MAIN HEATING MODES OVER THE TIBETAN PLATEAU IN JULY AND THE CORRELATION PATTERNS OF CIRCULATION AND PRECIPITATION OVER EAST ASIA*

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ABSTRACT

Based on the 1958—1999 monthly averaged NCEP/NCAR reanalysis data, the REOF analysis is applied to obtain the main spatial modes of normalized atmospheric heating source over the Tibetan Plateau (TP) in July. Results show that the four leading modes are located over the northeast TP, southwest TP, Kashmir and southeast TP respectively, and the cumulative variances are no more than one third of the total. It indicates that the heating source distribution is very complicated over the TP in July. In other words, it is difficult to depict the heating spatial distribution with a few modes. By using wavelet analysis, a 2—4-year variation period is identified in these modes. Moreover, correlation coefficients between each RPC and zonal wind U, meridional wind V, zonal moisture flux Q_u, meridional moisture flux Q_v, and precipitation rate over East Asia are calculated to construct correlation fields. Results show that different heating modes over the TP correspond to different circulation, moisture flux as well as precipitation patterns. Precipitation over North China (or Kashmir) is negatively (or positively) correlated with REOF1. Similarly, notable negative (or positive) correlation can be found between the rainfall over south part of Southwest China, South China, and the Philippines (or Japan) and the REOF3. Due to high localization of diabatic heating over the TP, it is not enough to study the influence of TP thermal forcing on the climate with an area-averaged heating index.

Key words: Tibetan Plateau (TP), atmospheric heating source, circulation, precipitation

I. INTRODUCTION

The Tibetan Plateau (TP hereafter) is the highest and largest highland in the world. In summer, acting as a massive elevated heating source, the TP exerts remarkable influences on the hemispheric or even global circulation and weather systems. As early as the 1950s, in terms of calculating and analyzing the thermodynamic structure over the TP, Yeh et al. (1957) and Flohn (1957) separately investigated the impacts of thermal forcing of the TP on the atmospheric circulation and indicated that there is a heating source over the summer plateau. By studying the evolvement of the South Asia high, Flohn (1960) pointed out that the formation of South Asia high is a result of the thermal forcing of the TP, but he did not involve the dynamical mechanism. With the aid of simulation of a rotating annulus, Yeh and Zhang (1974) further verified that the formation and maintenance of the South Asia high directly resulted from the thermal effect of the TP.

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Moreover, not long ago, Wu and Zhang (1998) revealed the linkage between the summer monsoon onset over the Bay of Bengal and the thermal and mechanical forcings of the TP.

In recent years, more and more papers focused on the influences of the thermal forcing of the TP upon the circulation and rainfall over the surrounding areas. Luo and Chen (1995) discovered that when the TP heating source is strengthened, the rainfall in the upper reaches of the Yangtze River and the valley of the Huaihe River will be more than normal, whilst the rainfall in the area of South China will be less. Based on the 1958 — 1997 NCEP/NCAR analysis data, Liu et al. (2002) found that, in the years with the stronger summer TP heating source, the subtropical anticyclone over the Western Pacific (SAWP) moves southward, airflow converges in the valley between the Yangtze and Huaihe Rivers, and results in more rainfall over there. By using observational data, Zhao and Chen (2001) indicated that when the heating source over the TP is stronger (or weaker) than normal, there is an anomalous cyclonic (or anticyclonic) circulation in the lower troposphere over the TP and surrounding areas, and abnormal southwest (or northeast) winds in the lower layer over the Yangtze River Valley, corresponding to the strong (or weak) East Asia summer monsoon.

As a matter of fact, all of these studies did not take the local features of the TP heating into account and the heating intensity was depicted only by a domain-averaged index. However, owing to the broad coverage and complicated topography, there must be an obvious difference in heating status among various regions of the TP, a heating index therefore is not enough indeed. In this work, we firstly find the main spatial modes and corresponding temporal coefficients (hereafter in REOF and RPC, respectively) of diabatic heating over the TP in July through using analysis of rotating empirical orthogonal function (REOF), and the characteristics of temporal evolvement of these main REOFs are investigated by using wavelet analysis on the corresponding rotating principal components (RPCs). Moreover, the correlation coefficients between each of these RPCs and the simultaneous zonal and meridional wind speeds (U and V), zonal and meridional moisture fluxes (Q_u and Q_v), as well as the precipitation rate fields are calculated to seek the possible influences of the TP thermal forcing on the circulation, moisture transportation, as well as rainfall over East Asia.

II. DATA AND METHODS

The heating rate, horizontal wind speed, moisture flux, and the precipitation data used in this paper are the July mean NCEP/NCAR reanalysis dataset during 1958 to 1999. The heating rate is provided at 28 σ layers in the vertical. The horizontal resolutions are $1.875° \times 1.875°$ for heating and precipitation rate, and $2.5° \times 2.5°$ for the other variables. Sensible heat (SH) comes from the integral of vertical diffusive heating that equals the land surface sensible heat flux. The totally atmospheric diabatic heating is the sum of the integrals of vertical diffusion, large-scale condensation, deep convection, shallow convection, long-wave radiation, and short-wave radiation heating. In view of the orographic complexity in East Asia, all p -coordinate data are interpolated to σ -coordinates when we investigate the TP heating-accompanied horizontal wind speed and moisture flux fields.

The totally atmospheric heating rate (or the heat source/sink in air column or the atmospheric heating intensity) can be written as

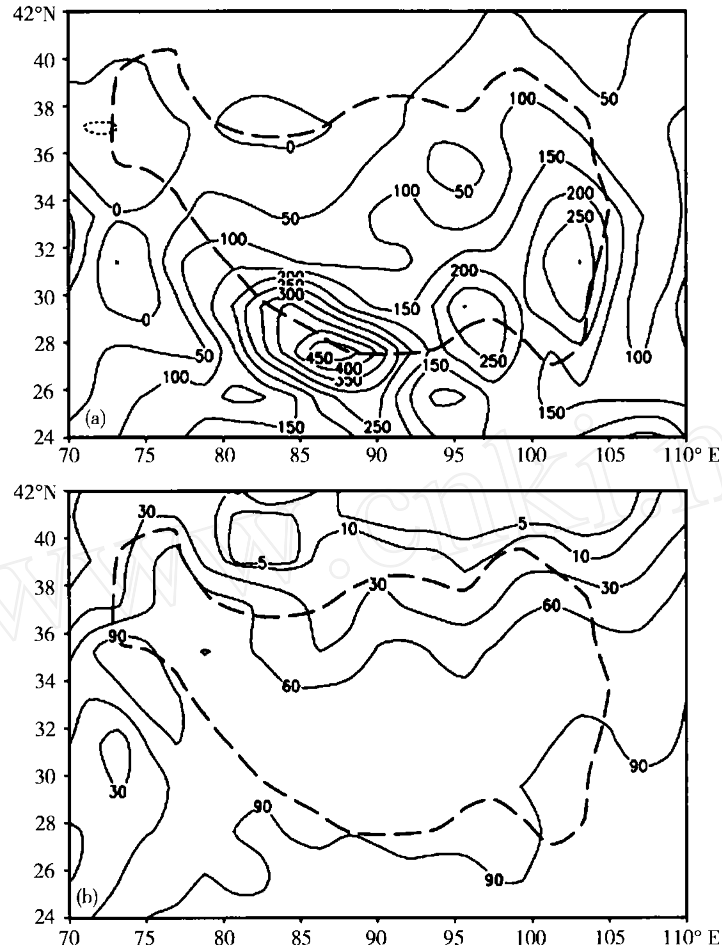

Fig. 1. July mean atmospheric heating source intensity H (a) and the percentage of latent heat to the sum of latent heat and sensible heat (b) over a rectangular domain centered at the Tibetan Plateau during 1958 to 1999. The unit of intensity of heating source is in W/m^2, and the area covered by thick dashed line means the orography with altitude more than 3000 m high.

$$H = \frac{c_p \cdot p_s}{g} \int_{0.995}^{0.0027} Q(\sigma) \mathrm{d}\sigma, \tag{1}$$

where c_p is the specific heat capacity at constant pressure, p_s denotes surface pressure, and g means the acceleration of gravity, and all of them are constants in integrating.

The total heating rate $Q(\sigma)$ is

$$Q(\sigma) = SH(\sigma) + LH(\sigma) + RD(\sigma), \tag{2}$$

where $SH(\sigma)$ represents the vertical diffusion heating rate due to sensible heating transport in the level of σ, $LH(\sigma)$ is a sum of the large-scale condensation latent heat release, deep convective heating, as well as shallow convective heating. $RD(\sigma)$ denotes the received or emitted net radiation heating, which equals the sum of net long-wave and short-wave radiation heating rate.

According to the above formula, we calculated the July mean totally atmospheric heating rate H over the TP and adjacent regions and showed the result in Fig. 1a in unit of

W/m^2. One can see that the spatial distribution is characterized by the gradually decreased intensity from south to north TP with two maximum centers located over the southern and southeastern plateau. This result generally agrees with what is given by Zhao and Chen (2001) based on the observations of 148 stations in the TP and neighboring regions from 1961 to 1990. But a pronounced discrepancy between them is that the NCEP/NCAR heating intensity over the southern TP is much stronger. In addition, the significance of *LH* is given by a percentage of *LH* to the sum of *LH* and *SH*, as shown in Fig. 1b, and it is shown that except in the north fringe of the TP, *LH* is the primary factor for the July diabatic heating over the TP.

Since *LH* is induced by precipitation, the validity of the NCEP/NCAR *LH* data can be tested by comparing the associated precipitation rate field with other rainfall data. Figure 2 then gives the July mean precipitation fields of NCEP/NCAR and Xie-Arkin during 1978 to 1998, it is easy to find some remarkable differences in southeast plateau and East

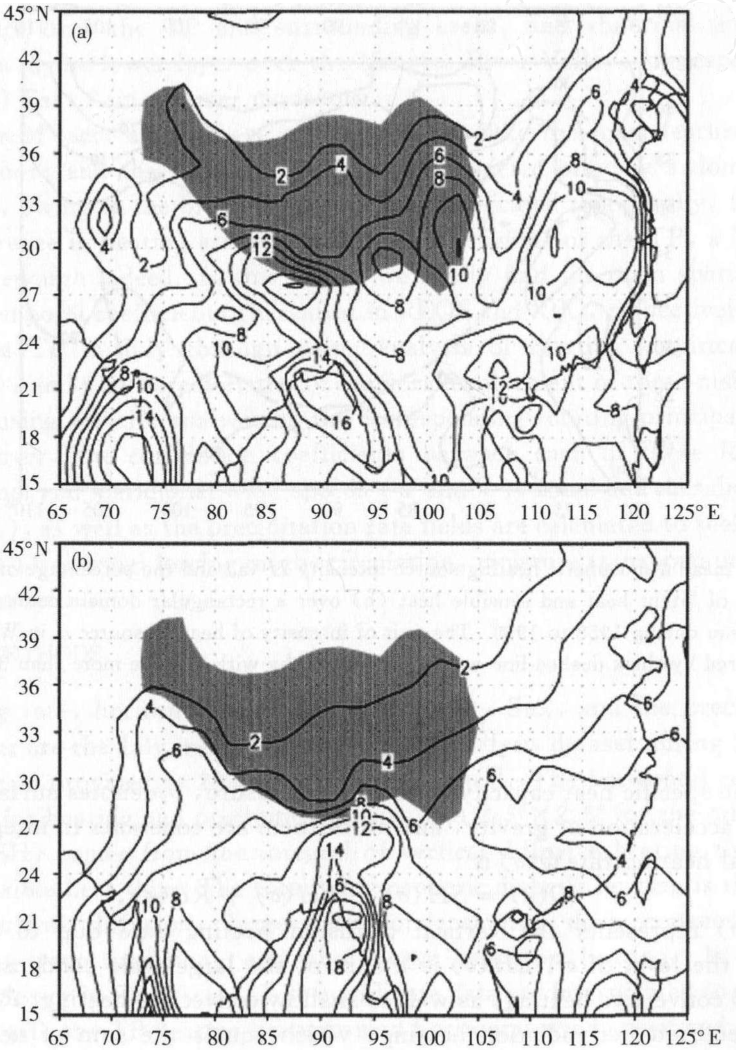

Fig. 2. July mean precipitation over East Asia. (a) NCEP/NCAR, (b) Xie-Arkin. Unit: mm/d. The shaded areas are the orography more than 3000 m high.

China, and this feature is represented by the larger magnitude and one more center over southeast TP in NCEP/NCAR data. Maybe these differences partly are attributed to the different data resolution. Furthermore, a strong precipitation center over the southwest TP cannot be found in Xie-Arkin data either. Owing to scarce observational stations in this region, it is not appropriate to make a conclusion about the quality of NCEP/NCAR precipitation data, people therefore should be prudent in using them. Despite all these discrepancies, the general distribution feature of these two datasets is basically same, particularly there is a common center in the position of 27°N, 95°E nearby. In view of qualitative analysis, the NCEP/NCAR precipitation data are still useful in East Asia. Due to the fact that the NCEP/NCAR dataset is based on a data-assimilation system, it is appropriate for dynamical analysis. On the other hand, our goal in this work is to investigate whether the localized heating mode is accompanied by distinct circulation as well as precipitation in East Asia, the uncertainty of data quality will not influence our study. Thereby we employ NCEP/NCAR reanalysis data for our purpose.

The REOF method (Horel 1981) is to rotate the output of EOF analysis orthogonally by using the variance maximum method. This procedure conserves the sum of the variance of the rotated principal components before and after rotating, and thereby keeps the advantage of the EOF analysis in compressing the complicated variability of the original data into a few temporally uncorrelated components. Moreover, it overcomes the shortcoming in the traditional EOF analysis in which each spatial pattern depicts the variation structure of the whole field with almost equal weights. Wu et al. (1995) have investigated the abnormal spatial modes of winter temperature over China with this method. Here we firstly get the normalized main spatial modes of diabatic heating over the TP by using EOF analysis. To identify the local information, the 18 leading spatial modes (with more than 90% accumulative variance contribution) are calculated with the rotating method mentioned above.

Some usual methods to isolate coupled modes between two fields with time series are singular value decomposition (SVD), canonical correlation analysis (CCA), principal component analysis with the fields combined (CPCA), etc. But there are two defects in these methods, one is for a given "left" field (e. g. heating field), we could get two different "left" heterogeneous correlation patterns after performing SVD with two different "right" fields (e. g. U and V fields); the other is for the reason that SVD is a special case of EOF analysis when the "left" field is the same as the "right" field, it is impossible to identify the localized features by using it. To tackle this problem, Cheng and Dunkerton (1995) developed a rotated SVD (known as RSVD) routine. However, due to the use of the same rotating procedure known as varimax rotation in RSVD and REOF, it virtually conflicts with the theory of SVD (i. e. maximizing the covariance of temporal coefficients in "left" and "right" data fields), and inevitably leads to somewhat deficient.

The purpose of this paper is to isolate the main localized patterns of heating fields over the TP and its neighborhood, and thereby get the associated circulation as well as precipitation fields over East Asia. Hence REOF analysis is performed on the diabatic heating field firstly, and then we calculate correlation coefficients between the leading RPCs and horizontal wind speed and moisture flux in low-level. This procedure can overcome the defects of RSVD. The streamline fields represented by the correlation coefficients between the horizontal wind fields and RPCs denote the anomalous circulations related to those heating modes of the TP. Similarly, divergence of the vectors constructed by the correlation coefficients between horizontal moisture flux and the RPCs can reflect the associated moisture transport. Finally, the similar correlation analysis between the leading RPCs and precipitation field can provide us information about heating-induced abnormal distribution of precipitation over China.

III. REOF ANALYSIS OF THE JULY ATMOSPHERIC HEATING SOURCE OVER TP

It is well known that there are some shortcomings in the traditional EOF analysis. For instance, the EOF1 always appears in a uniform mode (+ or −), EOF2 shows a pattern with opposite signs (+ −), and EOF3 exhibits a structure with alternative signs (− + − or + − +). Although these spatial distributions do usually provide the main spatial patterns of the variable field, it cannot reveal the localized signals yet. And this problem can only be solved by rotating the principal components (Huang 1987).

The REOF results of the heating source over the TP indicate the pronounced local information. Because the accumulative variance contribution of the seven leading eigenvectors is no more than the half of the total, it implies that the basic structure of the heating source over the TP is composed of many local modes. Figure 3 shows the four leading REOFs of the July heating source over a TP-centered rectangular domain (23.809−40.925°N, 75−100°E) with 150 grid points altogether. The value on each point is the correlation coefficient between the heating source time series on this point and the corresponding RPC, and its square represents the variance contribution of this mode to the series on this point. Furthermore, owing to the standardization of data series, the total variance on each point equals 1. Thereby the square is also the variance contribution rate to this point. For example, there are at least 64% (about 0.82×0.82) local variance that can be depicted by this mode in the domains with the absolute value more than 0.8 in Fig. 3. Thus obviously local feature only exists in the regions with large contour values. From the REOF1 shown in Fig. 3a, one can see a spatial pattern with uniform values in a large domain centered over northeast TP; the REOF2 represents a mode with heating center over the southwest TP; a heating mode with the center over Kashmir is shown in REOF3(Fig. 3c); and the REOF4(Fig. 3d) indicates a mode localized over the southeast plateau. All these four patterns explain 33% variance contributions for the data field, and the local variance in each pattern exceeds 80%.

The temporal evolvement features of the four leading REOFs have also been investigated by using Morlet wavelet analysis (Christopher and Gillbert 1998) on the corresponding RPCs. It turns out that a 2−4 year period component can be detected in all these patterns, and it is most obvious in the 1970s and 1980s. Owing to the limitation of space, here we only show the results of wavelet analysis and the significance test of RPC1 in Fig. 4. It is obvious that no periodic component can pass the significance test level of 99% during the whole data time period. Nevertheless, there is a pronounced interdecadal variation in RPC1. Considering the uncertainty of the data quality, this result needs a further verification by other new data.

IV. THE ASSOCIATED LOW-LEVEL STREAMLINE FIELDS

The anomalous low-level ($\sigma = 0.811$) circulation patterns associated with these heating modes are shown in Fig. 5. As mentioned before, they are represented by streamline fields of the artificial vectors constructed by the correlation coefficients between

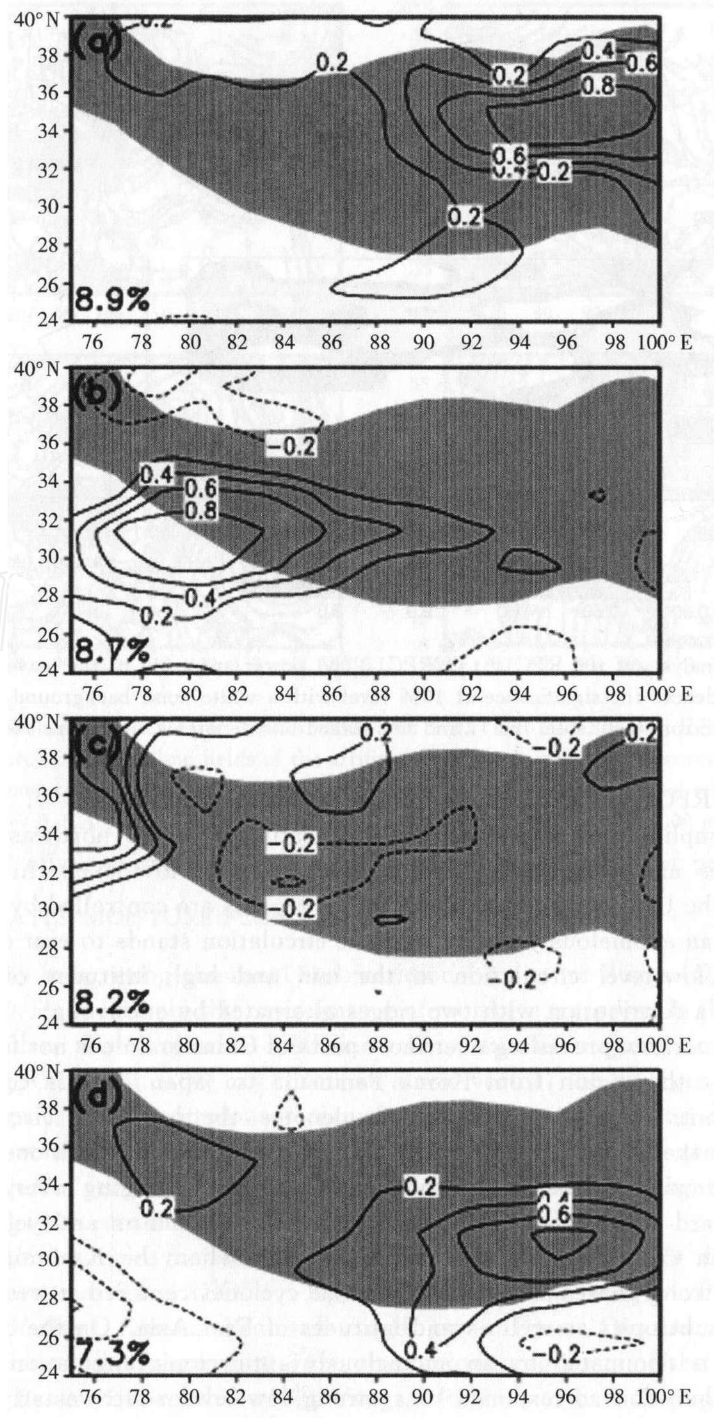

Fig. 3. The four leading REOFs of the atmospheric heating source over the TP in July. From top to the bottom they are the REOF1, REOF2, REOF3, and REOF4 respectively. The numbers at the bottom left are the percentage of variance contribution rate, and the meaning of the shaded areas as in Fig. 2.

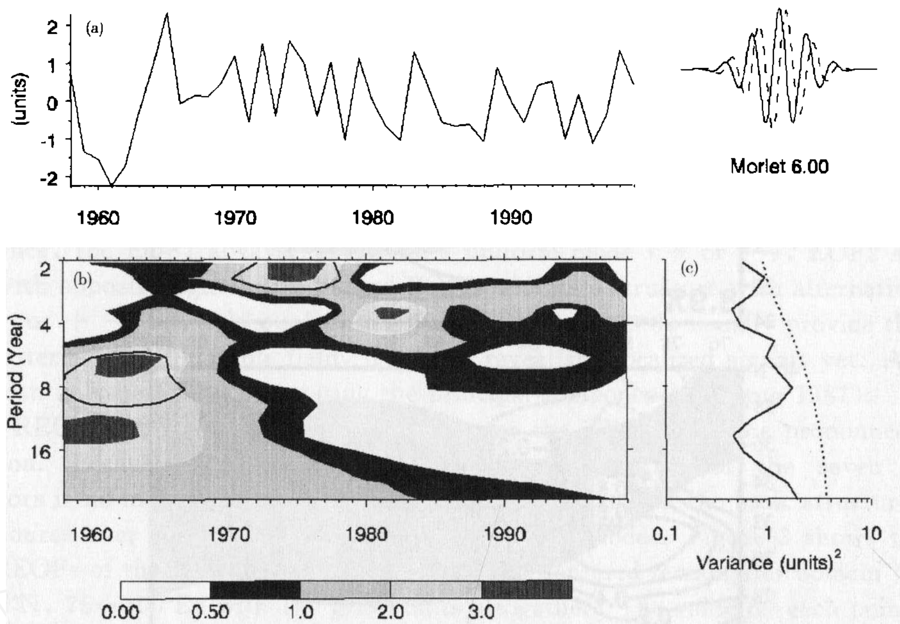

Fig. 4. Wavelet analysis of the RPC1. (a) RPC1, (b) power spectrum of the wavelet, the blacked contours denote the significance at 10% level with a white-noise background, and (c) global power spectrum test (solid line), and the dashed line denotes a significance test as same as in (b).

the four leading RPCs and zonal and meridional wind speeds (U and V).

Figure 5a implies that when the diabatic heating over the northeast TP is strong enough, there is an anomalously cyclonic circulation at low-level. In mid and high latitudes, both the Ural and the Far East coastal regions are controlled by an anticyclonic circulation, but an anomalously strong cyclonic circulation stands to east of Baikal Lake. Therefore, the low-level circulation in the mid and high latitudes of East Asia is characterized by a distribution with two ridges alternated by one trough. This circulation leads to the cold airflow prevailing over most parts of China and does not facilitate rainfall there. However, the region from Korea Peninsula to Japan Isles is controlled by an anomalous cyclonic circulation. Figure 5b denotes the low-level circulation pattern corresponding to the heating mode REOF2 shown in Fig. 3b, in which one can see a very different picture with northeasterly and southeasterly converging over the southwest plateau, southward airflows prevailing over North China, and an anticyclonic circulation controlling South China. In Fig. 5c, we know that when the Kashmir heating mode (REOF3) is in strong phase, an abnormally broad cyclone, centered at western Mongolia, exists over the subtropics as well as mid-latitudes of East Asia. On the other hand, the western Pacific is dominated by an anomalously anticyclonic circulation. This type of circulation configuration corresponds to a strong low-level southwesterly jet prevailing over East Asia and is in favor of more rainfall in North China. The point will be further verified in Section VI by performing a similar analysis on the precipitation field. Finally, Fig. 5d represents that airflows will converge over the Yangtze-Huaihe River Valley if the REOF4, in which the heating center is located at southeast TP, is dominant. Furthermore, the same routine is performed on the mid troposphere ($\sigma = 0.5$). Since the

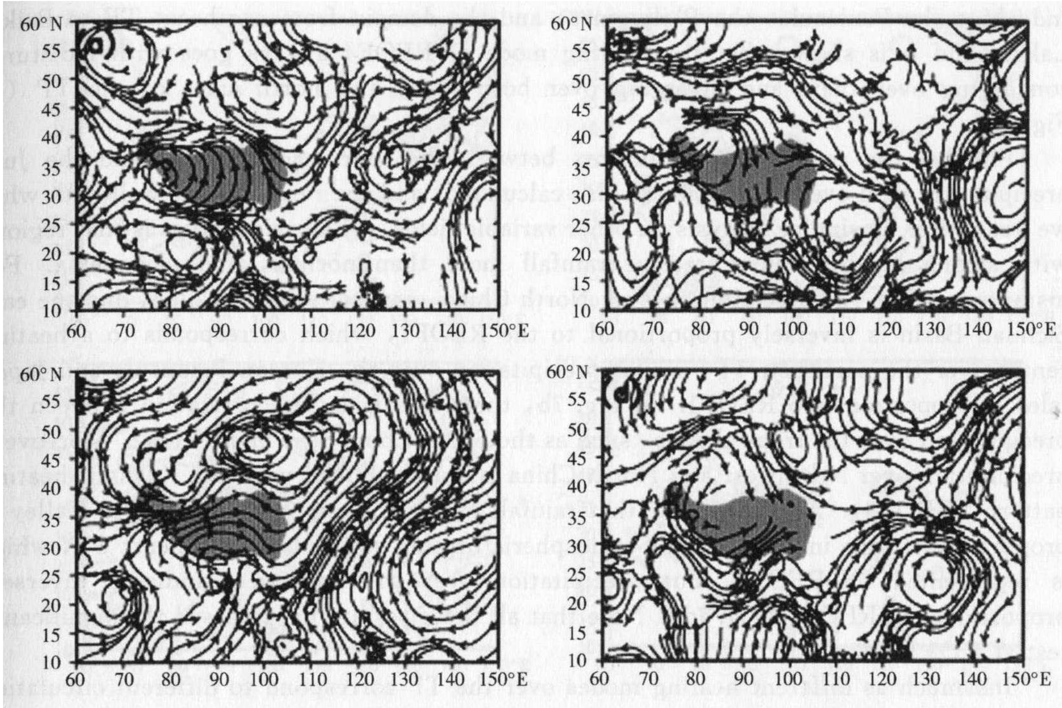

Fig. 5. Anomalous low-level circulation associated with the four leading REOFs, which are depicted by streamline fields of the artificial vectors constructed by correlation coefficients between the four leading RPCs and July zonal wind U and meridional wind V at the level of $\sigma = 0.811$, and the shaded areas are the orography more than 3000 m high.

results are generally consistent with those in low-level, the figures are not shown here.

V. THE ASSOCIATED MOISTURE FLUX AND PRECIPITATION FIELDS

By vertically integrating the zonal and meridional moisture fluxes (Q_u and Q_v) from $\sigma = 0.99$ to $\sigma = 0.5$, we obtain the basic feature of moisture transport in the lower and mid layers and calculate the correlation coefficients between the integrated moisture flux and the four leading RPCs. Thus we can construct a new vector, the divergence field therefore provides us a picture of anomalous moisture transport corresponding to those heating modes. These results are shown by Fig. 6, where positive and negative values mean moisture divergence and convergence, respectively. Because the magnitude only has a relative meaning, the contour value is not marked in these figures.

In Fig. 6a, the main moisture convergence regions, which are related to strong heating over northeast TP (REOF1), appear over the main body of TP, the Yangtze-Huaihe River Valley, Korean Peninsula, and Japan Isles. On the other hand, the pronounced moisture divergence appears in the surrounding areas of the TP with centers over the Tarim Basin, mid reaches of the Yangtze River, northern Bay of Bengal, and the Iran Plateau. However, when the atmospheric heating source over southwest TP is dominant, moistures will converge in situ and diverge over both south and north sides of the TP, Indian Peninsula, Indochina Peninsula, South China, as well as the Philippines (Fig. 6b). In Fig. 6c, main moisture converging areas, which are accompanied by an intense convective heating over the southwest plateau, present over the Kashmir, Indochina the Peninsula, the Philippines, and the domain from northeast TP to Baikal Lake. And it is shown that the heating mode of REOF4 always goes with moistures converging over there and diverging over both south and north sides of the TP (in Fig. 6d).

Finally, the correlation coefficients between the four leading RPCs and the July precipitation field over East Asia are also calculated, and the results agree well with what we get earlier by similar analysis on other variable fields. The basic feature is that regions with strong heating source receive rainfall more than normal, and vice versa. For instance, in Fig. 7a, precipitation over North China, southern South China, and the east Sichuan Basin is inversely proportional to the REOF1, which corresponds to a heating center over the northeast TP, whilst precipitation over the Korean Peninsula and Japan Isles is proportional to REOF1. In Fig. 7b, there is a negative correlation between the precipitation over the tropical Asia (such as the South China Sea) and REOF2. Moreover, precipitation over Northwest and North China is closely linked with the Kashmir heating pattern (REOF3). And it is clear that rainfall over the Yangtze-Huaihe River Valley is proportional to the intensity of the atmospheric heating source over southeast TP, which is represented by REOF4, but precipitation over the northwest India is inversely proportional to REOF4 (Fig. 7d). Note that all these results have passed the significance test at 95% level.

Inasmuch as different heating modes over the TP correspond to different circulation and precipitation patterns over East Asia, we should take the local features of diabatic

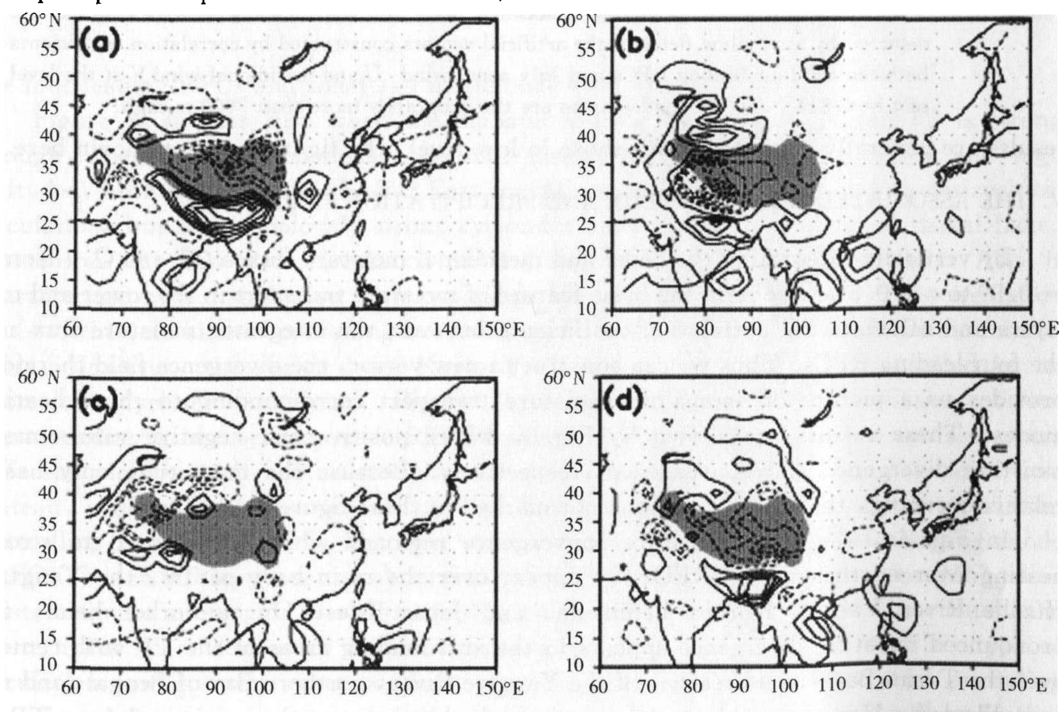

Fig. 6. Anomalous low and mid-level moisture flux fields associated with the leading REOFs, which are depicted by divergence of correlation coefficients between the four leading RPCs and the July zonal moisture flux Q_u and meridional moisture flux Q_v integrated from $\sigma = 0.995$ to $\sigma = 0.5$ in vertical, and the shaded areas denote the orography more than 3000 m.

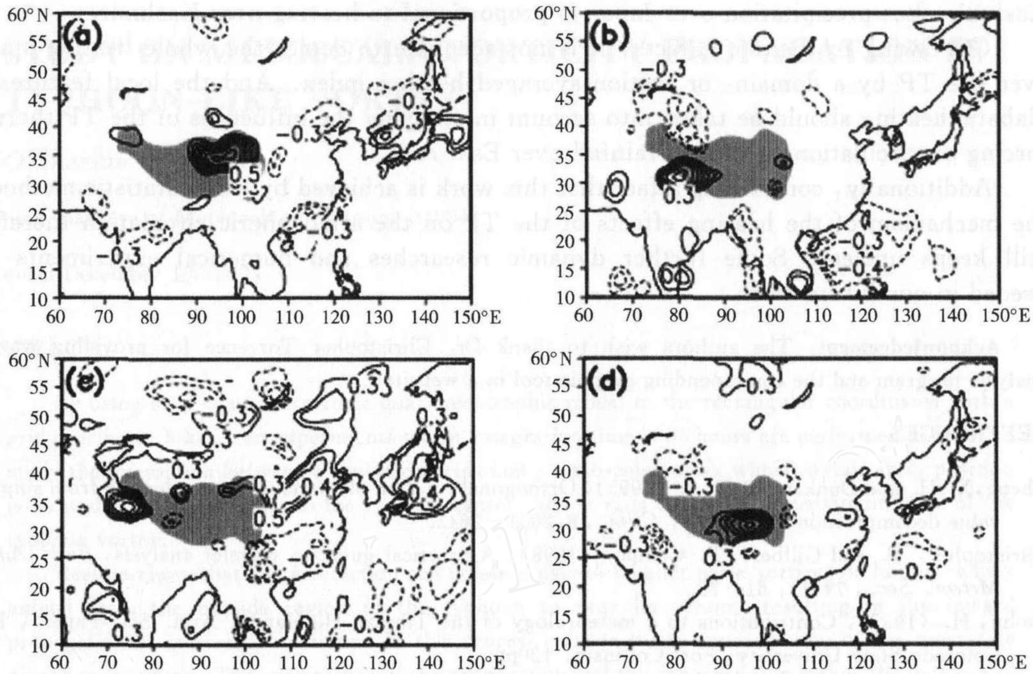

Fig. 7. Correlation coefficients between the four leading RPCs and the July precipitation over East Asia. Contours of 0.3 and 0.4 represent significance levels at 0.05 and 0.01, respectively, and the shaded areas denote the orography more than 3000 m high.

heating into account when studying influences of the TP thermal forcing upon the atmospheric circulation over surrounding areas. And it is not appropriate to depict the whole heating status of the TP only by a domain- or station-averaged heating index in midsummer.

VI. CONCLUSIONS AND DISCUSSION

In midsummer, the distribution of diabatic heating over the TP exhibits an obviously geographical difference, and the abnormity of heating status will exert visible impacts on the circulation as well as weather over East Asia. And the main conclusions in this paper may be drawn as below:

(1) The summer atmospheric heating source/sink over the TP is very complicated in spatial distribution. The four leading heating modes decomposed by REOF are centered in northeast TP, southwest TP, Kashmir Plateau, and southeast TP, respectively. Since the accumulative variance of the four leading modes can explain only about one third of the total variance of the variable field, thus it is impossible to depict heating spatial distribution with few modes. Moreover, wavelet analysis results indicate that a 2—4-year period component exists in all these patterns.

(2) Different heating modes over the TP also correspond to different circulation and rainfall pattern over East Asia. For instance, there is a negative (or positive) correlation between the precipitation over North China and the heating source over the eastern TP (or over the Kashmir Plateau). Precipitations over Southwest China, South China, and the Philippines are inversely proportional to the intensity of atmospheric heating source over

Kashmir. But precipitation over Japan is proportional to heating over Kashmir.

(3) Owing to the above facts, it is not adequate to depict the whole heating status over the TP by a domain- or station-averaged heating index. And the local features of diabatic heating should be taken into account in studying the influences of the TP thermal forcing on circulation as well as rainfall over East Asia.

Additionally, considering a fact that this work is achieved by using statistic methods, the mechanism of the heating effects of the TP on the atmospheric circulation therefore still keeps unclear. Some further dynamic researches and numerical experiments are needed in our future work.

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