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The Impact of Atmospheric Heat Sources over the Eastern Tibetan Plateau and the Tropical Western Pacific on the Summer Rainfall over the Yangtze-River Basin

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ABSTRACT

The variability of the summer rainfall over China is analyzed using the EOF procedure with a new parameter (namely, mode station variance percentage) based on 1951-2000 summer rainfall data from 160 stations in China. Compared with mode variance friction, the mode station variance percentage not only reveals more localized characteristics of the variability of the summer rainfall, but also helps to distinguish the regions with a high degree of dominant EOF modes representing the analyzed observational variable. The atmospheric circulation diagnostic studies with the NCEP/NCAR reanalysis daily data from 1966 to 2000 show that in summer, abundant (scarce) rainfall in the belt-area from the upper-middle reaches of the Yangtze River northeastward to the Huaihe River basin is linked to strong (weak) heat sources over the eastern Tibetan Plateau, while the abundant (scarce) rainfall in the area to the south of the middle-lower reaches of the Yangtze River is closely linked to the weak (strong) heat sources over the tropical western Pacific.

Key words: heat sources, eastern Tibetan Plateau, tropical western Pacific, summer rainfall, Yangtze River basin

1. Introduction

Previous studies (He et al., 1987; Murakami, 1987; Chen et al., 1991; Yanai et al., 1992; Zhang and Wu, 1999) have shown that the Tibetan Plateau has remarkable thermal effects on the breakout and evolution of the Asian summer monsoon as well as on the rainfall in eastern China due to its elevated topography. A further investigation (Luo and Chen, 1995) found that in the boreal summer half year, corresponding to the intensive heat sources over the eastern Tibetan Plateau (ETP), namely the intensified (suppressed) low-level southwesterlies and the Tibetan High, there is abundant (scarce) rainfall in the upper reaches of the Yangtze River basin and the Huaihe River basin but scarce (abundant) rainfall in southeastern China. The findings of that study were confirmed by Zhao and Chen (2001a, b) in their recent work on the connections between the heat sources over the Tibetan Plateau in boreal summer, the circulations in Asia and the summer precipitation in China with data of a longer period.

In addition to the atmospheric activities over the ETP, contributions can be identified from anomalous convection activities over the tropical western Pacific (TWP) warm pool and around the Philippines (Huang and Li, 1988; Nitta, 1987). Huang and Sun (1992, 1994) suggested that an abnormally warmer (colder) tropical western Pacific warm pool will lead to stronger (weaker) convection activities in the area from the Indochina Peninsula to the western Pacific, resulting in the northward (southward) shifting of the subtropical High in the western Pacific. This abnormal general circulation pattern will favor the scarcity (abundance) of rainfall in the summer in the Yangtze River-Huaihe River basins. Yang (2001) also pointed out that the precipitation anomalies in the Yangtze River basin are related to the atmospheric heat source anomalies over the western Pacific—the South China Sea and the southeastern Tibetan Plateau— the Bay of Bengal.

Although the summer rainfall over China has been studied with Empirical Orthogonal Function (EOF) analysis in many previous works (Wang and Wu, 1996; Zou and Ni, 1997; Shi et al., 2000), the relationship between the anomalous modes of summer rainfall in China and the atmospheric heat sources has not been

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addressed up to now. Furthermore, the relative importance of the thermal effects of the eastern Tibetan Plateau and the tropical western Pacific warm pool on the summer rainfall in China, especially in the Yangtze River basin, is still not clear and remains to be studied. To provide an insight into these issues, a new EOF parameter is designed in section 2. The results are shown in section 3, and a summary is given in section 4.

2. Data and methods

The data used in this study are the monthly precipitation measurements collected at 160 stations in China in boreal summer from 1951 to 2000. The daily wind, temperature, and vertical motion data in the period of 1966 to 2000 come from the 2.5°×2.5° National Centers of Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data.

The apparent heat source Q_1 (e.g., Yanai et al., 1973; Luo and Yanai, 1984) is computed by

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

where T is the temperature, L the latent heat of condensation, θ the potential temperature, q the mixing ratio of water vapor, ω the vertical $p-$velocity, p_0=1000 hPa, $\kappa = R/c_p, R$ and c_p are the gas constant and the specific heat at constant pressure of dry air, and V the horizontal wind. The heat source of the whole air column is calculated through the vertical integration of Q_1 from $p_{\rm t}$ (=100 hPa) to $p_{\rm s}$ (the pressure at the surface):

$$\langle Q_1\rangle=\frac{1}{g}\int_{p_{\rm t}}^{p_{\rm s}}Q_1dp\approx LP+S+\langle Q_{\rm R}\rangle\ , \qquad (2)$$

where P、S and $\langle Q_{\rm R}\rangle$ represent the precipitation, the sensible heat flux per unit area at the surface and the net radiative heating rate for the whole air column, respectively.

In the analysis of EOF decomposition, an important parameter, which called the mode variance friction, is usually used to measure the contribution of a derived EOF mode to the total variance of an analyzed field. However, the mode variance friction can not provide more detailed information about the spatial distribution of variance contribution for each EOF mode. For this purpose, a new parameter named the mode station variance percentage (MSVP) is introduced through estimating the variance percentage of the reconstructed time series at each station to the corresponding observed time series, based on the EOF modes and the corresponding principal components. The definition of MSVP is described as follows.

In the Empirical Orthogonal Function (EOF) analysis, suppose $\boldsymbol{X}_{m\times n}$ is the data matrix with elements x_{jk} representing the kth sample at the jth station or grid point, with λ_i as the ith eigenvalue, and with v_{ji} as the spatial value of the ith eigenvector at station j. The mode station variance percentage (MSVP) for the ith mode is defined as the percentage rate of the reconstructed time series variance related to the observed one at each station. The reconstructed field can be obtained based on the ith EOF eigenvector and corresponding principal component. For the ith EOF mode, the variance of the reconstructed time series at station j is $v_{ji}^2\cdot\lambda_i$, and the variance of the observed time series at station j is $\sum\limits_{i=1}^{m}{v_{ji}}^2\cdot\lambda_i$. Then the MSVP for the ith mode at station j is calculated by

$${\rm MSVP}_{ji}=[v_{ji}^2\cdot\lambda_i/\sum_{i=1}^{m}(v_{ji}^2\cdot\lambda_i)]\times100\%\ . \qquad (3)$$

3. Results

3.1 *Dominant modes of variability in the summer rainfall in China*

The characteristics in variability in the summer rainfall (June to August) in China are analyzed first with an EOF decomposition with the summer mean rainfall anomalies at each station as input. The outputs show that the mode variance frictions of the first three modes account for 16%, 12.2% and 6.8% of the total variance respectively.

The first EOF mode shows that the strongest anomaly is centered in central and eastern China along the Yangtze River basin, and the opposite sign anomaly is centered in southern China (Fig. 1a). The corresponding MSVP distribution (Fig. 1d) shows that along the Yangtze River basin the reconstructed field based on the first EOF mode contains a large portion of the information of the summer rainfall anomaly with an MSVP larger than 50%. Compared with the mode variance friction, the MSVP is more useful in terms of describing the local characteristics of the EOF modes. The principal component of the first EOF mode (Fig. 2a) shows that the first principal component (PC1) experiences an increasing trend from the late 1950s to the end of the 20th century, implying a long-term positive summer rainfall anomaly in the Yangtze River basin. The second EOF mode exhibits a dipole in the regions to the south and north of the Yangtze River (Fig1. b), with a larger MSVP of 30%–40% centered in southern China (Fig. 1e). This implies that the second mode mainly describes the variability of the summer rainfall in southern China. The second principal component (PC2) is characterized by negative anomalies in the period from the late 1970s to the early 1990s and positive anomalies from 1993 to 1999. These characteristics mean that there is less (more) summer rainfall in southern China during the former (latter) period.

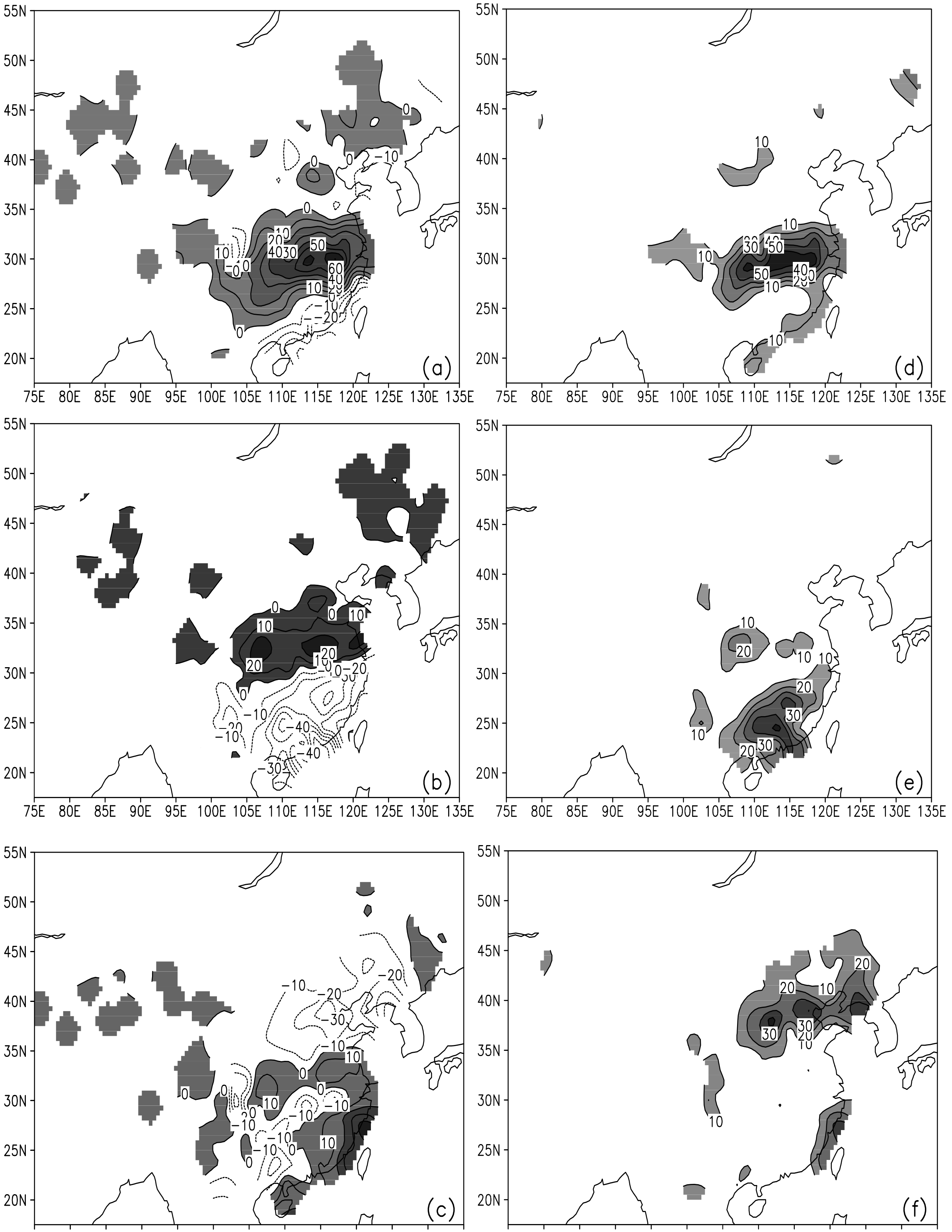

Fig. 1. Spatial patterns of the first three EOF modes (a–c, multiplied by the standard deviations of the corresponding principal component time series, units: mm) and the reconstructed mode station variance percentage (d–f) of the summer mean rainfall in China.

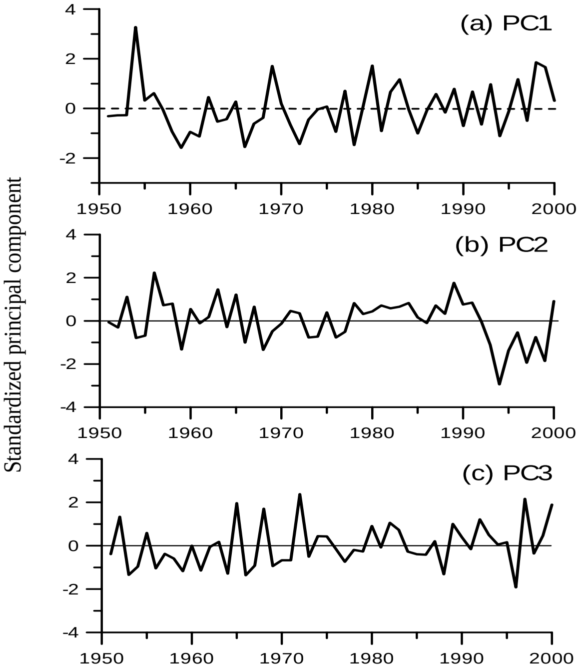

Fig. 2. The standardized (a) first, (b) second, and (c) third principal components of the EOF analysis for the summer mean rainfall in China.

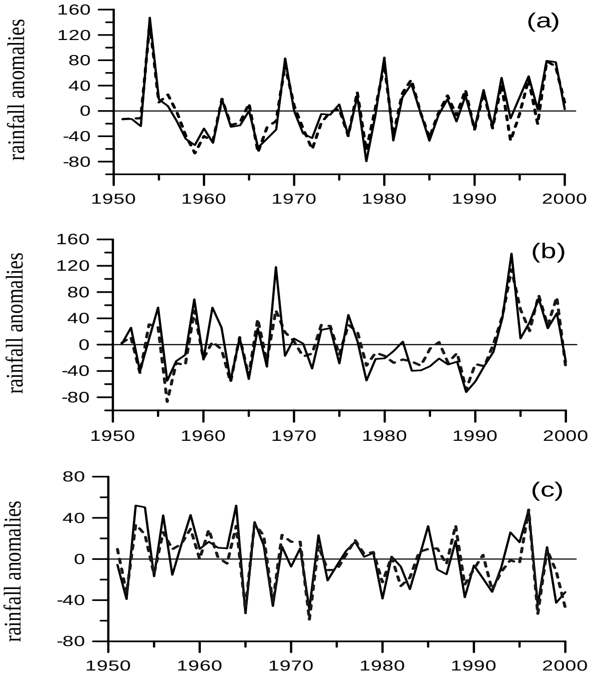

Fig. 3. The regionally averaged observed summer mean rainfall anomalies (solid) and reconstructed rainfall anomalies (dashed) in the regions of (a) the Yangtze River basin, (b) southern China, and (c) northern China with the reconstructed mode station variance percentage greater than 25% based on the first three EOF modes. (units: mm)

The third EOF mode shows two major anomaly regions with opposite signs in northern China and the southeastern coastal area of China (Fig. 1c) with an MSVP around 40% in northern China (Fig. 1f). The third principal component (PC3) (Fig. 2c) is characterized by the interannual variation signal mixed with a moderate interdecadal variation signal.

Based on the first three EOF modes, the reconstructed anomaly series are studied together with the observed summer rainfall anomaly series to highlight the local importance of each EOF mode. These time series are obtained by averaging the rainfall anomalies at 23 stations in the middle and lower reaches of the Yangtze River with MSVP values larger than 25% (Fig. 1d). The results show that the reconstructed summer rainfall anomaly series based on the EOF1 coincides very well with the observed anomalies (Fig. 3a). Similar results can be identified in Fig. 3b for southern China according to the EOF2 and in Fig. 3c for northern China according to the EOF3 due to 12 stations with MSVP values larger than 25% in the corresponding regions. These results prove that the first three EOF modes mainly represent the summer rainfall variability in the Yangtze River basin, southern China and northern China respectively.

3.2 *Relationship between atmospheric heat sources and the summer rainfall in the Yangtze River basin*

Since the variation of the summer rainfall in the region with an MSVP larger than 25% along the Yangtze River basin can be described mainly by the first EOF mode of the summer rainfall, the correlation coefficients are computed between summer $\langle Q_1 \rangle$ and the summer rainfall anomaly series within the region. The result shows that positive correlation coefficient values of 0.3 and 0.45 are centered in the regions of the ETP and Yangtze River basin and negative values of -0.3 and -0.45 are centered in the regions of the South China Sea and the TWP to the east of the Philippines (Fig. 4).

These results imply that heat sources over the ETP and the TWP are crucial to the summer rainfall in the Yangtze River basin. Therefore, a further analysis, called a partial correlation analysis (see Appendix A for details), is carried out to distinguish the contribution of the heat sources over the two areas to the summer rainfall in the Yangtze River basin. The data used in the partial correlation analysis are the 35-year samples from 1966 to 2000 and the summer rainfall at 160 stations in China. The processed data include the regionally averaged time series of the ETP (30°–35°N, 92.5°–100°E) and TWP (15°–20°N, 130°–150°E) heat sources in summer. After applying the partial correlation analysis to the processed data, the contributions of the ETP heat source (Fig. 5a) and the TWP heat

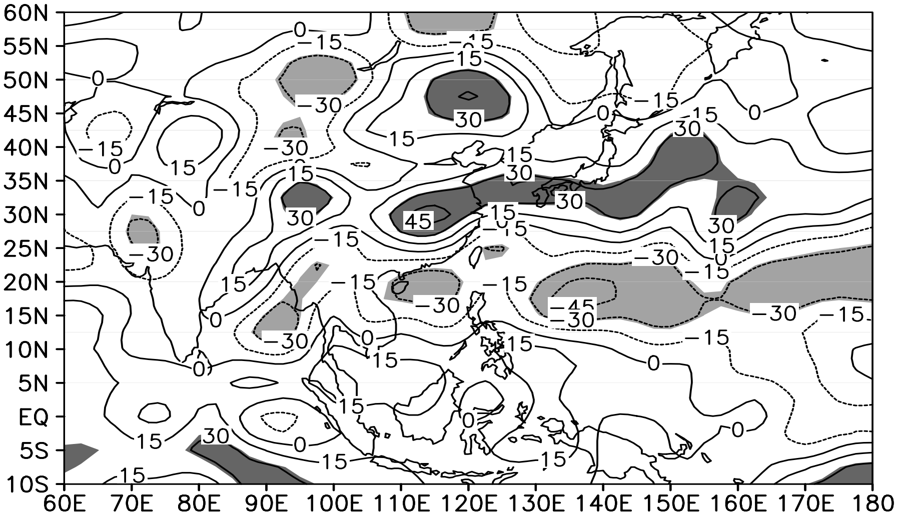

Fig. 4. Correlation between the vertically integrated heat source $\langle Q_1 \rangle$ and the regional mean rainfall in the Yangtze River basin in summer. Correlation coefficients have been multiplied by 100. Dashed lines denote negative values, and the shading denotes values above the 90% confidence level.

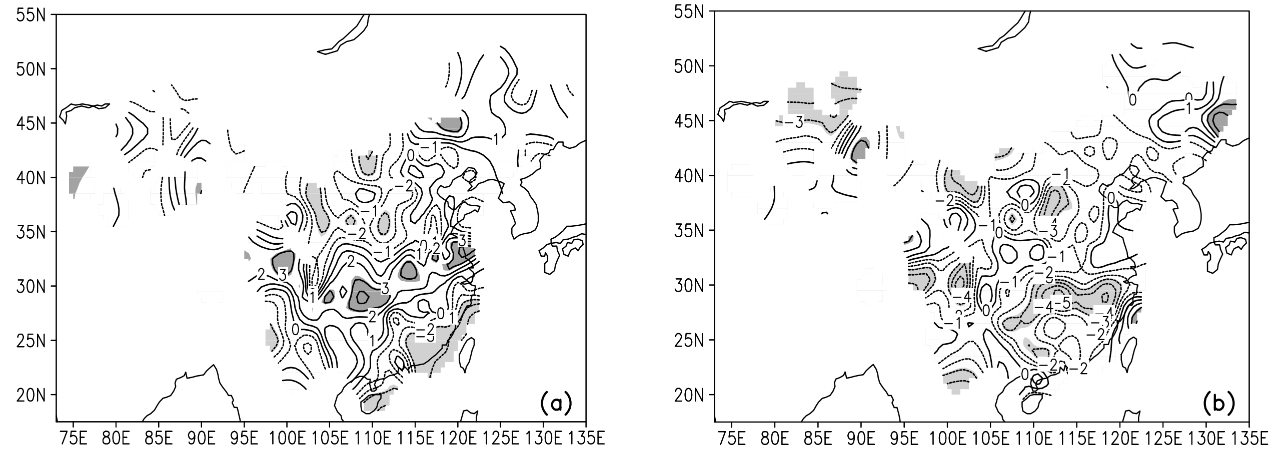

Fig. 5. Partial correlation between the summer rainfall at 160 stations in China and the area mean summer heat sources (a) over the eastern Tibetan Plateau (30°–35°N, 92.5°–100°E) and (b) over the tropical western Pacific (15°–20°N, 130°–150°E). The correlation coefficients have been multiplied by 10 with a contour interval of 1. The dashed lines denote negative values, and values with a confidence level above of 95% are shaded.

source (Fig. 5b) to the summer rainfall in Yangtze River basin can be identified. Figure 5a shows that the ETP summer heat source is positively correlated with the summer rainfall in a belt-shaped area from the upper-middle reaches of the Yangtze River northeastward to the Huaihe River basin. Consistent with the result shown in the last subsection, this result means that abundant (scarce) rainfall can be observed in the belt-shaped area in the intensive (weak) phase of the ETP heat source. Another striking feature in Fig. 5a is that there exists a large region of negative correlation in the southeastern coastal areas of China, which means scarce (abundant) rainfall can be observed in the coastal areas in the intensive (weak) phase of the ETP heat source.

The partial correlation analysis for the contribution of the TWP heat source to the summer Yangtze River rainfall (Fig. 5b) shows that significant negative correlations with a minimum of −0.6 appear in the region to the south of the middle-lower reaches of the Yangtze River. This means that scarce (abundant) rainfall appears over the aforementioned area in the intensive (weak) phase of the TWP heat source.

The conclusion can be drawn from Figs. 5a and

5b that, in summer, the TWP heat source is negatively related to the summer rainfall in the region to the south of the middle-lower reaches of the Yangtze River basin strongly, while the main positive correlation of the ETP heat source to the summer rainfall can be identified in the region stretching from the upper-middle Yangtze River to the Huaihe River basin.

4. Summary

With a new parameter (namely, mode station variance percentage) in EOF analysis instead of the mode variance friction, the EOF modes can reveal more localized characteristics of the variability of the summer rainfall. Besides, this indicator also clearly shows to what degree the observed variation of the analyzed variable can be represented by the dominant EOF modes.

With the new parameter, the EOF analysis shows that the variation of the summer rainfall in the Yangtze River basin is positively correlated with the atmospheric heat source anomalies over the ETP and negatively correlated with those over the TWP in summer. On the other hand, the TWP heat source is negatively correlated with the summer rainfall in the region to the south of the middle-lower reaches of the Yangtze River basin strongly, while the main positive correlation of the ETP heat source with the summer rainfall can be identified in the region stretching from the upper-middle Yangtze River to the Huaihe River basin.

The mechanisms for the impacts of the atmospheric heat sources over the ETP and over the TWP on the rainfall in the Yangtze River-Huaihe River basin still remain to be investigated in the future.

It should be pointed out that the variations of the atmospheric heat sources over the ETP and over the TWP, to some extent, are linked to each other but are out of phase because the correlation coefficient between the two time series of the heat sources is -0.39, which has a confidence level of 95% with a sample size of 35. However, the physical process between them also remains to be investigated.

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APPENDIX A

Definition of Partial Correlation

According to Guan et al. (2003), a partial correlation is defined as the correlation between two signals out of three or more, after the contributions from the rest of the signals have been removed. Let r_{12}, r_{23}, and r_{13} denote the conventional correlations between normalized time-series X_1 and X_2, X_2 and X_3, and X_1 and X_3, respectively. By regressing X_1 and X_3 respectively onto X_2, we obtain

$$\begin{cases} X_1 = X_1' + r_{12}X_2 \ , \\ X_3 = X_3' + r_{23}X_2 \ , \end{cases} \tag{A1}$$

where X_2 is defined as the second predictor while X_3 is predicted by the predictor X_1 after the influence of X_2 has been removed. The partial correlation coefficient $r_{31,2}$ between X_3 and X_1 is defined as

$$r_{31,2} = (r_{13} - r_{12}r_{23})/\sqrt{(1-r_{23}^2)(1-r_{12}^2)} \ . \tag{A2}$$

Similarly, the partial correlation coefficient $r_{32,1}$ between X_3 and X_2 is

$$r_{32,1} = (r_{23} - r_{12}r_{13})/\sqrt{(1-r_{13}^2)(1-r_{12}^2)} \ . \tag{A3}$$

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