Analysis of Summer Extreme Precipitation and Circulation Characteristics of Typical Years in Longdong Region, Gansu Province (Postprint)

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Abstract

This study employs daily precipitation data from 13 meteorological stations in the Longdong region and concurrent NCEP/NCAR reanalysis data, based on five extreme precipitation indices, and uses methods including Empirical Orthogonal Function (EOF) analysis and composite analysis to investigate the spatiotemporal characteristics of summer extreme precipitation and the circulation features in typical extreme precipitation years in this region from 1967 to 2015. The results indicate that: (1) Summer extreme precipitation indices are relatively low in the northwestern part of the Longdong region, higher in the southern and northeastern parts, and exhibit an overall increasing trend. (2) The first eigenvector from EOF analysis shows uniformly positive values, while the second eigenvector exhibits an anti-phase distribution with positive values in the south and negative values in the north; in years with maximum (minimum) temporal coefficients, the distribution of summer extreme precipitation in the study area along the north-south direction displays the most pronounced pattern of being stronger (weaker) in the south and weaker (stronger) in the north. (3) In typical years of strong (weak) summer extreme precipitation, there is (is no) convergence of cold and warm air; ascending (descending) motion is enhanced, outgoing longwave radiation shows negative (positive) anomalies, convection is strong (weak), corresponding to more (less) precipitation; water vapor flux divergence exhibits negative (positive) anomalies, which is favorable (unfavorable) for the occurrence of extreme precipitation.

Full Text

Preamble

Analysis of Extreme Summer Precipitation and Circulation Characteristics in Typical Years in Longdong Region, Gansu Province

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Abstract: This study employs daily precipitation data from meteorological stations and concurrent NCEP/NCAR reanalysis data in Longdong Region. Based on five extreme precipitation indices, we investigate the spatiotemporal characteristics of summer extreme precipitation from 1967 to 2015 and the circulation features in typical years using Empirical Orthogonal Function (EOF) and composite analysis. The results indicate: (1) Summer extreme precipitation indices are lower in the northwestern part of Longdong Region and higher in the southern and northeastern parts, showing an overall upward trend. (2) The first EOF eigenvectors are positive across the entire region, while the second eigenvectors exhibit a south-positive-north-negative dipole pattern. In years with maximum (minimum) time coefficients, the distribution of summer extreme precipitation in the study area shows the most pronounced pattern of being stronger (weaker) in the south and weaker (stronger) in the north. (3) In strong (weak) summer extreme precipitation years, there is (is not) convergence of cold and warm air masses; ascending (descending) motion is enhanced, outgoing longwave radiation shows negative (positive) anomalies, convection is strong (weak), corresponding to more (less) precipitation; water vapor flux divergence shows negative (positive) anomalies, which is favorable (unfavorable) for extreme precipitation occurrence.

Keywords: extreme precipitation; Longdong Region; circulation characteristics; dynamic ascending conditions; water vapor conditions

1. Data and Methods

1.1 Data Sources

This study uses daily precipitation observation data from 13 meteorological stations in Longdong Region, Gansu Province (34.8°–37.2°N, 106.4°–108.8°E). The stations are relatively uniformly distributed [Figure 1: see original paper]. The data have undergone quality control and are continuous without missing values, covering the period 1967–2015 with a time series length of 49 years.

NCEP/NCAR reanalysis monthly mean data are also employed, with a horizontal resolution of 2.5°$×$2.5°. Selected variables include geopotential height (hgt), zonal wind (u), meridional wind (v), specific humidity (q), surface pressure (ps), and outgoing longwave radiation (OLR). The OLR data span from 1974 to 2015 (42 years), while other variables cover 1967-2015.

1.2 Methods

1.2.1 Extreme Precipitation Indices Based on the extreme climate index set from the Statistical and Regional Dynamical Downscaling of Extremes (STARDEX) project, we selected five extreme precipitation indices according to their characteristics: PINT (precipitation intensity on wet days); R95p (very wet day precipitation) and R99p (extremely wet day precipitation) defined by the percentile method; and PNL90 (90th percentile precipitation threshold) and R90p (frequency of precipitation above the 90th percentile) defined by threshold methods. Using daily precipitation data, we calculated the above five indices for each summer (June-August) from 1967 to 2015.

1.2.2 Empirical Orthogonal Function Decomposition Empirical Orthogonal Function (EOF) decomposition represents n observations of a meteorological element at m spatial points (stations or grid points) in matrix form. The method decomposes the data matrix X into spatial function V and temporal function T:

$$\begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix} = \begin{pmatrix} v_{11} & v_{12} & \cdots & v_{1m} \\ v_{21} & v_{22} & \cdots & v_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mm} \end{pmatrix} \begin{pmatrix} t_{11} & t_{12} & \cdots & t_{1n} \\ t_{21} & t_{22} & \cdots & t_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_{m1} & t_{m2} & \cdots & t_{mn} \end{pmatrix}$$

where V is an m×m eigenvector matrix and T is an m×n time coefficient matrix. The physical significance of the decomposed eigenvectors is typically verified through significance tests. We employ both North' s rule of thumb and Monte Carlo tests to assess the analytical value of the eigenvectors obtained.

1.2.3 Composite Analysis In meteorological forecasting, composite analysis of meteorological variables with different characteristics is commonly used to highlight distinctive features. One approach analyzes the mean fields of meteorological variables in high-value and low-value years separately to examine their average states. Another method calculates anomaly fields by subtracting the climatological mean (1971-2000) from the variable fields in high (low) value years, thereby analyzing the causes of differences from the average state. Both methods are used in this study.

For anomaly fields, sample randomness makes it unlikely that variable means in characteristic years will exactly match the climatological mean, necessitating significance testing. The t-test method, which examines whether the difference between sample mean ( ) and population mean ($_0$) is significant, is frequently used for testing composite analysis results in meteorology. The null hypothesis H_0: = $_0$ defines the statistic t:

$$t = \frac{\bar{x} - \mu_0}{s/\sqrt{n}}$$

where s and n are the sample standard deviation and sample size, respectively. If |t| > t (the critical value at significance level α), the null hypothesis is rejected.

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2. Results

2.1 Spatiotemporal Characteristics of Summer Extreme Precipitation

Figure 2 shows the spatial distribution of long-term mean values for each index in Longdong Region. The PINT index is higher in the southeast, reaching a maximum of 8.19 $mm \cdot d^{-1}$, and lower in the northwest. The R95p index is higher in the south and northeast, with the highest value of 88.77 mm in the southwest. The R99p index shows similar patterns, with higher values in the south and northeast, peaking at 67.91 mm in the southwest, and lower values in the northwest with a minimum of 23.78 mm. The PNL90 index is higher in the south and northeast, with a maximum of 7.09 $mm \cdot d^{-1}$ in the south, and lower in the northwest. The R90p index is higher in the southwest, central, and southeast regions, with the highest value of 44.83 mm, and lower in the northwest with a minimum of 18.56 mm.

Figure 3 presents the spatial distribution of linear trend tests for summer extreme precipitation indices. The PINT index shows an upward trend across the entire study area, with three stations in the south reaching significance at the 0.05 level. The R95p index increases at all stations except for three in the central region and two in the northeast, though these changes are not significant. The R99p index shows similar patterns, with increases at all stations except three in the central region. The PNL90 index increases at all stations except two in the west, with only two stations in the south showing significant increases at the 0.05 level. The R90p index increases at all stations except three in the west, with only two stations in the south showing significant increases. Overall, the five summer extreme precipitation indices are dominated by upward trends, though most stations show non-significant increases; fewer stations show decreasing trends, mainly located in the western and central regions, and these are generally non-significant.

2.2 EOF Analysis of Summer Extreme Precipitation Indices

EOF decomposition was applied to the anomaly series of the five indices from 1967 to 2015 to separate spatial and temporal modes, obtaining eigenvectors and corresponding time coefficients that were subsequently tested for significance. The variance contributions of the first two modes for each index are substantial (Table 1), with cumulative contributions exceeding 45% and all passing the 0.05 significance level, indicating they well represent the primary spatiotemporal patterns of summer extreme precipitation indices in Longdong Region. Therefore, we focus on analyzing the first two eigenvectors and time coefficients.

The first eigenvectors of all five indices are positive across the entire study area (Figure 4 shows the PINT index as an example), reflecting a consistent variation pattern. The positive center for the PINT index is located in the southern part of Longdong Region, with large-value areas mainly in the central and southern parts. The corresponding time coefficients show an increasing trend, with PINT increasing significantly at a rate of 0.42 per decade, reaching maximum (minimum) values in 2010 (1997). The first-mode time coefficients of other indices also show upward trends, though not significant. In years with maximum (minimum) time coefficient values, summer extreme precipitation in Longdong Region is the strongest (weakest) on record.

The second eigenvectors of the indices exhibit a south-positive-north-negative dipole pattern in Longdong Region (Figure 4). The positive center is in the southern part of the region, while the negative center is in the north, indicating a north-south pattern of either stronger in the south and weaker in the north, or vice versa. The corresponding time coefficients show a non-significant upward trend, with maximum (minimum) values in 1999 (1972). In years with maximum (minimum) time coefficient values for each summer extreme precipitation index, the distribution pattern of being stronger (weaker) in the south and weaker (stronger) in the north is most pronounced.

2.3 Circulation Fields in Typical Summer Extreme Precipitation Years

Based on the EOF analysis results, we selected typical years for composite analysis. First, we calculated the standard deviation (σ) of the first-mode time coefficient T for each index. Years with $|T| > \sigma$ were selected as typical years. According to the sign of the time coefficients, the top three years with largest absolute values were designated as typical strong years (positive values) and weak years (negative values). The years that appeared most frequently among the five indices were selected as the final typical years (strong year: 2010; weak year: 1972).

Figure 5 shows the 500 hPa mean geopotential height fields and 850 hPa wind anomaly fields in typical strong and weak extreme precipitation years, with the thick black line representing the 5880 gpm characteristic line. In the strong extreme precipitation year, a shallow trough exists at mid-latitudes over China, with Longdong Region located behind the trough. The trough guides airflow southeastward, facilitating the input of cold air from the north into the study area. Simultaneously, the western Pacific subtropical high is stronger, with the

5880 gpm line extending westward to 130°E, allowing warm, moist air from the subtropical high to reach the study area. The convergence of cold and warm air masses favors extreme precipitation formation. In the weak extreme precipitation year, although Longdong Region is also located behind the trough with cold air inflow from the north, the western Pacific subtropical high is weaker, with the 5880 gpm line retreating eastward, preventing warm, moist air from reaching the study area to converge with the cold air.

The 850 hPa wind anomaly fields show that in the strong extreme precipitation year, Longdong Region experiences southeasterly wind anomalies. The southwesterly winds along the northwest side of the subtropical high reach the study area and turn northwestward, bringing abundant warm, moist air, while northerly wind anomalies in the north transport cold air southward. The convergence of cold and warm air masses favors precipitation generation. In the weak extreme precipitation year, the study area experiences southwesterly wind anomalies, with warm, moist air from the Indian Ocean passing through southwestern China to the study area, but lacking converging cold air from the north.

2.4 Dynamic Ascending Conditions for Summer Extreme Precipitation

Horizontal divergence, defined as the divergence of horizontal wind components, characterizes the intensity of horizontal convergence and divergence. Horizontal convergence/divergence generates vertical ascending or descending motion. By analyzing the vertical configuration of horizontal divergence at different levels, we can obtain the dynamic ascending conditions over the study area. Table 2 shows the horizontal divergence anomalies in typical strong and weak extreme precipitation years. In the strong extreme precipitation year, horizontal divergence anomalies are negative at 850 hPa, 500 hPa, and 200 hPa, indicating anomalous convergence from the lower to upper troposphere, with anomalous divergence at 100 hPa, resulting in strong ascending motion that favors extreme precipitation generation. In the weak extreme precipitation year, horizontal divergence anomalies are positive at 850 hPa and 500 hPa (anomalous divergence) and negative at 200 hPa and 100 hPa (anomalous convergence), indicating enhanced descending motion that is unfavorable for extreme precipitation.

Outgoing Longwave Radiation (OLR), determined by cloud top temperature, reflects convective activity. Low OLR values associated with deep clouds (high, cold cloud tops) indicate strong convection and heavy precipitation, while high OLR values indicate weak convection and light precipitation. Figure 6 shows OLR anomaly fields in typical strong and weak extreme precipitation years. In the strong extreme precipitation year, OLR anomalies are negative over Longdong Region, indicating weaker-than-normal outgoing longwave radiation, stronger convective activity, deep cloud layers, and correspondingly more extreme precipitation. In the weak extreme precipitation year, OLR anomalies are positive, indicating stronger-than-normal outgoing longwave radiation, weaker convective activity, thinner cloud layers, and correspondingly less extreme precipitation.

2.5 Water Vapor Conditions for Summer Extreme Precipitation

Figure 7 presents the vertically integrated water vapor flux and divergence anomaly fields in typical strong and weak extreme precipitation years. In the strong extreme precipitation year, water vapor flux anomalies are positive over Longdong Region, with moisture primarily originating from the western Pacific, containing abundant water content that reaches the study area via southeastern China, supplemented by westerly belt transport from the north. In the weak extreme precipitation year, water vapor flux anomalies are weakly positive, with moisture from the Indian Ocean passing through southwestern China to the study area as transient moisture, resulting in weaker extreme precipitation.

The water vapor flux divergence anomalies are negative in the strong extreme precipitation year (Figure 7), indicating smaller-than-normal divergence (i.e., convergence), acting as a moisture sink that favors moisture accumulation and extreme precipitation formation. In the weak extreme precipitation year, water vapor flux divergence anomalies are positive, indicating larger-than-normal divergence (i.e., divergence), acting as a moisture source where moisture flows out of the region, making extreme precipitation less likely to form.

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3. Discussion

Extreme summer precipitation in Longdong Region, Gansu Province, occurs with low probability but has direct and significant impacts on agricultural production, the ecological environment, and people' s lives due to the region' s semi-arid climate and fragile ecosystem. Global warming has accelerated global and regional hydrological cycles, making spatiotemporal precipitation distribution more uneven and increasing the probability of extreme precipitation events. This study focuses on the spatiotemporal characteristics and influencing factors of summer extreme precipitation in this context.

Regarding regional summer extreme precipitation characteristics, both trend tests and the first-mode EOF time coefficients show that summer extreme precipitation indices are dominated by upward trends, though these trends are generally not significant, consistent with the findings of Wang et al. The second eigenvector reflects a north-south dipole pattern of stronger (weaker) in the south and weaker (stronger) in the north, aligning with Zhao et al., who attributed this pattern to geographic location, topography, cold air intrusion paths, and weather system influences.

Concerning influencing factors, numerous studies have shown that atmospheric circulation anomalies are crucial causes of changes in extreme precipitation frequency and intensity in China. Our composite analysis of physical fields in strong and weak summer extreme precipitation years demonstrates that atmospheric circulation patterns, dynamic ascending conditions, and water vapor conditions all significantly influence anomalous changes in summer extreme precipitation in the study area. These results contribute to a deeper understanding of summer extreme precipitation characteristics in Longdong Region and provide important references for regional disaster prevention and mitigation, as well as for agricultural and economic planning.

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4. Conclusions

This study analyzed the spatiotemporal characteristics of summer extreme precipitation in Longdong Region and the circulation, dynamic, and water vapor conditions in typical years. The main conclusions are:

1) The long-term mean spatial distribution of summer extreme precipitation indices (PINT, R95p, R99p, PNL90, R90p) shows lower values in the northwestern part of Longdong Region and higher values in the southern and northeastern parts. All five indices are dominated by upward trends, though most stations show non-significant increases; fewer stations show decreasing trends, mainly in the western and central regions, and these are generally non-significant.

2) EOF analysis shows that the first-mode eigenvectors are positive across the entire study area, reflecting consistent variation patterns. The corresponding time coefficients show upward trends, with PINT increasing significantly. The second-mode eigenvectors exhibit a south-positive-north-negative dipole pattern, with positive centers in southern Longdong Region and negative centers in the north, indicating a north-south pattern of stronger in the south and weaker in the north, or vice versa. The corresponding time coefficients show upward trends, though not significant.

3) In strong (weak) summer extreme precipitation years, the 500 hPa mean height field shows Longdong Region located behind a trough with a stronger (weaker) western Pacific subtropical high. The 850 hPa wind anomaly field shows southeasterly (southwesterly) wind anomalies, with (without) convergence of cold and warm air masses, favoring (disadvantaging) precipitation generation.

4) Dynamic ascending conditions show that in strong (weak) summer extreme precipitation years, ascending (descending) motion is enhanced over Longdong Region. OLR anomalies are negative (positive), indicating stronger (weaker) convective activity, deeper (thinner) cloud layers, and correspondingly more (less) extreme precipitation.

5) Water vapor conditions reveal that in strong (weak) summer extreme precipitation years, water vapor flux anomalies are positive (weakly positive), and water vapor flux divergence anomalies are negative (positive), making

the study area a moisture sink (source) that is favorable (unfavorable) for extreme precipitation generation.

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Note: Figure translations are in progress. See original paper for figures.