Postprint: Seasonal Variation Characteristics of Precipitation Concentration Degree and Characteristic Variables in the Yarlung Tsangpo River Basin from 1981 to 2024

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Abstract

The Precipitation Concentration Index (PCI) effectively characterizes the intra-annual concentration of precipitation and has been widely applied in related research. Based on monthly precipitation and mean temperature observational data from 15 meteorological stations in the Yarlung Tsangpo River (hereinafter referred to as the Yarlung River) basin from 1981 to 2024, this study employs linear equations, Pearson correlation coefficient, and five change-point detection methods including Mann-Kendall and Cramer to analyze the spatiotemporal variation characteristics of PCI, seasonal precipitation, precipitation frequency, and precipitation intensity, as well as the causes of PCI changes in the Yarlung River basin over the past 44 years. The results indicate: (1) PCI in the Yarlung River basin increases from east to west, while annual precipitation, precipitation frequency, and precipitation intensity decrease from east to west. (2) Over the past 44 years, PCI in the Yarlung River basin has decreased by 0.26 per decade on average, with the intra-annual distribution of precipitation tending to become more uniform; precipitation from January to July and October shows an increasing trend (with the fastest increase rate in July); precipitation in other months exhibits a decreasing trend (with the largest decrease in September); the proportion of monthly precipitation to annual precipitation (MPAP) in February and April–July shows an increasing trend (most pronounced in May); MPAP in the remaining months tends to decrease (with the largest decrease amplitude in September). (3) In the Yarlung River basin, increased precipitation intensity in spring, summer, winter, and the entire year leads to increased precipitation; reduced precipitation frequency in autumn results in decreased precipitation. The increase in annual precipitation intensity is caused by the significant increase in the Tibetan Plateau-1 index and the Western Pacific Warm Pool intensity index. The decrease in PCI is related to the reduction of seasonal differences under the background of warming. (4) PCI was only low in the 2000s, but high in the other three decades, with a change-point occurring in the early 1990s; the change-points for annual precipitation, frequency, and intensity appeared in the early 2000s and the mid-to-late 1990s, respectively.

Full Text

Preamble

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Seasonal Variations of Precipitation Concentration Index and Characteristic Quantities in the Yarlung Zangbo River Basin from 1981 to 2024

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Abstract

The Precipitation Concentration Index (PCI) effectively characterizes the intra-annual concentration of precipitation and has been widely applied in relevant research. Based on monthly precipitation and mean temperature observations from 15 meteorological stations in the Yarlung Zangbo River Basin (YZRB) from 1981 to 2024, this study analyzes the spatiotemporal variation characteristics of PCI, seasonal precipitation amount, frequency, and intensity over the past 44 years, as well as the causes of PCI changes, using linear equations, Pearson correlation coefficients, Kendall trend tests, and five mutation detection methods including the Mann-Kendall and Cramer tests. The results indicate that: (1) The PCI in the YZRB increases from east to west, while annual precipitation amount, frequency, and intensity decrease from east to west. (2) Over the past 44 years, the average PCI has decreased at a rate of -0.26 per decade, indicating that precipitation distribution within the year has become more uniform. Monthly precipitation shows an increasing trend from January to July and in

October, with July experiencing the fastest increase, while other months exhibit decreasing trends, with September showing the largest decline. The proportion of monthly precipitation to annual precipitation (MPAP) increases in February and from April to July (most notably in May), while decreasing in other months (most significantly in September). (3) The increase in precipitation during spring, summer, and winter is primarily caused by enhanced precipitation intensity, whereas the decrease in autumn precipitation is mainly due to reduced precipitation frequency. The increase in annual precipitation intensity results from significant increases in both the Tibetan Plateau index and the Western Pacific Warm Pool intensity index. The decrease in PCI is related to reduced seasonal differences under the background of warming. (4) The PCI was lower only in the 2000s but higher in the other three decades, with an abrupt change occurring in the early 1990s. Abrupt changes in annual precipitation amount and frequency occurred around the early 2000s, while the mutation in annual precipitation intensity occurred in the mid-to-late 1990s.

Keywords: precipitation concentration; precipitation characteristic quantity; variation characteristics; atmospheric circulation index; sea surface temperature index; Yarlung Zangbo River Basin

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1. Introduction

Under global climate warming, the water cycle has become anomalous, altering the spatial and temporal distribution patterns of precipitation. Precipitation represents the most critical component of the water cycle, and its intra-annual variation holds significant importance for crop growth, water resource conservation, and management. Precipitation concentration characteristics reflect the comprehensive interplay of precipitation amount, duration, and processes, serving as a key indicator for evaluating whether regional precipitation distribution within a year is uniform. An Bin et al. summarized commonly employed methods for calculating precipitation concentration characteristics, including the Precipitation Concentration Degree (PCD) and Precipitation Concentration Period (PCP) defined by Martin-Vide based on daily precipitation data, the Precipitation Concentration Index (PCI) defined by Oliver based on monthly precipitation data, and the Precipitation Concentration Degree defined by Michiels et al. Domestic scholars have utilized these indices to analyze spatiotemporal variation characteristics across China, North China, Southwest China, and Northwest China. Overall, the PCI offers more intuitive physical meaning and simpler calculation compared to other precipitation concentration indices.

The Yarlung Zangbo River (YZR) is a major international river in Asia, and water resource issues in its basin have long been a focus of attention. It is also one of China' s rivers richest in hydropower potential, with abundant natural reserves of approximately 2.4×10^{8} kW, second only to the Yangtze River, accounting for about 13% of China' s total hydropower potential. Concurrently, it represents an important ecological security barrier and biodiversity conservation priority area in China. The YZR stretches 2,057 km within China, with a drainage area of 4.6$\times 10^{5}$ km^2, featuring distinct vertical vegetation zonality. Due to complex terrain and diverse climate, its ecosystem is extremely sensitive and vulnerable under global climate change. Since the 1980s, most areas of the YZRB have experienced increasing precipitation, while snow cover has significantly decreased, profoundly affecting water cycle processes and mechanisms. Precipitation changes in the YZRB also significantly impact the water system and ecosystem of the Tibetan Plateau. Currently, domestic scholars have conducted numerous studies on spatiotemporal variation characteristics of precipitation amount in the YZRB based on meteorological observations. However, research on intra-annual precipitation distribution characteristics, precipitation concentration, and seasonal variations in precipitation frequency and intensity remains scarce. Therefore, this study analyzes seasonal variation characteristics of precipitation concentration and precipitation frequency and intensity in the YZRB based on monthly precipitation and precipitation days from 1981 to 2024, which is significant for understanding intra-annual precipitation distribution patterns and water resource potential in the basin.

1.1 Data Sources

Monthly precipitation and precipitation days data from 15 meteorological stations in the YZRB from 1981 to 2024 were provided by the Tibet Autonomous Region Meteorological Information Network Centre and have undergone strict quality control. Atmospheric circulation indices including the Asian polar vortex, Western Pacific subtropical high, India-Burma trough, Tibetan Plateau index, and Tibetan Plateau Trough, as well as sea surface temperature indices including NINO 3.4 sea surface temperature anomalies, Indian Ocean warm pool area and intensity, Western Pacific warm pool area and intensity, and warm pool and cold tongue types, were obtained from the National Climate Centre. The study area and meteorological station distribution are shown in [Figure 1: see original paper].

1.2 Research Methods

1.2.1 Precipitation Concentration Index (PCI) The PCI was calculated using the method proposed by Oliver and improved by De Luís et al.:

$$\mathrm{PCI} = \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \times 100$$

where P_i represents monthly precipitation (mm) and i denotes the month.

1.2.2 Climate Tendency Rate The climate tendency rate was calculated using the following formula:

$$Y = a + bt$$

where Y represents the precipitation characteristic quantity (PCI, precipitation amount, frequency, or intensity); t represents time; a is the regression constant; and b is the regression coefficient. The term $b \times 10$ is referred to as the climate tendency rate per decade, with its significance tested using the correlation coefficient between t and Y.

1.2.3 Mutation Test Methods Five mutation detection methods were employed: Mann-Kendall test, Cramer test, moving t-test, Pettitt test, and Yamamoto test to examine abrupt changes in precipitation characteristics in the YZRB.

1.2.4 Data Processing and Mapping Seasons were defined as spring (March-May), summer (June-August), autumn (September-November), and winter (December-February). Data processing and statistical analysis utilized DPS V19.05 software. Line charts were produced using Excel, while spatial distribution maps of mean values were generated using the Inverse Distance Weighted (IDW) interpolation method in ArcGIS 10.8, which has been widely applied for meteorological elements on the Tibetan Plateau. Spatial distribution maps of trend rates were directly created using ArcGIS.

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2. Results

2.1 Variation Characteristics of Precipitation Concentration Index

2.1.1 Spatial Distribution of PCI As shown in [Figure 2: see original paper], annual PCI values in the YZRB range from 13.5 to 31.0, generally increasing from east to west, with the lowest value in Bomi and the highest in Lhatse. Specifically, PCI values are below 20 in Nyingchi City and Lhari, indicating seasonal precipitation with moderate intra-annual concentration. In contrast, PCI exceeds 20 in other areas, suggesting extremely concentrated intra-annual precipitation distribution with large monthly variations. The climate tendency rate reveals that PCI shows an increasing trend in Nyingchi City, central-eastern Lhasa, and Namling, while decreasing trends dominate other stations.

2.1.2 Intra-Annual Distribution Characteristics Average monthly precipitation in the YZRB exhibits a unimodal pattern, concentrated mainly from June to September, accounting for 78.2% of annual precipitation. Climate tendency rates indicate that monthly precipitation increased from January to July and in October, with July showing the fastest increase at 3.53 mm $\cdot$ $(10a)^{-1}$. Other months displayed decreasing trends, with September showing the largest decrease at -2.73 mm $\cdot$ $(10a)^{-1}$. The proportion of monthly precipitation to annual precipitation (MPAP) increased in February and from April to July (most notably in May), while decreasing in other months (most significantly in September). Analysis of the relationship between PCI and annual temperature range revealed a highly significant positive correlation ($P < 0.01$), suggesting that the more uniform intra-annual precipitation distribution may be attributed to reduced seasonal differences under warming conditions.

2.2 Seasonal Variation of Precipitation Characteristics

2.2.1 Seasonal Precipitation Amount Mean annual and seasonal precipitation amounts decrease from east to west. Average values for annual, spring, summer, autumn, and winter precipitation are 500.4 mm, 92.0 mm, 321.9 mm, 78.6 mm, and 7.7 mm, respectively. Maximum values for annual and seasonal precipitation (except summer) occur in Nyingchi City, while summer precipitation peaks in Bomi. Minimum values for spring and winter precipitation occur in Lhatse, while summer and autumn minima occur in Gyantse. The average annual precipitation shows an increasing trend of 6.64 mm $\cdot$ $(10a)^{-1}$, with summer increasing fastest at 4.63 mm $\cdot$ $(10a)^{-1}$ and autumn decreasing at -2.64 mm $\cdot$ $(10a)^{-1}$. Spatially, most stations show increasing trends in spring precipitation, while summer precipitation decreases in Nyingchi City, Mainling, and Gyaca. Autumn precipitation predominantly decreases (most notably in Bomi), with only Nagarzê and Lhari showing increases. Winter precipitation increases at most stations except in Nyêmo, Gyaca, and Bomi.

2.2.2 Seasonal Precipitation Frequency Annual and seasonal precipitation frequencies generally decrease from east to west. Average values for annual, spring, summer, autumn, and winter precipitation frequencies are 30.3%, 15.6%, 12.6%, 10.5%, and 1.6%, respectively. Maximum frequencies occur in Mainling for annual, spring, and summer; in Bomi for autumn; and in Lhari for winter. Minimum frequencies for all seasons and annual values occur in Lhatse, except for summer minimum in Gyantse. The average annual precipitation frequency shows a decreasing trend of -0.30% $\cdot$ $(10a)^{-1}$, with autumn decreasing fastest and winter increasing. Spatially, annual precipitation frequency increases at six stations (Mêdog, Gonggar, Nagartse, Nyêmo, Namling, and Lhatse) and decreases elsewhere. Spring precipitation frequency increases in Nyingchi City, Shigatse, and Zedang, while decreasing in other stations. Summer precipitation frequency increases in Namling, Nyêmo, Nagartse, Gonggar, and Mêdog, and decreases elsewhere. Autumn precipitation frequency predominantly decreases (most notably in Mainling), with only Lhatse, Namling, and Bomi showing increases. Winter precipitation frequency increases in most of Shigatse, Gonggar, Zedang, and Nyingchi City.

2.2.3 Seasonal Precipitation Intensity Annual precipitation intensity distribution generally decreases radially from Namling and Shigatse, with spring and winter intensities showing longitudinal patterns (higher in the east, lower in the west). Average values for annual, spring, summer, autumn, and winter precipitation intensities are 4.56 mm $\cdot$ d^{-1}, 2.74 mm $\cdot$ d^{-1}, 5.63 mm $\cdot$ d^{-1}, 3.80 mm $\cdot$ d^{-1}, and 1.03 mm $\cdot$ d^{-1}, respectively. Maximum intensities occur in Bomi for annual, autumn, and winter; in Shigatse for summer; and in Bomi for spring. Minimum intensities occur in Gyantse for autumn and annual values, in Lhatse for summer and winter, and in Gyantse for spring. The average annual precipitation intensity shows an increasing trend of 0.15 mm $\cdot$ d^{-1} $\cdot$ (10a)$^{-1}$, with spring, summer, and winter increasing and autumn decreasing. Spatially, annual precipitation intensity increases at all stations except Nyêmo and Bomi. Spring precipitation intensity increases at all stations, while summer intensity decreases only at Nyêmo, Nyingchi, and Bomi. Autumn precipitation intensity decreases in most of Shigatse, Nyêmo, Lhasa, Gonggar, and Bomi, and increases elsewhere. Winter precipitation intensity decreases only at Namling and Nyêmo.

In summary, precipitation amount, frequency, and intensity in the YZRB all show decreasing trends from east to west. Over the past 44 years, autumn precipitation amount and intensity have decreased, while other seasons and annual values have increased. Winter precipitation frequency has increased, while other seasons and annual frequency have decreased, most notably in autumn. The increases in spring, summer, winter, and annual precipitation amounts are primarily caused by increased precipitation intensity, with contribution rates of 50.3%, 59.3%, 50.8%, and 64.3%, respectively. The decrease in autumn precipitation is mainly due to reduced precipitation frequency, with a contribution rate of 64.3%.

2.3 Interdecadal Variation of Precipitation Characteristics

[Figure 13: see original paper] shows the decadal anomalies of annual and seasonal precipitation amount, frequency, and intensity in the YZRB from 1981 to 2020. During the 1980s, annual and seasonal precipitation amounts and frequencies were below normal, with autumn and winter showing the largest deficits, and all seasonal and annual precipitation intensities below normal. In the 1990s, spring and winter precipitation amounts and intensities, along with spring precipitation frequency, were above normal, while summer precipitation intensity was significantly below normal. The 2000s featured below-normal annual precipitation due to reduced autumn precipitation, with only spring precipitation frequency above normal and autumn precipitation intensity below normal. Overall, the 1980s showed negative anomalies for annual precipitation amount, frequency, and intensity; the 1990s showed positive anomalies; the 2000s had low precipitation amount and intensity but high frequency; and the 2010s had low precipitation amount and frequency but high intensity, particularly pronounced in the 2010s.

2.4 Mutation Analysis

The Mann-Kendall test results for annual PCI, precipitation amount, frequency, and intensity are shown in [Figure 9: see original paper]. The UF curve for PCI showed an oscillating trend during 1981-1993, a significant decreasing trend after 1993, and an increasing trend after 2010. The UF and UB curves intersected in 1991, indicating an abrupt change from a relatively high period to a low period. Similarly, annual precipitation amount and intensity experienced abrupt changes around 2001 and 1996, respectively, transitioning from relatively low to high periods, while annual precipitation frequency showed no significant abrupt change. Validation using five mutation detection methods confirmed these findings: three methods detected the PCI mutation in 1991; two methods detected precipitation frequency mutation in 2002; and two methods detected precipitation intensity mutation in 1996. Comprehensive analysis indicates that the PCI mutation occurred in the early 1990s, precipitation amount and frequency mutations occurred around the early 2000s, and precipitation intensity mutation occurred in the mid-to-late 1990s.

2.5 Relationships Between Precipitation Characteristics and Atmospheric Circulation/SST Indices

Using Pearson correlation analysis, relationships between precipitation characteristics and atmospheric circulation/SST indices were examined. Results show that precipitation intensity is significantly positively correlated with the Tibetan Plateau index ($P < 0.05$) and significantly negatively correlated with the Asian polar vortex intensity index ($P < 0.05$). Additionally, precipitation intensity shows significant positive correlations with both the Western Pacific Warm Pool intensity index and Indian Ocean Warm Pool intensity index ($P < 0.05$). The Tibetan Plateau index and Western Pacific Warm Pool intensity index have the greatest influence on precipitation intensity, with contribution rates of 57.7% and 42.3%, respectively. Both indices have shown significant increasing trends over the past 44 years, driving the increase in annual precipitation intensity in the YZRB.

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3. Discussion

The Second Tibetan Plateau Scientific Expedition indicates that the Tibetan Plateau has experienced significant warming and a "wet north, dry south" precipitation pattern. This study reveals a "warm-wet west, warm-dry east" pattern in the YZRB. Under this context, PCI shows an increasing trend in the east and decreasing trend in the west, suggesting increased climate risks of summer flooding and spring/autumn droughts in the east, while reducing spring/autumn drought probability in the west.

Compared with the Three Rivers Source region in northern Tibetan Plateau, the YZRB has higher PCI values, indicating extremely concentrated intra-annual precipitation distribution, whereas the Three Rivers Source region has PCI < 20, showing seasonal precipitation with moderate concentration. Both regions show decreasing PCI trends, likely related to reduced seasonal differences under warming background, consistent with Duan Yawen et al.' s findings. Meteorological stations on the Tibetan Plateau are concentrated in the east and southeast, with sparse coverage in central and northwestern areas. Zhu Yanxin et al. evaluated multiple precipitation datasets for the Tibetan Plateau, identifying the IGSNRR dataset as having good consistency with observations and small spatial heterogeneity. Du Juan et al. analyzed precipitation concentration in the Three Rivers Source region using CN05.1 daily gridded data. This study reveals seasonal precipitation distribution characteristics in the YZRB based on station observations, but the lack of long-term stations in the upper YZRB limits comprehensive understanding of basin-wide water cycle characteristics. Higher-resolution satellite fusion data are needed for further investigation of spatial heterogeneity mechanisms in precipitation seasonality.

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4. Conclusions

1. **Spatial patterns:** Precipitation amount, frequency, and intensity in the YZRB generally decrease from east to west, while PCI increases from east to west. Most areas show extremely concentrated intra-annual precipitation distribution. Over the past 44 years, PCI has decreased at -0.26 $\cdot$ $(10a)^{-1}$, with increases mainly in Nyingchi City and central-eastern Lhasa, and decreases at other stations.

2. **Temporal trends:** Monthly precipitation increased from January to July and in October, with July showing the fastest increase at 3.53 mm $\cdot$ $(10a)^{-1}$. Other months decreased, with September showing the largest decline at -2.73 mm $\cdot$ $(10a)^{-1}$. MPAP increased in February and April-July (most notably in May) and decreased in other months (most significantly in September). Autumn precipitation amount and intensity decreased, while other seasons and annual values increased. Winter precipitation frequency increased, while other seasons and annual frequency decreased, most notably in autumn. The increases in spring, summer, winter, and annual precipitation amounts were primarily caused by enhanced precipitation intensity, while the decrease in autumn precipitation resulted from reduced precipitation frequency.

3. **Interdecadal variation and abrupt changes:** Annual precipitation amount, frequency, and intensity were below normal in the 1980s; above normal in the 1990s; low amount and intensity but high frequency in the 2000s; and low amount and frequency but high intensity in the 2010s. PCI experienced an abrupt change in the early 1990s, precipitation amount and frequency around the early 2000s, and precipitation intensity in the mid-to-late 1990s.

4. **Driving mechanisms:** The increase in precipitation intensity during spring, summer, winter, and annually was mainly caused by significant increases in the Tibetan Plateau index and Western Pacific Warm Pool

intensity index. The decrease in PCI was related to reduced seasonal differences under the background of warming.

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