Study on the Characteristics and Persistence of Precipitation Changes in the Lower Reaches of Yangtze River Basin

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Abstract. To explore the differences in precipitation among different regions and the persistence of precipitation trends in the future over the lower reaches of Yangtze River Basin (LYRB), we used precipitation data from meteorological stations in the LYRB from 1980 to 2020. The Pettitt method, Mann-Kendall (M-K) test, and Hurst exponent method were applied to determine the occurrence of precipitation change points, spatial-temporal characteristics, and their persistence in the three sub-regions of the LYRB, namely mainstream region (MR), Taihu Lake region (TLR), and northeast region (MR). The results show that the change points for the three regions occurred in 2008, 2007, and 2013, respectively. The average annual precipitation in period 2 increased by 9.4%, 14.9%, and 23.9% relative to period 1, and the range of precipitation centers expanded significantly. In period 2, a new precipitation center appeared in the TLR. The precipitation changes in the LYRB ranged from -1.44 mm/a to 9.34 mm/a. The southern and northern parts of the TLR and the central part of the NR showed a significant increasing trend in precipitation. Most areas of the MR are projected to experience decreasing precipitation in the future, while the TLR and the NR are expected to continue experiencing an increasing trend. As the accumulation time of characteristic precipitation increases, the differences in precipitation trends among regions will become more pronounced, and more regions may exhibit opposite trends compared to the current conditions.

Keywords: the lower reaches of Yangtze River Basin; precipitation; trend; persistence; spatiotemporal characteristics

1 Introduction

Precipitation is the most active and critical climate element in the water cycle [1]. In the context of global climate change, precipitation in China has changed significantly [2]. The Yangtze River Economic Belt (YREB) casts its expansive net over 11 provinces and cities, embracing prominent metropolises like Shanghai, Jiangsu, and Zhejiang, across an impressive 2,052,300 km2, which accounts for 21.4% of China's entire territory. With its population and GDP surpassing 40% of the nation's total, the YREB

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emerges as a commanding strategic region intricately interwoven into the fabric of China's holistic developmental landscape. The lower reaches of the Yangtze River Basin (LYRB) are the core of the YREB, and precipitation has a significant impact on the economic, social, and natural environment of this region. An in-depth study of the spatial and temporal characteristics of precipitation in different areas of the LYRB, as well as its future persistence, helps reveal the evolution of the regional water cycle under changing environments. It also provides valuable references for the sustainable utilization of regional water resources and the defense against droughts and floods [3].

In recent years, both domestic and international scholars have studied the spatiotemporal characteristics of precipitation in China and its different regions using statistical methods and meteorological models. Su et al.[4] utilized the Mann-Kendall non-parametric test to analyze the global 55 km climate dataset released by the National Earth System Science Data Center and found that China's annual precipitation exhibited a fluctuating upward trend from 2001 to 2020, reaching its maximum in 2016. Zhang et al.[5] comprehensively analyzed observation data, global precipitation climate center reanalysis data, and results from the sixth phase of the Coupled Model Intercomparison Project simulations. They discovered a significant increase in precipitation in China's northwest region, while the central and southeast coastal semi-humid and humid regions showed no significant trend of change. In addition to nationwide analyses of large-scale precipitation variations, numerous scholars have conducted extensive research focusing on the Yangtze River Basin (YRB). Jiang et al.[6] applied the Mann-Kendall method to test the changing trend of precipitation in major river basins nationwide and found a significant increasing trend in annual precipitation for the YRB. Shi et al.[7] used the Mann-Kendall method to analyze precipitation data from 131 meteorological stations in the YRB and found that there is a significant variation in heavy precipitation. Li et al.[8] utilized a precipitation dataset interpolated from 2400 meteorological stations by the China Meteorological Administration and revealed an increasing trend in precipitation in the LYRB from 1961 to 2014, with a trend of 2.37 mm/year. Lu et al.[9] analyzed observed precipitation grid data from 1961 to 2020 and identified an increasing trend in precipitation for the entire country (0.59 mm/year) and the YRB (0.68 mm/year), indicating most areas in the LYRB also showed an increasing trend in precipitation. Extensive studies on both national and regional scales have indicated that while China's climate change lacks high global consistency [2], significant regional disparities exist [4, 10]. However, current research on precipitation changes in the LYRB often treats the region as a whole, overlooking the differences in precipitation among various areas and lacking in-depth analysis and investigation of the persistence of precipitation trends [7-9].

This study is based on observed precipitation data from 88 meteorological stations in the LYRB from 1980 to 2020. The Pettitt change-point test, Mann-Kendall trend test, and Hurst exponent method were employed to analyze the spatiotemporal characteristics of precipitation and its persistence in different regions of the LYRB. The research aims to provide a fundamental foundation for deciphering the variations in hydrological elements in the LYRB.

2 Data and methodology

2.1 Data

This study collected daily precipitation data from 106 meteorological stations in the LYRB, compiled by the China Meteorological Administration, covering the period from 1951 to 2020. Due to variations in station establishment times, the length of data series was inconsistent, which could potentially affect the accuracy of precipitation change-point and trend analysis when directly using data from all stations. Therefore, during site selection and analysis, efforts were made to use a greater number of stations and ensure their even distribution across the study area. Preference was given to stations with longer and more consistent data series. Ultimately, 88 meteorological stations with complete precipitation records from 1980 to 2020 (Figure 1) were chosen to analyze the precipitation changes in the LYRB.

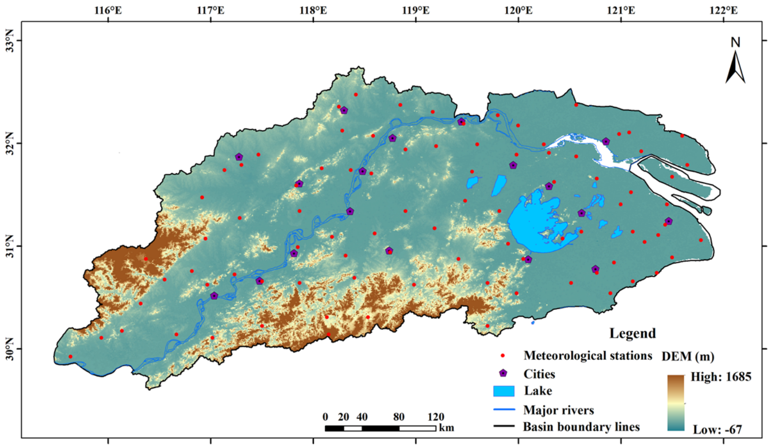

Fig. 1. The spatial distribution of the LYRB and meteorological stations.

2.2 Methodology

In this study, the Pettitt method was first applied to analyze the abrupt changes and spatial differences in annual precipitation in the LYRB, leading to the division of the study area into different regions based on these disparities. Subsequently, the Mann-Kendall (M-K) test was used to examine the change-point characteristics and trends in precipitation series from 1980 to 2020 in the LYRB. Finally, the Hurst coefficient was utilized to assess the persistence of precipitation series trends.

Change-point test.

The Pettitt test is a non-parametric method that aims to identify change points in a time series by examining the timing of mean value changes in the data [11]. It is commonly used to test whether hydro-meteorological time series exhibit abrupt changes and to assess the significance of such changes. The Pettitt test is favored for its ease of application, robustness in calculations, and ability to resist interference from outliers [11, 12]. If the statistic $|U_t|$ reaches its maximum value at time t, then t is considered the change point.

Trend test.

In time series trend analysis, the M-K test is a recommended and widely used non-parametric method by the World Meteorological Organization [13]. This test does not require the samples to follow a specific distribution and is not influenced by a small number of outliers, making it suitable for analyzing hydrological, meteorological, and other non-normally distributed data. It is commonly employed to analyze the changing trends and significance of time series data, such as precipitation, runoff, water level, sediment, air temperature, and water quality. The M-K test statistic, denoted as z, is positive if the time series exhibits an increasing trend and negative if it shows a decreasing trend. If $|z|$ is greater than or equal to $z_{a/2}$, where a is the confidence level typically set at 0.05 (corresponding to $z_{a/2} = 1.96$), the time series data indicates a significant change at the given confidence level.

Persistence test.

The Hurst exponent is commonly used to assess the persistence of hydrological series and provides a quantitative measure of long-term correlation in the data [14]. When H=0.5, it indicates that the correlation function value between past increments and future increments of the series is zero. When H<0.5, it suggests a negative correlation between past and future increments, implying an anti-persistent effect where past trends counteract future trends. Conversely, H>0.5 indicates a persistent effect, and when H>0.75, it is considered a strong positive persistence effect. The Hurst exponent is typically calculated using the R/S analysis method, and the calculation method is as follows:

$$H = In\left(\frac{R/S}{\tau/2}\right) \tag{1}$$

where H represents the value of the Hurst exponent, R and S denote the sample range and standard deviation, respectively, and τ stands for the length of the sample sequence.

3 Results & Discussion

3.1 Precipitation change-point characteristics

Using the Pettitt method to analyze the precipitation series from 88 meteorological stations, it was observed that in the LYRB, approximately 51% of the stations experienced a change in annual precipitation during the period from 2005 to 2012 (Figure 2). Considering the spatial distribution of the stations and the years of precipitation change, it was found that there were regional disparities in the precipitation change-point characteristics in the LYRB. Specifically, the mainstream region (MR) of the Yangtze River showed more scattered years of precipitation change, with the highest number of stations experiencing a change in 2008, accounting for 43.5% of the total stations during the period from 2005 to 2012. In the Taihu Lake region (TLR), 68.8% of the stations experienced a change in annual precipitation between 2005 and 2012. In the northeast region (NR), where a total of 10 meteorological stations were located, 40% of them had a change in precipitation in the year 2013. To account for this variability in the LYRB, the study divided the area into three regions: the MR, TLR, and NR, to investigate the characteristics of precipitation changes in a more detailed manner.

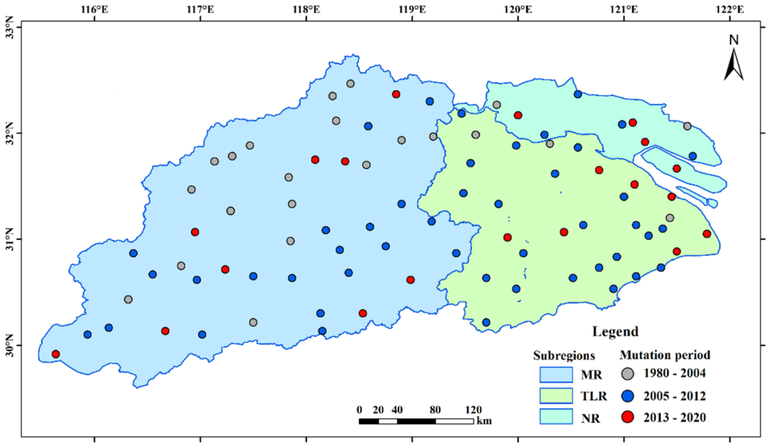

Fig. 2. The Pettitt test results for the annual precipitation of 88 meteorological stations from 1980 to 2020.

The Pettitt test statistics for the annual average precipitation in the three regions from 1980 to 2020 were separately calculated. The results indicate that the minimum values of the Pettitt test statistics correspond to the years 2008, 2007, and 2013 for the main-stem area, TLR, and northeast region, respectively (Figure 3). Therefore, the years 2008, 2007, and 2013 were chosen as the change points for the MR, TLR, and NR, respectively.

Based on the identified change points for the MR, TLR, and NR in terms of annual precipitation, the study periods for each region were divided into two segments using the change points as boundaries (Table 1). For the MR, the two segments are 1980-2007 and 2008-2020. The TLR has two segments of 1980-2006 and 2007-2020. Similarly, the NR has two segments of 1980-2012 and 2013-2020.

Table 1. Division of time periods for the three sub-regions.

Subregions	Period 1	Period 2
MR	1980-2007	2008-2020
TLR	1980-2006	2007-2020
NR	1980-2012	2013-2020

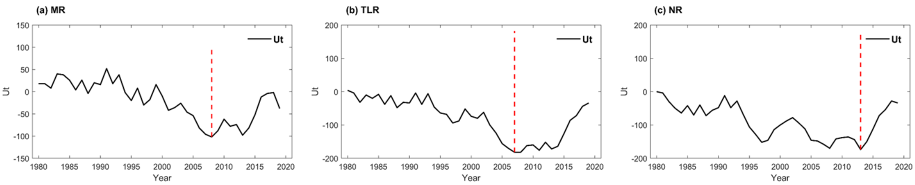

Fig. 3. Pettitt test of annual precipitation in the LYRB from 1980 to 2020.

3.2 The characteristics and persistence of annual precipitation changes.

Temporal changes and their persistence.

Figure 4 shows the interannual variation trends of annual precipitation for the MR, TLR, and NR during the two study periods from 1980 to 2020, along with their corresponding linear regression lines. Both the MR and the TLR exhibit a decreasing trend in annual precipitation during period 1, and an increasing trend during period 2, with the increasing trend surpassing 20 mm/a. On the other hand, the NR shows an increasing trend in annual precipitation for both period 1 and period 2, with trends of 0.34 mm/a and 4.18 mm/a, respectively. Additionally, the average annual precipitation in the MR is the highest among the three regions for both study periods, followed by the TLR, and the NR has the lowest average annual precipitation (Table 2).

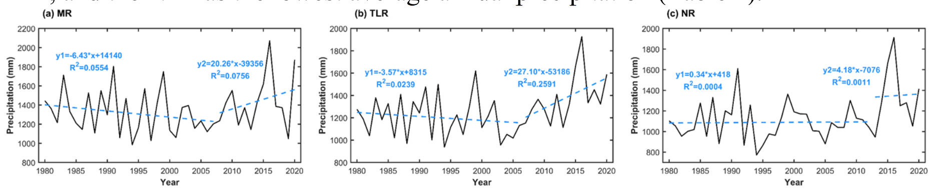

Fig. 4. Annual precipitation variations in the MR, TLR, and NR during different time periods from 1980 to 2020.

Table 2. Statistical values of annual precipitation and average annual precipitation for each subregion.

Subregions	Z	S (mm/a)	H	Period 1 (mm)	Period 2 (mm)	Increase rate
MR	0.44	1.16	0.35	1316	1440	9.4%
TLR	1.90	5.49	0.67	1202	1381	14.9%
NR	1.85	4.75	0.58	1089	1349	23.9%

The results of the M-K trend test for annual precipitation from 1980 to 2020 in the MR, TLR, and NR are presented in Table 2. From the table, it can be observed that all three regions show an increasing trend in annual precipitation during the period from 1980 to 2020, with growth rates (S) of 1.16 mm/a, 5.49 mm/a, and 4.75 mm/a, respectively. However, the corresponding Z-values are all less than 1.96, indicating that the increasing trend in annual precipitation is not statistically significant according to the M-K significance test.

In the second period, the annual precipitation in all three regions increased compared to the first period, with increases of 9.4%, 14.9%, and 23.9% for the MR, TLR, and NR, respectively.

Regarding the persistence of the trend in annual precipitation, the Hurst exponent was used for assessment. The Hurst exponent values for the TLR and NR are greater than 0.5, while for the MR, it is lower than 0.5. This indicates that the past trends in the TLR and NR will have a positive persistence effect on the future, meaning that the future precipitation will continue to increase. On the other hand, in the MR, the Hurst exponent indicates a negative persistence effect, suggesting that future precipitation in this region will decrease.

Spatial changes and their persistence.

Spatial grid data was obtained by interpolating the data from the 88 meteorological stations using the inverse distance weighting method. The analysis focused on the spatial variation of average annual precipitation and its changing trend in the study area from 1980 to 2020 for the two study periods. It was found that the annual precipitation in both study periods is concentrated in the southern region of the LYRB, exhibiting a spatial pattern of decreasing trend from southwest to northeast. In period 1, the center of annual precipitation is located in the southern part of the MR. While in period 2, the average annual precipitation is higher than in period 1, and the distribution range of the precipitation center has significantly expanded compared to period 1. Notably, in period 2, a new precipitation center has emerged in the western region of the TLR, which was not present in period 1 (Figure 5).

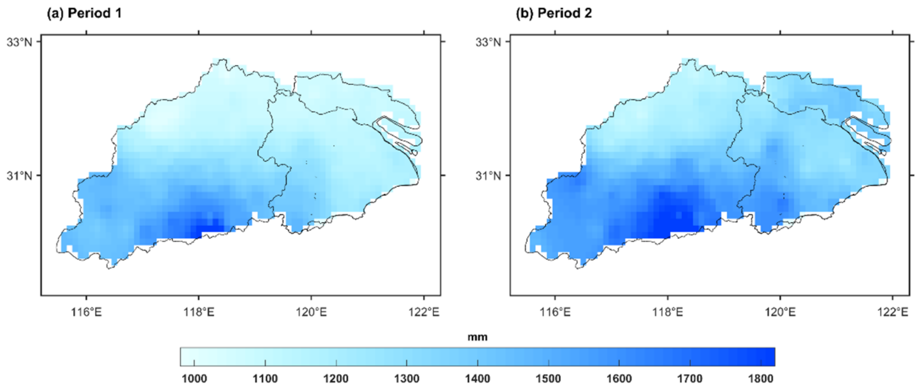

Fig. 5. Spatial distribution of mean annual precipitation in the LYRB during different time periods from 1980 to 2020.

Figure 6 represents the spatial distribution of the M-K trend test and Hurst index values of annual precipitation in the LYRB from 1980 to 2020. As shown in Figure 6a, most areas in the LYRB exhibit an increasing trend in precipitation, which is consistent with the findings of Lu et al[9]. Further analysis of the spatial variation of precipitation reveals that only a specific region in the western part of the MR shows a decreasing trend in precipitation. Overall, the variation range of precipitation in the LYRB fluctuates between -1.44 and 9.34 mm/a. In particular, the southern and northern parts of the TLR, as well as the central part of the NR, have passed the 95% significance test, indicating a significant increasing trend.

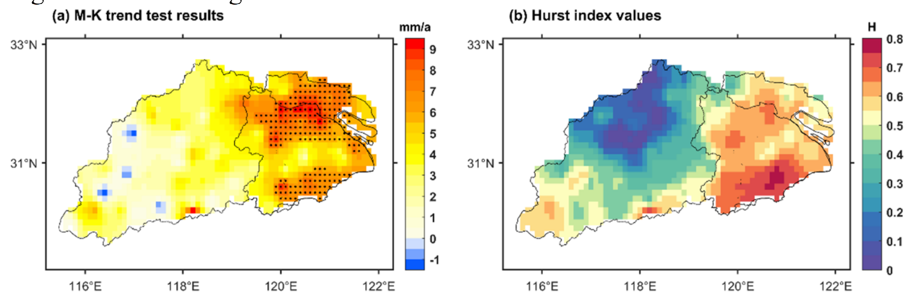

Fig. 6. Spatial distribution of (a) M-K trend test results and (b) Hurst index values of annual precipitation in the LYRB from 1980 to 2020. Note: Black dots in the figures indicate grid points where precipitation trends pass the 95% significance test.

Regarding the persistence of precipitation trends (Figure 6b), most areas in the TLR and NR have Hurst values exceeding 0.5, suggesting that precipitation will continue to increase in these regions. Moreover, in some localized areas in the southern part of the TLR, the Hurst value exceeds 0.75, indicating a strong persistence of increasing trends. Conversely, most areas in the MR have Hurst values below 0.5, with only some specific regions in the southern part having Hurst values exceeding 0.5, suggesting that most areas in the main stem region will experience a decreasing trend in precipitation, while only certain regions in the southern part will continue to experience an increasing trend in the future.

When analyzing the trend of annual precipitation from a spatial perspective, most areas in the TLR and NR have passed the significance test, while when analyzing the trend from a temporal perspective, none of the three regions' precipitation trends have passed the significance test. In the temporal analysis, the precipitation values for the three regions are the average values of the respective region's weather stations. Consequently, under the influence of averaging, none of the three regions' precipitation trends passed the significance test. In contrast, in the spatial analysis of annual precipitation trends, the trends in each region are not affected by averaging, which is why most areas in the TLR and NR have passed the significance test.

When conducting the temporal analysis, the Hurst index values for the three regions represent the average of all Hurst index values within each region. As a result, the MR, where the majority of the Hurst index values are below 0.5, shows a negative persistence effect, while the TLR and NR, where the majority of the Hurst index values are above 0.5, show a positive persistence effect.

These observations reflect how different spatial analysis scales can influence the analytical conclusions and emphasize that conducting analysis at a finer spatial level is more conducive to revealing the precipitation trends in specific areas within the lower reaches of the Yangtze River.

3.3 Spatiotemporal changes and persistence of characteristic precipitation

Temporal changes and persistence.

Statistical characteristics of annual maximum 1-day precipitation (Max1d), maximum 3-day precipitation (Max3d), maximum 5-day precipitation (Max5d), maximum 7-day precipitation (Max7d), maximum 15-day precipitation (Max15d), and maximum 30-day precipitation (Max30d) at 88 meteorological monitoring stations in the LYRB during 1980-2020 were analyzed using the M-K test and Hurst index to assess the trend and persistence of these precipitation variables. The results are shown in Table 3.

Table 3. Statistical values related to characteristic precipitation in each subregion. Note: The asterisk (*) means passing the 95% significance test.

	MR			TLR			NR		
	Z	S(mm/a)	H	Z	S(mm/a)	H	Z	S(mm/a)	H
Max1d	1.18	0.23	0.65	0.48	0.11	0.67	1.38	0.44	0.53
Max3d	1.20	0.56	0.46	1.25	0.51	0.67	2.62*	1.15	0.67
Max5d	0.48	0.29	0.25	1.07	0.64	0.47	2.28*	0.86	0.59
Max7d	0.23	0.17	0.28	1.25	0.56	0.47	1.85	0.87	0.48
Max15d	-0.06	-0.04	0.32	1.18	0.90	0.33	1.72	1.47	0.52
Max30d	0.55	0.87	0.37	1.52	1.37	0.23	1.00	1.12	0.30

For the MR, all the characteristic precipitation except Max15d show an increasing trend, but none of them pass the 95% significance test, indicating an insignificant trend. As for the persistence of trend, the Hurst index value for max1d is greater than 0.5, suggesting that the increasing trend of max1d will continue in the future. However, the Hurst index values for other characteristic precipitations are less than 0.5, indicating that their future trends will be opposite to the current ones. In the TLR, all characteristic precipitations show an increasing trend, but none of them pass the 95% significance test, indicating an insignificant trend. Regarding the persistence of trend, the Hurst index values for max1d and max3d are both 0.67, indicating that their increasing trends will persist in the future. However, the Hurst index values for other characteristic precipitations are less than 0.5, suggesting that their future trends will be opposite to the current ones. In the NR, all characteristic precipitations show an increasing trend, with max3d and max5d showing significant increasing trends at the 95% significance level. As for the persistence of trend, the Hurst index values for max1d, max3d, max5d, and max15d are all greater than 0.5, indicating that they will continue to show increasing trends in the future. However, the Hurst index values for other characteristic precipitations are less than 0.5, suggesting that their future trends will be opposite to the current ones.

Spatial changes and persistence.

Figure 7 presents the spatial distribution of characteristic precipitation trends in the LYRB from 1980 to 2020. Overall, there are significant differences in the trends of characteristic precipitation between the three regions and within each region, and these differences become more pronounced with increasing accumulation time of characteristic precipitation. For instance, the trend differences between max30d and max1d are more significant, both among the three regions and within each region.

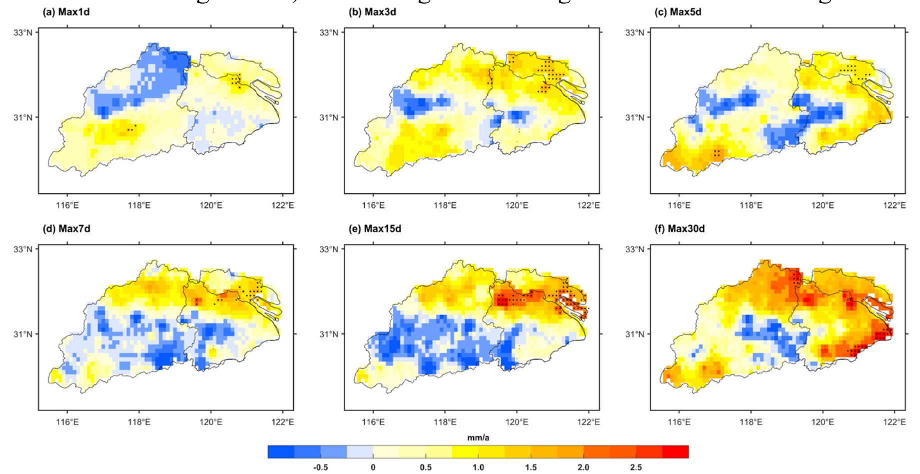

Fig. 7. Spatial distribution of M-K trend test results for characteristic precipitation in the LYRB from 1980 to 2020. Note: Black dots in the figures indicate grid points where precipitation trends pass the 95% significance test.

In the MR, except for max1d showing a decreasing trend, most of the characteristic precipitations in the northern part show an increasing trend, while those in the central part show a decreasing trend. In the southwestern part, they show an increasing trend. However, none of these trends pass the 95% significance test, indicating their insignificance. In the TLR, most of the characteristic precipitations in the central and western parts show a decreasing trend, while those in the northern, eastern, and southern parts show an increasing trend. Some areas, such as parts of the northern region (max1d, max3d, max7d, and max15d) and southeastern region (max30d), pass the 95% significance test, showing significant increasing trends. In the NR, only some areas in the southeastern and northern parts show a decreasing trend for max5d and max7d, while most of the other areas show an increasing trend for the characteristic precipitations. Some areas, such as parts of the central region (max3d, max5d, max7d) and southeastern region (max15d), pass the 95% significance test, indicating significant increasing trends.

Figure 8 shows the spatial distribution of Hurst indices for characteristic precipitation in the LYRB from 1980 to 2020. Overall, as the accumulation time of characteristic precipitation increases, the areas with Hurst values below 0.5 gradually expand, indicating that the regions showing opposite trends in the future to the present are increasing. For instance, the areas with Hurst values above 0.5 for max1d are relatively extensive and mostly distributed in the MR and TLR. However, for max30d, only a small part of the southwestern mainstream area and the southern part of the TLR have Hurst values greater than 0.5, while the rest have Hurst values less than 0.5.

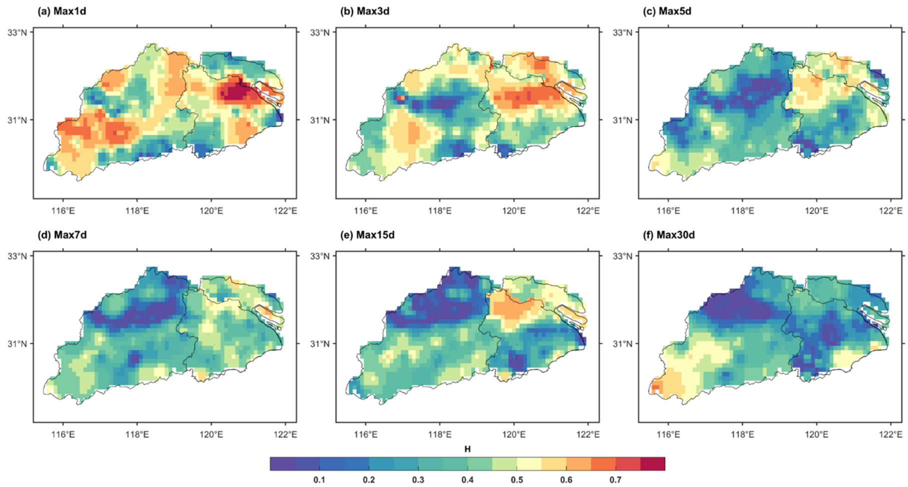

Fig. 8. Spatial distribution of Hurst index for characteristic precipitation in the LYRB from 1980 to 2020.

There is also significant variability in the Hurst indices within each region. In the MR, most areas in the northern and southwestern parts have Hurst values above 0.5 for max1d and max3d, indicating that most areas in the north will continue to exhibit a decreasing trend for max1d, while most areas in the north and southwestern part will have a continuing increasing trend for max3d. Overall, most areas in the MR for max5d, max7d, max15d, and max30d have Hurst values below 0.5, indicating that the characteristic precipitation in these regions will show trends opposite to the present. For the TLR, most areas in the northern part have Hurst values above 0.5 for max1d, max3d, max5d, and max15d, and even some areas in the northeastern part have Hurst values above 0.75 for max1d, indicating that the northern areas will continue to exhibit an increasing trend for max1d, max3d, max5d, and max15d, especially in the northeastern part. In the southern part, most areas have Hurst values below 0.5 for characteristic precipitation (except for max1d and max30d), indicating that max3d, max5d, max7d, and max15d will show relatively fewer trends in the future, while max1d and max30d will continue to increase. For the NR, most areas have Hurst values below 0.5 for max1d, max7d, and max30d, while max3d, max5d, and max15d have Hurst values above 0.5, indicating that most areas will exhibit a decreasing trend for max1d, max7d, and max30d, while max3d, max5d, and max15d will continue to increase.

However, only historical meteorological station observation data were used to assess future precipitation trends using the Hurst exponent in this research This method carries a certain level of uncertainty. Global climate models are effective tools for studying climate change mechanisms and estimating future climate conditions. The Coupled Model Intercomparison Project Phase 6 (CMIP6) has upgraded its new future scenarios, with the combination of radiative forcing levels of the representative concentration pathways used in the 5th phase of CMIP and the shared socioeconomic pathways, which makes them more reasonable. In subsequent research on future precipitation changes, incorporating further analysis based on the future precipitation changes provided by CMIP6 scenarios will enhance the comprehensiveness of this research.

4 Conclusions

Based on the daily precipitation data from 88 meteorological stations in the LYRB from 1980 to 2020, the Pettitt test was used to analyze the occurrence of abrupt changes in precipitation at each station. Based on this analysis, the LYRB was divided into three regions: the mainstream region (MR) the Taihu Lake region (TLR), and the northeast region (NR). The M-K test and Hurst index method were then used to analyze the spatiotemporal variations and persistence of precipitation in these three regions. This research aims to provide fundamental support for understanding the hydrological element changes in the LYRB. The main conclusions are as follows:

(1) The precipitation series in the LYRB showed abrupt changes, and these changes varied spatially. From the analysis of station precipitation, the majority of abrupt changes in the MR and TLR occurred between 2005 and 2012, accounting for 43.5% and 68.8%, respectively, while in the NR, most abrupt changes occurred between 2013 and 2020, accounting for 40%. The results of the analysis of regional precipitation changes showed that the abrupt changes in the MR, TLR, and NR occurred in 2008, 2007, and 2013, respectively.

(2) There were significant spatiotemporal differences in precipitation in the LYRB. The average annual precipitation in the MR, TLR, and NR during period 2 was higher than that in period 1, increasing by 9.4%, 14.9%, and 23.9%, respectively. The distribution of precipitation centers also expanded significantly compared to period 1, with a new precipitation center appearing in the TLR. Except for some areas in the western part of the MR, precipitation increased in most areas of the LYRB. The TLR and NR are expected to continue their increasing precipitation trend in the future, while most areas in the MR will experience a decreasing trend in precipitation.

(3) The characteristic precipitation in the LYRB generally showed an increasing trend, and there were significant differences in the trends among the MR, TLR, and NR, as well as within each region. These differences became more pronounced as the accumulation time of characteristic precipitation increased. Additionally, as the accumulation time increased, the areas with trends opposite to the present trends expanded.

In summary, an increase in precipitation in the LYRB may heighten the risk of flooding, posing a threat to the lives, property, and infrastructure of the people. It could also lead to an increase in pollution load in the water, affecting water quality. Additionally, the amplified precipitation complicates water resource allocation, intensifying the management pressure on water authorities.

To address these impacts, the local government and relevant management authorities need to construct and enhance flood control facilities to mitigate the impact of floods on people's lives, property, and infrastructure. Implementing improvements in flood control and drainage systems in farmlands is essential to reduce the impact of flooding on agriculture. Strengthening water quality monitoring and management is crucial to ensure water safety during floods. Furthermore, it is necessary to formulate and implement water resource management policies to ensure the rational allocation and utilization of water resources.

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