Warm-Season Precipitation Variation and Its Influencing Factors in the Hedong Region of Gansu, 1973–2020: A Postprint

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Abstract

Based on precipitation data from April to September during 1973–2020 at 60 national meteorological observation stations in Hedong, Gansu, and employing methods such as empirical orthogonal function decomposition and correlation analysis, this study analyzes the spatiotemporal distribution and variation characteristics of precipitation at different magnitudes, and discusses the influences of temperature, large-scale circulation, and topography on summer precipitation. The results show that: (1) The western part of Hedong is located at the terminal end of the monsoon region, where temperature changes have a relatively significant impact on precipitation. Specifically, the Gannan Plateau and the mountainous areas to its north have high altitudes and limited input moisture; the promotion of the water cycle by climate warming tends to increase precipitation. In other western regions, input moisture remains dominant, and the weakening of cold air activities tends to decrease precipitation. (2) The eastern part of Hedong has a gently transitioning topography, and precipitation is significantly influenced by the monsoon. After 1998, sea surface temperatures in the Niño 3.4 region (5°N–5°S, 120°–170°W) shifted to predominantly negative anomalies; with the strengthening of the monsoon and the northward shift of the rain belt, precipitation has consequently increased. (3) The primary characteristic of interannual precipitation variation in the Hedong region is that all stations increase or decrease simultaneously; however, during La Niña years, the feature of opposite-phase precipitation changes between the eastern and western parts is more likely to occur. When the Pacific Decadal Oscillation is in its negative phase, precipitation increases in the western region while decreasing at some eastern stations; when the Arctic Oscillation is in its negative phase, precipitation increases in the southeastern region while decreasing at some western stations. The analysis of precipitation variation and its influencing factors during the summer half-year in Hedong, Gansu, not only provides a reference for research on the differential impacts of atmospheric circulation and climate

warming on precipitation changes under complex topography, but also enriches the basis for precipitation prediction at the terminal end of the monsoon region.

Full Text

Variation Characteristics and Influencing Factors of Summer Half-Year Precipitation in Hedong Region of Gansu Province from 1973 to 2020

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Abstract

Based on precipitation data from 60 national meteorological observation stations in Hedong region of Gansu Province from April to September during 1973-2020, this study employs empirical orthogonal function (EOF) decomposition and correlation analysis to examine the spatiotemporal distribution and variation characteristics of precipitation across different magnitudes. The influences of temperature, large-scale atmospheric circulation, and topography on summer precipitation are also discussed. The results reveal three key findings: (1) The western part of Hedong is situated at the terminal edge of the East Asian monsoon region, where light and moderate rain account for the largest proportion of total precipitation, and temperature changes exert a relatively significant impact on precipitation. The Gannan Plateau and adjacent northern mountainous areas feature high elevations with limited input moisture; the enhancement of local water cycling due to climate warming tends to increase precipitation. In contrast, other western regions remain dominated by imported moisture, where weakened cold air activity leads to decreasing precipitation trends. (2) Eastern Hedong features a gentle topographic transition, with precipitation strongly influenced by the East Asian monsoon. Since 1998, sea surface temperatures in the Niño 3.4 region have shifted to predominantly negative anomalies. As the monsoon intensified and the rain belt migrated northward, precipitation in the eastern region increased accordingly. (3) The primary characteristic of interannual precipitation variation in Hedong is synchronous increase or decrease across all stations; however, La Niña years are more prone to exhibit opposite-phase variations between eastern and western regions. During the negative phase of the Pacific Decadal Oscillation (PDO), precipitation increases in the western region while decreasing at some eastern stations. During the negative phase of the Arctic Oscillation (AO), precipitation increases significantly in the southeast but decreases at some western stations. This analysis of summer half-year precipitation variation and its influencing factors in Hedong not only provides a reference for investigating differential impacts of atmospheric circulation and climate warming on precipitation changes under complex terrain conditions, but also enriches the basis for precipitation forecasting at the monsoon region' s terminal edge.

Keywords: summer half-year precipitation; spatiotemporal variation; temperature; circulation index; Hedong region of Gansu Province

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1 Study Area Overview

Hedong refers to the central and eastern part of Gansu Province, located at the convergence zone of the Qinghai-Tibet Plateau and the Loess Plateau [Figure 1: see original paper]. The terrain elevation ranges from 623 m to 4584 m, sloping from high in the west to low in the east. The southwestern Gannan Plateau lies on the northeastern edge of the Qinghai-Tibet Plateau, reaching the maximum altitude of 4584 m. To its east lies the Gansu section of the Minshan Mountains (Gan-Min mountainous area). Beyond this, elevation drops rapidly through the Qinling-Bashan mountainous transition zone, reaching its lowest point of 623 m in the Bailong River basin in the southeast. The climate is characterized by typical temperate continental monsoon features, with precipitation concentrated in the months from April to September (summer half-year). The dramatic topographic relief creates pronounced spatial precipitation differences, spanning humid, semi-humid, semi-arid, and arid climate zones from southeast to northwest. To analyze climatic differences in greater detail, the region is divided into eastern and western parts along the eastern foothills of the Gan-Min mountainous area at 105°E, based on moisture transport characteristics in northwest China.

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2 Data and Methods

The study utilizes daily precipitation and mean temperature data from 60 national surface meteorological stations in Gansu Province [Figure 1: see original paper], compiled by the Gansu Provincial Meteorological Information Center. Precipitation data from 1973 were missing and excluded from the analysis. Among circulation indices, the Oceanic Niño Index (ONI) was downloaded from the U.S. National Oceanic and Atmospheric Administration website (https://www.noaa.gov/), the Arctic Oscillation (AO) from the U.S. National Centers for Environmental Information (https://www.ncei.noaa.gov/), and the Pacific Decadal Oscillation (PDO) from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn/zh-hans/data). The East Asian summer monsoon index, defined such that a negative value indicates stronger northward monsoon development, was obtained from the same data center.

EOF decomposition was applied to analyze spatiotemporal precipitation variation characteristics in Hedong. The first eigenvector field is denoted as EOF1, the second as EOF2, with corresponding time coefficients PC1 and PC2. The mode with larger absolute time coefficient values each year was identified as the dominant precipitation pattern for that year, yielding typical years for both modes. Correlation analysis was used to determine relationships between precipitation and temperature as well as large-scale circulation indices. Daily precipitation categories were defined as: 0.1-9.9 mm (light rain), 10.0-24.9 mm (moderate rain), 25.0-49.9 mm (heavy rain), and $ $50.0 mm (torrential rain), with the sum of all categories representing total precipitation.

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3 Results and Analysis

3.1 Precipitation Distribution Characteristics

Figure 2 shows the spatial distribution of mean summer half-year precipitation, precipitation proportion, and precipitation frequency in Hedong. Total precipitation decreases from southeast to northwest, ranging from 169.4 mm annually at Jingtai station in the northwest to 642.5 mm at Kangxian station in the southeast—a 3.8-fold difference. Light and moderate rain decrease from south to north, while heavy rain and torrential rain decrease from east to west. Using the eastern foothills of the Minshan Mountains as a boundary, light and moderate rain account for over 75% of total precipitation in the western region, exceeding 80% in the Gannan Plateau and areas north of the Wushaoling Mountains. Notably, the Gannan Plateau exhibits high frequency of light and moderate rain and serves as a major precipitation center in Hedong, though precipitation drops sharply above moderate rain levels. In contrast, areas north of Wushaoling show low frequency and small totals for light and moderate rain, with even less precipitation at higher magnitudes. In the eastern region, light and moderate rain account for 60-75% of total precipitation, while the Jialing River basin shows high frequency of heavy rain and torrential rain, forming the major precipitation center for moderate rain and above.

3.2 Precipitation Trends

Figure 3 illustrates linear trends in interannual variation of summer half-year precipitation at each station. Total precipitation shows increasing trends primarily in the eastern region and western plateau/mountainous areas, while decreasing trends dominate the remaining western regions. A total of 37 stations (61.7%) exhibit increasing trends, with Maiji and Maqu stations showing the most significant increases at 4.5 $mm \cdot a^{-1}$ and 4.2 $mm \cdot a^{-1}$, respectively. Decreasing trends occur at 23 stations (38.3%), with Jingtai station showing the fastest decrease at -1.5 $mm \cdot a^{-1}$. Light rain shows decreasing trends except in the Gannan Plateau; moderate rain shows increasing trends at 27 stations (45.0%), mainly east of the Liupan Mountains and Wushaoling Mountains, with some stations in the Gannan Plateau also showing weak increases. Heavy rain and torrential rain show increasing trends at 46 stations (76.7%) and 39 stations (65.0%), respectively, with the most pronounced increases in the eastern region. Decreasing trends are concentrated in the narrow zone from the Gannan Plateau to the northern side of the Gan-Min mountainous area. Overall, except for the Gannan Plateau, most of Hedong shows decreasing trends for moderate rain and below, but increasing trends for heavy rain and above, indicating a general shift toward higher precipitation magnitudes.

3.3 Precipitation Variation Characteristics

To further analyze precipitation variation characteristics, EOF decomposition was applied to summer half-year precipitation in Hedong from 1973–2020. For analysis convenience, eigenvector fields show modes with increasing time coefficient trends [Figure 4: see original paper]. The first four eigenvector variance contributions for total precipitation and light, moderate, heavy, and torrential rain are 52.2%, 31.1%, 31.5%, 25.8% and 24.3%, 11.8%, 15.0%, respectively—far exceeding other modes. Therefore, the first two modes represent precipitation field variations in Hedong.

Observing the spatial distribution of the first two modes for total precipitation and different magnitudes reveals that EOF1 shows consistent positive or negative values across most regions, indicating that the primary characteristic of interannual precipitation variation in Hedong is synchronous increase or decrease throughout the entire region. EOF2 exhibits opposite-phase distributions between eastern and western regions. The transition zone between positive and negative values is located near the eastern or northern foothills of the Gan-Min mountainous area, demonstrating significant topographic influence on precipitation in Hedong.

Figure 5 shows the time coefficient of EOF1 for summer half-year precipitation in Hedong. The variation of total precipitation can be divided into three phases: predominantly positive phase before 1998 (a wet period), transitioning to negative phase with decreasing 9-year moving averages after 1998 (a dry period), particularly pronounced during 2004–2010 when multiple years exceeded one negative standard deviation; and returning to positive phase after 2015 with increasing moving averages, indicating a trend toward wetter conditions, especially evident in 2018 and 2020.

Comparing time coefficient interannual variations across different precipitation magnitudes reveals that moderate and heavy rain show phase transitions around 1998 and 2015, with cycles basically matching total precipitation, indicating these categories dominate interannual variation of total precipitation. Light rain shows a fluctuating upward trend, transitioning to negative phase in 1998 and back to positive in 2015. Torrential rain shows relatively independent temporal distribution with pronounced interannual variation, though its phase transition points are similar to those of EOF1.

Figure 6 presents the time coefficient of EOF2. During typical years of the first mode (PC1), the proportion of El Niño years is 20.6%, significantly lower than under PC1, while La Niña years account for 73.9%—much higher than under PC1. This indicates that during La Niña events, precipitation in Hedong is more likely to exhibit opposite-phase local variations between east and west.

Since Hedong belongs to the same East Asian monsoon influence zone, overall precipitation patterns are generally consistent, but La Niña years highlight differences between the east and west sides of the Minshan Mountains due to the northward shift of the western Pacific subtropical high and changes in monsoon intensity.

3.4 Influencing Factor Analysis

According to the IPCC Sixth Assessment Report, major climatic factors affecting precipitation changes include intensification of extreme wet and dry events caused by climate warming, and atmospheric circulation pattern changes affecting extreme event occurrence. This analysis focuses on these two aspects.

3.4.1 Temperature Figure 7 shows the spatial distribution of correlation coefficients between summer half-year precipitation of different magnitudes and mean temperature. Except for the Gannan Plateau, total precipitation and precipitation below torrential rain levels are generally negatively correlated with temperature, with light rain showing the strongest correlation—41.7% of stations have correlation coefficients below -0.3, mostly located in northern Hedong. Correlations for total precipitation, moderate rain, and heavy rain are weaker, mostly between -0.2 and -0.3, with better correlations in the eastern Qinling-Bashan mountainous area, Wei River basin, and Ziwuling forest region. The Gannan Plateau and its northern mountainous areas show positive correlations with temperature, indicating distinctly different temperature-precipitation relationships across regions.

Although temperature increases enhance surface water evaporation and atmospheric moisture content, favoring updraft development and precipitation enhancement, systematic precipitation is often accompanied by southward cold air movement that also blocks surface radiation and lowers temperature. Hedong is characterized by semi-humid, semi-arid, and arid climates with limited surface water systems. In most areas, the impact of warming on promoting local water cycling is extremely limited, and moisture sources still primarily depend on southerly warm-moist airflow transport. The influence of cold air activity on precipitation frequency is more significant, resulting in negative precipitation-temperature correlations in most regions. As precipitation magnitude increases, the correlation shifts toward positive values because stronger precipitation requires higher atmospheric instability more closely linked to temperature.

The western part of Hedong is located at the terminal edge of the East Asian monsoon region. With blocking from the Gannan Plateau and Gan-Min mountainous area, imported moisture is significantly weaker than in the eastern region, making temperature changes more influential. The Gannan Plateau and adjacent northern mountains have high elevations and have experienced faster warming rates than surrounding areas in recent decades, with abundant water resources from lakes and rivers including the Gahai Lake, Bailong River, Yellow River, Tao River, and Daxia River. Here, the proportion of climate warming' s promotion of local water cycling has increased, resulting in positive correlations for moderate rain and above, and increasing total precipitation. In other western regions with fewer surface water systems and greater dependence on imported moisture, warming leads to decreasing light and moderate rain, further reducing total precipitation and intensifying drought.

3.4.2 Atmospheric Circulation Comparing the two modal time coefficients reveals typical years for each mode. Correlation analysis between these time coefficients, total precipitation, and precipitation of different magnitudes with ONI, PDO, and AO indices shows distinct patterns . In typical years of the first mode, ONI is significantly negatively correlated with PC1, total precipitation, and moderate rain precipitation. When ONI is in negative phase (La Niña), the western Pacific subtropical high shifts northward, the monsoon strengthens, and the rain belt lifts northward, increasing precipitation in Hedong, particularly for moderate rain and above. Since 1998, the 9-year moving average of ONI has transitioned to an upward trend, with sea surface temperatures in the Niño 3.4 region (120°–170°W, 5°N–5°S) shifting from positive to negative phase [Figure 8: see original paper], consistent with precipitation variation patterns.

During typical years of the second mode, ONI shows poor correlation with precipitation amounts except for heavy rain. However, the PDO index is positively correlated with PC2. When PDO is in negative phase, the subtropical high shifts westward, facilitating monsoon penetration into northwestern inland areas and increasing precipitation in western Hedong, particularly moderate rain and above, while decreasing precipitation at some eastern stations. When PDO is in positive phase, the subtropical high retreats eastward, the monsoon extends northward along the eastern side of the Gan-Min mountainous area, increasing precipitation in the eastern region while decreasing it in the west.

The AO index shows significant negative correlation with PC1 and total precipitation, moderate rain, and heavy rain in typical first-mode years. When AO is in negative phase, cold air activity becomes more active, cold air masses penetrate more easily southward, and precipitation increases in Hedong, particularly moderate rain. In typical second-mode years, AO is positively correlated with PC2 and significantly positively correlated with moderate rain precipitation, but significantly negatively correlated with heavy rain and torrential rain. This occurs because western Hedong is at the monsoon terminal edge with multiple mountain barriers; when cold air is weaker, warm-moist airflow can penetrate further inland, increasing humidity and moderate rain frequency/area in western Hedong. However, heavy rain and torrential rain occur less frequently in the west, only increasing when cold air is strong enough to affect the southeastern region with more abundant moisture and energy.

4 Conclusions

(1) Light rain precipitation in Hedong is negatively correlated with temperature, with the correlation shifting toward positive values as precipitation magnitude increases. The western part of Hedong is located at the terminal edge of the East Asian monsoon region, where light and moderate rain account for over 75% of total precipitation, making temperature effects more prominent. The Gannan Plateau and adjacent northern mountains, with high elevations and abundant local water resources, have experienced significantly faster warming rates. The enhanced local water cycling due to climate warming promotes increased precipitation. In other western regions, southerly airflow with imported moisture remains dominant, and climate warming combined with weakened cold air activity leads to decreasing precipitation trends.

(2) Eastern Hedong features gentle topographic transitions, with precipitation significantly influenced by the East Asian monsoon. Since 1998, sea surface temperatures in the Niño 3.4 region have shifted to predominantly negative anomalies. As the monsoon strengthened and the rain belt moved northward, southerly airflow tended to extend northward along the eastern side of the Gannan Plateau and Gan-Min mountainous area, increasing precipitation in the eastern region with a trend toward higher magnitudes.

(3) The main characteristic of interannual precipitation variation in Hedong is synchronous increase or decrease across all stations. However, La Niña years are more likely to exhibit opposite-phase local variations between eastern and western regions. Since Hedong belongs to the same East Asian monsoon influence zone, overall precipitation patterns are generally consistent, but La Niña years highlight differences between the east and west sides of the Minshan Mountains. When PDO is in negative phase, the subtropical high shifts westward, increasing precipitation in the western region, particularly moderate rain and above, while decreasing precipitation at some eastern stations. When AO is in negative phase, cold air activity intensifies, significantly increasing precipitation in the southeast while decreasing it at some western stations.

Significant differences in geography and topography create markedly different relative impacts of temperature changes and circulation system adjustments on precipitation across Hedong, resulting in overall increasing precipitation trends in summer half-year with decreasing trends in some regions. This study provides a qualitative analysis of these issues, though quantitative analysis remains for future research.

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