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Evolution of Precipitation in Zhengzhou over the Past 42 Years and the Multi-scale Mechanisms of the "720" Extreme

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Abstract. Based on NASA MERRA-2 and Zhengzhou Meteorological Bureau precipitation data from 1982 to 2024, this study analyzes the evolution of annual precipitation in Zhengzhou and the mechanisms associated with the "7·20" extreme rainstorm. Results show an upward trend in grid-cell average annual precipitation at a climatic tendency rate of 6.2 $mm \cdot a^{-1}$, with substantial interannual fluctuations. The interannual variation in annual precipitation is closely associated with the frequency of heavy precipitation days (≥20 $mm \cdot d^{-1}$). The 2021 precipitation maximum was largely associated with a single extreme weather process that contributed 41.6% of the annual precipitation total, rather than with an increase in the number of heavy precipitation days. Mechanistic analysis indicates that the "7·20" rainstorm was associated with the anomalously northward-positioned western Pacific subtropical high, remote moisture transport by Typhoons In-Fa and Cempaka, and topographic forcing. The 2021 event highlights the potential for low-frequency, high-intensity precipitation extremes in Zhengzhou and the need for urban hydrological planning to consider scenario-based stress testing for such events.

Keywords: Zhengzhou, Extreme precipitation, Climatic trend, Topographic dynamic forcing, "7.20" extraordinary rainstorm

1. Introduction

Against the backdrop of global climate change, the increasing frequency of extreme weather events has emerged as a major threat to the sustainable development of human society. The IPCC Sixth Assessment Report (AR6, WG1) concludes that, globally, the intensity of extreme daily precipitation increases at a rate of about 7% per 1 °C of global warming [1]. As a region strongly influenced by the East Asian summer monsoon, China exhibits marked regional disparities: extreme precipitation has increased significantly south of the Yangtze River Basin, while parts of the northern Huang-Huai plain have shown weaker or even negative trends in recent decades.

Henan Province lies in the transitional zone between warm-temperate and subtropical monsoon climates in central China, with highly uneven spatiotemporal precipitation distribution and frequent rainstorm disasters [2, 3]. Zhengzhou (34°16′–34°58′N, 112°42′–114°14′E), the provincial capital, is located in the southern North China Plain on the southern bank of the lower-middle Yellow River, centered slightly north of Henan's geographic middle. The city spans two water systems: the Yellow River basin in the northwest (24.6% of municipal area) and the Huai River basin in the southeast

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(75.4%), with the Taihang Mountains to the north-northwest across the Yellow River and the Funiu Mountains to the southwest, while the urban core sits on the flat transition belt from the Funiu foothills to the Huang-Huai plain. This topographic setting makes Zhengzhou sensitive to both monsoon frontal precipitation and terrain-enhanced convective systems. The multi-year (1982–2024) average precipitation is 640.8 mm, with 60%–70% concentrated in the June–September flood season. Rapid urbanization and warming have amplified extreme-rainfall exposure: during 17–23 July 2021, the "7·20" extraordinary rainstorm caused 380 deaths or missing in Zhengzhou city proper (95.5% of Henan's provincial total of 398), according to the State Council investigation report [4].

Studies have explored the characteristics and causes of precipitation changes in Zhengzhou from different perspectives. Based on the data of Zhengzhou National Meteorological Station, Zhang Yuan and others used linear trend estimation and Mann-Kendall test to find that the annual precipitation in Zhengzhou has shown a fluctuating upward trend in the past 60 years, especially in the 1990s, which was at a low point and reached its peak in the 2020s. It should be noted that the precipitation from July to September 2020 accounted for 56.8% of the total annual volume [2]. Another study used the daily precipitation data of 7 meteorological stations in Zhengzhou. The author used the extreme point symmetric modal decomposition (ESMD) method for analysis. The results showed that 7 out of the eight extreme precipitation indexes showed a slight upward trend, among which the maximum 5-day precipitation trend was the most obvious, with a growth rate of 4.16 mm per decade [3].

However, the difference in the closing year of the data sequence may lead to deviations in the results of long-term trend estimates. However, the impact of the 2021 extreme rainstorm on these trend estimates has not been fully concerned by researchers. Therefore, this study analyzes the precipitation data of NASA MERRA-2 from 1982 to 2024, and systematically analyzes the long-term evolution characteristics of Zhengzhou precipitation and the cause mechanism of the "7·20" extreme rainstorm. The research focuses on portraying the long-term change trend of annual precipitation, and analyzing the abnormal characteristics and formation mechanism of extreme precipitation events in 2021.

2. Materials and methods

2.1. Study area and data sources

NASA POWER/MERRA-2 Data: The primary data for the long-term trend analysis (1982–2024) were obtained from the NASA Prediction of Worldwide Energy Resources (POWER) project. The meteorological fields are based on the Modern Era Retrospective-analysis for Research and Applications, Version 2 (MERRA-2) from the NASA Global Modeling and Assimilation Office (GMAO). Specifically, we used the bias-corrected total precipitation variable (PRECTOTCORR). The data feature a spatial resolution of 0.5°latitude by 0.625°longitude. For the Zhengzhou region (centered at 34.0°N, 113.0°E), data were extracted from the corresponding grid cell, representing the grid-cell areal average precipitation over the domain rather than point-scale station observations.

Zhengzhou Meteorological Bureau Data:To analyze the extremity of the "7·20" event, we integrated fine-resolution observational datasets. The hourly precipitation data for July 2021 were obtained from the Zhengzhou Meteorological Bureau, which provided in-situ station observations. These data are used to calculate event-specific metrics such as the peak hourly intensity (201.9 $mm \cdot h^{-1}$) and the cumulative rainfall of the process (534 mm).

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2.2. Research methods

Addressing the non-stationary characteristics of the precipitation series, this study employs a multi-scale analytical approach to elucidate the evolution of precipitation in Zhengzhou. First, a univariate linear regression model is applied to fit the long-term trend of annual precipitation and calculate the climatic tendency rate. Second, based on the precipitation intensity classification standards of the China Meteorological Administration, days with daily precipitation≥ 20 mm are defined as heavy precipitation days. By examining the coupling relationship between the number of heavy precipitation days and total annual precipitation, the evolutionary characteristics of the precipitation structure are identified. To analyze the extremity of the"7.20" extraordinary rainstorm in 2021, the study integrates background atmospheric circulation field data to qualitatively assess the formation mechanisms of the extreme precipitation from three dimensions: water vapor flux, topographic dynamic forcing, and the maintenance mechanisms of mesoscale convective systems.All statistical analyses were performed using Origin.

3. Results

3.1. Basic statistical characteristics of annual precipitation in Zhengzhou

According to the NASA precipitation data for Zhengzhou from 1982 to 2024(Figure 1), the annual precipitation in Zhengzhou exhibits an overall upward trend,with a univariate linear regression fitting slope of 6.2044 mm·a-1, i.e., the annual precipitation in Zhengzhou has increased at an average rate of approximately 6.2 mm·a-1 over the past 42 years. From the perspective of interdecadal variation, the average precipitation in Zhengzhou in the 1980s was basically maintained between 640 and 800 mm, with relatively small interdecadal variability. A staged decline occurred in the 1990s,bottoming out at 415.42 mm in 1997, which is the lowest value in the past 42 years.After 2000, the amplitude of annual precipitation fluctuation intensified, but the overall center of gravity shifted upward. The year 2021 set the maximum value of the series at 1277.9 mm, appearing as a significant outlier high value point in Figure 1.

To discern the compositional mechanism of total annual precipitation, this study further extracted the annual number of heavy precipitation days in Zhengzhou(daily precipitation≥20mm) and conducted an overlay analysis with annual precipitation(Figures 2 and 3). As illustrated in Figure 2, the interannual series of the number of heavy precipitation days also exhibits an upward trend, and its evolutionary trajectory is highly synchronized with that of annual precipitation in most years. This statistical synchronicity indicates that the interannual fluctuation of total annual precipitation in Zhengzhou is largely dominated by the frequency of heavy precipitation events, rather than contributed by ordinary-magnitude precipitation days. Figure 3 further demonstrates this coupling relationship: in most years, the annual precipitation and the number of heavy precipitation days show a consistent increasing or decreasing trend, confirming that variations in total annual precipitation are predominantly governed by the frequency of heavy precipitation days.

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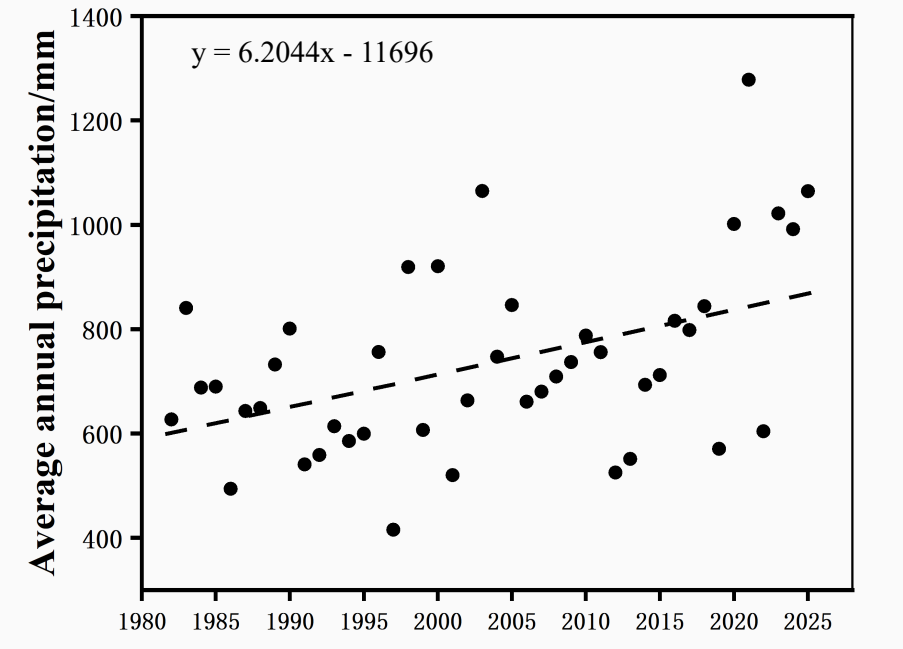


Figure 1. The annual average precipitation in Zhengzhou from 1982 to 2024

3.2. 2021: a key anomalous year for precipitation

From July 17 to 23, 2021, Henan Province encountered a historically rare extraordinary rainstorm. On July 19–20, the rainstorm center moved southward to Zhengzhou, forming a long-duration, ultra-intense extraordinary rainstorm process. In terms of cumulative area precipitation of the process, Zhengzhou ranked second in the province with 534 mm (second only to Hebi's 589 mm) [4]. In terms of maximum daily point precipitation, the single-day point precipitation in Zhengzhou reached 624.1 mm on July 20, which is close to the multi-year average annual rainfall of Zhengzhou (640.8 mm) [4, 5].

In terms of the intra-annual distribution of precipitation, the average annual precipitation in Zhengzhou in 2021 reached 1284.1 mm, equivalent to a total precipitation volume of 9.716 billion m^3, representing an increase of 123.9% over the previous year and 107.2% over the multi-year average, making it the year with the maximum precipitation since the availability of measured records in 1956. Among these, the precipitation in July was 587.0 mm, accounting for 45.7% of the total annual amount. The precipitation during the flood season (June–September) accounted for 87.4% of the whole year. The cumulative area precipitation of 534 mm from the "7.20" process (several days around July 20) alone is equivalent to 41.6% of the total annual amount—this proportion intuitively reveals the decisive contribution of extreme short-duration heavy precipitation to the anomalously high total annual precipitation [4].

From a climatic perspective, the extremity of the "7.20" rainstorm is manifested not only in the total amount, but also in the extreme distortion of the intensity-duration ratio: an hourly rain intensity of 201.9 $mm \cdot h^{-1}$ means that within one hour, Zhengzhou received an amount of precipitation close to one-third of its normal annual average rainfall. Meanwhile, the daily rainfall of 624.1 mm is close to the level of a normal entire year. This precipitation pattern, characterized by short duration, ultra-high intensity, and concentrated release, enabled the annual precipitation in 2021 to be elevated to a historical peak by a single extreme event despite no significant increase in the number of heavy precipitation days. This also explains the phenomenon observed in Figure 3—

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the synchronicity between total annual precipitation and the number of heavy precipitation days was broken in 2021, suggesting that under the background of climate warming, extreme precipitation events in Zhengzhou are exhibiting new characteristics of low frequency and high intensity, and their disaster-causing risks are far higher than those of traditional multi-day continuous heavy precipitation.

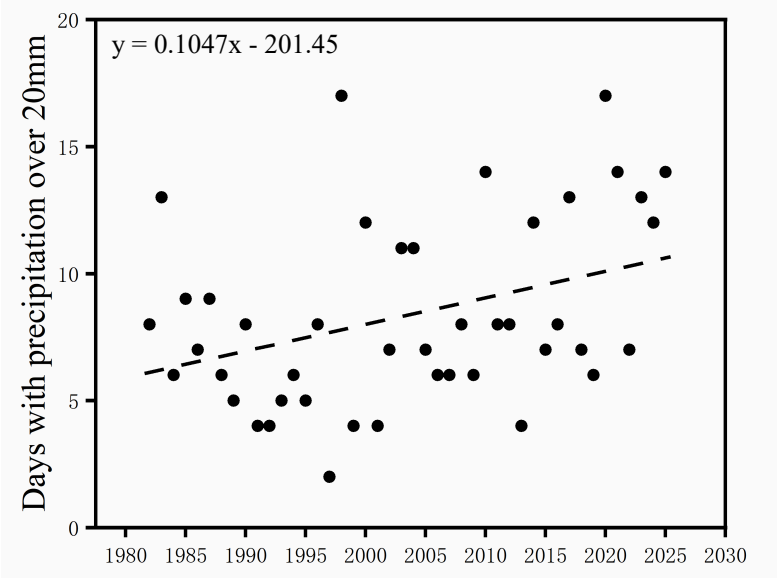


Figure 2. Trends in heavy precipitation frequency in Zhengzhou from 1982 to 2024

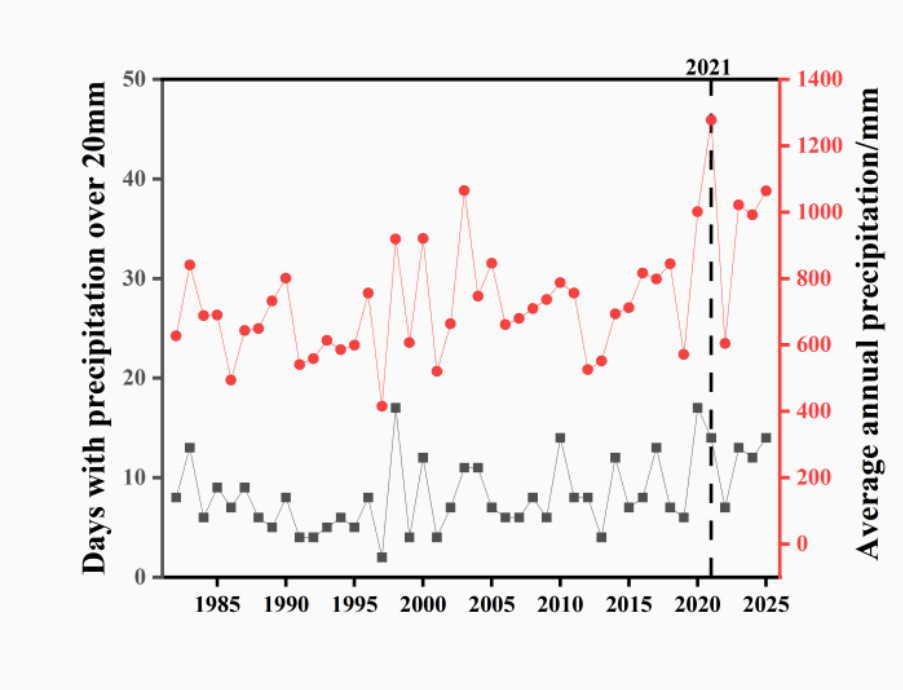


Figure 3. Combination of annual precipitation and fluctuations in the number of heavy rainfall days

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3.3. Formation mechanisms of the "7.20" extraordinary rainstorm

The "7·20" heavy rainstorm is essentially the result of the joint action of multi-scale weather systems under specific terrain. In mid-July 2021, atmospheric tripping showed a rare abnormal configuration. The Western Pacific subtropical high pressure (WPSH) is abnormally north and stable, and the easterly airflow on its western edge forms a continuous water vapor channel. The extreme nature of this process depends not only on large-scale cIRC, but also on the maintenance mechanism of small and medium-scale systems. The existence of typhoons "Fireworks" and "Chapaka" not only transported abundant water vapor from the Western Pacific Ocean and the South China Sea from a long distance, but more importantly, caused the low-level airflow in the Huanghuai area to show cyclone bends, thus strengthening the low-altitude rapids to northern Henan [5]. When this deep wet rapid reaches Mount Taihang and Mount Funiu, the forced uplift of the terrain causes the momentum to spread downwards and accumulate in front of the mountain, resulting in strong low-level convergence in the lower layers of the toposphere [6]. This interaction between the terrain and the airflow causes the medium-scale convection system (MCS) to move slowly and even stagnate over Zhengzhou [7]. In addition, the deep vertical structure formed by high-level radiation and low-level radiation, as well as extremely high convection effective potential energy (CAPE), eventually trigger extreme heavy precipitation [8]. Therefore, the precipitation extreme in 2021 is not accidental, but the result of the high coupling of the circiping background, water vapor conditions, topographic dynamics and flow triggering mechanism at a specific time and space point.

Furthermore, under the background of climate warming, the increase in atmospheric water-holding capacity (following the Clausius-Clapeyron equation) leads to a shift of the intensity distribution curve of precipitation events toward the extreme end. In addition, changes in urban underlying surfaces, such as the urban heat island effect and changes in roughness, have objectively provided favorable conditions for the triggering and maintenance of convective systems [9, 10].These factors, combined with the multi-scale circulation and topographic drivers described above, collectively contributed to the extremity of the "7·20" event, though quantitative partitioning of their relative contributions requires targeted numerical experiments not performed in this study.

4. Discussion

Based on the observation data from 1982 to 2024, this study reveals that the annual precipitation in Zhengzhou shows a significant linear upward trend, and the climate tendency rate is about 6.2 $mm \cdot a^{-1}$. However, the magnitude of the trend and its statistical robustness show high sensitivity to multiple analysis parameters. The data source and its spatial resolution are the primary influencing factors: research based on station observation (such as Zhang, 2023) can keenly capture local extreme characteristics, and the MERRA-2 reanalysis data used in this study characterizes the average state on the grid scale, which inevitably smoothes the local abnormal signal. More importantly, the inclusion of the "7·20" extreme precipitation event in 2021 has a decisive impact on the trend estimate. Statistics show that the single-year precipitation accounts for 41.6% of the total annual volume of the sequence. Without proper statistical processing, such extreme outlies will significantly overestimate the slope of the linear trend. In addition, the difference in the selection of the study period - especially whether the deadline covers 2021 - largely explains the inconsistency of the conclusions in the existing literature (Ju et al., 2025). Although the statistical significance of the upward trend is still maintained after excluding the 2021 data, its magnitude shows obvious sensitivity to the abnormal value.

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The "7·20" event in 2021 revealed an important climatic statistical feature: a single short-term extreme precipitation can dominate the statistical characteristics of annual precipitation without the premise of an increase in the frequency of heavy precipitation. This "quantity-frequency decoupling" phenomenon highlights the limitations of simply relying on linear trends or heavy precipitation days to assess the impact of climate change. From the physical mechanism, under the background of global warming, the enhancement of atmospheric water holding capacity provides a thermodynamic basis for extreme high-intensity precipitation. However, the actual occurrence of heavy rains in 2021 depends on the rare synchronous configuration of the abnormal north of the subtropical high pressure in the Western Pacific, the transmission of double typhoon water vapor and the forced elevation of the terrain. This shows that the extreme intensity of the event is consistent with thermodynamic expectations, but its specific trigger is the product of a specific multi-scale weather flow configuration, rather than the definite result of climate change.

Finally, it should be pointed out that there are certain limitations in the mechanism analysis of this study. The comprehensive discussion on the interaction of subtropical high pressure, typhoon and topography in the Western Pacific is mainly based on the existing literature [6-9] and lacks independent numerical test support. In addition, although this study qualitatively discusses urbanization and global warming as background factors, the specific contribution of the two to the extreme nature of the "7·20" event still needs to rely on high-resolution numerical simulation, which is beyond the scope of this observational study. Future research should use regional climate patterns or convection analysis simulation to further clarify the relative role and nonlinear interaction mechanism of thermodynamics, dynamics and human factors in the formation of extreme precipitation events.

5. Conclusion

The annual precipitation in Zhengzhou shows a significant upward trend, and its interannual variability is closely related to the number of days with daily precipitation ≥20 mm. Although extreme events in 2021 have a significant impact on the trend of annual precipitation, if the year is excluded, the upward trend is still valid.

In 2021, without increasing the number of heavy precipitation days, a short-term heavy precipitation event contributed 41.6% of the total annual precipitation, pushing the total annual precipitation to a record high. This shows that even if the frequency of heavy precipitation does not change, a single extreme event can still disproportionately increase the total annual precipitation.

The "7·20" rainstorm is caused by the abnormal north of the Western Pacific subtropical high pressure, the long-distance water vapor transport of typhoons "Fireworks" and "Chapaka", and the topographic forcing of Taihang Mountain and Funiu Mountain. The above factors have prompted a medium-scale convection system to maintain semi-stationary over Zhengzhou. Although this mechanism is consistent with the conclusions of many studies, the quantitative attribution of the above factors still needs further numerical tests.

The risk of precipitation in Zhengzhou not only involves the gradual change of the total annual precipitation, but also includes the threat of sudden and high-impact extreme events concentrated within a few hours. In addition to relying on traditional historical precipitation statistics, urban hydrological planning should also incorporate scenario-based stress tests to consider the short-term rainfall intensity comparable to the 2021 event.

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