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NUMERICAL STUDY OF THE EFFECTS OF PERSISTENT WARMER SEA SURFACE TEMPERATURE IN TROPICAL INDIAN OCEAN ON ATMOSPHERIC CIRCULATION IN THE EARLY SUMMER IN EAST ASIA IN 1991

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ABSTRACT: By employing the CCM1 ($R_{15}L_{12}$) long-range spectral model, study is undertaken of the effects of sea surface temperature anomaly(SSTA) for tropical Indian ocean on circulation transformation in the early summer in East Asia in 1991. The results indicate that warmer SSTA contributes to the increasing of the temperature over the Plateau in early summer, resulting in the intensification of tropical easterly jet on 100 hPa and northward shift of Northern Hemisphere subtropical westerly jet in May. It is obviously favorable for the subtropical high enhancement over western Pacific Ocean in May and subtropical westerly jet maintaining at 35～40 °N in June, making the Mei-Yu come earlier and stay over the Changjiang basin in 1991. Furthermore, warmer SSTA is also advantageous to averaged temperature rise in East Asia land region and Nanhai monsoon development. These roles are helpful in accelerating the seasonal transition for East Asia in early summer.

Key words: persistent warmer SSTA; season transition in early summer; numerical simulations

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1 INTRODUCTION

The land-sea differences are so peculiar between the Indian Ocean and the Asian continent that they affect the generation and development of the Asian summer monsoon. Some meteorologists worked on the effect of SSTA of the Indian Ocean on monsoon circulation[1 – 3] while others deal with the statistic relationship between the former and precipitation during the Mei-yu period over the Changjiang-Huaihe River valleys[3, 4], laying the foundation for long-term weather forecasts. Over recent years, the anomalous state of the waters in the Indian Ocean has caused much concern in research community in terms of its role in regional and global climate variability. Webster et al.[5] first proposes a possible mechanism for interactions in the Indian Ocean waters and Wu et al.[6] study the allocation of SST in the Indian Ocean – Pacific Ocean and its importance in the variation of the general circulation. Furthermore, how does SSTA in the Indian Ocean affect the general circulation in East Asia? Particularly, will the persistent warming of wintertime SST speed up the transition of early summer in East Asia? As we know, East Asian seasonal transitions are the most dominant in the Northern Hemisphere and as the season shifts, drastic changes are taking place in various physical quantities of the general circulation and the drought / floods in summer are affected. It is then very important to study the anomalous variation of the general circulation of East Asia in early summer. Through numerical experiments, the current work simulates and studies the effects of persistently warming SST in tropical Indian Ocean on the variation of the general circulation in 1991.

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2 MODEL INTRODUCTION, EXPERIMENTS DESIGN AND VERIFICATION OF LONG-TERM FORECAST RESULTS

2.1 *Model introduction*

Taking full account of physical processes, surface hydrological processes and their interactions with the atmosphere, the CCM1 ($R_{15}L_{12}$) climate model from NCAR has been widely and successfully used over the past years in climate simulations. Improvements are made over the old model — the model initial values are supplied with any daily objectively analyzed data instead of data of fixed NCAR cases, as practiced previously, initialization techniques for non-linear equivalent equation are used to filter the gravity inertial waves in the initial values[7], and the method of iterative differences on the p-σ plane is used to increase the accuracy of initial values[8]; real terrain replaces the one in the old model to make model terrain more realistic; marine underlying data is set up that is updated monthly. With the above improvements, the CCM1 ($R_{15}L_{12}$) model has been successfully used in routine operation[9] and scientific research[10] of long-term numerical prediction with good results.

2.2 *Experiments design*

In the numerical experiment, the tropical Indian Ocean SSTA refer to those within the range of 30°S – 20°N. For the period from January to June 1991, the SST in the tropical Indian Ocean are anomalously warmer, with the monthly mean SSTA more than 0.38°C (the SST dataset is taken from the OISST monthly mean dataset of NCEP/NCAR and interpolated to 5°×5° gridpoints) and the number of gridpoints with positive anomalies all over 69% (Tab.1), over the region of experiment. Specifically, the mean SST anomaly is 0.64°C for May 1991 and the number of gridpoints with positive anomalies take up 90%, displaying a typical pattern of anomalously warmer SST in the tropical Indian Ocean.

For the two numerical experiments in the current work (Exp.<A> and Exp.<B>), the NCEP global objectively analyzed data at 12:00 UTC, January 1, 1991, are used as the initial field and integrated to June 30, 1991. Monthly mean real SST is used in the marine part of the underlying surface data in Exp.<A> and monthly climatological mean SST in Exp.<B>, while real monthly SST is used in other parts of the ocean. To remove the effects of other factors, all other parameters are made consistent in the two experiments and the characteristics of the difference field for Exp.<A> and Exp.<B> are thought to be the response of the general circulation to the SSTA in the tropical Indian Ocean.

Tab.1 Characteristics of the distribution of positive SSTA in the tropical Indian Ocean (30°S – 20°N) from January to June, 1991

Time	Regional mean / 0.1 ℃	Positive points	Effective points	Percentage / %
Jan. 1991	4.4	75	105	71
Feb. 1991	3.8	69	99	69
Mar. 1991	4.7	73	103	70
Apr. 1991	4.9	82	105	78
May 1991	6.4	93	103	90
Jun. 1991	5.8	88	99	88

2.3 *Verification of long-term forecast results*

To verify the results of Exp.<A>, the global domain is selected as Region 1 and the area within 0° – 90°N, 0° – 120°W in the Northern Hemisphere as Region 2. The r. m. s. error for the forecast of the geopotential height and temperature fields ε_f and the correlation coefficient of anomalies r are determined for a number of representative layers. It is known from Tab.2 that the r. m. s. error for the forecast of the two fields are both larger than the persistence error $\varepsilon_{\text{pers}}$ (for the calculation of which the monthly mean climatological mean as the initial field of forecast is used), showing that Exp.<A> has good long-term forecast effect. The error is about 3 geopotential meters for the height field while it is mostly less than 2°C for the temperature field. The coefficient is all above 0.20 for the correlation between the two fields in long-term simulation forecast and the result for Region 2 is better than that Region 1.

Then, comparisons and verifications are made of the distribution of the easterly and westerly jet streams. Fig.1a and 1b give the Exp.<A> result of the 500-hPa zonal wind field and corresponding observed field for May 1991. It is seen that the extent of the westerly zone in both the Southern and Northern Hemispheres and the low-latitude easterly zone are all simulated and particularly, the locations of two westerly jet streams centers near 30°N over North Africa and North Pacific and a 25-m/s wind speed center agree with the observation. The westerly jet streams at 30°S – 60°S in the Southern Hemisphere and south Pacific off the southeastern Pacific are well simulated, with basically the same location and intensity as the field observed.

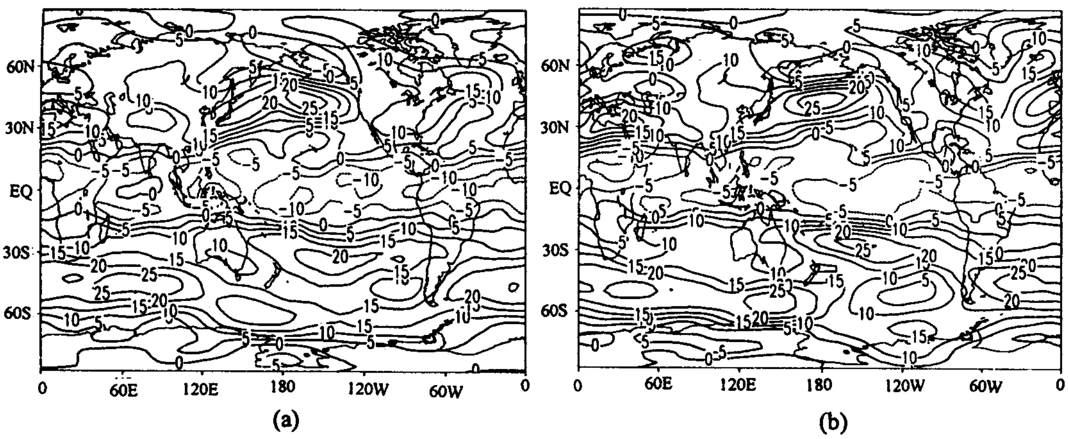

Fig.1 Simulated and observed zonal wind fields at 500 hPa in May 1991. a. Exp.<A>; b. Observation; unit: m/s

Tab.2 The r. m. s. error ε for the fields of monthly mean geopotential height and temperature and the coefficient for anomalies correlation r in Exp.<A>

1991			ε_f	$\varepsilon_{\text{pers}}$	r
Geopotential height field (unit: dgpm)	200 hPa	May, Reg.1	3.8	4.6	0.19
		Jun. Reg.2	3.7	3.9	0.23
	500 hPa	May, Reg.1	3.1	3.2	0.17
		Jun. Reg.2	2.1	2.0	0.19
	700 hPa	May, Reg.1	2.6	3.1	0.26
		Jun. Reg.2	2.6	2.8	0.34
Temp. field (unit: °C)	200 hPa	May, Reg.1	1.3	1.7	0.21
		Jun. Reg.2	1.4	1.3	0.33
	500 hPa	May, Reg.1	1.0	1.4	0.21
		Jun. Reg.2	1.3	1.5	0.26
	850 hPa	May, Reg.1	1.4	1.5	0.32
		Jun. Reg.2	1.7	2.2	0.25

As shown in the verification above and the results of simulation forecasting, the model well simulates long-term tendency of the general circulation, which is why it can be useful in experimenting with the role of SSTA in the general circulation.

2.4 *Characteristics of circulation in the early summer of 1991*

For easy comparisons with the simulated results, the characteristics of East Asia circulation in the early summer of 1991 are given. The general situation during the 1991 Mei-yu (sustained rain) period is characteristic of early onset, long duration and stable rain bands. The sustained rain began around May 20th, about a month earlier than usual and lasted for 56 days, twice as long as in normal years[11]. In May, the western Pacific subtropical high is anomalously strong at 500 hPa with the ridge line south of 20°N. In July, the ridge line stayed between 19°N and 24°N, making the rain band shifting around the valley of the Changjiang River. In May 1991, the South China Sea monsoon was significant and cross-equatorial flows started to establish near 45°N and between 80°E and 85°E and got strengthened in June and July. Meanwhile, the cross-equatorial flow was so weak over the western Pacific to form any significant channels, resulting in inactive ITCZ, fewer typhoons over the ocean, unlikely northward progression of the western Pacific subtropical high and prolonged duration of the sustained rain in the Changjiang River valley.

3 NUMERICAL STUDY OF THE EFFECT OF PERSISTENTLY WARM SST IN TROPICAL INDIAN OCEAN ON THE EARLY SUMMER GENERAL CIRCULATION IN EAST ASIA

3.1 *Effects of persistently warm SST in tropical Indian Ocean on the temperature field of the Eurasian – Pacific region*

Fig.2 gives the difference field of the Eurasian – Pacific region temperature field obtained with Exp.<A> and Exp.<B>, which is used to stand for the response of the temperature field to the SSTA in the tropical Indian Ocean (the same below). At 100 hPa in the upper level of the troposphere, there is an obvious warming area in the southern part of the Eurasian continent. The 1°C warming contour encompasses an extensive region from the Arabian Peninsula to the East Asia coast, from south of the Plateau to areas south of 50°N, with the center (a 5°C increase) over the Lake Balkhash through the Qinghai-Tibetan Plateau, which forms a well-defined zone of warming across the Eurasian – Pacific region together with a 4°C warming center east off the Sea of Japan. Such intense warming response in the 100-hPa temperature field is apparently favorable

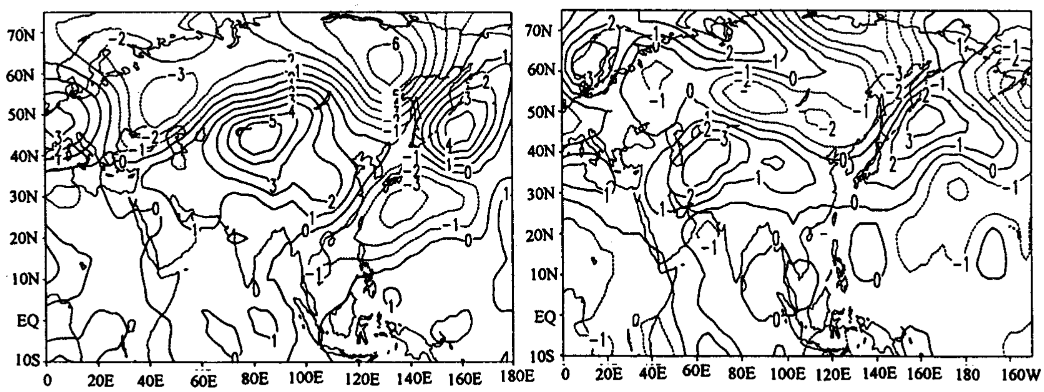

Fig.2 The field of temperature difference for the Eurasian-Pacific region by subtracting Exp.<B> from Exp.<A>. a. 100 hPa in June; b. 500 hPa in May; unit: °C

for atmospheric heating over the plateau. The response in the 500-hPa temperature field in the middle troposphere (Fig.2b) is also very obvious, which displays as an east-west warming zone between 30°N and 40°N in the Eurasian – Pacific region (Fig.2b), extending from the Mediterranean via the plateau to the ocean east off Japan. There is a warming center of 2°C – 3°C over the plateau and waters east off Japan while there are zones of obvious temperature decrease on either sides of the warming zone. The warming effect is such that it would change the longitudinal distribution of large-scale temperature and strengthen north-south temperature gradient in the northern plateau but weaken it in the southern part. With its mechanism still not clear, the warming shows that the formation of thermal effect of the Qinghai-Tibetan Plateau is attributed not only by the warming by sensible heat over the plateau and upward transportation of latent heat due to forced lifting by massive landform[12 – 13], but also by the effect of warm SSTA in the tropical Indian Ocean.

Tab.3 gives the calculations of the response by mean temperature field of the plateau in May. The area bounded by 20°N – 42.5°N, 70°E – 105°E and which is higher than 1500 m is selected in the study. As shown in the calculation, there is a general trend of warming in the mean temperature field over the region of plateau in each of the upper, middle and lower levels of the troposphere with the warming amplitude more than 0.4°C and even 0.82°C at 200 hPa. In addition, the mean geopotential height field also shows a trend of increase, particularly at 200 hPa where the increase is nearly 6 dgpm. The variation of the temperature and pressure fields is favorable for the formation of a warm high over the plateau and further for the establishment and strengthening of the South Asia high over there. Zhang et al.[14] once stressed that its formation may be related with the effect of the anomalous cold and heat sources of the ocean. This numerical experiment shows that the warm SST in tropical Indian Ocean helps establish the south Asia high over the plateau in early summer.

Tab.3 also computes the response of characteristics of regional mean temperature fields for the Qinghai-Tibetan Plateau. The continental part of East Asia within the domain of 20°N – 50°N, 90°E – 150°E is selected, which covers the middle part of the plateau in the west and Japan in the east. It is apparent that except for the level of 500 hPa at which there is some decrease, the mean temperature field of continental East Asia rises significantly at all other levels of the troposphere — the increase is 1.2°C at 200 hPa, 0.5°C at 850 hPa and about 0.9°C near the surface. It is obvious that persistently warm SST in the tropical Indian Ocean favors the rise of temperature field in continental East Asia in early summer.

Tab.3 The characteristics of the response of elements fields in the region of Qinghai-Tibetan Plateau and continental East Asia in May

Levels of geopotential height	Qinghai-Tibetan Plateau			East Asia continent
	Temp. field/ 0.1 ℃	Geopotential height field/ gpm	Zonal wind field/ 0.1 m/s	Temp. field/ 0.1 ℃
200 hPa	5.14	56.73	-39.36	12.07
500 hPa	8.21	29.21	-5.23	-0.43
850 hPa	4.07	20.67	11.83	4.86
1000 hPa				9.09

3.2 *Effects of persistently warm SST in tropical Indian Ocean on the zonal wind field in Eurasian-Pacific area*

Fig.3 gives the difference field at individual levels of geopotential height of zonal wind fields as determined with Exp.<A> and Exp.<B>. At the level of 100 hPa (Fig.3a), an east-west negative zone is located over the tropical Indian Ocean, Arabian Sea and south of the plateau, with the easterly strengthening to 1 m/s or more at the centers. The negative center south of the plateau remains strong in June (figure omitted). Such a strong and persistent zone of negative values is favorable for the strengthening and northward movement of the tropical easterly flow and further for the generation of the tropical easterly jet stream south of the plateau. The trend of variation found in the tropical easterly flow is obviously related with the generation and variation of thermal winds, which is resulted from the increase of temperature fields in Fig.2a that reverse the meridional gradient of temperature over the plateau region. One of the significant characteristics at the 200-hPa level in the troposphere is the presence of the westerly increase (decrease) zone aligning east-west. A negative zone is obvious near the zonal circle of 30°N in May with the westerly weakened by 10 m/s – 15 m/s while the westerly is strengthening in a zone near 40°N, favoring the weakening and northward movement of a southern branch of the westerly jet stream in East Asia. It is also shown in Tab.3, i.e. the regional mean zonal westerly weakens by nearly 4 m/s at 200 hPa over the plateau. Such trends of variation of the westerly jet stream is mainly caused by the variation of a northward temperature gradient, as shown in Fig.2b. According to the principle of thermal winds, the westerly weakens south of the plateau but strengthens north of it. In June (Fig.3c), an east-west zone of positive centers is still over an area from the Asian continent to north Pacific between 35°N and 40°N, with the westerly stronger but location more northward than usual, while the westerly jet stream is more southward than usual in June (figure omitted). The simulation agrees with the observation. It suggests that the warm SST in the tropical Indian Ocean indeed affects the movement and variation of the East Asian westerly jet in early summer, which not only helps the circulation to transform seasonally but also cause anomalous precipitation in the sustained rain season in the valleys of the Changjiang-Huaihe Rivers by altering the location of the frontal area.

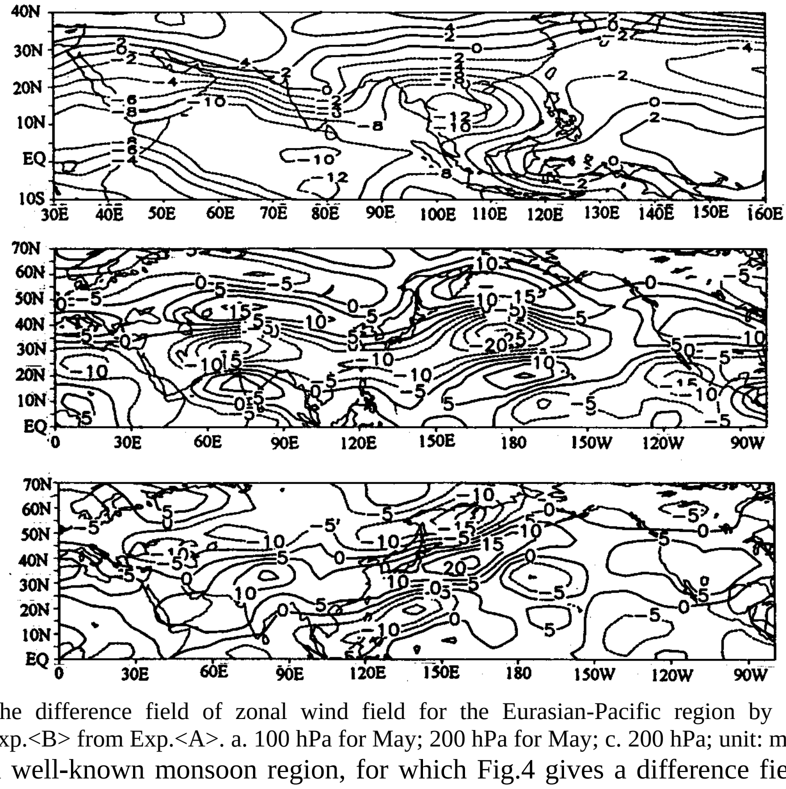

Fig.3 The difference field of zonal wind field for the Eurasian-Pacific region by subtracting Exp.<B> from Exp.<A>. a. 100 hPa for May; 200 hPa for May; c. 200 hPa; unit: m/s

Asia is a well-known monsoon region, for which Fig.4 gives a difference field of monthly mean wind fields at 850 hPa as determined in Exp.<A> and Exp.<B>, without discussing the response of low-level tropospheric wind fields in early summer. The figure shows that an increased flow of southerly that crosses the equator near 60°E – 80°E in the Southern Hemisphere in May and changes to a westerly when it arrives at the equator. An enormous anti-cyclonic circulation over the western Pacific is obviously for the strengthening of the subtropical high in western Pacific, with the southeasterly on its periphery increasing the southerly over the South China Sea and eastern China and thus favoring the development and strengthening of summer monsoon in the South China Sea and eastern coast of China. The warm SST in June keeps increasing the southerly near 40°E and 80°E in the Southern Hemisphere and the latter crosses the equator to reach the southern part of the Arabian Sea. At the same time, southwesterly flows begin to increase in the Bay of Bengal and southerly flows in the South China Sea continue to show trends of strengthening while the northerly wind in the Chinese eastern coast, which has something to do with the more southward location and persistence of a southern branch of frontal zone. The two flows meet around the area of the Changjiang and Huaihe Rivers valleys near 30°N, favoring the generation and development of the sustained raining period there. As shown in Fig.4, there are no obvious channels of southerly cross-equatorial flow nor wind field changes that are favorable for cyclonic circulation. It agrees with the analysis in a previous work of the circulation field in the early summer of 1991. It may lead to inactivity of ITCZ over the equatorial western Pacific[11] and thus does not favor more northward jumps of the subtropical high in the western Pacific and results in the extended sustained rain period in the area.

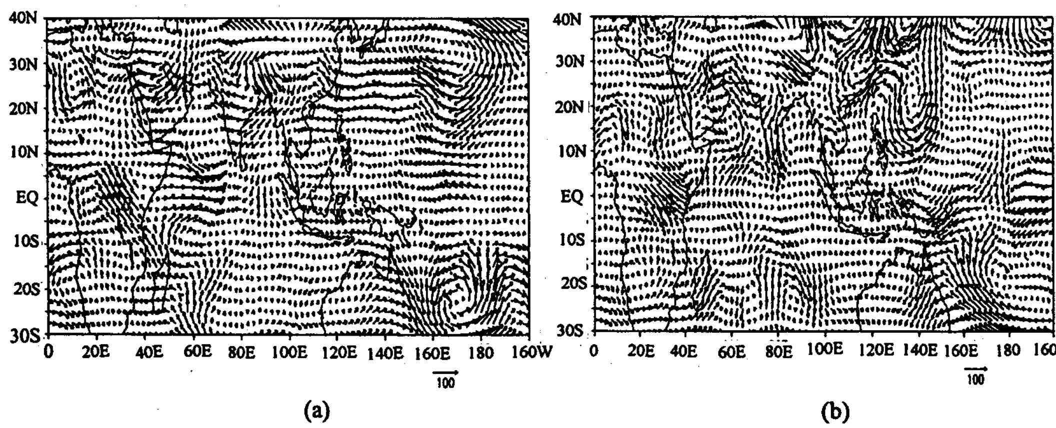

Fig.4 The difference field of monthly mean wind field at 850 hPa for May (a) and June (b) by subtracting Exp.<B> from Exp.<a>. unit: 0.1 m/s.

Tab.5 gives the calculations of the response by monthly mean meridional southerly component in individual monsoon areas in Asia, which are used to describe the effects of warm SST in tropical Indian Ocean on the intensity of the summer monsoon. In May, the southerly wind has a mean increase of about 1 m/s in the monsoon area in the east of China but has a mean decrease of about 0.8 m/s in the Indian Monsoon area and Southwest Monsoon area. In June, the southerly wind still has some tendency to grow in the monsoon area of the South China Sea but shows signs of reduction in other monsoon areas. The computation in Fig.5 is consistent with the trend of variation of the flow field as shown in Fig.4. Due to the increase of the northerly over the Indian Peninsula and its northern plateau, the mean summer monsoon in the Indian Monsoon area and Southwest Monsoon area is showing signs of reduction. On the whole, the warm SST of the tropical Indian Ocean is favorable for the development of the southerly wind in the South China

Sea monsoon area in early summer, the strengthening of the southeasterly wind in the monsoon area of eastern China, and the increase of the southwesterly wind in the Bay of Bengal in June (Fig.4b) while obviously unfavorable for the strengthening of the meridional southerly wind in Monsoon area and Southwest Monsoon area.

Tab.5 The anomalous variation of meridional southerly component in the Asian summer monsoon area at 850 hPa (unit: 0.1 m/s)

Monsoon areas	May	June
India (70°E – 95°E, 15°N – 30°N)	-6.36	-7.25
South China Sea (100°E – 120°E, 5°N – 25°N)	12.93	3.52
East China (110°E – 120°E, 20°N – 40°N)	9.93	-2.67
Southwest Monsoon (75°E – 105°E, 15°N – 30°N)	-3.02	-8.65

3.3 *Effects of persistently warm SST in tropical Indian Ocean on the subtropical high in western Pacific*

The strengthening of the subtropical high in the western Pacific is the signal that marks the transition of season in the early summer of East Asia. Fig.5 gives the difference field in the geopotential altitude of May as determined with Exp.<A> and Exp.<B>, which shows the effect of the warm SST in the tropical Indian Ocean on the subtropical high in the western Pacific. A zone of highly positive values is located from East Asia to the northern Pacific and geopotential height field spanning from the Philippines to the south and eastern plateau to the west is showing trends of increase. Particularly, the height field increases by 6 gpm over waters east off Japan and 3 gpm over the continent of East Asia. The distribution and intensity of height increases are apparently favorable for the strengthening and northward progression of the subtropical high, which is consistent with the anomalous development of an anti-cyclonic difference field in the western Pacific. In addition, a zone of positive values over the Arabian Peninsula is also favorable for the increase of the subtropical high over the continental part. The fact that the subtropical high intensifies and jumps northward is consistent with the observation that its ridge line progresses to areas north of 20°N (figure omitted)[11], which is favorable for earlier onset of the sustained rain in the valleys of the Changjiang – Huaihe Rivers. In the current work, the characteristics of warm SST in the Indian Ocean have been highlighted in the design to form differences of heating in both meridional and zonal directions. The difference in the heating field contributes much to the north-south shifts of the subtropical high in the western Pacific[15, 16],

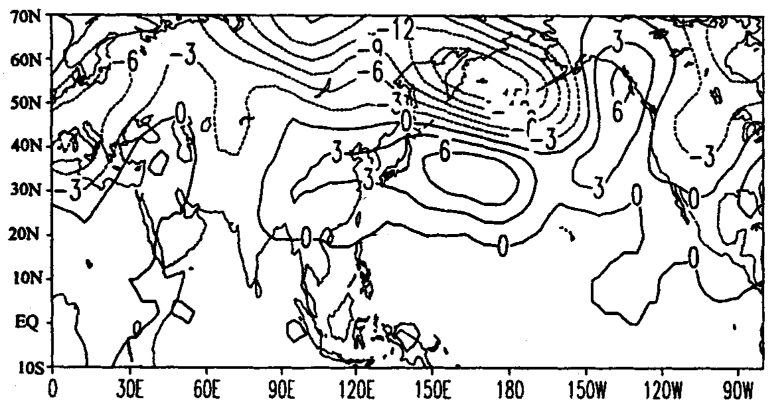

Fig.5 The difference field of the 500-hPa geopotential altitude field for the Eurasian-Pacific region in May by subtracting Exp.<B> from Exp.<A>. unit: dgpm.

resulting in changes in the Walker cell that in turn oscillate the location of the subtropical high[17]. It is decided that the thermal effect induced by the SST distribution must be the basic factor that affects the oscillation of the location of the subtropical high in the western Pacific.

4 RESULTS AND DISCUSSIONS

With an improved version of the CCM1 ($R_{15}L_{12}$) model, two schemes were designed in which the SST in the tropical Indian Ocean is sought for either climatological mean or monthly observation mean to run long-term numerical simulation, and the effects of persistently warm SST in the region in January – June, 1991 on the general circulation of East Asia in early summer are studied. Main findings are as followed:

a. Persistently warm SST in the tropical Indian Ocean is favorable for the atmospheric heating over the plateau in early summer so that temperature rises by 5°C from Lake Balkhash to the Tibetan Plateau at the level of 100 hPa in June and the plateau-averaged geopotential altitude increases by nearly 6 gpm at 200 hPa. They eventually lead to the establishment and strengthening of the south Asia high over the plateau. Meanwhile, it also brings about the appearance of an east-west warming zone between 30°N and 45°N at the middle and higher levels of the troposphere in the Eurasian-Pacific region, which favors the change in the gradient of meridional temperature that goes northward over the region of the plateau.

b. As warm SST results in the strengthening of the warming effect of the plateau in early summer, the tropical easterly jet stream south of the plateau is favored in its establishment and a southeastern branch of the westerly jet stream is weakened in its northward shift, reducing the latter to 10 m/s – 15 m/s in May. The warm SST is also favorable for the strengthening and northward progression of the subtropical high in the western Pacific in the month and causes mean temperature to rise by about 0.9°C in the near-surface layer over East Asia and plays an active role in the development of austral cross-equatorial flow and the increase of the meridional southerly wind in the South China Sea monsoon area in early summer. The responses of the above fields of temperature, wind and geopotential altitude hasten the pace at which season shifts in East Asia in early summer.

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