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ON THE RELATIONSHIPS BETWEEN THE SUMMER RAINFALL IN CHINA AND THE ATMOSPHERIC HEAT SOURCES OVER THE EASTERN TIBETAN PLATEAU AND THE WESTERN PACIFIC WARM POOL

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ABSTRACT: The relationships between the summer rainfall in China and the atmospheric heat sources over the eastern Tibetan Plateau and the western Pacific warm pool were analyzed comparatively, using the NCEP/NCAR reanalysis daily data. The strong (weak) heat source in summer over the eastern Tibetan Plateau will lead to abundant (scarce) summer rainfall in the Yangtze River basin, and scarce/abundant summer rainfall in the eastern part of Southern China. While the strong (weak) heat source in summer over the western Pacific warm pool will lead to another pattern of abundant (scarce) summer rainfall in the middle-lower reaches of the Yangtze River and scarce (abundant) summer rainfall in Southern China and in the region of northern Jiangsu to southern Shandong. Comparatively, the heat source over the eastern Tibetan Plateau affects a larger area of summer rainfall than the heat source over the western Pacific. In both cases of the heat source anomalies over the eastern Tibetan Plateau and over the western Pacific, there exist EAP-like teleconnection patterns in East Asia. The summer rainfall in China is influenced directly by the abnormal vertical motion, which is related closely to the abnormal heat sources in the atmosphere. The ridge line of the western Pacific High locates far south (north) in summer in the case of strong (weak) heat sources over the two areas mentioned above.

Key words: eastern Tibetan Plateau; western Pacific; heat sources; summer rainfall

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1 INTRODUCTION

Due to its uniquely lofty landform, the Tibetan Plateau significantly affects the onset and evolution of Asian summer monsoon via its thermodynamic effects and interannual variations. By altering the thermodynamic condition and circulation right over it, the thermodynamic effects influence the circulation and weather / climate in regions adjacent to the plateau. With the sounding data from 23 measuring stations in the eastern plateau from 1983 to 1992, Luo et al[1]. calculate and analyze the effects of summertime atmospheric heat source anomalies in the eastern Tibetan Plateau on the circulation and precipitation, discovering that when they increase, low-level southwest monsoon and high-level plateau high strengthen and precipitation increases over the valleys of the upper reach of the Changjiang R. (Yangtze) and Huaihe R. but decreases in the southeastern China. More recently, with an apparent atmospheric source obtained with the direct algorithm for the plateau region in 1961 – 1995 (35 years), Zhao et al[2, 3]. study its relationships with the general circulation and precipitation in China. Their results show that the intensity of the plateau heat source in summer is associated with the intensity and location of the south Asia high, in addition to its significant correlation with convective activity in neighboring

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areas, and the heat source is also in significant positive correlation with the precipitation in the valley of the Changjiang R. Apart from the work above, numerical simulation experiments also show that not only the dynamic and thermodynamic processes of the plateau play an important role in the formation and persistence of mean troughs and ridges in the boreal general circulation[4] but also have significant effect on medium-term weather process in the summer of East Asia[5].

On the other hand, a lot of work has also indicated that the anomalies of the convective heat sources in the warm pool of the tropical western Pacific can cause anomalies in the summer climate of East Asia. Nitta[6] and Huang[7] all reported that convection over areas in and around the Philippines affect the summer climate in East Asia. When convection intensifies over warm pool in the tropical western Pacific, a teleconnection pattern of atmospheric anomalies, East Asia – Pacific (EAP), appears from the southeast Asia to the west coast of North America by way of East Asia. Then, the study by Huang et al[8, 9]. further indicates that a warmer western Pacific warm pool in the tropics will be associated with strengthened convection over areas from the Indochina Pen., South China Sea and areas east off the Philippines, a more northward subtropical high and less precipitation in the valleys of the Changjiang and Huaihe Rivers but more precipitation in South China and North China, in summer. Otherwise, convection will weaken in and around the Philippines, the western Pacific subtropical high stays more southward, there is more precipitation in the valleys of the Changjiang and Huaihe Rivers but less precipitation in the valley of the Yellow R., easily resulting in droughts there. As shown by Zhao et al[10]., the interdecadal variation of the thermodynamic condition of the warm pool and climatic jumps have close relationships with the distribution of summertime precipitation in China.

As shown in the study above, the anomalies of the atmospheric heat sources in the regions of both the Tibetan Plateau and the warm pool in the tropical western Pacific are closely linked with the precipitation anomalies in the summer of China, especially the valley of the Changjiang R. Are there any significant regional differences between the two anomalies? Do they vary in phase in the change of intensity? Few studies have addressed the issues up till now. In addition, previous work used relatively short periods of dataset. It is the aim of the current work that longer spans of observations are used to calculate the atmospheric sources and sinks and to probe into the questions raised above.

2 DATA AND COMPUTATION METHODS

The dataset used in the work is the daily reanalysis data by NCEP/NCAR covering a period from 1951 to 2000, including the wind field and temperature, with horizontal resolution at 2.5°× 2.5° and 12 mandatory isobaric layers from 1000 hPa to 100 hPa. Besides, monthly precipitation data from 160 weather stations in China are used that cover the years 1951 – 2000.

The reverse algorithm is used to determine the apparent heat source in the atmosphere based on the thermodynamics equation[11] as follows.

$$c_p\left[\frac{\partial T}{\partial t}+\vec{V}\cdot\nabla T+\left(\frac{p}{p_0}\right)^{\kappa}\omega\frac{\partial\theta}{\partial p}\right]=Q_1 \tag{1}$$

where T is the temperature, L the latent heat from condensation, θ the geopotential temperature, q the specific humidity, ω the vertical velocity in the p-coordinates, p_o the level of 1000 hPa, $\kappa=R/c_p$, $\vec{V}$ the horizontal wind vector, and Q_1 the apparent heat source of the atmosphere. The vertical integration of the atmospheric heat source can be expressed as

$$\langle Q_1\rangle=\frac{1}{g}\int_{p_T}^{p_s}Q_1\,\mathrm{d}p\approx LP+S+\langle Q_R\rangle \tag{2}$$

where P, S and $< Q_R >$ are the precipitation, surface sensible heat flux and the term of radiative heating that is vertically integrated, respectively, and p_S and p_T are the pressure on surface and at the top of the atmospheric layer (which takes 100 hPa).

3 ANALYSIS OF THE RESULTS

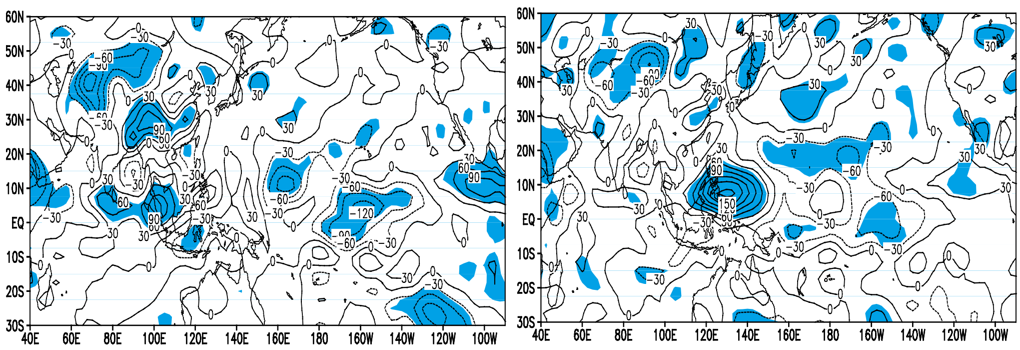
3.1 *Composite analysis of <Q_1> for strong and weak years of atmospheric heat source in the eastern Tibetan Plateau and western Pacific*

Years have to be grouped by the intensity of the atmospheric heat source for composite analysis. With previous relevant work reviewed, <Q_1> averaged over two regions (90°E – 100°E, 30°N – 35°N) and (125°E – 135°E, 5°N – 10°N) are taken to represent the eastern plateau and the warm pool in the tropical western Pacific (to be simplified as Warm Pool thereafter). Following the temporal curves of heat sources that are averaged over the summer and normalized for the two regions, a threshold of ±1 is used to isolate years with either strong or weak atmospheric heat sources in each of the regions. The results are presented in Tab.1.

Tab.1 Years of strong or weak atmospheric heat sources in the eastern plateau and Warm Pool

Eastern plateau	Strong years (10):	1955	1967	1969	1974	1977	1980	1987	1988	1991	1998	
	Weak years (9):	1952	1953	1957	1959	1960	1961	1962	1963	1978		
Warm Pool	Strong years (11):	1951	1952	1953	1977	1982	1983	1985	1987	1993	1994	1995
	Weak years (9):	1958	1960	1961	1962	1963	1967	1968	1972	1974		

Next comes an analysis of composite distribution of the intensity of summertime atmospheric heat sources. Fig.1a gives the distribution of the differences between strong and weak atmospheric heat sources for the plateau (by subtracting weak years from strong years). It shows that the atmospheric heat source intensifies significantly in strong years over areas from the plateau to the valley of the Changjiang R. and from the northern Indian Ocean off the southern tip of the Indian Pen. to the “continental bridge” in the east, while it weakens significantly in the central part of the Eurasian continent, forming a north-south wavetrain between 90°E and 110°E that alternates positive with negative values. In addition, the heat sources in the central and eastern equatorial Pacific are significantly decreasing and increasing, respectively. During the years of weak heat sources, the variation is just in the opposite phase to those of strong heat sources.



(a) (b)

Fig.1 The difference of composite <Q_1> in years of strong or weak atmospheric heat sources in summer in the eastern Tibetan Plateau (a) and the Warm Pool (b), which is obtained by subtracting weak years from strong years. Unit: W/m^2, with the shaded area passing the t-test of 95% confidence.

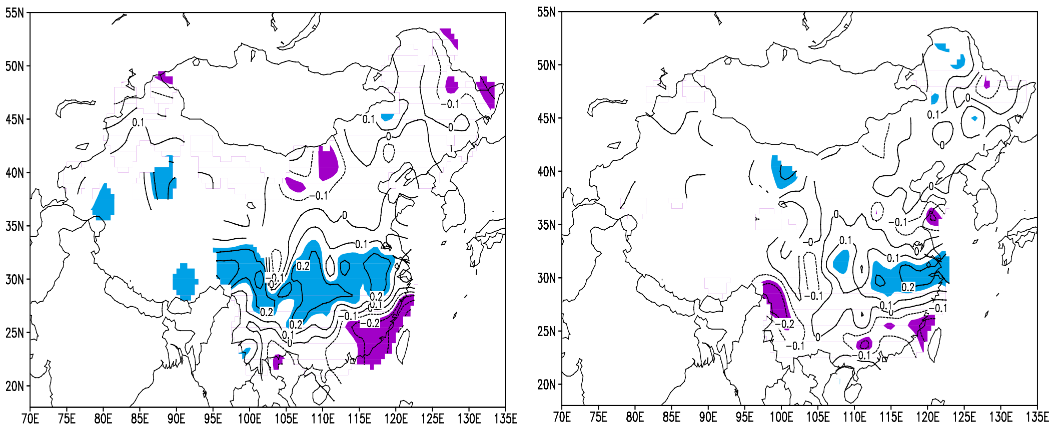
The distribution of the differences between strong and weak heat sources of the atmosphere for the Warm Pool is listed in Fig.1b. It differs from Fig.1a mainly in the Asian monsoon region. It shows that a wavetrain alternating positive with negative values is found stretching from the Warm Pool to the eastern China and then further north to Lake Bajkal, suggesting a much stronger heat source in the Warm Pool in strong years together with a weakened heat source in northern South China Sea and a much stronger heat source in the middle and lower reaches of the Changjiang R. During the weak years, however, the variation is just the opposite to strong years. Compared with the north-south wavetrain between 90°E and 110°E in Fig.1a, the wavetrain in Fig.1b has weaker amplitude.

The coefficient is 0.36 for the correlation between the time series of the mean atmospheric heat sources in the eastern plateau and the Warm Pool and passes the test of 95% confidence, suggesting largely in-phase variation between the regions. The variation is mainly displayed on the interdecadal scale (figure omitted) while the years with strong or weak heat sources still differ much. From Tab.1, it is noted that only two years are the same when the heat source is strong and only four years are the same when the heat source is weak, in the two regions.

As what will be shown in the study below, the composite analysis of heat sources conducted above is closely related with anomalous summer precipitation in China and anomalous general circulation in East Asia.

3.2 *Correlation between the atmospheric heat sources in the eastern plateau and Warm Pool and summer precipitation in China*

The distribution of the coefficients of the correlation between the atmospheric heat sources in the eastern plateau and Warm Pool and the summer precipitation in China are shown in Fig.2. It



(a) (b)

Fig.2 The correlation coefficients for the summertime atmospheric heat sources versus summertime precipitation in 160 weather stations in China in the eastern Tibetan Plateau (a) and the Warm Pool (b). The shaded areas pass the test of 95% confidence.

should be specified that the correlation coefficient is determined with 150 samples of monthly anomalies in summer (JJA) over a period of 50 years (with the anomalies obtained by subtracting original value of a specific month from the multi-year mean of that month). It is known from the distribution of correlation coefficients for the atmospheric heat source in the eastern plateau and summer precipitation (Fig.2a), significant positive correlation is mainly seen in the valley of the

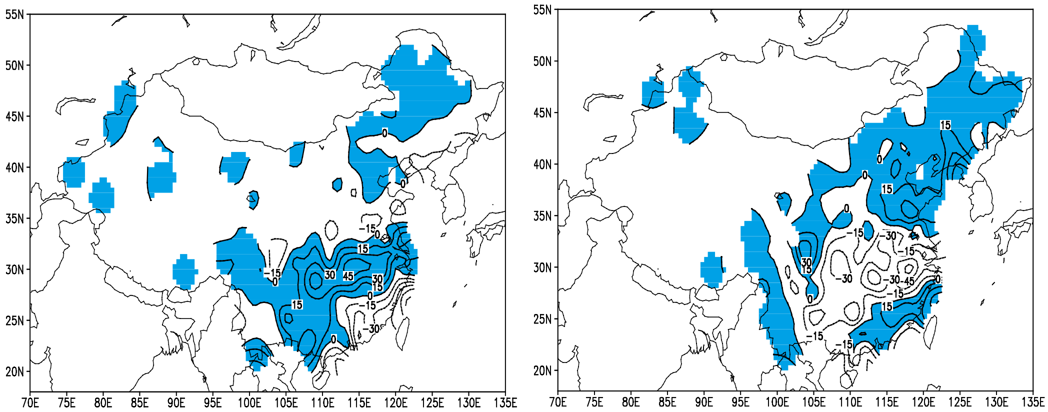
Changjiang R., with the area from the eastern plateau to the middle reach of the river being mostly so. There is also a center of positive correlation in the lower reach of the river. Significant negative correlation is found in the southern China, western Inner Mongolia and Helongjiang province. There are some differences between these results and those by Zhao et al[2]. who use mean summer data over a 35-year period. Our direct correlation center in the lower reach of the river is more southward than the center over the Changjiang and Huaihe Rivers as reported in their work and our results indicate significant negative correlation in southern China. It may attribute to the differences in selecting regions of heat sources for the plateau as well as the methods for their computation. For the latter, Zhao et al[2]. use the data from observation stations and immediate algorithm while we use homogeneous gridpoint data and reverse algorithm. From the distribution of correlation coefficients for the atmospheric heat source in the Warm Pool and summer precipitation (Fig.2b), we know that significant positive correlation is chiefly found in the middle and lower reaches (mainly the latter) of the Changjiang R., while significant negative correlation is seen in southern China and northwestern Yunnan, northern Jiangsu and southern Shandong.

From the analysis above, it is known that the summer precipitation in China is affected by the atmospheric heat source in the eastern plateau in an area much larger than by that in the Warm Pool. As far as the precipitation in the Changjiang R. valley is concerned, nearly the whole valley is significantly influenced by the heat source in the eastern plateau, particularly so in the middle and upper reaches. The heat source in the Warm Pool mainly affects the precipitation in the lower reach of the Changjiang R.

Fig.3 gives the composite anomalies of summer mean precipitation in the 160 weather stations in China in either strong or weak years of the atmospheric heat sources. In the strong years (Fig.3a), positive precipitation anomalies are seen from the eastern plateau to northern China and over most of the southwestern China, or, the wetness is high, with a significant anomalous precipitation center over the middle reach of the Changjiang R.; significant negative anomalies appear in the eastern part of South China, or, the wetness is low, in addition to a negative anomalous center each over the lower reach of the Yellow R. and northwestern Sichuan. In the weak years, however, the summer precipitation anomalies are distributed generally out of phase with the strong years — negative anomalies are found in the valley of the Changjiang R. and nearby regions and most of the southwestern China, or, there is less precipitation, while there is more precipitation in the eastern part of South China, the lower reach of the Yellow River and northwestern Sichuan.

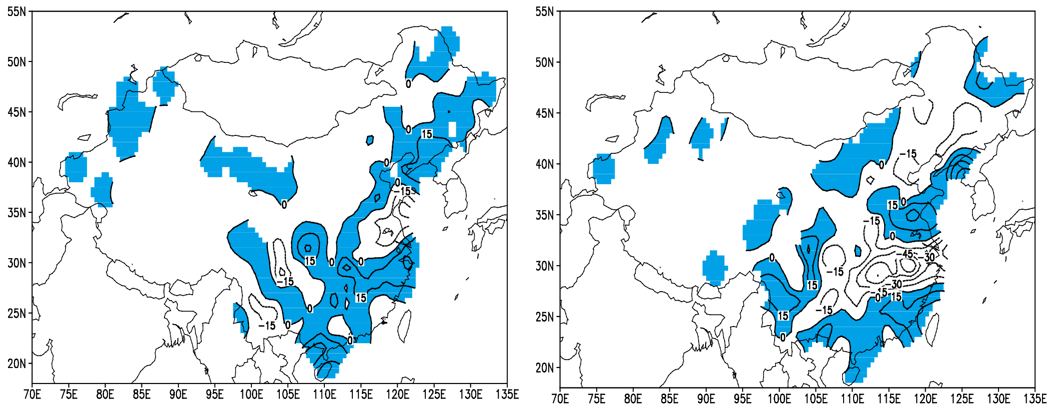
Fig.4 gives the distribution of summertime mean precipitation anomalies for the 160 weather stations in China in strong and weak years of the atmospheric heat sources in the Warm Pool. In the strong years (Fig.4a), main zones of positive precipitation anomalies are over the area south of the Changjiang R.valley, eastern Sichuan and Liaodong Pen., while main zones of negative precipitation anomalies are over the valley of the Huaihe R. and eastern Shandong, together with two centers of negative anomalies in southwestern China. In the weak years (Fig.4b), a significant anomalous zone covers the middle and lower reaches of the Changjiang R. and precipitation is also less in most of the northeastern China; positive precipitation anomalies appear in the southern China, the area north of the Huaihe R. and south of the lower reach of the Yellow R. and most of the southwestern China, or, there is more precipitation. Comparing the distribution of precipitation anomalies between the strong and weak years, we note that positive and negative anomalies are out of phase mainly over the middle and lower reaches of Changjiang R, which is just a zone of significant positive correlation between the atmospheric heat source in the Warm Pool and precipitation at the 160 weather stations in China (Fig.2b).

Comparing Fig.3 and Fig.4, we also note that the summertime precipitation anomalies in the years of a strong heat source over the plateau is much more significant than those over the Warm Pool (Fig.4a), while they are close to each other in the years of weak heat sources and have similar spatial distribution of the anomalies (Fig.3b and Fig.4b). Studying the composite samples, it is known that it is contributed by the fact that of the nine years of weak heat sources for both the plateau and Warm Pool, four are the same, and of the years of strong heat sources (10 for the plateau and 11 for the Warm Pool) only two are the same (Tab.1). It should be noted that an unusual flood in 1998 rare in history was one of the sample years in which the heat source was strong.



(a) (b)

Fig.3 Anomalous composite of mean precipitation in summer at the 160 weather stations in China for strong (a) and weak (b) heat sources in the eastern Plateau. Unit: mm/month.

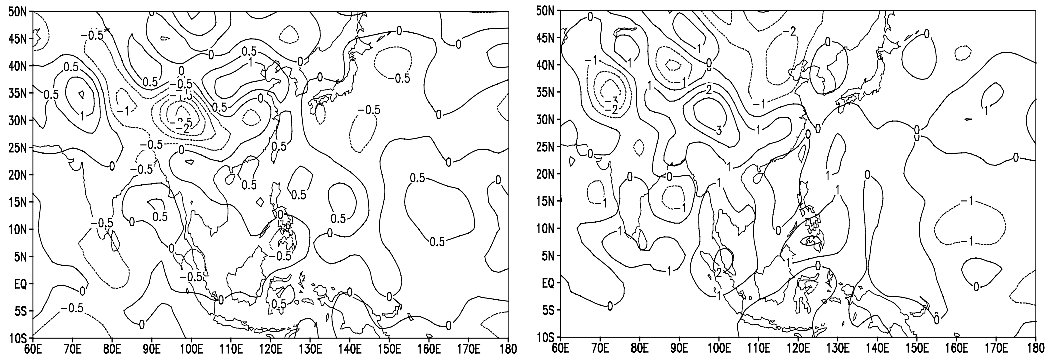


(a) (b)

Fig.4 Same as Fig.3 but for the Warm Pool. Unit: mm/month.

3.3 *Composite analysis of the vertical motion field and geopotential field at 500 hPa and horizontal wind field at 850 hPa in strong and weak years of atmospheric heat sources*

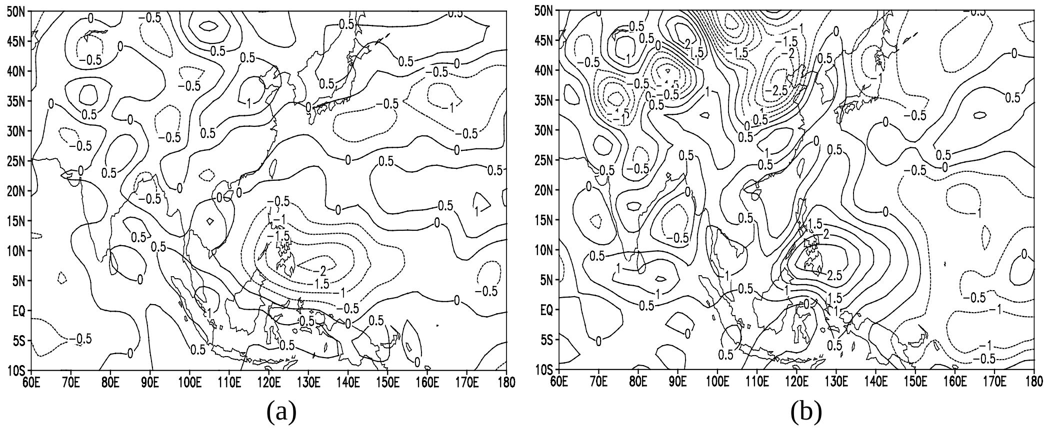
The anomalies of the atmospheric heat sources are closely related with those of the vertical motion fields. Fig.5 gives the anomalous composite of the vertical motion field in the 500-hPa *p*-coordinates in years of strong and weak heat sources for the plateau. In the strong years (Fig.5a), with the strengthening of the atmospheric heat source in the region from the eastern plateau to the valley of the Changjiang R.(Fig.1a), the ascending motion also significantly strengthens there, mostly so in the eastern part of the plateau. On the other hand, ascending motion weakens or descending motion strengthens over the southern China, central and northern parts of the South China Sea and northern China. The anomalous distribution of the vertical motion field generally agrees with the anomalous distribution of summertime precipitation in China in the years of strong plateau heat sources — there is more precipitation over the area of enhanced ascending motion and otherwise is true. The situation for the years of weak heat sources is generally the opposite to the years of strong ones (Fig.5b).



(a) (b)

Fig.5 The anomalous composite of the vertical motion field in the 500-hPa *p*-coordinates in years of strong (a) and weak (b) heat sources for the plateau. Unit: 10^{-2} Pa/s.

Fig.6a gives the anomalous composite of the vertical motion field in the 500-hPa *p*-coordinates in years of strong and weak heat sources for the Warm Pool. It shows that the most prominent center of negative anomalies in the Asian monsoon region is right over the Warm Pool near the islands of the Philippines, with an elongated and narrow strip of weak positive anomalies to its north that spans eastward from the waters off the southern China coast and a zone of weak negative anomalies south of the middle and lower reaches of the Changjiang R., i.e. ascending motion gets stronger and there is more precipitation there (Fig.4a). The spatial distribution shows that the anomalously strengthening of the atmospheric heat source over the Warm Pool also increases the local ascending motion and further affects the local meridional circulation. The situation of the weak years is basically the opposite of the strong years (Fig.6b) but with the

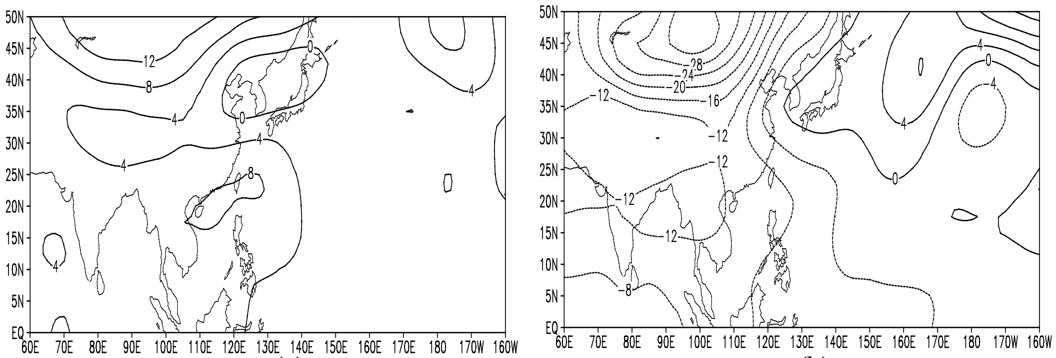


(a) (b)

Fig.6 Same as Fig.5 but for the Warm Pool.

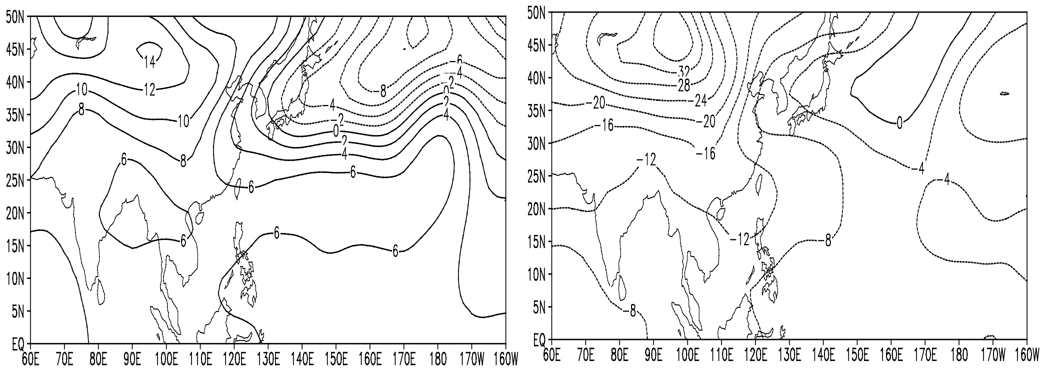
anomalous values generally more significant than those in the strong years. In addition, regardless of strong or weak years with heat sources, the spatial distribution of the anomalous field of vertical motion also shows a north-south wavetrain similar to the anomalous distribution of the heat sources (Fig.1b), which looks much like the EAP teleconnection pattern.

Subject to the anomalies of heat sources, the location of the subtropical high in the western Pacific, which closely links with the anomalous precipitation in the eastern China in summer, also varies significantly in either strong or weak years. Fig.7a gives the anomalous composite of the geopotential height field at 500 hPa in years of strong and weak heat sources for the plateau. In the strong years (Fig.7a), there is an anomalous center of large magnitude from the northern South China Sea to the Balintang Channel while there is a low-value zone extending to the east from the plateau. Such distribution shows that the location of the ridge line of the subtropical high in the western Pacific is more southward than usual, making the northeasterly wind anomalies in the middle and lower troposphere in the eastern China north of 27°N merge with the southwesterly wind anomalies south of the latitude (Fig.9a), resulting in enhanced ascending motion and thus more precipitation. Except for a positive zone in the northern Pacific Ocean east of Japan, the geopotential altitude anomalies composed for the weak years are all negative in the Asian monsoon region (Fig.7b). The distribution shows that the ridge line of the subtropical high in the western Pacific is more northward than usual, contributing to consistent southerly wind anomalies in the lower troposphere in eastern China (Fig.9b), i.e. the summer monsoon gets stronger to cause more precipitation in the region of northern China but less precipitation in the



(a) (b)

Fig.7 The composite anomalous fields of 500-hPa geopotential altitude in strong (a) and weak (b) years of atmospheric heat sources in the summer of the eastern plateau. Unit: gpm.

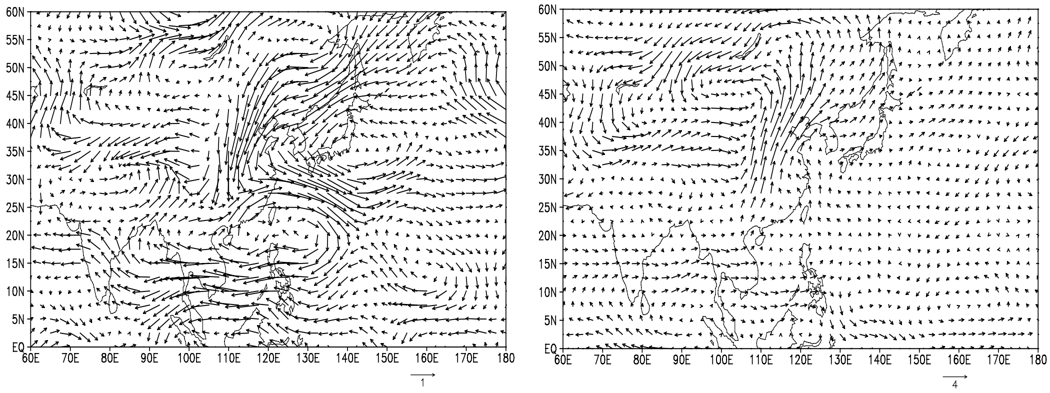


(a) (b)

Fig.8 Same as Fig.7 but for the Warm Pool.

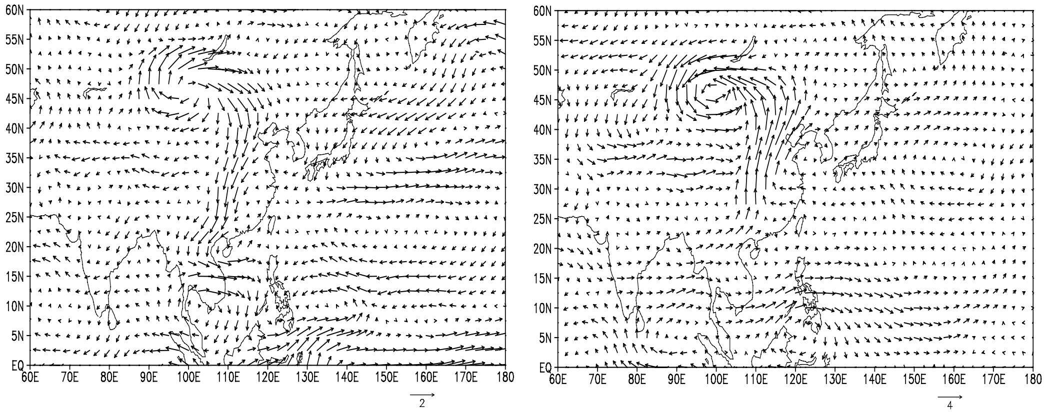
valley of the Changjiang R.

Fig.8a gives the anomalous composite of summertime geopotential altitude field at 500 hPa in years of strong and weak heat sources for the Warm Pool. The anomalous distribution that features a slope going down to the north in areas east of 110°E reflects more southward location than usual of the ridge line of the subtropical high, which is similar to the case with years of strong heat sources in the plateau (Fig.7a). Corresponding to the anomalous geopotential height field, there are consistent northerly wind anomalies at 850 hPa in eastern China (Fig.10a), where the summer monsoon is strong so that precipitation is less in the middle and lower reaches of the Changjiang R. In addition, what Fig.8b is different from Fig.7b is that there is no minimum of negative anomalies over the plateau in the former figure.



(a) (b)

Fig.9 The composite anomalous 850-hPa wind fields in strong (a) and weak (b) years of atmospheric heat sources in the summer of the eastern plateau. Unit: m/s.



(a) (b)

Fig.10 Same as Fig.9 but for the Warm Pool.

4 RESULTS AND DISCUSSIONS

In the current work, the effects of the anomalies of atmospheric heat sources in the summer of the eastern Tibetan Plateau and the Warm Pool in the western Pacific Ocean on precipitation in China over the same period are compared and analyzed. As shown in the results, the variation of the atmospheric heat source in the eastern plateau is in significant positive correlation with precipitation in the eastern plateau and the valley of the Changjiang R. in summer, mostly so in the middle and lower reaches of the river and the eastern plateau, while it is in significant negative correlation with precipitation in the eastern part of South China, western Inner Mongolia and Heilongjiang province. In other words, if the heat source is significantly stronger (weaker) in the summer of the eastern plateau, there will be significantly more (less) precipitation in the valley of the Changjiang R. but significantly less (more) precipitation in the eastern part of South China, during the summer, together with a weak (strong) summer monsoon in East Asia. The atmospheric heat source in the summer of the Warm Pool is, on the other hand, mainly in significant positive correlation with simultaneous precipitation in the middle and lower reaches of the Changjiang R. but in negative correlation with precipitation in the southern China, northern Jiangsu and southern Shandong. It shows that a significantly stronger (weaker) heat source over the Warm Pool is accompanied by wet (dry) spans in the middle and lower reaches of the Changjiang R. and dry (wet) spans in the southern China, northern Jiangsu and southern Shandong, indicating weak (strong) summer monsoon in East Asia. It is then known that the anomalies of heat sources have different influences on the summertime precipitation in China, with the heat source from the eastern plateau affecting larger area than that from the Warm Pool. It should be noted that the area of interest selected in the current work covers waters south of the Philippines in the Warm Pool, which is more southward than that used by Huang et al[7]. in their study of convection in the region of the Philippines. Our conclusions are therefore not contradictory to those reached by Huang et al[9].

From the prospective of forecasting, we also analyzed the correlation between the heat sources of the plateau and Warm Pool in May – July and precipitation in June – August in China. The results are similar to those of simultaneous correlation in summer, only that the area of correlation is smaller (figure omitted).

When the summertime heat sources are strong (weak) in either the plateau or the Warm Pool, the ridge line of the subtropical high in the western Pacific is more southward (northward) than usual. Regardless of the plateau or the Warm Pool that shows anomalies of heat sources, there are always teleconnection wavetrains similar to the EAP pattern in the general circulation in East Asia. The anomalies of the atmospheric heat sources directly affect the anomalies of the vertical motion field and further influence the summertime precipitation in China. In addition, the variation of the heat sources in both the plateau and the Warm Pool is in significant positive correlation, i.e. it is basically in phase, but they differ greatly in the years of significant strong or weak heat sources.

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