all crucial to EASM. The vertically integrated water vapor transport fluxes in summer are calculated by using the method detailed in Huang et al. (1998), and their relationships with spring LMIO are presented in Fig.13 which is rather similar to the correlation vector distribution between lower level circulation and spring LMIO, and denotes that although the transport fluxes through Somali jets increase due to the warming trend of the whole basin IO SST, while they change the direction to southeastward around 10°N, 80°E and the transport fluxes to India do not increase but decrease; although the transport fluxes to middle and lower reaches of the Yangtze River increase, while to North China decrease.

7. Conclusions and discussions

The LMIO is extracted, and its spatial and temporal characters are discussed. Then its relationship with ISM and CSR is explored, and then, its impacts on the circulation and subsystems of ASM and on the summer water vapor transports are investigated. Major conclusions may be drawn as follows:

(1) The LMIO is a large-scale and long-time scale mode characterized by the warming trend of the whole IO SST, and it has distinctive quasi-3- and quasi-11-yr oscillations and remarkably interdecadal warmings in 1976/1977 and 1997/1998. After twice abrupt warmings, the IO SST remains at a higher level respectively.

(2) The LMIO impairs the lower level circulation of ISM.

(3) The LMIO is associated with the southward shifting of China summer rainband. It is closely related with reductions in the summer precipitation in North China, southern Northeast China, eastern South China, and western Southwest China, and with increases in the summer precipitation in the middle and lower reaches of the Yangtze River, northern Northeast China and Northwest China.

(4) The LMIO is associated with the weakening of SAH, the easterlies south of the Tibetan Plateau and the cross-equatorial flows over 10°–20°N, 40°–110°E at the upper level; with the strengthening of Somali cross-equatorial jet but the weakening of the

circulation of ISM in the sector of India, and the strengthening of south winds over the middle and lower reaches of the Yangtze River and South China but the weakening of southwesterly winds over North China at the lower level; and with the increase in the ground surface pressure over the Asian Continent. Changes in the moisture flux transports integrated vertically over the whole troposphere associated with LMIO are similar to those in the lower level circulation.

To sum up, the LMIO is one of the important causes for the weakening of the ASM circulation and the southward shifting of the rain belt of China. In many studies, the researchers took the interdecadal oscillation of Pacific SST for the reason inducing the ASM weakened and making the summer rainband of China shift southward; the conclusions in this study indicate that the SST warming trend of the whole IO basin is also close to such changes, which embody the co-variability of India-Pacific Oceans. The relationship between the LMIO and different regions of the Pacific Ocean will be detailed in the sequent study.

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