Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 13 No 4, 1765 doi: 10.2166/wcc.2022.013

Temporal variations characteristic of precipitation in the Three Gorges Reservoir area from 1961 to 2016

Li Sheng[a,†], Dianying Liu[b,c,†], Baihui Wang[d,e], Shunhui Yu[f,*], Youwei Zuo[g] and Fengtai Gu[f]

[a] School of Environmental Science and Engineering, Nanjing University of Information Science and Technology, Nanjing 210044, China
[b] Yiyang Meteorological Bureau, Yiyang 413000, China
[c] Hunan Provincial Key Laboratory of Meteorological Disaster Prevention and Mitigation, Changsha 413000, China
[d] Key Laboratory of Karst Georesources and Environment, Ministry of Education, Guizhou University, Guiyang 550025, China
[e] College of Resources and Environmental Engineering, Guizhou University, Guiyang 550025, China
[f] Key Laboratory of Water Environment Evolution and Pollution Control in the Three Gorges Reservoir Region, Chongqing Three Gorges University, Wanzhou 404100, China
[g] Key Laboratory of Eco-environments in the Three Gorges Reservoir Region, School of Life Science, Southwest University, Chongqing 400715, China
*Corresponding author. E-mail: ysh_dch@163.com
†These authors contributed equally to this work.

SY, 0000-0001-5168-6880

ABSTRACT

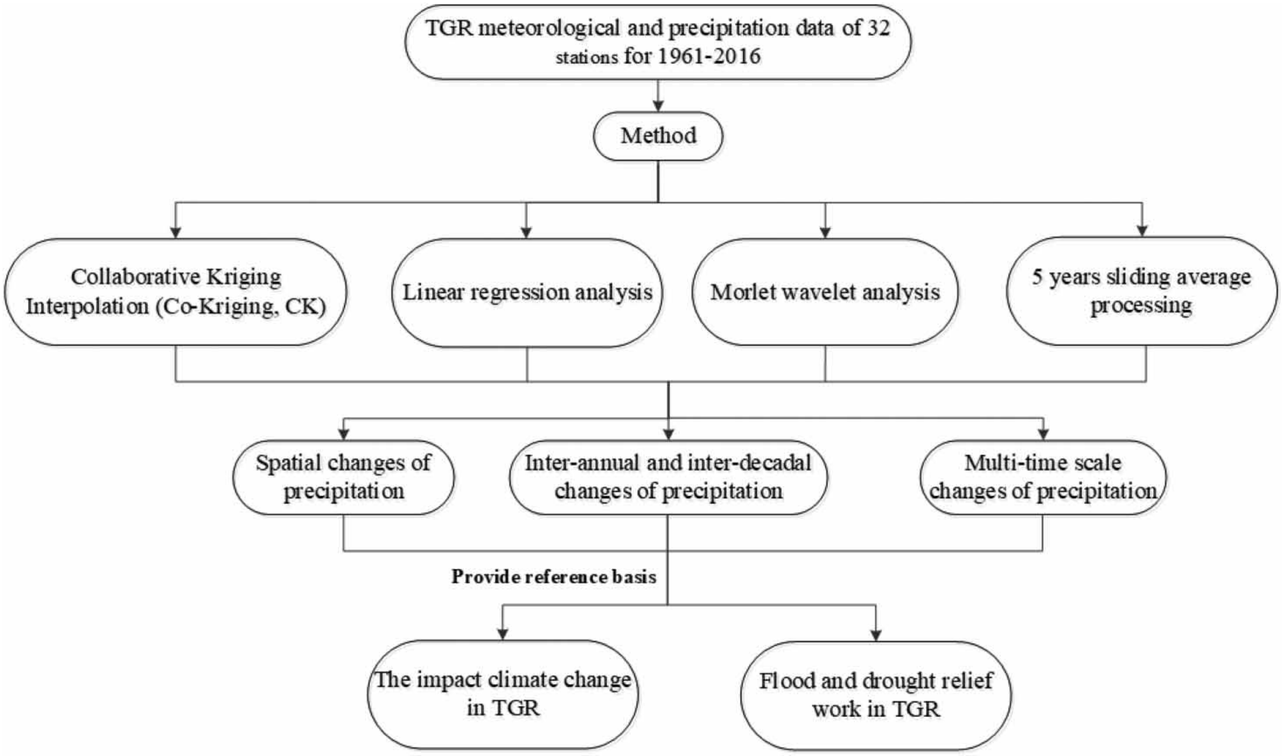
As a hot issue, the precipitation characteristics of the Three Gorges Reservoir (TGR) area drew widespread interest from domestic and overseas academic circles. Based on China's surface-based meteorological monthly precipitation data from 1961 to 2016 in the TGR area, the spatial, inter-annual and inter-decadal, and multi-time-scale changes of precipitation in the TGR area are analyzed by using Collaborative Kriging (Co-Kriging, CK) Interpolation, linear regression analysis, Morlet wavelet analysis and 5-year sliding average processing, which provide the reference basis for further discussion on the impact of climate change, flood control and drought relief work in the reservoir area. Research shows that in the past 56 years, the average annual precipitation in most areas of the TGR ranges from 1,000 to 1,200 mm; the variation of precipitation in the TGR area shows a weak decreasing trend, with great fluctuation between year and generation, and the precipitation in each decade has a 'less-more-less' changing trend; the annual precipitation in the TGR area has periodic changes on multi-time scales, mainly including 25, 16 and 8 years. The smaller the scale the shorter the average period of precipitation change.

Key words: decadal change, inter-annual change, multi-time scale, precipitation, Three Gorges Reservoir area

HIGHLIGHTS

- The average annual precipitation of the TGR ranges from 1,000 to 1,200 mm.
- Inter-annual and inter-decadal of precipitation shows a 'less-more-less' changing trend.
- Multi-time scale changes of precipitation mainly including 25, 16 and 8 years.

GRAPHICAL ABSTRACT



1. INTRODUCTION

As the Intergovernmental Panel on Climate Change (IPCC) noted in the fifth global climate assessment report: from 1880 to 2012, the global average temperature rose by 0.85 °C. And the average global surface temperature is projected to rise by 0.3–0.7 °C over the next 20 years (compared with 1986–2005) (IPCC 2016). In recent years, with global climate change, extreme precipitation events in mid-latitude regions have occurred frequently, which has had a great impact on people's production and life. In order to grasp the change law of precipitation, Chang *et al.* (2012) used the M–K nonparametric test to analyze the spatial and temporal distribution characteristics of precipitation at low and middle latitudes. Zhai *et al.* (1999) had detected the variation trend and regional characteristics of precipitation extremum in China by combining the heavy precipitation and the number of heavy precipitation days. Zhang & Miao (2007) studied the variation trend of annual precipitation and seasonal precipitation on the Qinghai-Tibet Plateau. Tang *et al.* (2011) calculated the precipitation frequency and precipitation ratio and so obtained the diurnal variation characteristics of precipitation in southwest China. Zhang & Ma (2011) researched the periodic characteristics of extremely heavy precipitation in Sichuan and the regional differences of disaster damage risk based on the precipitation data and disaster data. From the observational data of precipitation, the number of precipitation days and temperature, Zhou *et al.* (2008) analyzed the main characteristics of climate change in Chongqing.

The Three Gorges Reservoir (TGR) area, as the area involved in the water impounding after the construction of the Three Gorges Dam (TGD), and the change of precipitation within its scope will affect the flood control and drought relief operation in the TGR and the middle and lower reaches of the Yangtze River directly. In 1966, since the TGD was constructed, many scholars have studied the climate change in the reservoir area and found that the annual precipitation in the TGR area showed an insignificant trend of decrease over the years. After the reservoir impounding, the annual precipitation and seasonal precipitation in the reservoir area had no significant changes (Zhang *et al.* 2010a, 2013; Chen *et al.* 2013). However, under the background of climate change in the future, the temperature in the TGR area will continue to increase, the annual precipitation will decrease in the early 21st century, and increase in the middle and later period gradually (Liu *et al.* 2010b). In the meantime, the maximum precipitation for five consecutive days of the TGR area will show an increasing trend (Zhang *et al.* 2010b). Most of these studies focus on the inter-annual and inter-decadal changes of precipitation, the spatial distribution and periodic analysis of rainfall are rarely involved and the data period is not long enough to grasp the large-scale interdecadal changes. Therefore, in this paper, based on the precipitation data of the total 56 years from 1961 to 2016, the precipitation cycle characteristics and precipitation space range of the TGR area in the past 56 years are analyzed taking the TGR area as an example, which provides the reference basis for further discussion on the impact of climate change, flood control and drought relief work.

2. MATERIALS AND METHODS

2.1. Study areas

The TGR area is located at the junction of the Sichuan Basin and the plains of the middle and lower reaches of the Yangtze River, spanning the valleys of the central Hubei mountains and the Eastern Sichuan Mountains. From Jiangjin in Chongqing in the west to Yichang in Hubei in the east, which consists of 22 counties (districts) of Chongqing and 4 counties of Hubei province (as shown in Figure 1), the total length is 660 km, as a narrow area spanning several kilometers on both sides of the Yangtze River, with a total area of about 58,000 km^2. The special geographical location determines the heterogeneity of precipitation spatial distribution in the reservoir area (Wu *et al.* 2010).

2.2. Data sources

The precipitation data of 56 years from 1961 to 2016 used in this paper come from the Meteorological Data Center of China, Meteorological Administration (website: http://data.cma.cn/). In this study, monthly precipitation data from 32 meteorological stations in the TGR area were selected for the study (Figure 2). And in the following analysis, the average value of these 56 years was taken as the average precipitation data.

2.3. Research methods

2.3.1. Cooperative Kriging interpolation

As an extended form of the ordinary Kriging method, Cooperative Kriging (Co-Kriging), two or more variables are used, one of which is the principal variable, and the other is the auxiliary variable. The spatial autocorrelation of the principal variable and the interaction correlation between the primary and secondary variables are combined for the unbiased optimal

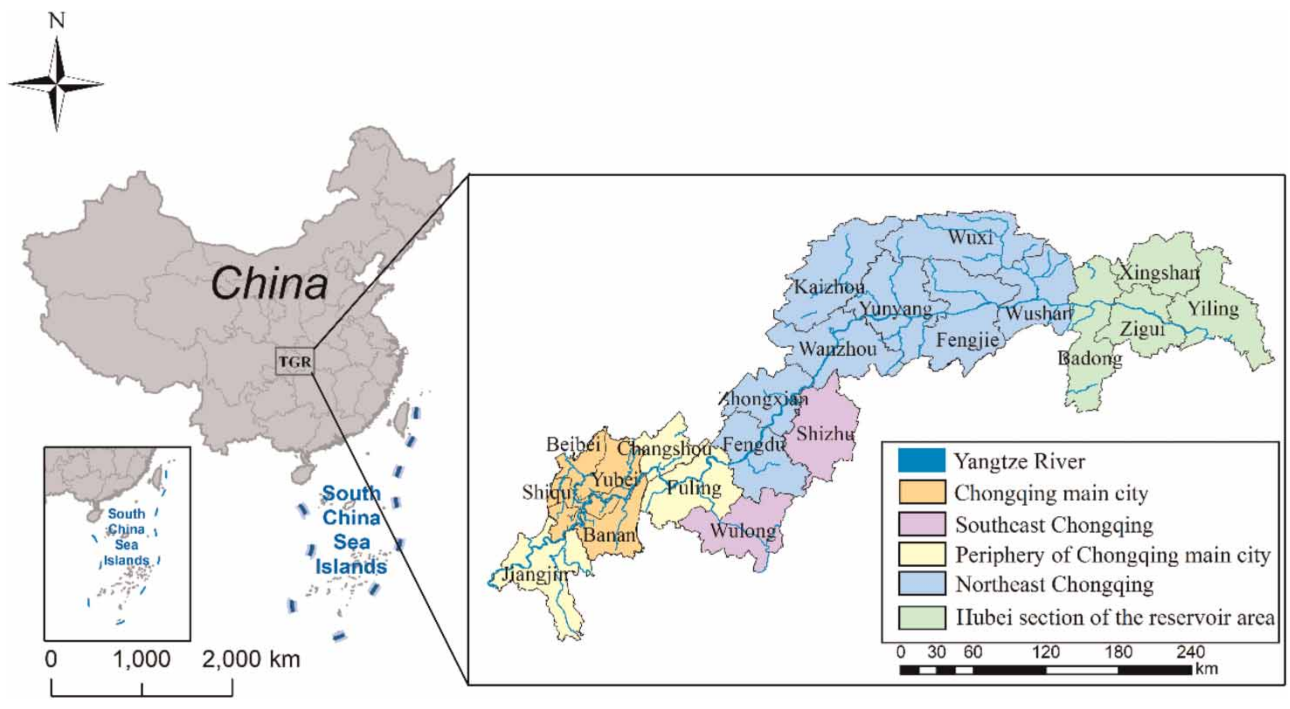


Figure 1 | Administrative map of the TGR area and its regional division.

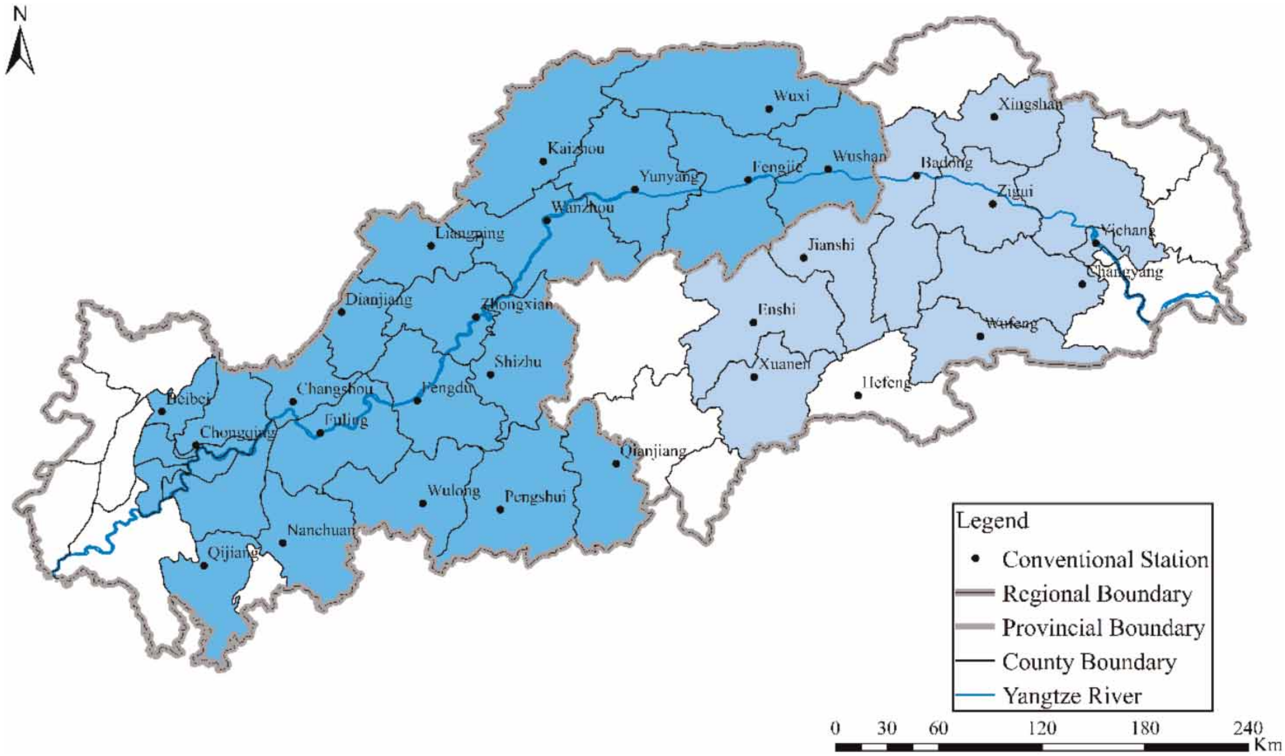


Figure 2 | Meteorological stations in the TGR area.

valuation. In addition to longitude and latitude, precipitation is sometimes affected by altitude (Marquínez *et al.* 2003; Daly *et al.* 2010). The relationship between precipitation and altitude is complex and generally increases with the rise of altitude (Smith 1979). However, in some regions, there is no obvious relationship between precipitation and altitude (Wu *et al.* 2010). At the beginning of interpolation, the correlation between annual average precipitation and altitude is analyzed. The results show that the linear correlation between annual average precipitation and altitude is obvious, and the correlation coefficient is 0.60 ($P < 0.01$). Therefore, Co-Kriging is adopted in this paper and introduces elevation as the second influencing factor in the spatial interpolation of rainfall (Wu *et al.* 2010). Co-Kriging, which considers the influence of elevation, can be expressed as follows:

$$z(x_0) = \sum_{i=1}^{n} \lambda_i (z(x_i) + \lambda[y(x_0) - m_y + m_z])$$

where $z(x_0)$ is the predicted value of the x_0 point; $z(x_i)$ is the measured value of the i station; $y(x_0)$ is the elevation of the x_0 point; n is the number of rainfall stations measured; m_y and m_z are the global average values of elevation and rainfall and λ_i and λ are the Co-Kriging weight coefficients. Similarly, the spherical model was chosen as the theoretical model of variotype, and the site search range was also 12 adjacent sites. In this study, Co-Kriging was used to interpolate the annual average precipitation of 32 stations and compared with the interpolation results of 32 stations.

2.3.2. Linear regression analysis

Linear regression is a regression analysis method that uses the least square function in the linear regression equation to model the relationship between independent variables and dependent variables. In this work, using time series as independent variable x, precipitation series as dependent variable y, a linear regression equation is established:

$$y = bx + c$$

where slope *b* represents the climate trend rate, which is used for quantitative analysis of the linear variation trend of precipitation. Several studies also used linear regression methods to calculate slope, intercept and trends (Almazroui *et al.* 2021; Ibrahim *et al.* 2021; Ali *et al.* 2022).

2.3.3. Wavelet analysis

As a kind of the mathematical method, wavelet analysis developed gradually in the middle and late 20th century, which is regarded as the breakthrough progress of the traditional Fourier analysis method (Sun *et al.* 2005). As an innovative mathematical tool that provides the time–frequency descriptions of time series or signals (Wahiduzzaman *et al.* 2020), wavelet analysis has been widely used in climate multi-scale analysis in recent years, and it can reveal a variety of change periods hidden in time series. The results of wavelet transform can reflect the changing trend of the system in different time scales (Liu & Du 2003; Jiang *et al.* 2009; Jian *et al.* 2011). Wahiduzzaman *et al.* (2020) used Morlet wavelet to find the relationship between echo cycle frequency and density variation over time. In this work, the Morlet wavelet analysis method was used to carry out continuous wavelet transform for the precipitation sequence in the TGR area, the curves of wavelet variance are produced by Matlab software and then the multi-time-scale variation characteristics of the precipitation in the TGR area are analyzed.

3. RESULTS

3.1. Spatial range analysis of annual precipitation

Figure 3 was obtained by means of the Co-Kriging method; it can be seen that, in most districts and counties, the average annual precipitation is 1,000–1,200 mm, which accounts for 79.8% of the reservoir area (1,100–1,200 mm: 55.1%). The areas with annual average precipitation of more than 1,200 mm are mainly located in the south of Kaizhou, Wanzhou, Fengjie and Padang, accounting for 17.6% of the reservoir area. However, the average precipitation of less than 1,000 mm is located at the northern end of the Xingshan and Yiling area, which accounts for only 2.6%.

3.2. Spatial range analysis of seasonal variation of precipitation

The interpolation results of monthly average precipitation in the TGR area were superimposed to analyze the inter-seasonal variation of precipitation in the reservoir area (as shown in Figure 4). As shown in Figure 4, precipitation in the TGR area is

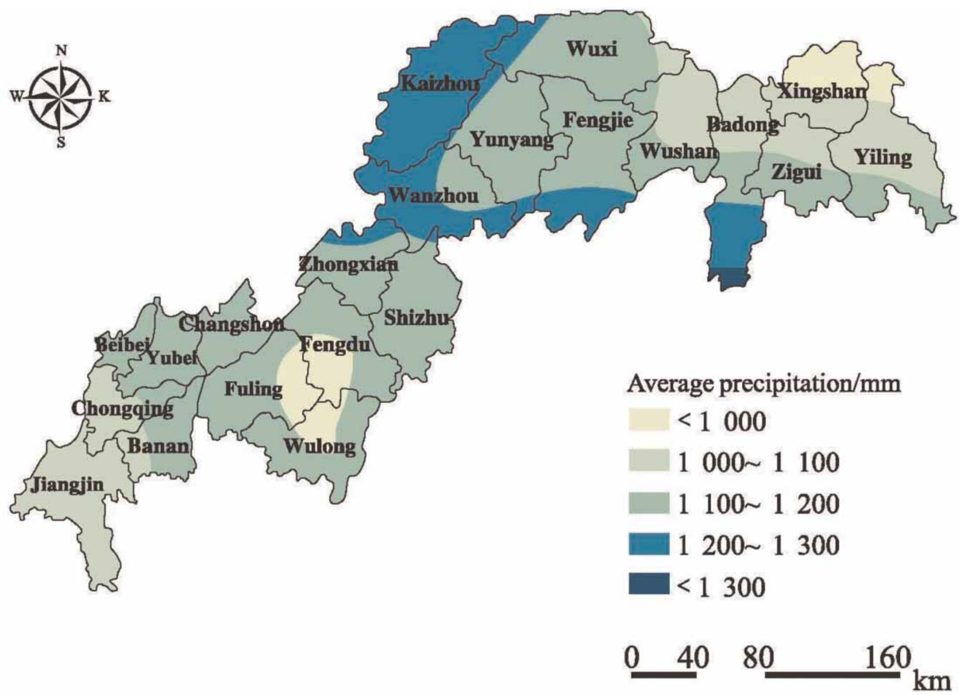


Figure 3 | Spatial distribution of annual average precipitation in the TGR area.

mainly in summer (from June to August), with 408–556 mm. The lowest precipitation in the reservoir area is 45–134 mm in winter (from December to February) and 236–416 and 20–330 mm in spring (from March to May) and autumn (from September to November), respectively. By analyzing the spatial distribution of precipitation in each season, it can be found that the center of gravity of precipitation is not consistent. The areas with the highest precipitation in spring are located in Wanzhou, Fuling and southern Badong; the areas with the highest precipitation in summer are located in Kaixian and southern Badong, while Fuling is in the area with the lowest precipitation; the highest area of precipitation in autumn is in the western part of Kaizhou and Wuxi and the northern part of Yunyang; the highest area of precipitation in winter shifts to the south of Badong, Zigui and Yiling; and the lowest area of precipitation is located in Kaizhou and the north of Wuxi.

3.3. Analysis of inter-annual and inter-decadal changes of precipitation

According to Figure 5, the climatic tendency rate of precipitation sequence in the TGR area is −0.927 mm/year, which shows that the overall linear decreasing trend of precipitation is not statistically significant, but the inter-annual and interdecadal fluctuations are large. During 1961–2016, the average annual precipitation in the TGR area is 1,132.6 mm, 1998 was the most (1,542 mm) and the great flood disaster occurred throughout the Yangtze River basin. 2006 is the least after reservoir storage, but also the year of historical water shortage (901.2 mm). During 1956–2002, for 47 years, the annual precipitation increased slightly in the whole country (Zhang *et al.* 2010a). During 2004–2016, the precipitation increased significantly. Due to the low spatial persistence of precipitation, the difference between the national average and regional average is significant. The largest and smallest annual precipitation in the TGR area occurred in the last 20 years, which shows that the annual precipitation in the reservoir area has a large variation in recent years.

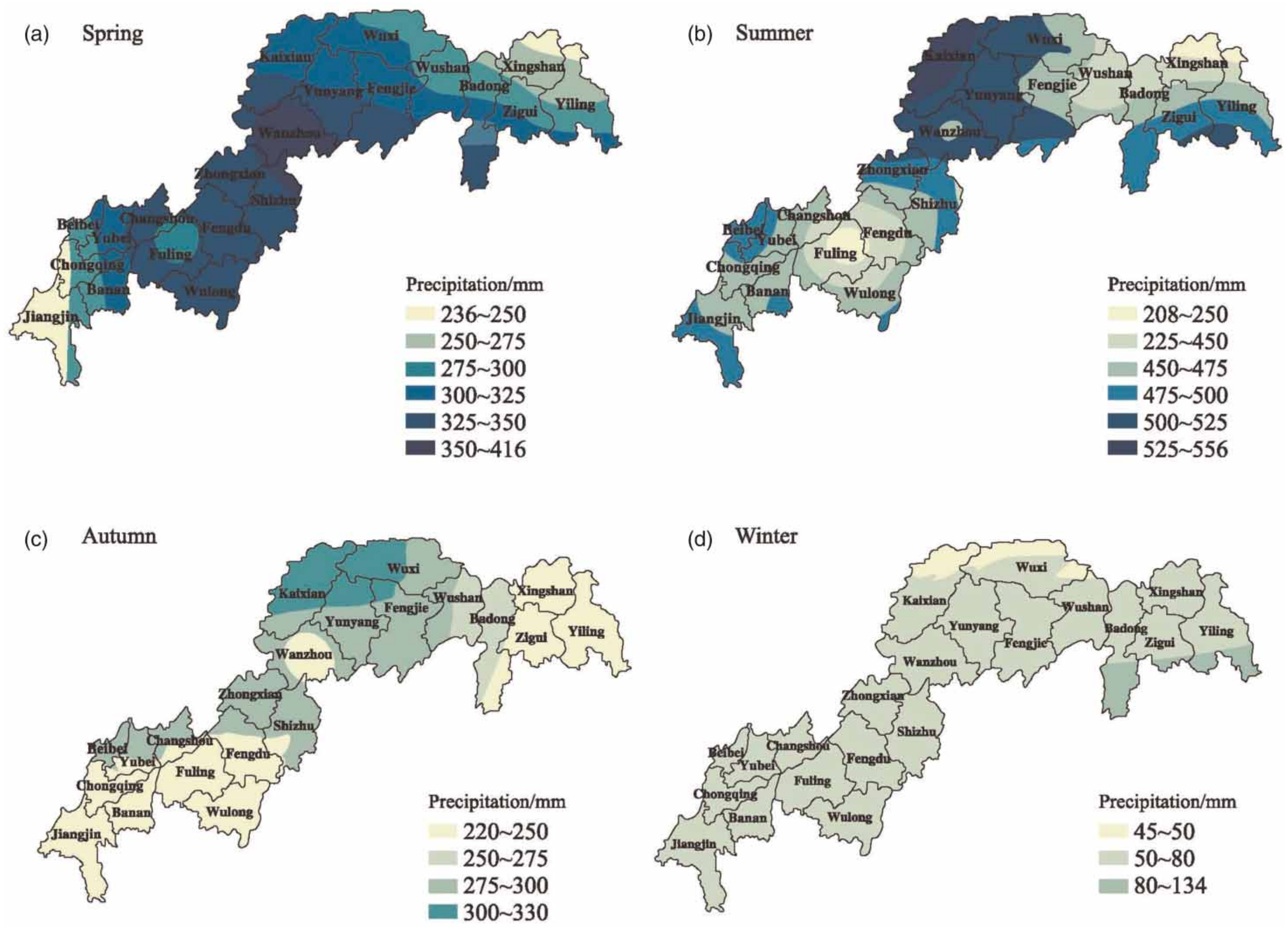


Figure 4 | Spatial distribution of seasonal average precipitation in the TGR area.

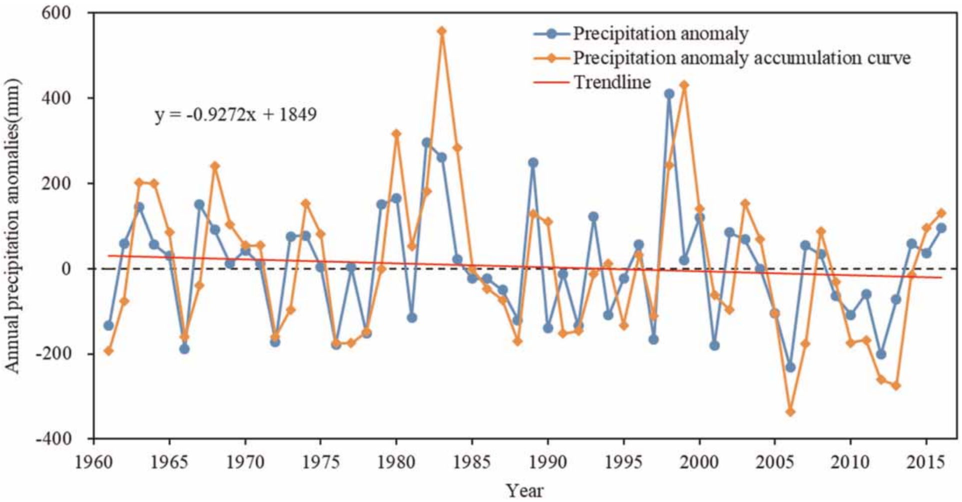


Figure 5 | Inter-annual interdecadal precipitation changes of the TGR area in a year during 1961–2016.

In Figure 5, according to the curves of precipitation and accumulation, in 1999–2002, 2003–2006 and 2008–2013, the fluctuation of the anomaly accumulation curve in the TGR area decreased, indicating a period of less rainfall. And 1997–1999, 2002–2003, 2006–2008 and 2013–2016 are rainy with the fluctuation of the cumulative curve rises. From the perspective of year-by-year generational changes, the precipitation in the TGR area is slightly more in the 1970s and 1980s, slightly less in the 1960s and 1990s and in the early 21st century is also slightly less. Since the 21st century, the main reason for the low precipitation is that the number of precipitation days is seriously less, among which the numbers of light rain, heavy rain and rainstorm days and above days are relatively less, compared with other years, the numbers of light rain and rainstorm and above days are the highest (Table 1). From the contribution of seasonal precipitation, the main reason for the less precipitation in the early 21st century is the less precipitation in summer and autumn. However, in the 1960s, it was slightly less mainly in summer, while in the 1990s, it was lower spring and autumn.

During the past 56 years, the precipitation in summer and winter in the TGR area has increased linearly, and the rates of change are 9.33 and 3.00 mm/decade, respectively. And in spring and autumn, it is decreasing linearly. In spring, it decreases by 5.50 mm/decade, and in autumn, it decreases by 14.02 mm/decade, which was reduced significantly (Figure 6). Figure 6 shows that the seasonal precipitation varies from year to year (relative to 1971–2000), which indicates that in spring, the precipitation in the reservoir area was less in the 1980s and 1990s, high in other years; in summer, it was high in the 1980s and 1990s, but less in other years; in autumn, the area was higher in the 1960s and 1970s, other years are less; and in winter, the 1970s less, other years are more.

From the changes in annual precipitation in the past 56 years, the annual precipitation in the TGR area presents an insignificant trend of decrease on the whole, and the inter-annual and interdecadal changes of precipitation are relatively large. The variation trend of precipitation in the TGR area in each era during the past 56 years is 'less-more-less'. The precipitation trend of this area is consistent with that of the Sichuan Basin (Ma *et al.* 2006) and the Chongqing area (Zhou *et al.* 2008).

Table 1 | Decadal changes of different precipitation over the TGR area

		1960s	1970s	1980s	1990s	2001–2016
Precipitation (mm)	Precipitation	−9.0	4.9	5.1	−10.0	−53.6
Rain day (d)	Precipitation days	1.0	−1.2	1.2	0.0	−8.5
	Light rain days	0.6	−1.9	1.0	0.9	−7.5
	Moderate rain days	0.9	0.4	0.6	−1.0	−0.6
	Heavy rain days	−0.2	0.3	−0.6	0.3	0.0
	Days above rainstorm	−0.3	0.0	0.1	−0.1	−0.4

3.4. Multi-time-scale analysis of precipitation

3.4.1. Periodic analysis of precipitation

The curves of wavelet variance can reflect the distribution of fluctuating energy with the time scale, and the scale at the corresponding peak is the main time scale of the time series, which can be used to determine the main period in the process of precipitation change. In order to extract the actual fluctuation of precipitation series, the annual precipitation anomaly value is used for analysis. It can be seen from Figure 7, that there are three relatively obvious peaks in the figure, corresponding to years 8, 16 and 25 in turn. The 25-year time-scale wavelet square difference is the largest, indicating that the oscillation energy is the strongest and the change period is the most obvious, which is the first main period; the following 16-year time scale is the second main period and the 8-year time scale is the third main period. In addition, although the 5-year scale also corresponds to a peak value, compared with the other three scales, the peak value is lower and cannot be used as the main period.

3.4.2. Analysis of main period variation of precipitation

According to the results of the wavelet square test, the wavelet coefficients of three main periods of 25, 16 and 8 years that control the annual precipitation change characteristics in the TGR area are drawn (Figure 8).

From the main cycle trend chart, we can analyze the average cycle and the alternating characteristics of abundance and underabundance of annual precipitation in the TGR area under different time scales. On the 25-year characteristic time scale, the precipitation change has experienced about 3 cycles of abundance and underabundance alternation, the average period of the change is about 20 years; 16 years, experienced about 5 cycles, the period is about 12 years; 8 years, experienced about 11 cycles, the period is about 5.5 years. This indicates that the smaller the time scale is, the more frequent the precipitation oscillation is, and the shorter the average change period is. The results of wavelet analysis show that the precipitation

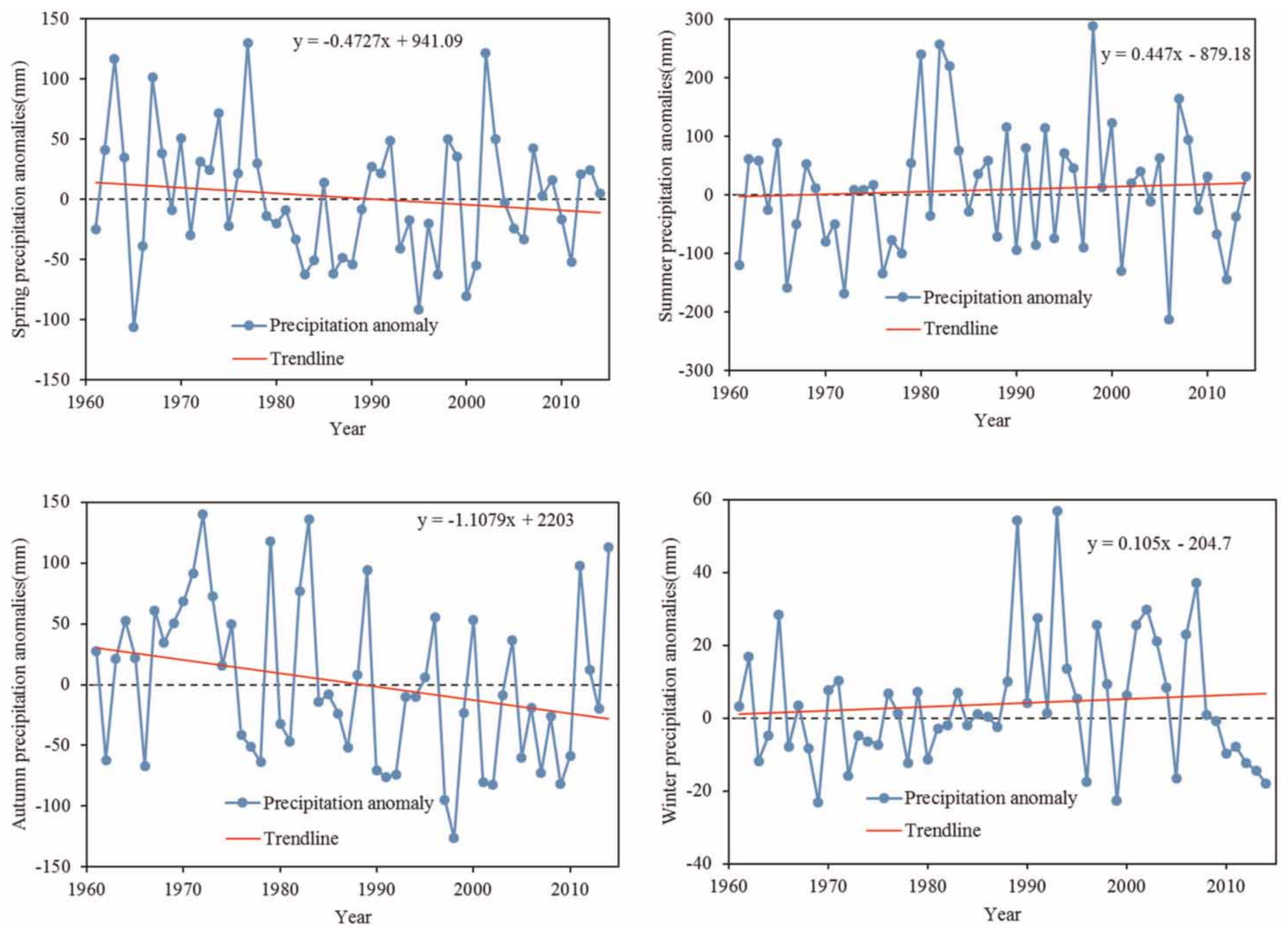


Figure 6 | Precipitation variations of TGR in season during 1961–2016.

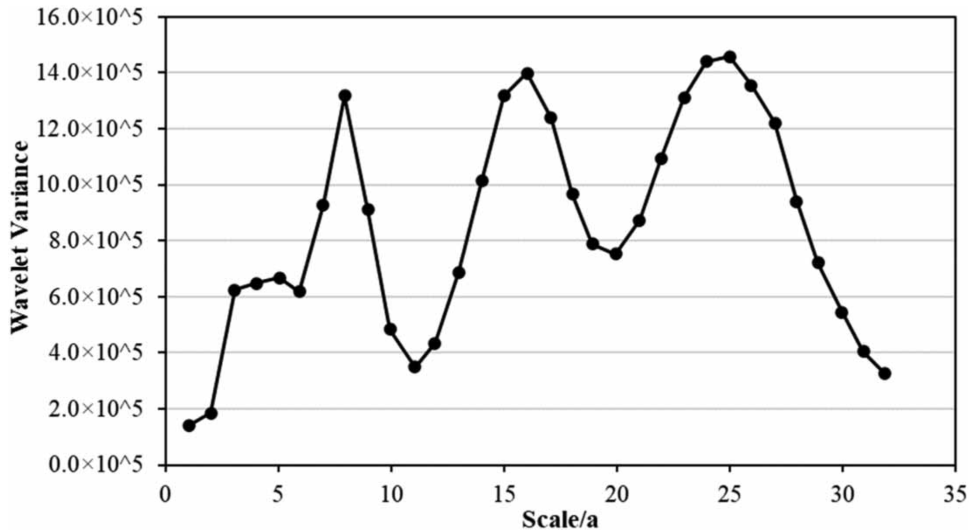


Figure 7 | Curves of wavelet variance of the TGR precipitation during 1961–2016.

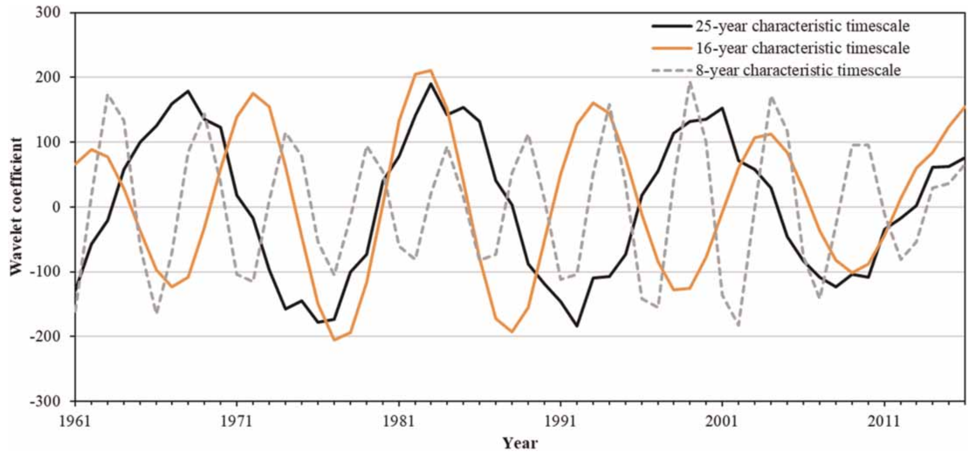


Figure 8 | Main period variation of precipitation in the TGR area during 1961–2016.

variation characteristics in the TGR area in the past 56 years are mainly controlled by three time-scale cycles, which are 25, 16 and 8 years, respectively. Zhou *et al.* (2008) analyzed the climate change in Chongqing in the past 46 years, concluded that the precipitation change period of Chongqing is basically within 10 years, and there is no obvious interdecadal scale cycle. But in this work, based on the longer precipitation time series, the interdecadal scale changes of 25 and 16 years are found. In addition, based on the data of 30 stations in Chongqing, Liu *et al.* (2010a) found that there is a quasi-15-year cycle oscillation of Chongqing precipitation, which is only 1 year different from the conclusion obtained in this paper, and indicates that the results of the periodic analysis are reliable.

4. DISCUSSIONS AND CONCLUSION

First, in this study 32 meteorological stations were selected in the TGR area and the annual and monthly average precipitation are interpolated based on the Co-Kriging interpolation method. The results show that the average annual precipitation in most areas is between 1,000 and 1,200 mm, but the precipitation is unevenly distributed during the year, and it is mainly in summer, accounting for about 45% of the annual precipitation. This is consistent with the results of the climate characteristics of the TGR area from the studies of Xiang *et al.* (2018). In addition, in mountainous areas with complex topography, due to air disturbance and obstruction, precipitation may also be closely related to small topographic factors such as slope direction, slope, proximity to water bodies and topographic shading (Wu *et al.* 2010).

Secondly, the average annual precipitation in most areas of the TGR area is 1,000–1,200 mm.

Thirdly, from the annual precipitation variation chart, the annual precipitation in the TGR area shows a weak linear decreasing trend in the past 56 years, but the inter-annual and interdecadal fluctuations are large. From the 1950s to the 1960s, there was a less rainfall period, the 1970s to the 1980s is a high rainfall period and the 1990s to the 21st century was less rainfall period. In general, the precipitation in each period showed a changing trend of 'less-more-less'. The variation of annual precipitation in the TGR area accords with the trend of annual precipitation reduction in the Sichuan Basin and the Chongqing area.

Lastly, the wavelet analysis results show that the annual precipitation in the TGR area has obvious multi-scale periodic variation, and the annual precipitation mainly has the variation of the time scale of 25, 16 and 8 years. The smaller the time scale is, the more frequent the precipitation oscillation is, and the shorter the average change period is. The average cycle of annual precipitation change on the time scale of 25 years is 20 years, the time scale of 25 years is 12 years and the time scale of 25 years is 5.5 years. The time scales of 16 and 8 years are consistent with existing studies, but there is still uncertainty in the larger scale of 25 years, indicating that the study of climate characteristics needs a longer time and more comprehensive data to better reflect the periodic change characteristics of climate series.

The above conclusions indicate that the annual precipitation in the TGR area fluctuates greatly, which is closely related to its special geographical location. With the Qinghai-Tibet Plateau in the west and the Indian Ocean in the south, in addition to its complex terrain, the precipitation may be influenced by the Qinghai-Tibet Plateau, summer monsoon, subtropical high and other factors (Wang & Yan 2014). In this paper, precipitation changes and cycle characteristics of the TGR in the past 56 years are analyzed by using precipitation data in the TGR area, but the specific changes and the annual distribution of future precipitation are not clear, and more detailed studies on precipitation are needed in the future by using data such as precipitation days and precipitation intensity.

AUTHORS' CONTRIBUTIONS

L.S. presented the first version and compiled the final version of the manuscript based on writing and comments by DyL, BhW and ShY. All authors read and approved the final manuscript.

FUNDING

This reach is supported by the National Natural Science Foundation of China (No. 41301248) and the Key Laboratory of Fundamental Water Environment Evolution and Pollution Control in the Three Gorges Reservoir Region (No. WEPKL2016LL-05).

AVAILABILITY OF DATA AND MATERIAL (DATA TRANSPARENCY)

The data used to support the findings of this study are available from the corresponding author upon request. If you want to use the data in the text, please contact this E-mail: ysh_dch@163.com.

CONFLICT OF INTEREST

The authors declare no competing financial interests.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Ali, M. A., Bilal, M., Wang, Y., Qiu, Z., Nichol, J. E., de Leeuw, G., Ke, S., Mhawish, A., Almazroui, M., Mazhar, U., Habtemicheal, B. A. & Nazrul Islam, M. 2022 Evaluation and comparison of CMIP6 models and MERRA-2 reanalysis AOD against satellite observations from 2000 to 2014 over China. *Geoscience Frontiers* **13**, 101325.

Almazroui, M., Ashfaq, M., Islam, M. N., Rashid, I. U., Kamil, S., Abid, M. A., O'Brien, E., Ismail, M., Reboita, M. S., Sörensson, A. A., Arias, P. A., Alves, L. M., Tippett, M. K., Saeed, S., Haarsma, R., Doblas-Reyes, F. J., Saeed, F., Kucharski, F., Nadeem, I., Silva-Vidal, Y., Rivera,

J. A., Ehsan, M. A., Martínez-Castro, D., Muñoz, Á. G., Ali, M. A., Coppola, E. & Sylla, M. B. 2021 Assessment of CMIP6 performance and projected temperature and precipitation changes over South America. *Earth Systems and Environment* **5**, 155–183.

Chang, Y., Hou, X., Wu, T. & Yu, L. 2012 On spatial-temporal dynamics of precipitation in global mid-low latitudes from 1998 to 2010. *Advances in Water Science* **23**, 475–484.

Chen, X., Song, L. & Guo, Z. 2013 Climate change over the Three Gorge Reservoir and upper Yangtze with its possible effect. *Resources and Environment in the Yangtze Basin* **22**, 1466–1471.

Daly, C., Helmer, E. H. & Quinones, M. 2010 Mapping the climate of Puerto Rico, Vieques and Culebra. *International Journal of Climatology* **23**, 1359–1381.

Ibrahim, M. H., Zhu, Z., Lu, R., Shahid, S. & Bleiweiss, M. P. 2021 Spatio-temporal investigations of monsoon precipitation and its historical and future trend over Sudan. *Earth Systems and Environment* **5**, 519–529.

IPCC 2016 Climate change 2013: the physical science basis: summary for policymakers [R/OL]. In *Working Group I Contribution to the IPCC Fifth Assessment Report*.

Jian, H., Luo, Y. & Xie, D. 2011 Precipitation variation feature research based on Mann-Kendall and Wavelei analysis – taking the Shapingba in Chongqing as an example. *Journal of Southwest China Normal University(Natural Science Edition)* **36**, 217–222.

Jiang, X., Liu, S., Ma, M., Zhang, J. & Song, J. 2009 A wavelet analysis of the precipitation time series in Northeast China during the last 100 years. *Geographical Research* **28**, 354–362.

Liu, Y. & Du, X. 2003 Multi-time ranges character of rainfall anomaly in summer and autumn in Chongqing. *Journal of Guizhou Meteorology* **27**, 15–18.

Liu, X., Yang, Q., Cheng, B., Kong, F., Zhang, T. & Yang, B. 2010a Characteristics of change in precipitation resources in Chongqing during 1961–2006. *Journal of Southwest China Normal University (Natural Science Edition)* **32**, 93–100.

Liu, X., Yang, Q., Cheng, B. & Zhang, T. 2010b Scenario projections of 21st century climate change in the Three Gorges Area. *Resources and Environmental in the Yangtze Basin* **19**, 42–47.

Ma, Z., Peng, J., Gao, W. & Tian, H. 2006 Climate variation of Southwest China in recent 40 years. *Plateau Meteorology* **25**, 633–642.

Marquínez, J., Lastra, J. & García, P. 2003 Estimation models for precipitation in mountainous regions: the use of GIS and multivariate analysis. *Journal of Hydrology* **270**, 1–11.

Smith, R. B. 1979 The influence of mountains on the atmosphere. *Advances in Geophysics* **21**, 87–230.

Sun, R., Pan, B., Niu, Z. & Liu, Z.-G. 2005 Wavelet analysis on the temporal series of surface water resources in the Hexi Corridor of Gansu Province since recent 50 years. *Arid Land Geography* **28**, 455–459.

Tang, H., Gu, J., Yu, S., Zhang, H. & He, H. 2011 Analysis on diurnal variation of precipitation in Southwest China. *Plateau Meteorology* **30**, 376–394.

Wahiduzzaman, M., Yeasmin, A., Luo, J. J., Ali, M. A. & Qiu, Z. 2020 Statistical approach to observe the atmospheric density variations using swarm satellite data. *Atmosphere* **11**, 897.

Wang, Y. & Yan, F. 2014 Regional differentiation and decadal change of precipitation in China in 1960–2010. *Progress in Geography* **33**, 1354–1363.

Wu, C., Lin, D., Zhou, Z., Wang, P., Xiao, W. & Teng, M. 2010 Spatial interpolation methods and temporal-spatial distribution of precipitation in the Three Gorges Reservoir Area. *Resources and Environment in the Yangtze Basin* **19**, 752–758.

Xiang, F., Wang, L., Yao, R. & Niu, Z. 2018 The characteristics of climate change and response of vegetation in Three Gorges Reservoir Area. *Earth Science* **43**, 42–52.

Zhai, P., Ren, F. & Zhang, Q. 1999 Detection of trends in China's precipitation extremes. *Acta Meteorologica Sinica* **57**, 208–216.

Zhang, S. & Ma, Z. 2011 Change tendency and cyclicity analysis of extreme precipitation over Sichuan Provice during 1961–2009. *Journal of Natural Resource* **26**, 1919–1929.

Zhang, L. & Miao, Q. 2007 Precipitation changes in the Tibetan Plateau during the last four decades. *Arid Land Geography* **30**, 240–246.

Zhang, T., Fan, L. & Sun, J. 2010a Characteristics of climate in the Three Gorges Reservoir Area during 1961–2008. *Resources and Environment in the Yangtze Basin* **19**, 52–61.

Zhang, T., Fang, L., Sun, J., He, Y., Dong, X. & Ren, Y. 2010b Characteristics of climate in the Three Gorges Reservoir Area during 1961–2008. *Resources and Environment in the Yangtze Basin* **19**, 52–61.

Zhang, S., Lu, Z. & Zhang, L. 2013 Analysis of influence of Three Gorges Dam storage on reservoir region precipitation. *Water Resources and Power* **31**, 21–23,62.

Zhou, H., Yang, B. & Cheng, B. 2008 Analysis of characteristics of climate change over last 46 years in Chongqing. *Chinese Journal of Agrometeorology* **29**, 23–27.

First received 18 January 2022; accepted in revised form 22 February 2022. Available online 15 March 2022