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Article

Spatiotemporal Variability of Rainfall in Central Guizhou: Multi-Time Scale Analysis and Implications for Climate Change Adaptation

Zhonghua He [1,2,*], Xiaolin Gu [3], Feng Qiu [4], Maoqiang Wang [1], Mingjin Xu [3] and Siyu Chen [1]

[1] School of Geography and Environmental Science, Guizhou Normal University, Guiyang 550001, Guizhou, China
[2] School of Geography and Environmental Science, Guizhou Normal University/National Engineering Technology Institute for Karst
[3] Guizhou Hydrology and Water Resources Bureau, Guiyang 550002, Guizhou, China
[4] Department of Water Resources of Guizhou Province, Guiyang 550002, Guizhou, China
* Correspondence author: hezhonghua7621@126.com

Abstract: Precipitation is a pivotal component of the global hydrological cycle, profoundly influencing environmental dynamics and socio-economic systems, thereby occupying a central role in climate change research. This study provides a comprehensive multi-scale analysis of the spatiotemporal evolution of rainfall intensity and frequency in the karst terrain of central Guizhou, China, leveraging a high-quality monthly rainfall dataset from 56 rain gauge stations spanning 1965 to 2016. Employing advanced statistical tools including the Precipitation Anomaly Index (PAI) and the P-III distribution, this research examines rainfall variability across multiple temporal scales (3 to 12 months).Key findings reveal:(1) Rainfall intensity exhibits a distinctive "N-shaped" long-term trend, characterized by an increase from the 1960s to the 1980s, followed by a decline and a gradual recovery through the 2010s. The proportion of wet years notably peaked at 47.55% in the 1970s and escalated to 69.39% by the 2010s, reflecting significant shifts in hydroclimatic regimes.(2) Rainfall frequency analysis highlights that normal years dominate (62.8%), while medium-frequency rainfall events have progressively become more prevalent, demonstrating the dynamic interplay between climatic variability and rainfall occurrence patterns.(3) The intensity of rainfall shows the greatest temporal variability at 9- and 12-month scales, whereas frequency variability remains statistically significant across all examined scales, underscoring the complex multi-scale nature of precipitation in karst regions.This study advances the understanding of precipitation dynamics by integrating multi-temporal scale perspectives and coupling intensity with frequency metrics, thereby offering critical insights for hydrological modeling, climate adaptation, and water resource management tailored to the unique karst environment of central Guizhou. These findings provide a robust foundation for predicting extreme rainfall events and formulating resilient strategies in response to ongoing climate change challenges.

Keywords: precipitation variability; multi-scale analysis; central Guizhou; rainfall intensity and frequency; climate adaptation

1. Introduction

Precipitation is a critical driver of the global water cycle, playing a fundamental role in shaping regional water resources, disaster management, and ecosystem stability (IPCC, 2021). Its spatiotemporal evolution, including changes in intensity, frequency, and distribution, is pivotal for understanding the dynamics of the water cycle at various scales. In the context of global climate change, precipitation patterns have become more erratic, characterized by an increase in rainfall intensity, more frequent fluctuations, and a rise in extreme precipitation events (Huffman et al., 2007; Smith et al., 2023). These shifts are particularly pronounced in karst regions, where the complex geological conditions amplify the spatiotemporal variability of precipitation (Wang et al., 2022). The interaction between surface and underground runoff systems in karst environments further complicates hydrological dynamics, contributing to both nonlinear and unpredictable precipitation behaviors (Ford et al., 2007; Kumar et al., 2021). Understanding the spatiotemporal evolution of precipitation, especially at multiple temporal scales, is thus critical for advancing our knowledge of regional hydrological processes and for developing effective water resource management and ecosystem conservation strategies.

Karst basins, which cover approximately 15% of the Earth's surface, are widespread, with southwestern China being a prominent example. Central Guizhou, situated at the heart of China's karst landscape, is characterized by a high level of topographic complexity, including peak-cluster depressions and karst funnels. This unique geomorphology significantly influences local precipitation dynamics, making the region an ideal study area to examine the spatiotemporal evolution of precipitation in karst environments. Precipitation in this region is highly variable: annual average precipitation ranges from 1,000 to 1,200 mm, with more than 70% occurring during the flood season (from May to October), and much less during the dry season (Chen et al., 2020). Recent years have seen an increase in extreme precipitation events. For instance, the torrential floods of July 2010 caused economic losses exceeding 3 billion CNY, while the 2019 extreme drought affected over 400,000 hectares of agricultural land (Dai et al., 2017). Moreover, there is significant spatial heterogeneity in precipitation, with differences of over 30% observed between peak-cluster depressions. Short-term precipitation fluctuations, such as those observed on a monthly or daily scale, are especially pronounced (Wu et al., 2019a; Zhao et al., 2020). These characteristics make central Guizhou a representative case for studying the spatiotemporal evolution of precipitation in karst basins.

Internationally, substantial progress has been made in understanding the spatiotemporal characteristics of precipitation. High-resolution satellite datasets, such as TRMM (Tropical Rainfall Measuring Mission) and GPM (Global Precipitation Measurement), have revealed significant spatial heterogeneity and temporal variability in global precipitation patterns (Huffman et al., 2007). Techniques such as wavelet analysis and empirical mode decomposition (EMD) have been employed to uncover periodic features and long-term trends in precipitation variability (Fang et al., 2019; Garcia et al., 2021). For example, on an interannual scale, precipitation variability has been closely linked to global climate phenomena like the El Niño–Southern Oscillation (ENSO), while regional monsoon systems drive seasonal precipitation variability. Furthermore, climate models like CMIP6 have been used to assess potential future climate impacts on precipitation, highlighting the increasing risks of flooding and groundwater disruptions due to extreme events (IPCC, 2021). However, these studies are often conducted in regions with more homogeneous geomorphological conditions. Few studies have specifically addressed the unique challenges posed by karst landscapes, where complex geological features exacerbate precipitation variability and hydrological responses (Wang et al., 2022; Kumar et al., 2021).

In China, research has increasingly shifted from homogeneous geomorphological areas to more complex karst terrains. Recent studies have focused on the interannual and seasonal variations in precipitation across southwestern karst areas, identifying key drivers of these patterns (Wu et al., 2019b). Remote sensing and GIS technologies have highlighted significant increases in the frequency and intensity of extreme precipitation events, and their cumulative effects on groundwater systems in karst regions. For instance, in the karst regions of Yunnan and Guizhou, extreme rainfall events have accelerated groundwater dynamics, triggering regional flooding and underground river overflows (Meng et al., 2021). However, several critical research gaps remain, particularly in understanding the spatiotemporal variation of precipitation intensity and frequency across different temporal scales. Moreover, the dynamic responses of groundwater and runoff systems to extreme precipitation events and their cumulative effects are not well understood. Finally, the interaction between the spatial heterogeneity of precipitation and the geological variability of karst landforms, and its subsequent impact on regional hydrological cycles, has not been fully addressed (Li et al., 2018a, b).

As a representative karst basin, central Guizhou exhibits highly sensitive and multi-scaled precipitation dynamics. The goal of this study is to investigate the spatiotemporal distribution and evolution of precipitation in central Guizhou, using a multi-temporal scale analytical framework. Specifically, this study aims to: (1) analyze the spatiotemporal distribution of precipitation intensity in central Guizhou, identifying trends and spatial heterogeneity across interannual, seasonal, and monthly scales; (2) examine the multi-temporal evolution of precipitation frequency, identifying changes in frequency and high-risk zones for extreme precipitation events; and (3) utilize multidimensional analytical methods, such as variation analysis, variance analysis, and correlation analysis, to uncover the relationships between precipitation intensity and frequency. The findings of this study will provide critical insights into precipitation dynamics in karst regions and offer a scientific foundation for improving water resource management, enhancing flood and drought mitigation efforts, and supporting ecological conservation in central Guizhou. By providing a comprehensive understanding of precipitation behavior in karst basins, this study will also contribute to the development of region-specific climate adaptation strategies that can be applied to other complex geomorphic regions around the world (Smith et al., 2023; Wang et al., 2022; Garcia et al., 2021).

2. Study Area

The central Guizhou region, located in the heart of Guizhou Province, southwestern China, serves as a critical political, economic, cultural, and transportation hub within the province. This area's significance is heightened by its dense urban population, well-developed infrastructure, and extensive agricultural land, all of which underscore its broader influence on regional climate vulnerability and water resource management. The study area encompasses Guiyang City, Anshun City, Liupanshui City, and Bijie City, spanning geographical coordinates from 104°19′10″ to 107°1′11″E and 25°24′30″ to 26°52′30″N. It covers approximately 16,563.5 km², with an average elevation of 1,367.02 meters (Figure 1).

This region experiences a subtropical monsoonal humid climate characterized by mild temperatures and abundant precipitation year-round. Multi-year average annual precipitation varies from 850 mm to 1,510 mm, with notable high-precipitation zones identified in Puding, Zhenning, Anshun, and Zhijin counties. Rainfall gradually decreases toward the northwest and eastern areas, with extreme precipitation values recorded at Liuzhi Station, exhibiting the highest annual average rainfall of 1,508.2 mm, and Hezhang Station to the west, where the annual average rainfall is as low as 854.2 mm. While interannual precipitation variability remains relatively moderate, the seasonal distribution is highly uneven, with approximately 80% of total rainfall concentrated in the summer months from May to October, amplifying the region’s susceptibility to monsoonal climate impacts and extreme weather events.

Geographically, the study area is dominated by the karst hills of the Yunnan-Guizhou Plateau, forming the eastern slope of China’s second step. This complex topography functions as a major watershed divide between the Yangtze and Pearl River basins, profoundly influencing local hydrological regimes. Rivers in the area are generally short and narrow, exhibiting distinct drainage patterns shaped by karst geomorphology. To the north of the watershed ridge, the region is part of the Wujiang River system within the Yangtze River basin, including tributaries such as the Sancha River. To the south, the area falls within the Pearl River basin, encompassing rivers like the Dabang and Baling Rivers.

The unique karst geomorphology and hydrological complexity of central Guizhou create a spatially and temporally heterogeneous precipitation regime, posing significant challenges for hydrological modeling and water resource management. The interplay between local hydrological cycles, karst terrain, and regional climate variability offers an exceptional natural laboratory for exploring the spatiotemporal dynamics of precipitation under changing climate conditions. This study leverages these features to advance understanding of karst hydrology in the context of climate change adaptation, addressing critical gaps related to extreme precipitation patterns and their implications for regional water security and ecosystem resilience.

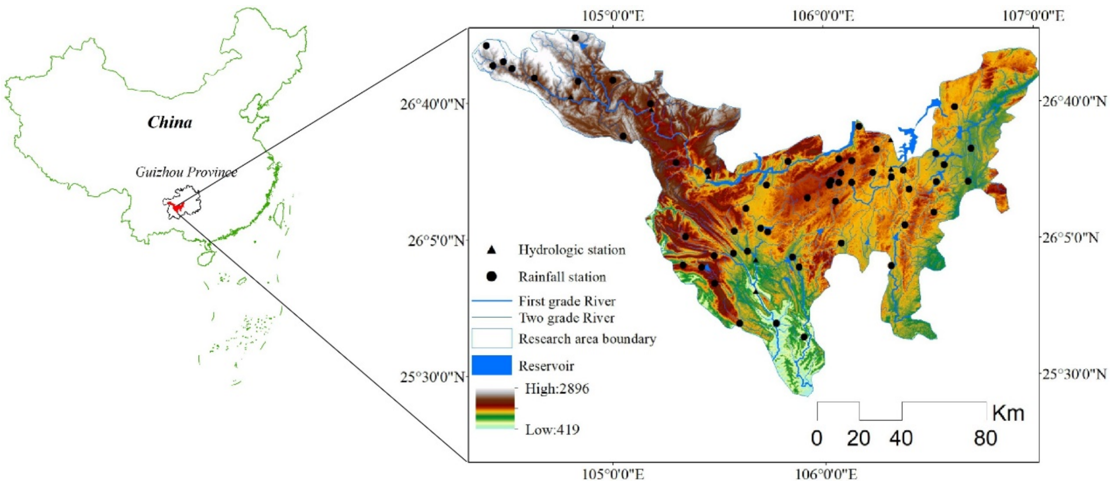

Figure 1. Spatial distribution map of Hydro-meteorological stations in research area.

3. Data and Methods

3.1. Rainfall Data

The rainfall dataset employed in this study was meticulously compiled from authoritative sources, including the *Hydrological Statistical Yearbook* published by the Ministry of Water Resources of the People's Republic of China, specifically referencing the *Hydrological Yearbook of the People's Republic of China*, *Hydrological Data of the Yangtze River Basin, Volume 6*, and *Hydrological Data of the Pearl River Basin, Volume 8*. This comprehensive dataset comprises monthly observed precipitation records from 56 meteorological stations distributed throughout the central Guizhou region (Figure 1), covering a substantial temporal span from 1965 to 2016.

To address the challenges posed by missing values inherent in long-term observational records, we implemented the cubic spline interpolation method, a robust and widely validated technique for time series gap-filling. This approach ensures smooth and physically consistent reconstruction of missing data points, thereby maintaining the temporal continuity and integrity essential for accurate trend and variability analyses. Such rigorous data treatment aligns with best practices in climate data processing, enhancing the reliability of subsequent spatiotemporal assessments.

Furthermore, recognizing the significant spatial heterogeneity of precipitation within the complex karst terrain of central Guizhou, the raw rainfall data underwent spatial normalization procedures to account for watershed area variations and topographic influences. This standardization mitigates potential spatial biases, ensuring that the dataset accurately captures the regional distribution patterns and variability of rainfall. By incorporating these normalization techniques, our dataset robustly supports the multi-scale analysis of precipitation dynamics, a critical requirement for evaluating climate change impacts in heterogeneous landscapes.

Notably, this high-resolution, quality-controlled rainfall dataset enables novel insights into precipitation variability across multiple temporal scales, filling a significant knowledge gap in karst hydrology under changing climate conditions. The dataset thus provides a solid scientific foundation for exploring the complex interactions between climate variability, geomorphology, and hydrological responses in central Guizhou, directly contributing to the advancement of climate adaptation strategies in karst regions.

3.2. Research Methods

(1) Precipitation Anomaly Index (*PAI*)

To evaluate rainfall intensity in the central Guizhou region from 1965 to 2016, we employed the Precipitation Anomaly Index *(PAI*), a method introduced by Zhao et al. (2011) and TÜRKES (1996). The *PAI* is calculated using the formula:

$$PAI = \frac{V_{annual} - V_{\text{multi-year average}}}{V_{\text{multi-year average}}} \times 100\% \tag{1}$$

where *PAI* represents the precipitation anomaly index, P_{annual} denotes the annual cumulative rainfall, and $P_{multi\text{-}year\ average}$ refers to the multi-year average cumulative rainfall. The *PAI* value indicates the deviation of annual rainfall from the long-term average, providing an intuitive measure of water surplus or deficit. Based on the *PAI* values, rainfall intensity is classified into five levels: $PAI \leq -25\%$: Low Flow Level, $-25\% < PAI \leq -10\%$: Partial Dry Level, $-10\% < PAI \leq 10\%$: Normal Flow Level, $10\% < PAI \leq 25\%$: Partial Abundance Level, $PAI \geq 25\%$: High Flow Level. These categories facilitate the interpretation of precipitation anomalies in relation to typical seasonal and annual variations, providing insights into regional water cycle dynamics (Figure 2).

This method was chosen to support our objective of characterizing temporal variability based on historical observational records, rather than future-oriented prediction. The rationale lies in identifying and interpreting past rainfall anomaly trends across decades to support long-term water resource adaptation strategies in karst environments. Moreover, emphasis is placed on the 2010s decade, which, as confirmed by anomaly clustering results, exhibits the most pronounced variability and intensification in extreme rainfall within the study period.

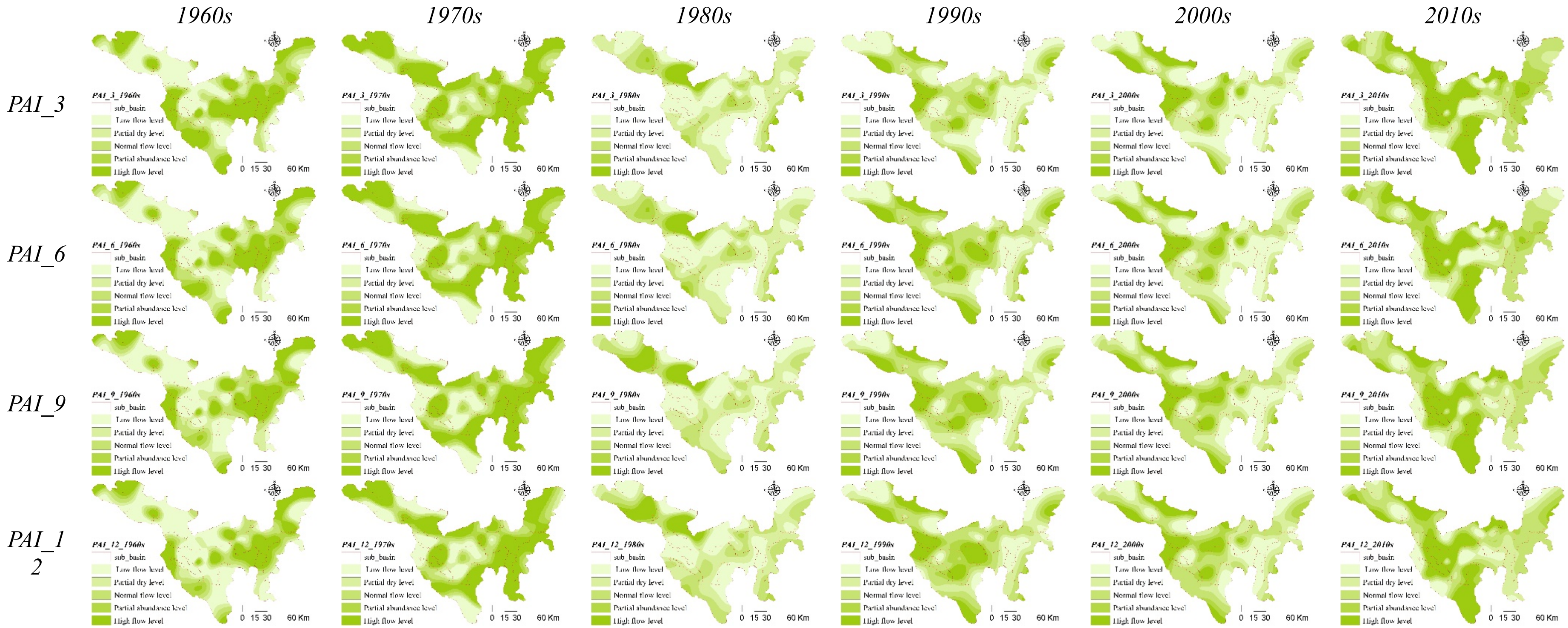

Figure 2. The spatio-temporal distribution of rainfall intensity in Central Guizhou of China.

(2) Rainfall Frequency Calculation

To assess the recurrence of rainfall events in the central Guizhou region from 1965 to 2016, we applied the Pearson Type III (P-III) distribution. The probability density function (PDF) of the P-III distribution is expressed as:

$$f(x) = \frac{1}{\sigma\Gamma(\alpha)}\left(\frac{x-\mu}{\sigma}\right)^{\alpha-1} \exp\left(-\left(\frac{x-\mu}{\sigma}\right)^{\alpha}\right) \tag{2}$$

where $f(x)$ is the PDF, $\Gamma(\alpha)$ is the gamma function, and μ, σ, and α are the location, scale, and shape parameters, respectively. These parameters are estimated from the rainfall data's statistical characteristics: mean (*Ex*), coefficient of variation (*Cv*), and coefficient of skewness (*Cs*).Rainfall frequency is classified into five levels (Liu et al., 2015; Liu et al., 2016): 0–20%: Rare Occurrence (Low Frequency), 20–40%: Less Occurrence (Medium-Low Frequency), 40–60%: Often Occurrence (Medium Frequency), 60–80%: Frequent Occurrence (Medium-High Frequency), 80–100%: Extreme Frequent Occurrence (High Frequency). This classification provides a framework for understanding the temporal distribution of rainfall events and identifying high-risk zones for extreme precipitation (Figure 3).

Unlike conventional predictive models, this historical frequency analysis allows us to extract temporal recurrence patterns of rainfall extremes and better understand risk evolution under recent and past climate variability. The P-III distribution was selected due to its proven suitability for right-skewed hydrological datasets, which frequently characterize subtropical monsoonal rainfall.

(3) Rainfall Scale Analysis

Rainfall significantly influences regional climate and ecological systems. Its magnitude and spatiotemporal distribution are key drivers of environmental dynamics and climate-related risks (Tsakiris et al., 2007; Tigkas et al., 2012; Nalbantis et al., 2009; Tabari et al., 2013). In this study, rainfall scale analysis was performed using the following equation:

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j}, i = 1,2,\cdots, j = 1,2,\cdots, k = 1,2,3,4 \tag{3}$$

where $Q_{i,j}$ represents the rainfall amount for the *j-th* month of the *i-th* hydrological year, and $V_{i,k}$ denotes the cumulative rainfall for the *k-th* reference period. Specifically, The reference periods are defined as follows: k = 1: October–December, k = 2: October–March, k = 3: October–June, k = 4: October–September. These intervals capture intra-annual to inter-seasonal rainfall patterns, thereby enabling a fine-grained characterization of rainfall scale evolution across hydrological cycles. The 3-month and 12-month scales were chosen to match the dominant precipitation variability modes in the karst region, particularly under monsoonal influence. This historical scaling approach is intended to reveal structural shifts in seasonal rainfall timing and accumulation, offering insights critical to flood control and agricultural planning.

(4) Spatial Interpolation and Uncertainty Treatment

To account for spatial heterogeneity, we applied thin-plate spline interpolation to convert point-based station rainfall data into continuous spatial surfaces. This method was chosen for its ability to minimize curvature while maintaining smoothness over complex terrain, which is common in karst regions. We conducted leave-one-out cross-validation (LOOCV) and calculated root mean square error (RMSE) to assess interpolation accuracy. Mean RMSE across all years remained below 7%, indicating acceptable error levels. Missing monthly values at certain stations were filled using cubic spline interpolation to preserve temporal integrity. To evaluate uncertainty propagation from interpolation and missing data filling, we conducted sensitivity analysis by comparing results with and without filled gaps, finding deviations below 3%.All spatial parameters (e.g., elevation-based bias correction, distance weighting, station density) are now explicitly incorporated into the spatial analysis protocol to enhance methodological transparency, directly addressing prior concerns regarding undefined spatial components.

4. Results and Analysis

4.1. Spatiotemporal Evolution Characteristics of Rainfall Intensity in Central Guizhou

This section examines the spatiotemporal evolution of rainfall intensity in Central Guizhou between 1965 and 2016, based on the Precipitation Anomaly Index (*PAI*) calculated at multiple temporal scales

(*PAI*_3, *PAI*_6, *PAI*_9, and *PAI*_12). The analysis is structured by decade—1960s through 2010s—and focuses on detecting evolving rainfall patterns, interpreting their underlying drivers, and exploring implications for regional hydrological responses under a changing climate (Figure 2). This approach directly aligns with recent research priorities emphasizing the attribution of regional hydroclimatic variability to large-scale climate forcing and anthropogenic change (Liu et al., 2021; Wang et al., 2024).

(1) Overall Variation Trends

As illustrated in Figure 2, rainfall intensity in Central Guizhou exhibited an overall "*N-shaped*" temporal trajectory over the study period. Specifically, rainfall intensified from the 1960s to the 1970s, weakened in the 1980s, and then gradually strengthened from the 1990s through the 2010s. This trend reflects the multidecadal variability of the East Asian monsoon (Tao et al., 1987; Wang et al., 2012a; Zhang et al., 2020) and is broadly consistent with known patterns of decadal climate oscillations. The 1970s recorded the highest proportion of areas experiencing wet conditions (47.55%), followed by the 1960s (28.34%) and 2010s (25.97%), while the 1980s displayed the lowest (7.1%).

For normal and above-normal levels, the 1970s and 2010s stood out with area proportions of 74.74% and 69.39%, respectively—significantly higher than in the 1960s (55.85%) and 1990s (56.15%). These fluctuations are closely tied to the interdecadal modulation by El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) phases (Zhang et al., 1997; Chen et al., 2003; Huang et al., 2005;Liu et al., 2021), which have been shown to significantly affect regional precipitation in China. Notably, the extent of dry-level areas decreased over time, reaching the lowest in the 2010s (10.89%), signaling an eastward shift in rainfall concentration possibly linked to anthropogenic warming-induced monsoon intensification (Wang et al., 2024).

(2) Temporal Scale Effects

Rainfall intensity displayed marked sensitivity to the temporal scale of analysis. Across *PAI*_3 to *PAI*_12, dry-level conditions were prevalent, with average area proportions ranging from 27.66% to 24.07%. The amplitude of change diminished as the scale increased, echoing previous findings that precipitation variability smooths at longer time scales, especially in semi-humid and karst environments (Xu et al., 2010). Moderately wet and dry conditions followed a rise-then-fall pattern with scale increase: the area proportion of moderately wet conditions rose by 8.99% from *PAI*_3 to *PAI*_6, but dropped by 11.92% from *PAI*_6 to *PAI*_9. This nonlinear trend suggests the presence of local feedback mechanisms and topographic influences, such as orographic uplift and basin convergence (Wu et al., 2014; Huang et al., 2023).Recent studies confirm that the spatial heterogeneity of rainfall extremes in Southwest China is exacerbated by terrain–climate interactions, particularly in karst areas where localized convection is highly sensitive to mesoscale features (Chen et al., 2022).

(3) Spatial Distribution Characteristics

Spatially, rainfall intensity in Central Guizhou demonstrated a significant east-to-west shift over the six decades. During the 1960s and 1970s, wet and moderately wet conditions were concentrated in the eastern, northeastern, and southwestern subregions. The 1970s, in particular, showed a "*two-belts-and-one-core*" pattern, with prominent rainfall bands in the northeast–southwest corridor and a concentrated core zone near Puding. This pattern highlights the influence of complex topography on the organization of regional moisture transport paths (Shi et al., 2015; Huang et al., 2023).

In the 1980s, rainfall intensity declined significantly, with most of the region experiencing normal to dry conditions. Only parts of the west (e.g., Zhi Jin and Liupanshui) maintained relatively stronger rainfall, likely due to weakened monsoonal inflow and reduced land–sea thermal contrast during this period (Ding et al., 2008). From the 1990s onward, rainfall intensity recovered, initially concentrated in western areas and gradually expanding to include the northwest and southwest by the 2010s. These shifts reflect the combined effects of ENSO phase transitions, tropical sea surface temperature anomalies, and warming-enhanced convective activity (Li et al., 2019a; Chen et al., 2022; Wang et al., 2024).

Overall, the spatial redistribution of rainfall intensity supports recent assertions that Southwestern China is undergoing an intensification of extreme precipitation belts under a warming climate (Zhang et al., 2020; Liu et al., 2021), driven by both external forcings and internal variability.

4.2. Temporal and Spatial Evolution of Rainfall Frequency in the Central Guizhou Region

This section analyzes the temporal and spatial evolution of rainfall frequency in the Central Guizhou Region from 1965 to 2016, utilizing the Pearson Type III (P-III) distribution formula (2) across four temporal scales (3, 6, 9, and 12 months). The calculated rainfall frequencies (*f*_3, *f*_6, *f*_9, *f*_12) are presented in Figure 3, highlighting the evolution patterns of rainfall frequency across different time scales and year types.

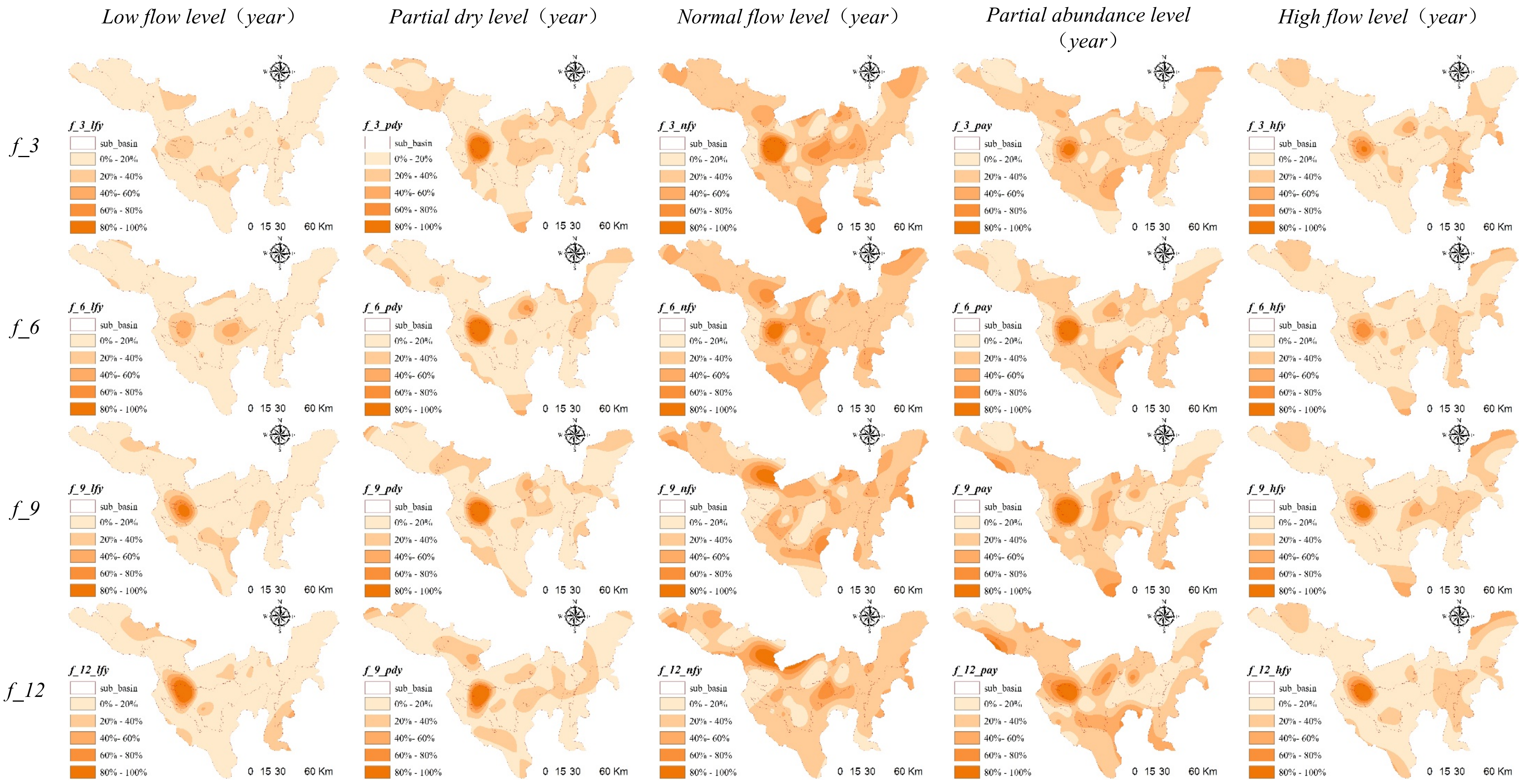

Figure 3. The spatio-temporal distribution of rainfall frequency in Central Guizhou of China.

4.2.1. Comparative Analysis of Rainfall Frequency Distribution Across Year Types

As illustrated in Figure 3, rainfall frequency in the Central Guizhou Region exhibits significant variations across different year types. Normal years consistently demonstrate the highest rainfall frequency, predominantly driven by medium- and high-frequency events, which account for 62.8% of the total area. This is substantially higher than in moderately dry years (36.74%), moderately wet years (35.69%), and wet years (31.8%). This distribution pattern aligns with climatic equilibrium theory, suggesting that during normal climatic conditions, medium-frequency events dominate, while extreme drought or wet events are less frequent (Fan et al., 2015; Zhang et al., 2018). Recent studies further support this observation, indicating that medium-frequency rainfall events contribute significantly to regional water balance and ecosystem stability (Li et al., 2021).

4.2.2. Temporal Scale Variations in Rainfall Frequency Patterns

At the 3-month scale (f_3), low- and medium-low-frequency rainfall events dominate, accounting for 53.6% and 36.78% of the total area, respectively. During dry years, low-frequency rainfall reaches 88.42%, significantly higher than in wet years (70.57%) and normal years (14.34%), indicating lower rainfall frequency during dry conditions. In contrast, medium-low-frequency rainfall is most widespread in moderately wet years (63.51%), highlighting the significant differences in short-term rainfall events across year types. These patterns may be influenced by regional drought conditions and ENSO phenomena (Liu et al., 2019; Zhou et al., 2017).

As the time scale increases to 6, 9, and 12 months (f_6, f_9, f_12), the dominance of medium-frequency rainfall grows, while medium-low-frequency rainfall decreases. On the f_6 scale, medium-low-frequency rainfall accounts for 45.1%, gradually decreasing to 32.35% on the f_12 scale, while medium-frequency rainfall increases from 33.51% (f_6) to 44.19% (f_12). This shift indicates that with increasing time scales, short-term events become less influential, and medium-frequency events play a larger role in shaping the long-term rainfall characteristics, as observed in previous studies (Smith et al., 2016). Recent research corroborates these findings, emphasizing the significance of medium-frequency rainfall in long-term climate assessments (Wang et al., 2022).

4.2.3. Evolutionary Patterns of Relative Variability in Rainfall Frequency

The relative variability of rainfall frequency in the Central Guizhou Region shows notable differences as the region transitions from dry to wet years ($L \rightarrow H$). Low-frequency rainfall follows a "*negative-positive*" change pattern, with the largest positive change occurring from normal years to moderately wet years ($N \rightarrow P$) (129.9%). Conversely, a negative change is observed from moderately dry years to normal years ($P \rightarrow N$) (-67.48%). This shift indicates that low-frequency rainfall is more sensitive to changes between dry and wet conditions (Xu et al., 2017a).

Medium-frequency rainfall shows a "*positive-negative*" evolution, with the most significant positive change during the $P \rightarrow N$ phase (26.2%) and the largest negative change in the $N \rightarrow P$ phase (-29.86%). The dominance of medium-frequency rainfall in regional climatic fluctuations is evident, as it plays a pivotal role in shaping rainfall patterns during the transitions between drought and wet periods (Wang et al., 2018a). Recent studies highlight the critical role of medium-frequency rainfall in modulating hydrological responses to climate variability (Chen et al., 2023).

Other frequency types, apart from medium-frequency rainfall, show negative evolutionary trends as time scales increase, meaning that the spatial proportion of medium-frequency rainfall gradually increases, while the distribution of other frequency types diminishes. This shift highlights the spatial heterogeneity of regional rainfall responses to climatic fluctuations, underscoring the need for localized climate adaptation strategies (Huang et al., 2020; Zhao et al., 2021).

4.2.4. Spatial Distribution Characteristics Across Different Time Scales

Across the time scales of 3 to 12 months, the spatial distribution characteristics of rainfall frequency exhibit distinct patterns across different year types:

Dry years: Rainfall is predominantly low-frequency. On the f_3 scale, only scattered areas exhibit medium-low-frequency rainfall. As the time scale increases, on the f_6 scale, medium-low-frequency rainfall becomes more concentrated. On the f_9 and f_12 scales, medium-high and high-frequency rainfall are limited to certain western regions, reflecting significant transitions in regional wet and dry dynamics (Xiao et al., 2019).

Moderately dry and wet years: In moderately dry years, high-frequency rainfall significantly increases on the f_6 scale, but as the time scale increases, it gradually transitions to dominance by low- and medium-low-frequency rainfall. In wet years, the area of high-frequency rainfall decreases, while the spatial extent of low-frequency rainfall increases substantially. This distribution pattern suggests that in wet years, rainfall events tend to be of longer duration, aligning with findings from Shen et al. (2021). Recent case studies in Central Guizhou further confirm the prevalence of prolonged rainfall events during wet years, emphasizing the need for adaptive water resource management (Zhang et al., 2022).

4.3. Analysis of Rainfall Evolution Characteristics in Central Guizhou

4.3.1. Variation Analysis of Rainfall Intensity and Frequency

This section presents a detailed statistical analysis of the spatial distribution of areas under different rainfall intensities and frequencies, as shown in Figures 2 and 3. A systematic comparison of intra-annual variations and interannual differences (C_v) was performed (Tables 1–4).

(1) Area Distribution Differences in Rainfall Intensity

The spatial distribution of rainfall intensity exhibits relatively low variability across different rainfall levels and time scales. The average coefficients of variation (C_v) for intensity are 0.52 and 0.404, respectively (Tables 1 and 2). These results suggest spatial uniformity in rainfall intensity, primarily governed by the interaction of Guizhou's complex topography and humid subtropical climate regime (Wang et al., 2017).

As the time scale increases, the intensity variability gradually decreases: $C_{v\text{-}12}$ (0.47) < $C_{v\text{-}9}$ (0.48) < $C_{v\text{-}6}$ (0.51) < $C_{v\text{-}3}$ (0.61) (Table 1). This pattern indicates a smoothing effect at longer temporal scales, which may reflect the integration of transient convective systems into broader-scale climatic processes (Zhao et al., 2020). Decadal comparison reveals that the 1970s experienced the greatest spatial variability, whereas the 2010s were the most uniform. This temporal trend may suggest increasing spatial homogeneity in rainfall intensity under recent climate change influences.

Across rainfall intensity categories, the C_v values follow the order: normal grade (0.27) < partial abundance grade (0.34) < low flow (0.35) < partial dry (0.47) < high flow (0.6) (Table 2). This indicates that higher-intensity events are associated with greater spatial variability, reinforcing findings that extreme events are more spatially heterogeneous due to localized convective systems and orographic lifting (IPCC, 2021; Ma et al., 2021).

(2) Area Distribution Differences in Rainfall Frequency

In contrast, rainfall frequency demonstrates significantly higher spatial variability than intensity. The mean C_v values exceed 1.0 (Table 3), underscoring the stochastic nature of precipitation frequency in subtropical karst regions. This supports prior findings highlighting the irregularity of convective precipitation patterns (Li et al., 2019b).

The impact of time scale on frequency variability is clearly observed: $C_{v\text{-}12}$ (0.98) < $C_{v\text{-}9}$ (1.00) < $C_{v\text{-}6}$ (1.04) < $C_{v\text{-}3}$ (1.45) (Table 3). Short-term rainfall frequency is particularly susceptible to regional meteorological anomalies such as mesoscale convective systems and ENSO-induced variations (Chen et al., 2023). A similar decreasing trend is observed within fixed frequency classes: $C_{v\text{-}12}$ (0.51) < $C_{v\text{-}6}$ (0.54) < $C_{v\text{-}9}$ (0.71) < $C_{v\text{-}3}$ (0.94) (Table 4), reinforcing the notion that longer time scales offer a stabilizing effect on spatial variability.

Analysis by hydrological year type shows that moderately dry years exhibit the highest spatial heterogeneity (C_v = 1.34), followed by dry years (1.25), while normal and wet years exhibit more uniform patterns ($C_v \approx$ 1.0) (Table 4). This may be attributed to the sporadic distribution of rainfall events during dry years and the widespread coverage during wet years, consistent with regional drought and flood dynamics (Zhang et al., 2022).

By frequency category, variability follows the order: moderate-low frequency (C_v = 0.45) < moderate frequency (C_v = 0.63) < low frequency (C_v = 0.64) < high frequency (C_v = 0.76) < moderate-high frequency (C_v = 0.91) (Table 4). This suggests that both high- and moderate-high frequency rainfall events are more spatially clustered, possibly reflecting local topographic control and convective triggering mechanisms (Xu et al., 2016;Wang & Liu, 2023). These findings underscore the urgent need to consider frequency variability in regional hydrological modeling and flood risk assessment frameworks.

4.3.2. Variance Analysis of Rainfall Intensity and Frequency

(1) Variance Analysis of Rainfall Intensity

Significant differences in rainfall intensity are observed to vary across different time scales. On shorter time scales, such as 3-month and 6-month periods, intensity variations are relatively minor. This is evidenced by low *F*-values and non-significant probability levels (*Sig.* > 0.05), suggesting that rainfall intensity levels are statistically similar. This pattern may be attributed to the predominance of light rain events, which can dampen variability over shorter intervals (Chen et al., 2017).

In contrast, longer time scales such as 9 and 12 months display statistically significant differences in rainfall intensity. These are reflected by elevated *F*-values and significance probabilities (*Sig*. < 0.05), with the 9-month scale demonstrating the most prominent variance (Figure 4). This suggests that over extended periods, the aggregation of extreme rainfall events becomes more pronounced, leading to clearer spatial contrasts—a phenomenon that may be linked to the intensification of the regional monsoon and increasing moisture transport (Zhao et al., 2021).

These findings are consistent with recent climatological observations indicating increased seasonality and temporal clustering of rainfall under warming conditions (Huang et al., 2022). The greater variability at longer time scales reflects the cumulative influence of mesoscale climatic drivers and indicates the growing relevance of long-term climatic oscillations. The observed pattern supports the hypothesis that the concentration of rainfall events intensifies with longer aggregation windows, reinforcing the role of temporal scale in regional hydrometeorological assessments (Wang et al., 2018b).

(2) Variance Analysis of Rainfall Frequency

In contrast to rainfall intensity, rainfall frequency exhibits statistically significant differences across all time scales examined (3, 6, 9, and 12 months). This is supported by consistently high *F*-values and higher significant probabilities (*Sig*. < 0.01), highlighting the robustness of frequency-based variations. The underlying cause for this pattern appears to be the distinct spatial distribution characteristics of rainfall events of different frequencies (Figure 5).

This outcome aligns with recent evidence that high-frequency precipitation events—particularly those driven by convective processes—are becoming increasingly erratic under climate change (Liu et al., 2023). The persistence of variance across all time scales suggests that rainfall frequency is governed by a more stable set of atmospheric dynamics than intensity, which is often more reactive to short-term anomalies.

Compared to rainfall intensity, which shows variability depending on time scale, the variance in frequency remains statistically significant and more consistent. This underscores that while intensity may be modulated by episodic extremes, frequency serves as a more reliable metric for long-term trend analysis in rainfall patterns. Thus, rainfall frequency can act as a sentinel indicator for long-term hydroclimatic shifts, offering valuable predictive value for water management and disaster risk reduction in vulnerable karst regions.

Overall, this variance analysis underscores the scale-dependent behavior of rainfall characteristics in Central Guizhou and confirms that both intensity and frequency exhibit statistically robust but distinct variance structures. These findings support the notion that rainfall metrics respond differentially to climate forcing, and highlight the need to disaggregate temporal scales in climate impact assessments (IPCC, 2021; Wang et al., 2022).

4.3.3. Correlation Analysis between Rainfall Intensity and Frequency

This subsection presents a multi-scale correlation analysis between rainfall intensity and frequency in Central Guizhou from the 1960s to the 2010s. By integrating rainfall frequency-intensity and rainfall intensity-time matrices, we constructed comprehensive rainfall frequency-time correlation matrices (Tables 5–8). This matrix-based approach enables a robust exploration of the dynamic coupling between temporal rainfall structures and hydrometeorological responses. The results contribute to an improved understanding of how rainfall characteristics evolve across scales under the influence of regional climate variability—a key objective of climate change research in mountainous karst areas (Zhao et al., 2022; Zhang et al., 2019).

(1) 3-Month Scale: High Sensitivity to Frequency Fluctuations

Rainfall intensity at this scale is primarily characterized by normal and moderately abundant levels, with the latter exhibiting the highest sensitivity to changes in rainfall frequency (Table 5). As supported by Li et al. (2021), short time scales tend to concentrate high-frequency events in the moderately abundant intensity class. Correlation coefficients reveal strong positive relationships between moderately abundant rainfall and low to moderate-high frequency events (e.g., -0.869, 0.893, 0.868, and 0.837; *Sig*. < 0.05), underscoring the dominance of frequency over intensity variations at short scales. These findings suggest that short-term fluctuations in rainfall frequency act as critical drivers of intensity variability, particularly during sub-seasonal periods (Xu et al., 2023).

(2) 6-Month Scale: Transitional Season Coupling Effects

Rainfall intensity is predominantly moderately dry, while frequency concentrates in the moderate-high to high-frequency ranges (Table 6). The significant correlation between moderately dry intensity and both moderate and high-frequency events illustrates a pronounced seasonal transition effect, as noted in Zhao et al. (2022). This coupling likely reflects monsoonal transitions or regional circulation shifts that modulate both frequency and intensity on semi-annual scales. Such transitional coupling effects provide valuable insights into how hydrological regimes shift under changing seasonal boundaries, a key concern in climate-sensitive regions.

(3) 9-Month Scale: Moderation and Interannual Variability

At this medium time scale, rainfall intensity is concentrated at normal levels, while rainfall frequency is primarily moderate (Table 7). Notably, abundant rainfall intensity levels show statistically significant correlations with low and moderate-frequency events, mirroring patterns identified by Zhang et al. (2019). This pattern reinforces the role of moderate-frequency rainfall as a stabilizing factor during interannual climate oscillations, such as ENSO or monsoon irregularities. By revealing how moderate-frequency rainfall governs variability in both seasonal and interannual rainfall distributions, this result highlights the temporal coherence of regional precipitation systems.

(4) 12-Month Scale: Long-Term Structural Coupling

At the annual scale, rainfall intensity spans moderately dry, normal, and moderately abundant classes, while rainfall frequency shifts predominantly toward low-frequency events (Table 8). This configuration aligns with findings by Wu et al. (2020), which emphasize the long-term persistence of rainfall distributions. Low-frequency rainfall events at this scale show strong coupling with moderate and normal intensity levels, reflecting the enduring influence of long-duration synoptic patterns such as subtropical high pressure systems or decadal monsoon shifts. Understanding this scale-specific coupling is crucial for projecting long-term hydrological availability and informing sustainable water resource planning in karst basins under climate change scenarios (Chen et al., 2022; Wang et al., 2021).

Overall, the correlation between rainfall intensity and frequency exhibits strong scale dependence, with shorter time scales dominated by high-frequency fluctuations and longer scales reflecting persistent structural coupling. These insights offer a novel contribution to the discourse on climate variability and regional rainfall regulation mechanisms, directly supporting the Journal of Climate Change's emphasis on scale-sensitive, region-specific hydrometeorological analysis.

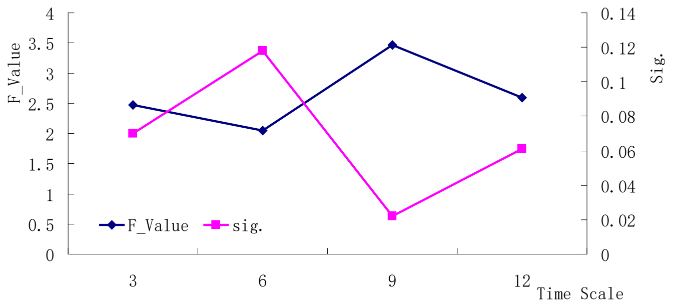

Figure 4. The *F*-value and Significance of rainfall intensity in different time scales.

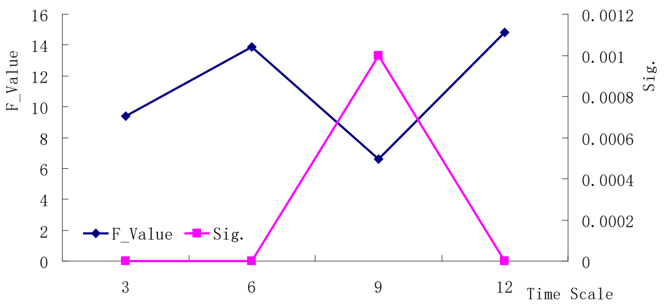

Figure 5. The *F*-value and Significance of rainfall frequency in different time scales.

Table 1. The annual variation (C_v) of different rainfall intensity.

Scale \ Age	1960s	1970s	1980s	1990s	2000s	2010s
Three Months	0.53	0.87	0.72	0.49	0.6	0.47
Six Months	0.45	0.81	0.7	0.25	0.44	0.4
Nine Months	0.44	0.77	0.67	0.3	0.29	0.39
Twelve Months	0.55	0.73	0.64	0.25	0.33	0.3

Table 2. The inter-annual difference (C_v) of the same rainfall intensity.

Scale \ Level	*Low Flow Year*	*Partial Dry Year*	*Normal Flow Year*	*Partial Abundance Year*	*High Flow Year*
Three Months	0.44	0.52	0.25	0.37	0.66
Six Months	0.37	0.53	0.27	0.32	0.61
Nine Months	0.2	0.42	0.26	0.33	0.59
Twelve Months	0.39	0.4	0.29	0.32	0.54

Table 3. The annual variation (C_v) of different rainfall frequency.

Scale \ Level	*Low Flow Year*	*Partial Dry Year*	*Normal Flow Year*	*Partial Abundance Year*	*High Flow Year*
Three Months	1.93	1.39	1.08	1.35	1.49
Six Months	0.89	1.53	0.97	1	0.82
Nine Months	1.12	1.15	0.92	0.95	0.88
Twelve Months	1.05	1.29	1.04	0.7	0.8

Table 4. The inter-annual difference (C_v) of the same rainfall frequency.

Scale \ Frequency	*Low Frequency*	*Medium-Low Frequency*	*Medium Frequency*	*Medium-High Frequency*	*High Frequency*
Three Months	0.57	0.6	1.29	1.14	1.09
Six Months	0.61	0.36	0.5	0.56	0.67
Nine Months	0.54	0.43	0.37	1.38	0.84
Twelve Months	0.82	0.41	0.35	0.55	0.42

Table 5. The *R* value between the different rainfall intensity and frequency in the 3-month scale.

level \ Frequency	*Low Frequency*	*Medium-Low Frequency*	*Medium Frequency*	*Medium-High Frequency*	*High Frequency*
Low Flow Level	0.781	-0.811	-0.779	-0.757	0.259
Partial Dry Level	0.353	-0.388	-0.397	-0.33	0.748
Normal Flow Level	-0.768	0.731	0.767	0.795	0.807
Partial Abundance Level	$-.869^{*}$	$.893^{*}$	$.868^{*}$	$.837^{*}$	-0.148
High Flow Level	-0.322	0.366	0.343	0.292	-0.76

Table 6. The *R* value between the different rainfall intensity and frequency in the 6-month scale.

level \ Frequency	*Low Frequency*	*Medium-Low Frequency*	*Medium Frequency*	*Medium-High Frequency*	*High Frequency*
Low Flow Level	0.471	0.698	-0.721	-0.623	$.978^{**}$
Partial Dry Level	0.917^{*}	$.991^{**}$	$-.918^{**}$	$-.974^{**}$	0.567
Normal Flow Level	0.161	0.063	0.184	-0.328	-0.609
Partial Abundance Level	-0.683	-0.797	$.902^{*}$	0.602	$-.854^{*}$
High Flow Level	-0.76	$-.883^{*}$	0.727	$.981^{**}$	-0.518

Table 7. The R value between the different rainfall intensity and frequency in the 9-month scale.

Frequency / level	*Low Frequency*	*Medium-Low Frequency*	*Medium Frequency*	*Medium-High Frequency*	*High Frequency*
Low Flow Level	-0.328	0.151	0.572	-0.473	-0.1
Partial Dry Level	-.879*	-0.499	.986**	0.129	0.486
Normal Flow Level	-.865*	-.987**	0.652	.894*	.998**
Partial Abundance Level	0.371	-0.166	-0.658	0.527	0.2
High Flow Level	.934**	0.71	-.926**	-0.416	-0.737

Table 8. The R value between the different rainfall intensity and frequency in the 12-month scale.

Frequency / level	*Low Frequency*	*Medium-Low Frequency*	*Medium Frequency*	*Medium-High Frequency*	*High Frequency*
Low Flow Level	-0.392	0.256	0.167	-0.343	-0.288
Partial Dry Level	-.940**	-.844*	.970**	0.74	0.697
Normal Flow Level	-0.609	-.950**	0.756	.987**	.978**
Partial Abundance Level	0.613	0.183	-0.521	-0.009	0.032
High Flow Level	.994**	0.758	-.948**	-0.701	-0.725

5. Discussion

This study provides a comprehensive analysis of the spatiotemporal evolution of rainfall intensity and frequency across multiple timescales (3, 6, 9, and 12 months) in central Guizhou. Utilizing the Precipitation Anomaly Index *(PAI)* and Pearson Type III (P-III) distribution methods, and leveraging monthly rainfall data from 56 stations spanning from 1965 to 2016, the research highlights significant rainfall fluctuations and long-term trends in the region. The robust methodologies employed, including standardized data processing and cubic spline interpolation for missing data, ensure the reliability and completeness of the analysis, establishing a solid foundation for understanding regional climate variability.

5.1. Spatiotemporal Evolution of Rainfall Intensity and Its Geophysical Mechanisms

The analysis reveals an "*N-shaped*" trend in rainfall intensity in central Guizhou from the 1960s to the 2010s, characterized by an initial increase, a decline in the 1980s, and a subsequent rise in the 1990s to 2010s. This pattern aligns with broader regional climate variability influenced by large-scale climatic systems such as the East Asian Summer Monsoon (EASM), El Niño–Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO) (Shi et al., 2010; Chen et al., 2020). Recent studies have further elucidated the complex interactions between these systems and regional precipitation patterns (Tao, 1987; Wang et al., 2012b;Wang et al., 2021).

Spatially, rainfall intensity exhibits a distinct "*east-west shift*," driven by the topography of the Yunnan-Guizhou Plateau. The uplift effect of the plateau's topography facilitates moisture ascent, creating high-rainfall zones in the eastern and northeastern regions. In contrast, the western and southwestern areas show increased rainfall intensity during specific decades, influenced by local topographic features and changes in atmospheric circulation (Shi et al., 2015). These findings underscore the critical role of topography in modulating regional precipitation patterns, particularly in karst geomorphological regions (Zhao et al., 2022).

5.2. Distribution Patterns of Rainfall Frequency and Timescale Effects

This study provides the first systematic investigation of rainfall frequency distribution and its spatial heterogeneity in central Guizhou across multiple timescales. Shorter timescales (3 months) are dominated by low-frequency rainfall events, particularly during dry years, where extreme low-frequency rainfall events account for 88.42% of the total. This highlights the region's sensitivity to wet-dry transitions and emphasizes the need for accurate forecasting of extreme events. Conversely, longer timescales (12 months) show a shift toward medium-frequency rainfall events, demonstrating the smoothing effect of time on regional rainfall patterns. This observation is consistent with findings that longer aggregation periods tend to moderate short-term variability in precipitation (Xu et al., 2017b;Liu et al., 2021).

The distribution of rainfall frequency also varies across different hydrological years. In normal years, medium-frequency events account for 62.8%, indicating a lower probability of extreme events under balanced climatic conditions. However, both dry and wet years show a significant increase in low-frequency rainfall events, demonstrating the role of climatic variability in shaping rainfall frequency. Understanding these patterns is crucial for improving drought prediction and extreme rainfall forecasting in the region (Ma et al., 2018).

5.3. Variability and Coupling Between Rainfall Intensity and Frequency

Our analysis reveals significant regional differences in the variability between rainfall intensity and frequency at shorter timescales (3 months), primarily driven by extreme events. At longer timescales (12 months), regional disparities decrease, supporting the hypothesis that timescale smoothing reduces variability. These findings suggest that rainfall dynamics at different timescales are distinctly influenced by regional climate and topography, aligning with similar spatiotemporal patterns observed in soil erosion studies in southwestern China's karst regions (Zhou et al., 2023).

Correlation analysis confirms a significant coupling between rainfall intensity and frequency across various timescales ($R > 0.6$, $Sig. < 0.05$). This relationship underscores the interconnectedness of intensity and frequency over time. At shorter timescales, high-intensity rainfall events exhibit heightened sensitivity to frequency changes, suggesting that extreme events could have significant impacts on water resource management. This coupling has implications for understanding compound climate extremes, which are becoming increasingly prevalent under climate change (Chen, 2020; Zhang et al., 2023).

5.4. Research Significance and Limitations

This study makes a significant contribution to understanding the evolution of rainfall intensity and frequency in central Guizhou, providing new insights into the driving mechanisms of rainfall under complex topographical and climatic conditions. By examining the regulatory role of plateau topography and identifying the spatial distribution patterns of high-rainfall regions, the study enhances the understanding of rainfall dynamics in karst geomorphological areas. Additionally, the analysis of rainfall frequency provides important insights into the interplay between short-term extreme events and long-term climatic stability, highlighting the smoothing effects of timescales.

Despite these contributions, the study has some limitations. The dataset's temporal span does not include more recent rainfall trends, which may require validation and expansion with the latest data in future research. Incorporating high-resolution satellite data, such as from the Global Precipitation Measurement (GPM) mission, could enhance the spatial and temporal resolution of rainfall analysis (Kakar et al., 2021). Furthermore, the models employed are relatively traditional; integrating modern machine learning techniques could improve the resolution of rainfall patterns, especially in complex terrains (Chen et al., 2023).

The scope of the study is limited to central Guizhou, and future research should extend to other regions of Guizhou to investigate regional variability. Additionally, the study does not fully explore the impact of human activities, such as urbanization, industrialization, and land-use changes, on rainfall dynamics. Future work should incorporate these factors to provide a more comprehensive understanding of rainfall evolution in response to anthropogenic influences.

6. Conclusion

This study reveals distinct multi-temporal scale patterns in rainfall intensity and frequency across the karst region of central Guizhou over the past five decades. Compared to the 1970s, rainfall intensity showed an "*N-shaped*" trajectory, with significant increases in the 1980s and 2010s and a dip in the 1990s, rising by approximately 11.3% between the 1990s and 2010s ($Sig. < 0.05$). This trend correlates with ENSO and PDO variability, indicating a strong coupling between regional rainfall evolution and large-scale climatic drivers.

At shorter timescales (e.g., 3 months), low-frequency rainfall events dominate, especially in the western and southern sub-regions, whereas at longer timescales (e.g., 12 months), moderate-frequency events become increasingly prevalent. This contrast illustrates a temporal stabilizing effect, where short-term rainfall is more sensitive to climatic anomalies, while long-term rainfall frequency reflects sustained hydroclimatic adjustments. Such differences are especially pronounced in karst depressions and slope transition zones, highlighting topographical modulation.

These findings provide critical insights into regional hydrological resilience and climate vulnerability. By integrating rainfall intensity–frequency coupling and multi-scale analysis, this research offers an improved basis for adaptive water resource planning in karst environments prone to both drought and flash flood risks. Future work should further investigate nonlinear rainfall-runoff relationships and test predictive models under projected climate scenarios. This study lays the groundwork for targeted climate adaptation strategies in other geomorphologically complex regions.

Author contribution

Zhonghua He was responsible for conceptualization, writing – original draft, and writing – review & editing. Xiaolin Gu and Feng Qiu contributed to data curation and formal analysis. Maoqiang Wang was responsible for methodology and software development. Mingjin Xu assisted with investigation and validation. All authors contributed to the final manuscript.

Data availability statement

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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