Journal of Environmental Informatics Letters 6(1) 1-9 (2021)

Journal of Environmental Informatics Letters

www.iseis.org/jeil

Extreme Summer Precipitation Events in China and Their Changes during 1982 ~ 2019

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Received 19 March 2021; revised 23 June 2021; accepted 24 July 2021; published online 16 August 2021

ABSTRACT. This work analyzed the spatial and temporal variations of the extreme precipitation over China during the period 1982 to 2019, based on GPCC data. Meanwhile, the spatially clustering characteristic of China is evaluated based on the trends of summer precipitation through K-means. This is the first to clustering based on the trend of summer precipitation. The results indicated that the spatial distribution of MK trends for the summer precipitation indices over China during 1982 ~ 2019 shows increasing and decreasing trends in different regions. The extreme precipitation has been found mainly in Pearl River Basin, Southeastern River Basin, Huaihe River Basin, and the lower reaches of the Yangtze River. The risk of floods in SERB (the Southeastern River Basin), especially those caused by short-term heavy precipitation, may increase in recent decades. Four clusters are identified through K-means, which can be named as stable (59%), extreme wetter (5%), dryer (19%), and wetter (17%) zones. Combining the spatial distribution of the multi-year average of precipitation indicators and four clusters, the 'wet to wetter and dry to dryer' is found in China summer precipitation.

Keywords: extreme precipitaion, cluster analysis, China

1. Introduction

Precipitation is an essential climate variable to assess the fresh water supply of a region or nation (Yu et al., 2020). Precipitation varies from year to year and over decades and changes in quantity, frequency and intensity with a direct influence of global warming (Trenberth, 2011). The impact of extreme precipitation events on the populations and economies in affected areas has drawn widespread attention (Fan et al., 2020; He et al., 2021). The unusual behavior of summer precipitation often causes local flooding during summer. Therefore, it is essential to explore the recent changes in the summer precipitation pattern and the background circulation all over the word.

China is located in east Asia (Figure 1). Because of large landmass and various climate regions, weather and climate extremes bring frequent damage to the country (Wang et al., 2021b). The spatiotemporal variations of summertime precipitation and their possible causes and underlying mechanisms therefore have been attracting considerable concerns previously (Lin and Wang, 2016; Zhang et al., 2017). For example, persistent heavy rainfall over the Yangtze River basins during the 1998 meiyu season caused floods (Long and Chen, 2000). Moreover, floods in 1998 caused $16 billion in direct economic losses and more than 1300 people killed in the Yangtze geophysical processes. In summer 2020, the extreme Yangtze precipitation caused flooding and landslides that resulted in loss of life (Zhou et al., 2021). Researchers found that these extreme conditions are all related to the variation of total and extreme precipitation. Thus, changes in total and extreme precipitation have attracted much attention. In recent years, substantial effort has been devoted to investigating the variability of precipitation over China, especially in summer. For example, on the basis of daily precipitation analysis, Zhai et al. (1999) have analyzed the trend in normalized annual precipitation anomalies and in some annual extremes for the period 1951 ~ 1995 for 361 stations in China, and suggested that changes in extreme and total precipitation might be closely related. Ren et al. (2000) showed an increasing trend in summer precipitation over the mid lower reaches of the Yangtze River and a decrease trend over the Yellow River basin, but almost no change in the high-latitude areas. Zhai et al. (2005) have found negative trends of the annual mean precipitation and extreme precipitation events from southern Northeast China to the upper Yangtze River valley and positive trends over northwestern and southern China.

Zhai et al. (2005) analyzed the observed trends in extreme precipitation events in China during 1961 ~ 2001, and found that the annual mean precipitation increases significantly in southwest, northwest, and east China, and decreases significantly in central, north and northeast China. Qian et al. (2007) have examined the long-term trends of the precipitation frequencies in China for a wide range of precipitation rates (1 ~ 50 mm per day)

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ISSN: 2663-6859 print/2663-6867 online
 doi:10.3808/jeil.202100066.

and detected an overall negative trend in the frequency of light precipitation events and a positive trend in the frequency of extreme precipitation. Xu et al. (2015) have found that the summer precipitation over northwestern China has increased obviously since the late 1970s, which may be related to the local surface warming. Huang et al. (2013) studied the feature of the interdecadal change of the summer precipitation around the late 1990s and its association with the atmospheric circulation anomalies over East Asia by using the long-time observational precipitation datasets and monthly and daily NCEP/NCAR reanalysis datasets. Xu et al. (2015) have addressed the spatial patterns of the decadal variation of summer precipitation over China and found that the summer precipitation over China experienced different decadal variation features from north to south after the late 1990s. Recently, Liu et al. (2020) have evaluated the intraseasonal variability of China summer precipitation. He et al. (2021) used K-means clustering to capture spatiotemporal characteristics of extreme precipitation events during summer over eastern China subregions from 1961 to 2018.

2. Materials and Methods

2.1. Overview of Study Area

The terrain of China is high in the west and low in the east. Mountains, plateaus, and hills account for about 67% of the land area, and basins and plains account for about 33% of the land area. The mountains are mostly east-west and northeast-southwest. In the west, there is the Qinghai-Tibet Plateau, the largest in the world, with an average altitude of more than 4,000 meters, which is known as the "Roof of the World". China has a vast territory, a wide span of latitudes, and a large distance from the sea. In addition, the terrain is different in height, and the terrain types and mountain directions are diverse. Therefore, the combination of temperature and precipitation is diverse, forming a variety of climate types. Affected by the alternating winter and summer monsoons, and China is the most typical monsoon and monsoon climate in the world. Compared with other parts of the world at the same latitude, the temperature in China is relatively low in winter, while the temperature in summer is relatively high. The annual temperature varies greatly. Precipitation is concentrated in summer. Summer precipitation is a critical water source for China, which contributes to 40% (in wet areas) — over 60% (in dry areas) of annual precipitation nationwide (Lei et al., 2011). China has the largest population in the world. More than 70% of the total population lived in eastern China (Zhu et al., 2011), with many megacities such as Beijing, Shanghai, and Guangzhou. However, the society and socio-economy in eastern China are remarkably vulnerable to summer precipitation changes (Ding et al., 2008).

The frequency of extreme precipitation events in China is projected to increase under the Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios (Chen et al., 2020; Duan

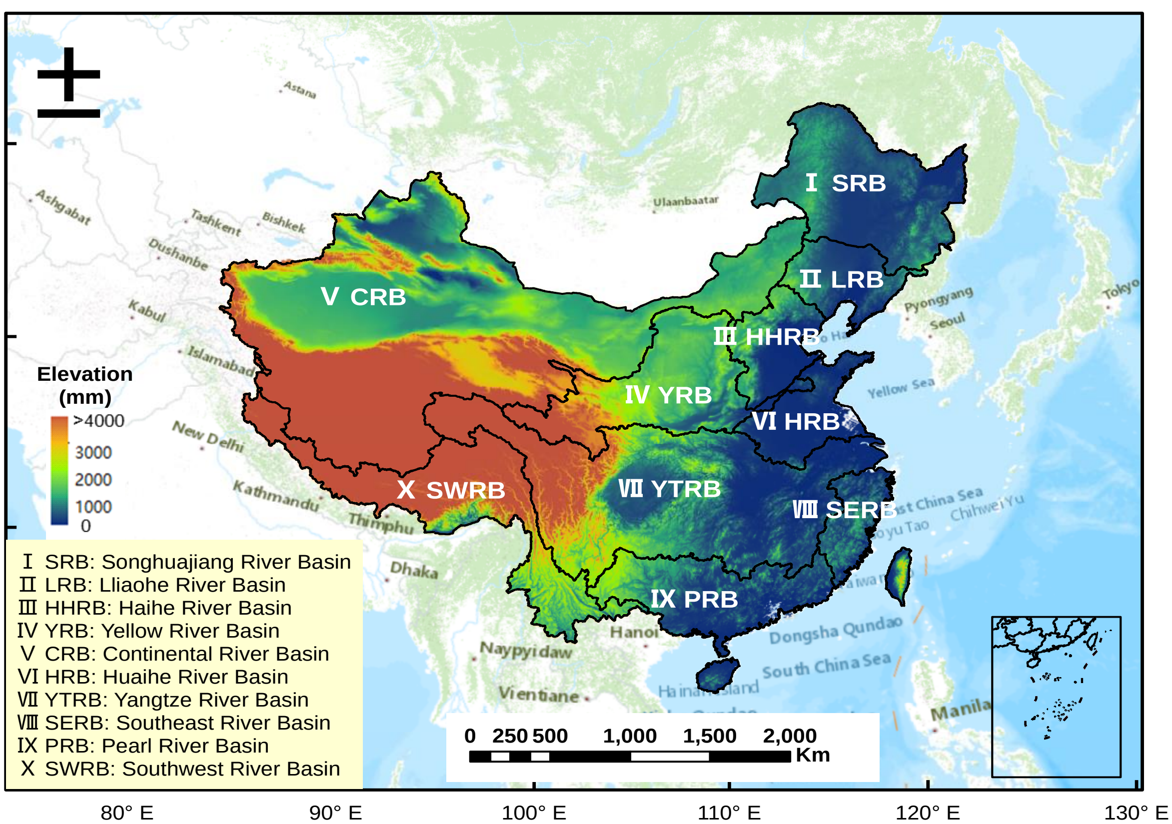

Figure 1. The study area.

et al., 2021). Thus, a better understanding of the spatiotemporal variations of extreme precipitation events over China, as well as of the related physical mechanisms, could improve the forecasting of current weather and the projections of future climate change (He et al., 2021; Wang et al., 2021c). However, the previous studies are limited in their scope and data use. Their results also need to be reexamined since the statistical significance of trends was not rigorously assessed. Therefore, as an extrusion of the previous efforts, the objective of this study is to update the temporal and spatial trends of summer precipitation, especially for extreme precipitation over China for revealing the response of climate change.

There are many rivers in China, which flow through different climatic and topographical regions. As shown in Figure 1, the main river basins in China include Songhuajiang River Basin (SRB), Liaohe River Basin (LRB), Haihe River Basin (HHRB), Yellow River Basin (YRB), Continental River Basin (CRB), Huai River Basin (HRB), Yangtze River Basin (YTRB), Pearl River Basin (PRB), Southeastern River Basin (SERB), and Southwestern River Basin (SWRB).

2.2. Data and Methods

We obtained daily precipitation from Full Data Daily Analysis Version 2020 published by the Global Precipitation Climatology Centre (GPCC) at 0.5° spatial resolution. The daily land-surface precipitation from rain-gauges built on GTS-based and historic data. The data set covers the period from 1982 to 2019 and is available from https://opendata.dwd.de/climate_environment/GPCC/full_data_daily_v2020/. The GPCC precipitation has been used in many previous studies for analysis of hydro-climatic extremes.

Table 1. Extreme Index Definition

Index	Definition	Units
SumP	Total precipitation amount in summer	mm
RX1day	Maximum 1-day precipitation amount in summer	mm
RX5day	Maximum consecutive 5-day precipitation amount in summer	mm
RD	Count of rain days (defined as precipitation >= 1.0 mm) in summer	days
R10mm	Number of heavy precipitation days (defined as precipitation >= 10 mm) in summer	days
R20mm	Number of very heavy precipitation days (defined as precipitation >= 20 mm) in summer	days

Focusing on the changes of temperature and precipitation extreme events, the Expert Team on Climate Change Detection and Indices (ETCCDI) defined a set of 27 widely used indices calculated from surface station observations. This allows for the analysis of the distribution and changes of climate extremes in global scale. Here, we examine six extreme precipitation indices from the ETCCDI (Yu et al., 2020) to investigate extreme summer precipitation events over China. They are the total precipitation (SumP), the maxima of 1-day (RX1day) and 5-day (RX5day) precipitation, the number of rain days (RD) with daily precipitation not less than 1 mm, the number of days with daily precipitation more than 10 mm (R10mm) and 20 mm (R20mm). This study focuses not only on precipitation events but also on the trends of precipitation amount and precipitation days. More detailed information is shown in Table 1.

For each grid point, we performed the MK test (Mann-Kendall test) to the significance of the possible trends of the six aforementioned precipitation indices for 1982 ~ 2019 (Mann, 1945; Kendall, 1975). As a nonparametric test, the MK test has been widely used in the fields of hydrology, climatology, and meteorology (Helsel and Hirsch, 1992; Yue and Wang, 2004; Khaliq et al., 2009; Wang et al., 2021a). The proportion of concordant pairs minus the proportion of discordant pairs in the sample (i.e., defined as a statistic Z), is used to identify the temporal trend in the MK test:

$$\begin{cases} Z_{\text{ij}} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{N} sgn\left(Y_j\text{-}Y_i\right) \\ sgn\left(Y_j\text{-}Y_i\right) = \begin{cases} 1 & Y_j\text{-}Y_i > 0 \\ 0 & Y_j\text{-}Y_i = 0_i \\ -1 & Y_j\text{-}Y_i < 0_i \end{cases} \end{cases} \quad (1)$$

where Y_i and Y_j are the precipitation indices in the time series and n is the size of the sample (n = 38 in this study). The trend is judged by the Z statistic, with Z_{ij} lower than zero represents the downward trend, and larger than zero represents the upward trend. The absolute value of Z_{ij} larger than 1.69 indicates that the precipitation indices have a trend at a 5% significant level. The strength of the MK test is that as a nonparametric procedure it does not assume a specific joint distribution of the precipitation indices, which is minimally affected by departures from normality (Han et al., 2014). The limitations of this trend test are frequently associated with its own null hypothesis (H0), which assumes that the precipitation indices are independently and identically distributed (Wang et al., 2020). More details about MK test are available in (Blain, 2013).

To evaluate the spatially clustering characteristic of China based on the trends of summer precipitation, K-means is applied in this study. As one of the simplest clustering methods, K-means is an unsupervised learning approach used to group similar features using specific mathematical criteria. The goal of K-means is to minimize the sum of the squared error between the empirical mean of a cluster and the points in the cluster. Previously, K-means is independently discovered in different scientific fields by (Ball and Hall, 1965; Drineas et al., 2004). With the advantage of easy implementation, simplicity, efficiency, and empirical success, K-means is still one of the most widely used algorithms for clustering (Jain, 2010). A good overview of K-means is available in (Jain, 2010).

3. Spatial Patterns of Extreme Precipitation Indices

The GPCC Full Data Daily Analysis Version 2020 covering

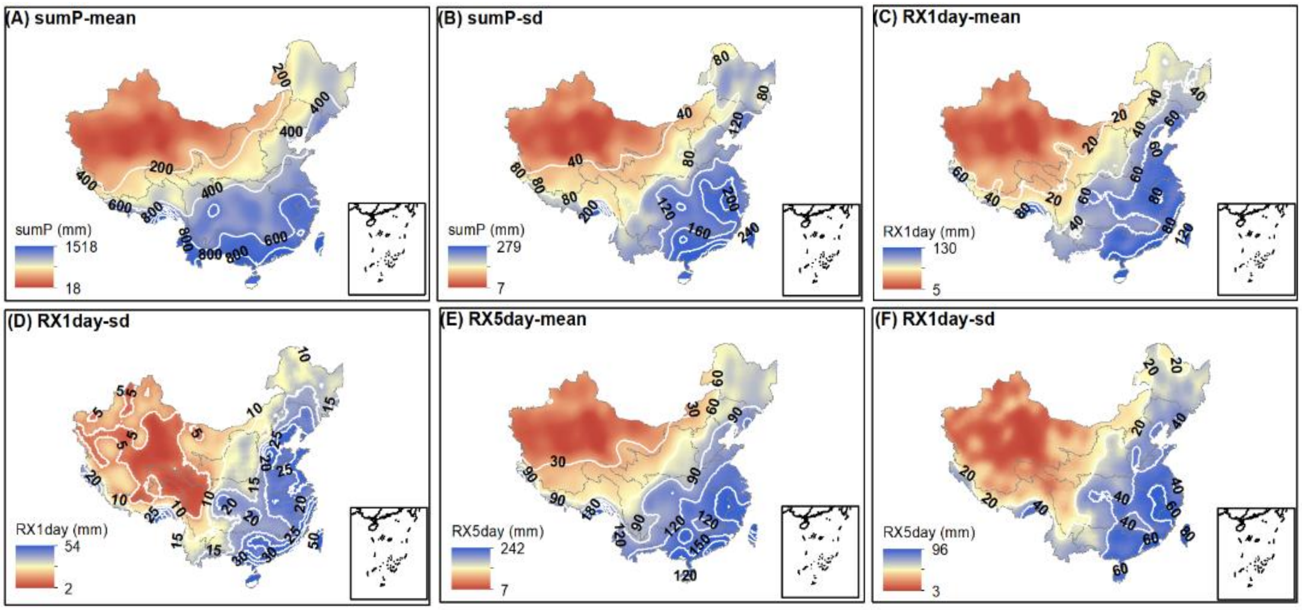

Figure 2. Spatial distribution of extreme summer precipitation index: (A) mean of sumP; (B) variance of sumP; (C) mean of RX1day; (D) variance of RX1day; (E) mean of RX5day; (F) variance of RX5day.

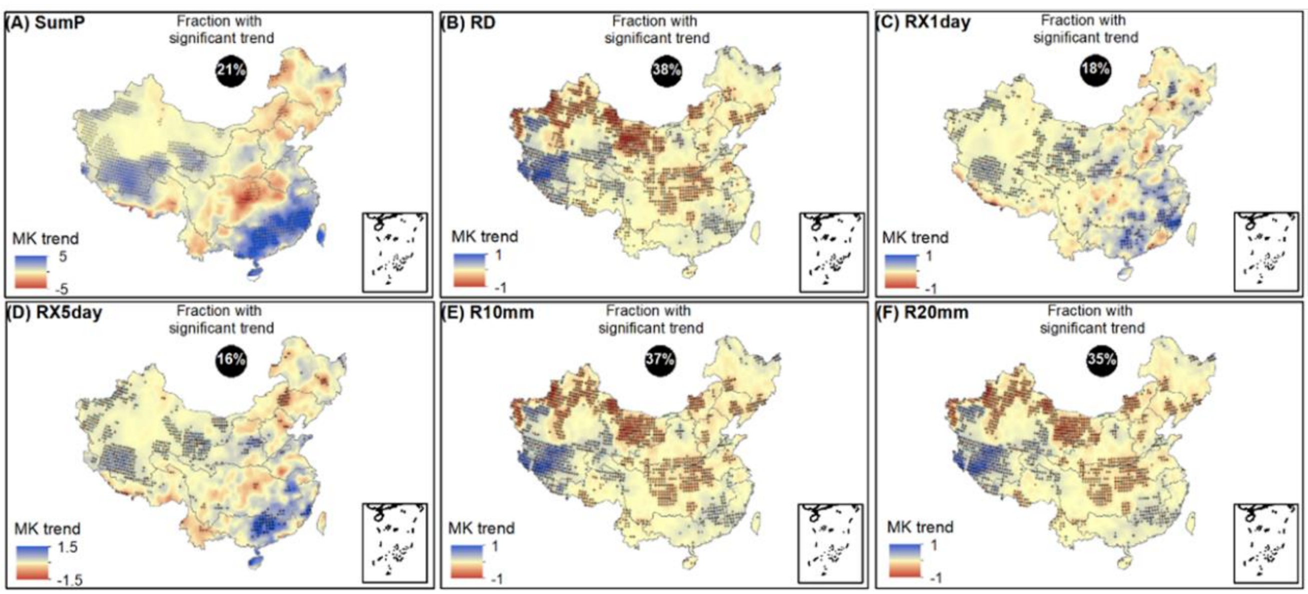

Figure 3. Spatial distribution of MK trends for: (A) sumP; (B)RD; (C) RX1day; (D) RX5day; (E) R10mm; (F) R20mm. The dot represents that the MK trend is statistically significant at the 0.05 level.

the years from 1982 to 2019 regraded at 0.5° ×0.5 °resolution was directly used to calculate the indices sumP, RX1day, and RX5day grid-by-grid. Figure 2 demonstrates the Spatial Patterns of these indices in terms of the multi-year mean and variance over mainland of China. The various climates of China are decisively determined by the winter and summer monsoon (Domroes and Peng, 1988). The monsoon system together with the effects of topography yields a remarkable change in total summer precipitation, from less than 18 mm in the remote northwest to more than 1500 mm in the southeast. As shown in Figures 2(D) and 2(D), China shows remarkable change in the max one-day precipitation, from less than 5 mm in the remote northwest to more than 130 mm in the southeast.

Spatially, precipitation of RX1day and RX5day are generally in phase. The RX1day and RX5day are typically used to describe changes in potential flood risks. The results indicate that extreme precipitation have been found mainly in Pearl River Basin, Southeastern River Basin, Huaihe River Basin, and the lower reaches of the Yangtze River. A decreasing trend of summer total precipitation was observed from the southern part of northeast China to the mid-low Yellow River valley and the upper Yangtze River valley, which is consistent with previous study. For instance, Qian and Lin (2005) found that persistent wet days and strong rainfall have contributed to the increasing frequency of floods in southeast China and the Xinjiang region in the last two decades.

4. Trend of Extreme Precipitation Indices

Figure 3 presents the spatial distribution of MK trends for the summer precipitation indices over China during 1982 ~ 2019, which shows increasing and decreasing trends in different regions. From Figure 3(A), 21% of grid points in China have a statistically significant change trend at 0.05 level in terms of the total precipitation in summer. In detail, significant decreasing trends occurred mainly in the middle and lower reaches of the Yangtze River, as well as north China, while statistically significant increasing trends occurred in southeast China, and is the Qinghai-Tibet Plateau. These are generally consistent with the results of Lu et al. (2015). The increase in precipitation in some areas in northwest China is as large as 5 mm/a, indicating that the dry conditions in some areas in the arid/semi-arid southeast China have been gradually alleviated over the last 38 years. The increased summer precipitation over northwestern China may be related to the local surface warming (Zhou and Huang, 2010). On the other hand, the decrease in precipitation of approximately 5 mm/a in middle reaches of the Yangtze River. From Figure 3(B), it can be found that, the amount of rain day (precipitation >1 mm) has significantly changed in 38% China's area, mainly increased in the Qinghai-Tibet Plateau (west China) and decreased in northwest China. This suggests that the precipitation increase in western China is due to the increase in both precipitation frequency and intensity, which is consistent with the results of Shang et al. (2019). Figures 3(C) and 3(d) show the trends of RX1day and RX5day, where 18% and 16% of grid points in China have a statistically significant change trend. The Rx1day and Rx5day is typically used to describe changes in potential flood risks (Wang et al., 2013). The results indicate that significant increases in extreme precipitation have been found mainly in Pearl River Basin, Southeastern River Basin, the lower reaches of the Yangtze River, and the south of Continental River Basin. At the same time, from Figures 3(E) and 3(F), it can be found that, 37% and 35% of China's area show increasing and decreasing trends in R10mm and R20mm in different regions. Spatially, trends in R10mm and R20mm are generally in phase. R10mm is used to diagnose the wet part of the precipitation distribution. This suggests that the number of the days of very heavy precipitation (i.e., R20mm) may have a close relation with that of heavy precipitation (i.e., R10mm).

Figure 4 presents the statistics of significant MK trend by watershed over China. The top three basins with the largest changes in total summer precipitation sumP are SERB (39%), CRB (35%), and PRB (26%). This means that the drought in the northwest deserts would be eased due to climate change. As to the extreme precipitation, the trends of RX1day and RX5day are not synchronized in different regions. For instance, 26% and 29% of CRB show a statistically significant trend in terms of RX1day and RX5day. At the same time, 30% of SERB shows a significant trend in term of RX1day, while only 7% of it shows a significant trend in term of RX5day. This means that the risk of floods in SERB (the Southeastern River Basin), especially those caused by short-term heavy precipitation, may increase in recent decades. From Figure 4, it can be found that the trends in RD, R10mm, and R20mm are generally in phase, which means that number of the days of heavy precipitation (i.e., R10mm), very heavy precipitation (i.e., R20mm) may have a close relation with that of precipitation (i.e., RD). The top three basins with the largest changes in precipitation frequency of different magnitudes are CRB (52 ~ 55%), SWRB (37 ~ 50%), and YTRB (35 ~ 37%).

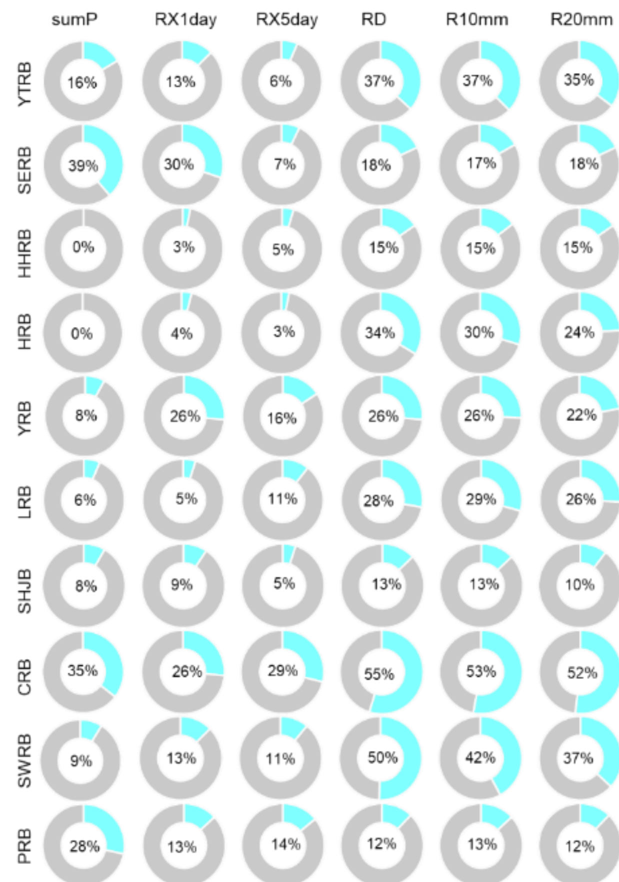

Figure 4. The Statistics of significant trend by watershed over China.

5. Clustering Analysis

K-means is one of the widely used clustering methods. The only parameter of the K-means algorithm is that the number of clusters, K (Hardy, 1996). In this study, we estimate the number of clusters using Bayesian information criterion (BIC). As shown in Figure 5, the BIC/K significantly decreased with the number of clusters increased from 1 to 4, and increased after that. In this study, four clusters are chosen under which the clustering is the most efficient. Figure 6 presents the cluster results based on K means, which shows strong spatial clustering. 5% of grids over China belong to the Cluster 2, which mainly located in the southeastern China, presenting a banded distribution spatially. 19% of grids belong to the Cluster 3, which mainly located in the middle reaches of the Yangtze River and part of northeastern China. 17% of grids belong to the Cluster 4, which mainly located in the Qinghai-Tibet Plateau and area around the Cluster 2. The rest 59% of grids belongs to the Cluster 1, which mainly located in the Northwestern and middle China. Figure 7 presents the boxplot of summer precipitation trends for different clusters.

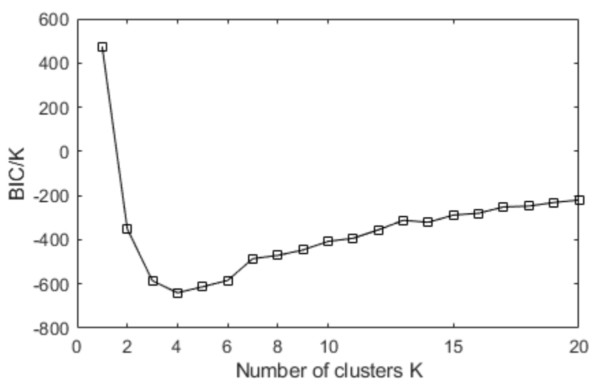

Figure 5. Optimum number of clusters in K mean clustering using Bayesian information criterion (BIC).

As shown in Figure 7, significant differences between the four clusters are observed. In detail, the main feature of cluster 1 is that there is little change in extreme precipitation indicators in summer. The mean MK trends of the six indicators are all around 0. The cluster 1 can be named as stable zone. The main feature of cluster 2 is that the total amount of summer precipitation and extreme precipitation have increased significantly. For example, the average MK trend of SumP is higher than 4 mm/a; the average MK of RX5day is higher than0.75 mm/a, which is significantly higher than other clusters. The cluster 2 can be named as extreme wetter. The main feature of cluster 3 is that the total summer precipitation and extreme precipitation are significantly reduced. For example, the average MK trend of SumP is lower than -1.5 mm/a; the average MK of RX5day is lower than -0.25 mm/a, which is significantly lower than other clusters. The cluster 3 can be named as stable dryer. The main feature of cluster 4 is that the total amount of summer precipitation and extreme precipitation have increased significantly, but the increase rate is lower than that of cluster 1. For example, the average MK trend of SumP is higher than 2 mm/a; the average MK trend of RX5day's is higher than 0.15 mm/a. The cluster 4 can be named as wetter. Overall, there are significant differences between the four clusters, which can be named as stable, extreme wetter, dryer, and wetter zones. Combining the spatial distribution of the multi-year average of precipitation indicators in Figure 2, and the spatial distribution of the four clusters in Figure 6, the results show that summer precipitation in China shows wet to wetter and dry to dryer.

6. Conclusions

In this study, the temporal and spatial trends of summer precipitation, especially for extreme precipitation over China are analyzed for revealing the response of climate change. Meanwhile, the spatially clustering characteristic of China is evaluated based on the trends of summer precipitation through K-means. The main conclusions are as follows:

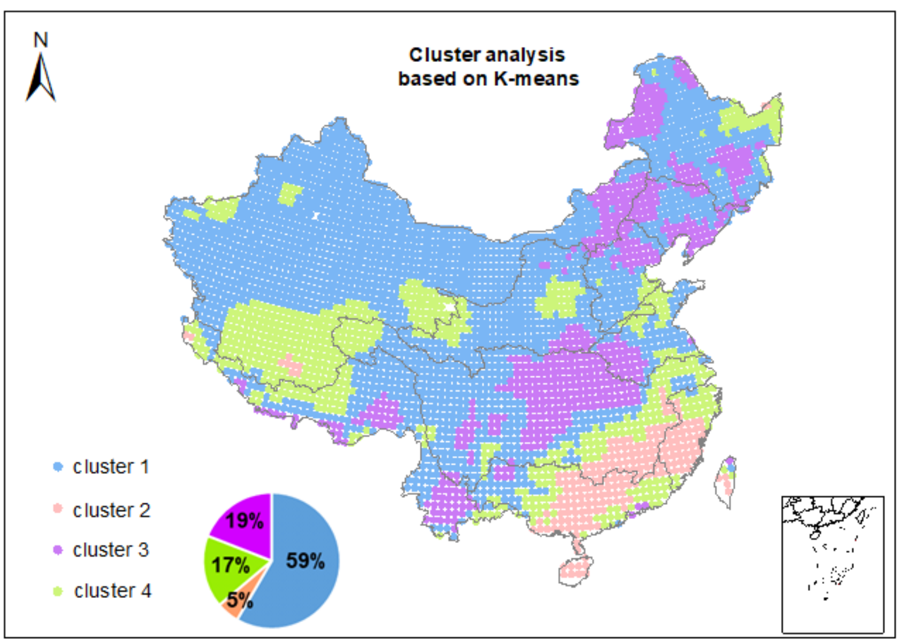

Figure 6. The MK trend of summer extreme precipitation over China.

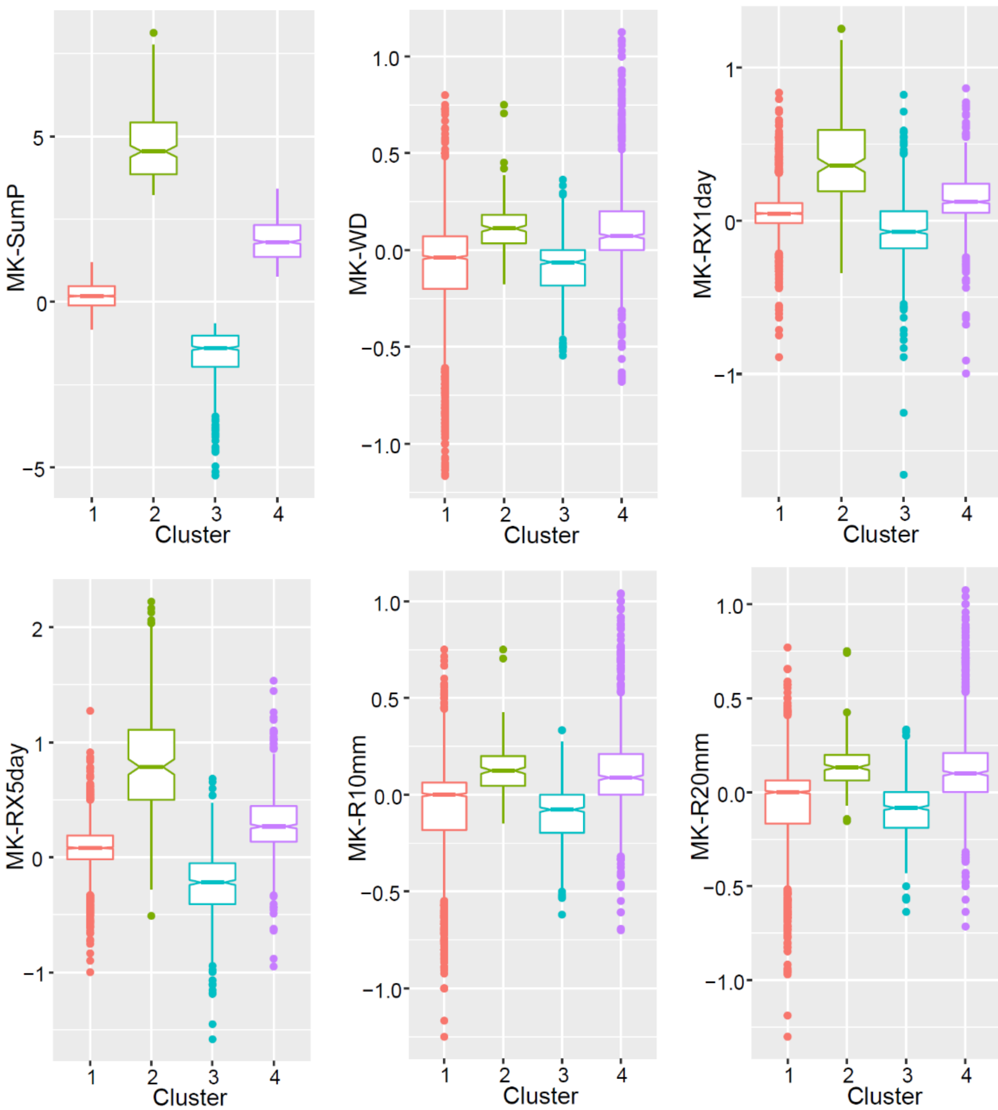

Figure 7. The boxplot of summer precipitation trends for different clusters.

The spatial distribution of MK trends for the summer precipitation indices over China during 1982 ~ 2019 shows increasing and decreasing trends in different regions. The extreme precipitation have been found mainly in Pearl River Basin, Southeastern River Basin, Huaihe River Basin, and the lower reaches of the Yangtze River. The risk of floods in SERB (the Southeastern River Basin), especially those caused by short-term heavy precipitation, may increase in recent decades. Four clusters are identified through K-means, which can be named as stable (59%), extreme wetter (5%), dryer (19%), and wetter (17%) zones. Combining the spatial distribution of the multi-year average of precipitation indicators and four clusters, the "wet to wetter and dry to dryer" is found in China summer precipitation. This is the first to clustering based on the trend of summer precipitation.

The above analyses are obtained only from reanalysis data GPCC. Climate model-based studies with numerical simulations are necessary to further interpret and verify the results, and will be the focus of a future follow-up study.

Acknowledgments. This research was supported by the National Key Research and Development Plan (2016YFA0601502).

References

Ball, G.H. and Hall, D.J. (1965). ISODATA, a novel method of data analysis and pattern classification. *Stanford Research Inst Menlo Park CA*.

Blain, G.C. (2013). The Mann-Kendall test: the need to consider the interaction between serial correlation and trend. *Acta Scientiarum. Agronomy*, 35(4), 393-402. https://doi.org/10.4025/actasciagron.v35i4.16-006

Chen, H.P., Sun, J.Q., Lin, W.Q. and Xu, H.W. (2020). Comparison of CMIP6 and CMIP5 models in simulating climate extremes. *Science Bulletin*, 65(17), 1415-1418. https://doi.org/10.1016/j.scib.2-020.0-5.015

Ding, Y.H., Wang, Z.Y. and Sun, Y. (2008). Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences. *International Journal of Climatology*, 28(9), 1139-1161. https://doi.org/10.1002/joc.1615

Drineas, P., Frieze, A., Kannan, R., Vempala, S. and Vinay, V. (2004). Clustering large graphs via the singular value decomposition. *Machine learning*, 56(1-3), 9-33. https://doi.org/10.1023/B:MACH.00-000-33113.59016.96

Han, J.C., Huang, G.H., Zhang, H., Li, Z. and Li, Y.P. (2014). Heterogeneous precipitation and streamflow trends in the Xiangxi River watershed, 1961–2010. J*ournal of Hydrologic Engineering*, 19(6), 1247-1258. https://doi.org/10.1061/(ASCE)HE.1943-55-84.0000898

He, L.Q., Hao, X., Li, H. and Han, T.T. (2021). How do extreme summer precipitation events over Eastern China subregions change? *Geophysical Research Letters*, 48(5), 1-9. https://doi.org/10.1029/2-020GL091849

Helsel, D.R. and Hirsch, R.M. (1992). *Statistical Methods in Water Resources*, 49. Elsevier. ISBN: 0-444-88528-5

Huang, R.H., Liu, Y. and Feng, T. (2013). Interdecadal change of summer precipitation over Eastern China around the late-1990s and associated circulation anomalies, internal dynamical causes. *Chinese Science Bulletin*, 58(12), 1339-1349. https://doi.org/10.1007/s11434-012-5545-9

Hardy, A. (1996). On the number of clusters. *Nu Computational Statistics and Data Analysis*, 23(1), 83-96. https://doi.org/10.1016/S0167-9473(96)00022-9

Domroes, M. and Peng, G.B. (1988). *The Climate of China.* Spring-Verlag, pp 361. ISBN: 978-3-642-73335-2

Duan, R.X., Huang, G.H., Li, Y.P., Zhou, X., Ren, J.Y. and Tian, C.Y. (2021). Stepwise clustering future meteorological drought projection and multi-level factorial analysis under climate change: A case study of the Pearl River Basin, China. *Environmental Research*, 196, 110368. https://doi.org/10.1016/j.envres.2020.110368

Fan, Y.R., Huang, K., Huang, G.H., Li, Y.P. and Wang, F. (2020). An uncertainty partition approach for inferring interactive hydrologic risks. *Hydrology and Earth System Sciences*, 24(9), 4601-4624. https://doi.org/10.5194/hess-2019-434

Jain, A.K. (2010). Data clustering: 50 years beyond K-means. *Pattern Recognition Letters*, 31(8), 651-666. https://doi.org/10.1016/j.patrec.2009.09.011

Kendall, M.G. (1975). *Rank Correlation Measures.* Charles Griffin, London, 202: 15.

Khaliq, N., Ouarda, T.B.M.J. and Gachon, P. (2009). Identification of temporal trends in annual and seasonal low flows occurring in Canadian rivers: The effect of short- and long-term persistence. *Journal of Hydrology*, 369(1), 183-197. https://doi.org/10.1016/j.jhydrol.2009.02.045

Lin, Z.D. and Wang, B. (2016). Northern East Asian low and its impact on the interannual variation of East Asian summer rainfall. *Climate Dynamics*, 46(1-2), 83-97. https://doi.org/10.1007/s00382-015-2570-9

Lu, E., Zeng, Y.T., Luo, Y.L., Ding, Y., Zhao, W., Liu, S.Y., Gong, L.Q., Jiang, Y., Jiang Z.H. and Chen H.S. (2015). Changes of summer precipitation in china: the dominance of frequency and intensity and linkage with changes in moisture and air temperature. *Journal of Geophysical Research*, 119(22), 12575-12587. https://doi.org/10.1002/2014JD0224-56

Lei, Y.H., Hoskins, B. and Slingo, J. (2011). Exploring the interplay between natural decadal variability and anthropogenic climate change in summer rainfall over China. Part I: observational evidence. *Journal of Climate*, 24(17), 4584-4599. https://doi.org/ 10.1-175/2010JCLI3794.1

Liu, F., Ouyang, Y., Wang, B., Yang, J. and Hsu, P.C. (2020). Seasonal evolution of the intraseasonal variability of china summer precipitation. *Climate Dynamics*, 54(11-12), 4641-4655. https://doi.org/1-0.1007/-s00382-020-05251-0

Mann, H.B. (1945). Nonparametric test against trend. *Econometrica*, 13(3), 245-259. https://doi.org/10.2-307/1907187

Qian, W.H., Fu, J.L. and Yan, Z.W. (2007). Decrease of light rain events in summer associated with a warming environment in China during 1961–2005. *Geophysical Research Letter*, 34(11), 224-238. https://doi.org/-10.1029/2007GL029631

Qian, W. and Lin, X. (2005). Regional trends in recent precipitation indices in China. *Meteorology and Atmospheric Physics*, 90(3-4), 193-207. https://doi.org/10.1007/s00703-004-0101-z

Ren, G.W., Wu, H. and Chen, W. (2000). Spatial patterns of change trend in rainfall of China. *Quarterly Journal of Applied Meteorlolgy*, 11(3), 322-330.

Shang, H., Xu, M., Zhao, F. and Tijjani, S.B. (2019). Spatial and temporal variations in precipitation amount, frequency, intensity, and persistence in China, 1973–2016. *Journal of Hydrometeorology*, 20(11), 2215-2227. https://doi.org/10.1175/JHM-D-19-0032.1

Trenberth, K.E. (2011). Changes in precipitation with climate change. *Climate Research*, 47(1), 123-138. https://doi.org/10.3354/cr00953

Wang, F., Huang, G.H., Cheng, G.H. and Li, Y.P. (2021a). Impacts of climate variations on non-stationarity of streamflow over Canada. *Environmental Research*, 197, 111118. https://doi.org/10.1016/j.envres.2021.111118

Wang, F., Huang, G.H, Cheng, G.H. and Li, Y.P. (2021b). Multi-level factorial analysis for ensemble data-driven hydrological prediction. *Advances in Water Resources*, 153, 103948. https://doi.org/10.1016/j.advwatres.2021.103948

Wang, F., Huang, G.H., Fan, Y.R. and Li, Y.P. (2020). Robust subsampling ANOVA methods for sensitivity analysis of water resource and environmental models. *Water Resources Management*, 34(10), 3199-3217. https://doi.org/10.1007/s11269-020-02-608-2

Wang, F., Huang, G.H., Fan, Y.R. and Li, Y.P. (2021c). Development of clustered polynomial chaos expansion model for stochastic hydrology prediction. *Journal of Hydrology*, 595, 126022. https://doi.org/-10.1016/j.jhydrol.2021.126022

Wang, Y.Q. and Zhou, L. (2005). Observed trends in extreme precipitation events in China during 1961–2001 and the associated changes in large- scale circulation. *Geophysical Research Letters*, 32(9), L09707. https://doi.org/10.1029/2005gl022574

Wang, H.J., Chen, Y.N. and Chen, Z.S. (2013). Spatial distribution and temporal trends of mean precipitation and extremes in the arid region, northwest of China, during 1960–2010. *Hydrological Processes*, 27(12), 1807-1818. https://doi.org/10.1002/hyp.9339

Xu, Z.Q., Fan, K. and Wang, H.J. (2015). Decadal variation of summer precipitation over China and associated atmospheric circulation after the late 1990s. *Journal of Climate*, 28(10), 4086-4106. https://doi.org/10.1175/JCLI-D-14-00464.1

Yue, S. and Wang, C.Y. (2004). The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. *Water Resources Management*, 18(3), 201-218. https://doi.or-g/10.1023/B:WARM.0000043140.61082.60

Yu, Y., Schneider, U., Yang, S., Becker, A. and Ren, Z.H. (2020). Evaluating the GPCC full data daily analysis version 2018 through ETCCDI indices and comparison with station observations over mainland of China. *Theoretical and Applied Climatology*, 142(4-3), 835-845. https://doi.org/10.1007/s00704-020-0335-2-8

Zhang, Q., Zheng, Y.J., Singh, V.P., Luo, M. and Xie, Z. (2017). Summer extreme precipitation in eastern China: mechanisms and impacts. *Journal of Geophysical Research: Atmospheres*, 122(5), 2766-2778. https://doi.org/10.1002/2016JD025913

Zhou, Z.Q., Xie, S.P. and Zhang, R.H. (2021). Historic Yangtze flooding of 2020 tied to extreme indian ocean conditions. *Proceedings of the National Academy of Sciences of the United States of Anerica*, 118(12), e2022255118. https://doi.org/10.1073/ pna-s.2022255118

Zhu, Y.L., Wang, H.J., Wen, Z. and Ma, J.H. (2011). Recent changes in the summer precipitation pattern in East China and the background circulation. *Climate Dynamics*, 36(7-8), 1463-1473. https://doi.org/ 10.10-07/s00382-010-0852-9

Zong Y.Q., and Chen X.Q. (2000). The 1998 flood on the yangtze, China. *Natural Hazards*, 22(2), 165-184. https://doi.org/10.1023/A:1008119805106

Zhai, P.M., Zhang, X.B., Wan, H. and Pan, X.H. (2005). Trends in total precipitation and frequency of daily precipitation extremes over China. *Journal of Climate,* 18(7), 1096-1108. https://doi.org/10.1175/-JCLI-3318.1

Zhai, P.M., Sun, A.J., Ren, F.M., Liu, X.N., Gao, B. and Zhang, Q. (1999). Changes of climate extremes in China. *Climatic Change*, 42(1), 203-218. https://doi.org/10.102-3/A:1005428602279

Zhou, L.T. and Huang, R.H. (2010). Interdecadal variability of summer rainfall in northwest China and its possible causes. *International Journal of Climatology,* 30(4), 549-557. https://doi.org/10.1002/joc.1923