



Spatial and Temporal Variability of Drought and Precipitation Using Cluster Analysis in Xinjiang, Northwest China

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Abstract

Analyses of drought and precipitation require long-term historical data and reasonable drought index to ensure reliable monitoring and prediction, especially for the Xinjiang Uygur Autonomous Region, where is sensitive and vulnerable to drought disasters. Drought characteristic was expressed using the observational precipitation data and calculated precipitation threshold at 105 meteorological stations from 1979 to 2014. The results showed that the variation of drought and precipitation was not spatially uniform. Analysis in sub-areas was conducted based on mutli-statistical methods. The historical drought and precipitation situation in Xinjiang is better characterized by three clusters. Cluster 1 is the driest, cluster 2 has a clear increasing trend of precipitation, while cluster 3 is the wettest with the mean annual precipitation approximates to 300 mm. In addition, the precipitation concentration and distribution is becoming uniform, there is a faster rate of increasing precipitation in cool-season rather than in warm-season. The results provide critical support for the drought disasters management and mitigation, it also provide a base for in-depth investigation on the possible mechanisms of regional drought.

Keywords Cluster analysis · Drought · Precipitation threshold · Xinjiang

1 Introduction

Drought as a natural phenomenon can last for weeks, months, even years. It is generally considered as a negative water balance caused by the timing deficiency and ineffectiveness of precipitation, or a sustained lack of available water resources for an extended period of time (Wilhite and Glantz 1985). The

spatial extent of drought is commonly larger than other natural disasters (Hisdal et al. 2001).

The Inter-governmental Panel on Climate Change (IPCC) has indicated that large uncertainty, and great concern exists in regard to the ‘future vulnerability, exposure, and responses of interlinked human and natural systems’ (IPCC 2014). Under the climate change, drought investigation is one of the hot fields, i.e., Choi et al. (2016) estimated the projection of future drought condition using multi regional climate models. Sheffield et al. (2012) conducted a global assessment of drought based on PDSI over the past 60 years. Numerous studies based on different drought indexes have been investigated (Gocic and Trajkovic 2013; Wang et al. 2015; Byun et al. 2008). In addition, the effect of climate change on precipitation variation is attracting more and more attention (Kim et al. 2016).

Previous study has indicated that drylands have warmed, and will continue to warm, more than humid lands (Huang et al. 2017). The spatiotemporal variability of droughts in arid and semi-arid region has received considerable attention due to their serious detrimental impacts. Huang et al. (2015) indicated the expansion of drylands. Dai (2012) pointed out the severe and widespread droughts over many land areas in the next 30–90 years. Xinjiang Uygur Autonomous Region

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(noted as Xinjiang hereafter) located in the arid and semi-arid, is sensitive to climate change. The effect of global warming may result in greater circulation of water masses over the Tibetan plateau and consequently more precipitation (Feng et al. 2006). The atmospheric water humidity and content increased significantly in Xinjiang. Shi et al. (2002) found a significant change in snowmelt in the west Tianshan region since 1987. The impacts of droughts appear to be multifaceted and often difficult to quantify over large areas and long time scales, various drought indexes were used in the process of drought monitoring (Zhang et al. 2012a; Wang et al. 2015). Zhang et al. (2012b) found that north Xinjiang is wetter than south Xinjiang, and the whole region exhibited a wetting tendency with a higher frequency of heavy precipitation extremes since 1980.

A variety of indexes have been used for drought evaluated depending on research objectives. The indexes represent the relationship between precipitation and stream flow, is widely used for hydrological droughts assessment. While drought index with predetermined thresholds are effective because precipitation is one of the main reasons that cause severe droughts. Precipitation-derived time series are used to investigate drought duration, severity, and frequency (Yevjevich 1967). Considering of the complex topography and landforms in the study area, the k-means cluster was used for regional analysis. In this study, drought was defined based on precipitation threshold, and then the regionalization of Xinjiang was conducted using a clustering algorithm in conjunction with drought properties as a starting point for partitioning sites of interests. Subsequently, drought and precipitation characteristics were investigated at each cluster.

The research is organized as follows. Section 1 presents a brief introduction to narrate the motivation of this work. Section 2 introduces the study area and data set, and the statistical technique used in this study. Section 3, drought and precipitation characteristics are performed for the whole Xinjiang as well as each sub-area. Section 4 discusses the precipitation concentration and distribution; and Section 5 presents the conclusions.

2 Materials and Methods

2.1 Study Area and Data Collection

The study area Xinjiang (73°40′–96°18′E and 34°25′–48°10′N) is an arid and semi-arid area located in the northwest of China. It covers 1.6 million km² and exhibits large elevations ranging from 158 m below sea level to 7390 m. Xinjiang can be geographically divided into northern and southern halves by the Tianshan mountain, one of the seven largest mountains in the

world. The extensive development of inland rivers results in the formation of unique “mountain-oasis-desert” ecosystems in the arid region. Generally, it has a temperate continental climate with limited precipitation. Daily precipitation data from 105 meteorological stations (see Fig. 1) were selected from 1979 to 2014. The using data is scientific, reliable, and objective enough in this study, which is almost double that of previous studies, which were downloaded from the official Chinese meteorological website (<http://data.cma.cn>). In order to insure the accuracy of the provided data, data quality control and homogeneity assessment were checked by the RclimDex software package (<http://etccdi.pacificclimate.org/software.shtml>).

2.2 Drought Evaluation Indicator System

2.2.1 Drought Properties

This study collected daily precipitation data over 105 stations throughout the Xinjiang area for more than 30 years. Drought properties as its duration and severity were determined by long-term mean of monthly precipitation, the calculation of the precipitation threshold as shown below (Yoo et al. 2012). In the calculation, the long-term mean of “year n ” was calculated by using up to “year $n-1$ ”, which is identical to the Standardized Precipitation Index (SPI).

$$t_{(n,i)} = \frac{x_{(s,i)} + x_{(s+1,i)} + \dots + x_{(n-1,i)}}{n-s}$$

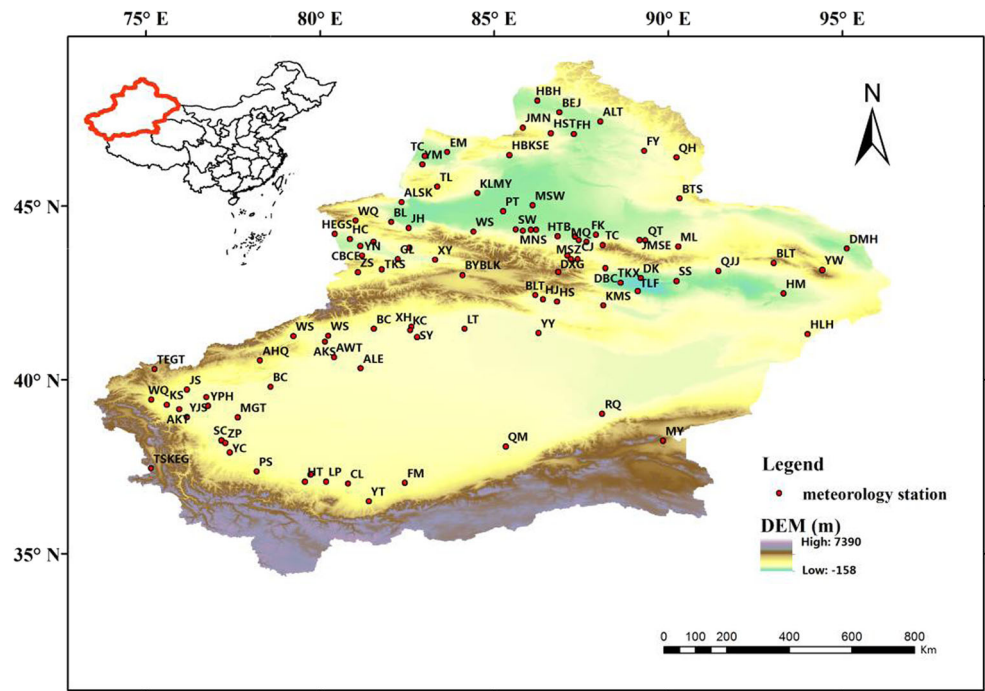
where, $t_{(n,i)}$ is the precipitation threshold of a given i th month and n th year, s is the first year of data collection. (Instruction: In this paper, when $n = s$, $t_{(s,i)}$ is represented as i th month and $s-1$ th year).

Figure 2 illustrates a detailed graphical representation for drought properties. Drought duration and severity were extracted from time series of monthly precipitation for each station. The duration while successive precipitation less than the given precipitation threshold over a month is identified as drought duration; and the accumulated sum of precipitation deficit during drought duration is considered as drought severity.

2.2.2 Precipitation Concentration Index

Annual precipitation distribution is connected with the drought situation. Precipitation concentration index (noted as PCI hereafter) represents the long-term series of precipitation distribution characteristics on monthly scale. It was a pointer of precipitation concentration (Oliver 1980), which is widely

Fig. 1 Location of the study area and 105 meteorological stations in Xinjiang, China



used for precipitation concentration monitoring during a year. The PCI is calculated as:

$$PCI_{annual} = \frac{\sum_{i=1}^{12} P_i^2}{(\sum_{i=1}^{12} P_i)^2} \times 100$$

where P_i is the monthly precipitation for month i . It can also be characterized by seasonal precipitation. Theoretically, the lowest value of PCI is 8.3 when same amount of precipitation occurs in each month, indicating a perfect uniformity in precipitation distribution, while a PCI value of 16.7 indicates that

the total rainfall is concentrated in half of the period and a PCI value of 25 evinces that the total rainfall occurred in one-third of the period (Luis et al. 2011).

2.3 Statistical Methods

2.3.1 Mann-Kendall Method

The non-parametric statistical Mann-Kendall (MK) method (Mann 1945; Kendall 1975) has wide applications in climate modeling, trend detection, environmental studies and

Fig. 2 Definition of drought properties

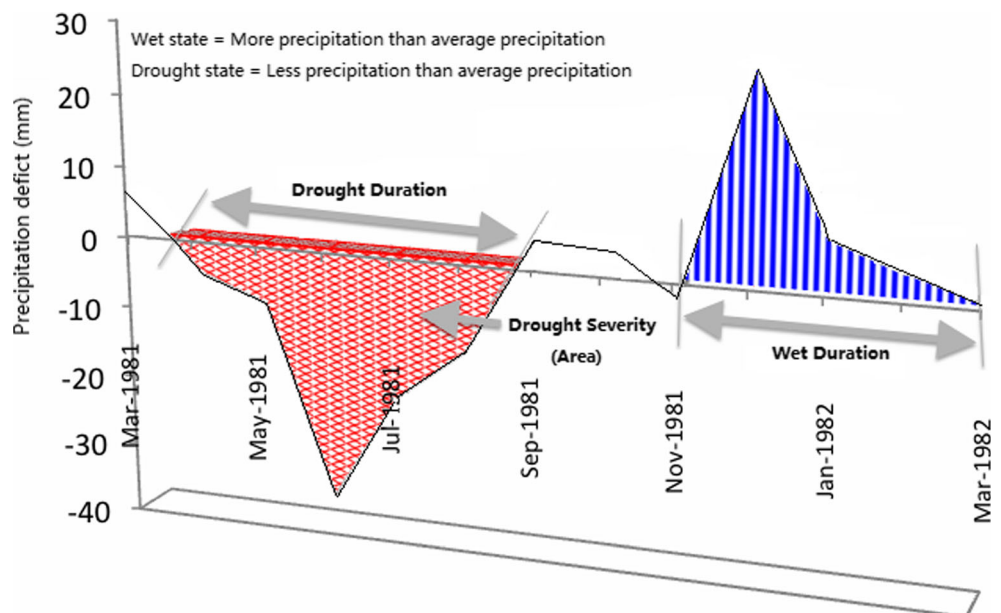


Table 1 Heterogeneity test

Name	Duration			Severity		
	H(1)	H(2)	H(3)	H(1)	H(2)	H(3)
Cluster 1	-1.2795	-1.3821	-1.3945	-0.4699	-1.0307	-0.9543
Cluster 2	1.1615	0.4315	0.4937	-0.9202	-0.3232	-0.4267
Cluster 3	0.1180	0.9506	0.9908	-0.4699	1.3539	1.3810

hydrology. It is a non-parametric test requiring no specific assumption of the joint distribution of the data, and thus it is generally not affected by departures from normality.

2.3.2 Spearman's Rho Test

Spearman's Rho test is a non-parametric method used to verify the absence of trends (Mergenthaler 1979; Sneyers 1991).

$$D = 1 - \frac{6 \sum_{i=1}^n (R(x_i) - i)^2}{n(n^2 - 1)}$$

$$Z_{SR} = D \sqrt{\frac{n-2}{1-D^2}}$$

where $R(x_i)$ is the rank of i th observation x_i in the time series, n is the length of the time series, Z_{SR} reflect the change trend of time series data, when $|Z_{SR}| > t_{(n-2, 1-\alpha/2)}$, the null hypothesis is rejected and shows a significant trend.

2.3.3 K-Means Cluster Method

Different basins and hydrological factors cause different impacts on local water resources and precipitation, and thus the frequency and severity of drought can vary significantly in different sub-areas. The sites of interest are partitioned by the clustering algorithms based on the K-Means method widely used in geoscience studies, whose advantage is the simple implementation in the search of clusters. It is a non-hierarchical clustering method which begins with the calculation of the centroids for each cluster, followed by the calculation of the distances between the current data vector and each of the centroids, and finally assigning vector to cluster whose centroid is the closest. The iterative steps involved in the K-Means clustering include: (Sönmez 2009) the first, all samples are selected randomly into the k clusters, each of which is represented by a centroid; then compute the centroid of each cluster by averaging its sample vectors; finally, all samples are redistributed to the nearest cluster according to the distance between the cluster centroid and sample, and the centroid of the cluster is recalculated. Steps 2 and 3 are repeated until the clusters become stable.

2.3.4 Heterogeneity Measures

The heterogeneity measures (Hosking and Wallis 1997) shown in Table 1 are used to evaluate the homogeneity of

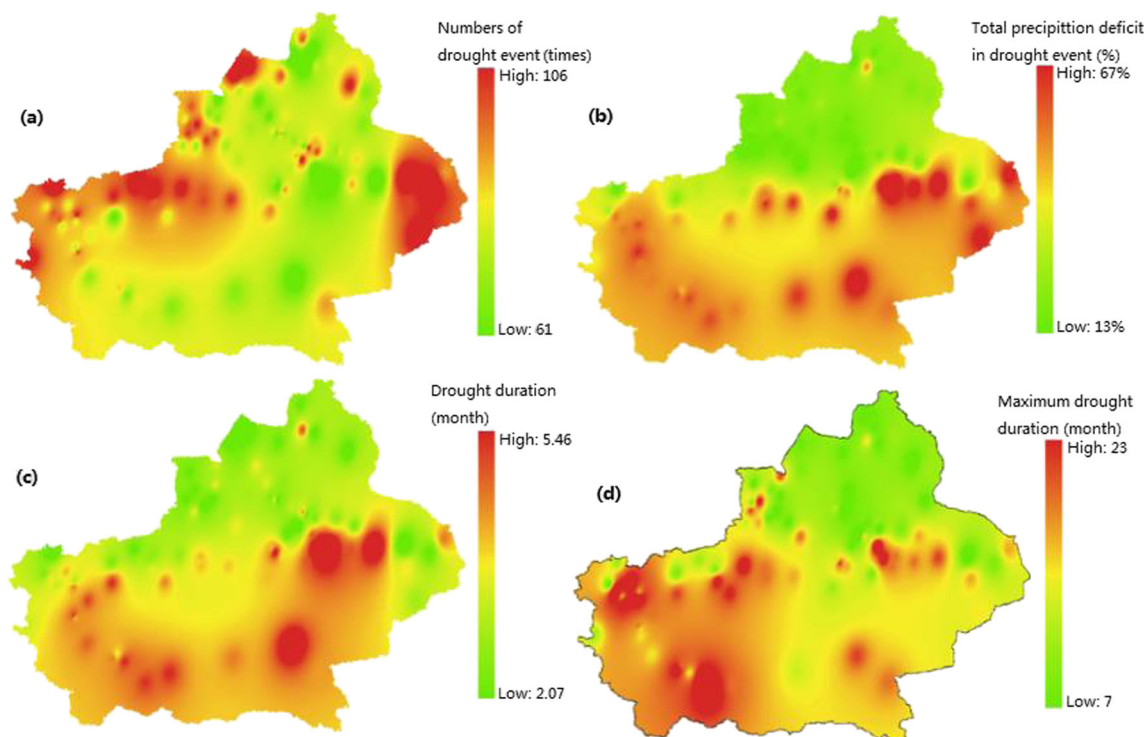


Fig. 3 Spatial distribution of drought properties: **a** numbers of drought event, **b** total precipitation deficit (%), **c** drought duration, and **d** maximum drought duration

the areas by comparing the dispersion of sample L-moments among sites with the L-moment for the group of sites. The heterogeneity test should follow the following principles: the region is treated as acceptably homogeneous if $H < 1$; possibly heterogeneous if $1 < H < 2$; and definitely heterogeneous if $H > 2$, respectively. The heterogeneity H statistic and V statistic for the sample and simulated regions can be represented as follow:

$$H = \frac{V - u_v}{\sigma_v}$$

$$V = \sqrt{\left\{ \frac{\sum_{i=1}^N n_i (\tau^i - \tau^R)^2}{\sum_{i=1}^N n_i} \right\}}$$

where u_v is the average of simulated V values, σ_v is the standard deviation of simulated V values, τ^i is the sample L-moment at each site, τ^R is the averaged sample L-moment at a regional scale, and n_i is the length of the time series at site i , respectively. The $H(1)$, $H(2)$, and $H(3)$ are calculated by the L-

coefficient of variation, L-skewness and L-kurtosis used as the L-moment, respectively.

3 Result

3.1 Spatio-Temporal Variation of Drought in Xinjiang

Based on the statistic datum from recent more than 30 years, the frequency of happened droughts indicates drought-prone areas in Fig. 3a; the precipitation deficit (expressed as a percentage) indicates the severe-drought areas in Fig. 3b. The distribution of precipitation deficit (Fig. 3b) is quite similar to drought duration (Fig. 3c): southern Xinjiang is relative arid, especially for the east part area. In addition, the maximum drought duration in Fig. 3d present the longer drought duration in south Xinjiang, it also reveals that the west part of southern Xinjiang is more easily to experience long-duration drought.

Fig. 4 The whole Xinjiang, **a** Annual variability of precipitation observations and threshold, **b** Monthly variability of precipitation observations and threshold, and **c** data series of drought properties

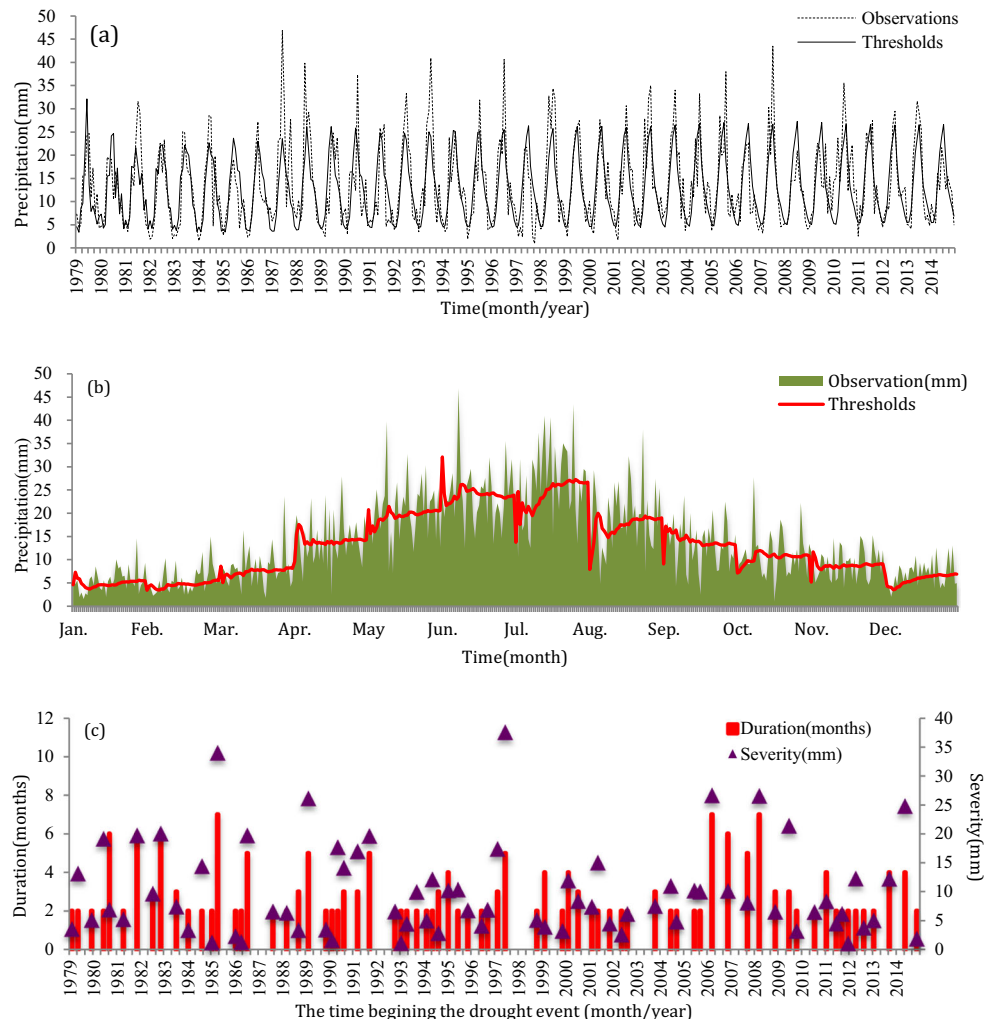


Table 2 The descriptive statistics of drought properties associate with clusters

Name	Numbers of site	Average elevation (mm)	Numbers of drought event	Duration		Skewness	Severity		
				Average (month)	Max (month)		Average (mm)/%	Max (mm)	Skewness
Cluster 1	43	981.62	3678	3.4	23	1.76	9.05/18.28%	97.7	-0.83
Cluster 2	23	1082.04	2770	2.87	22	0.14	15.83/12.02%	118.13	0.52
Cluster 3	39	1257.50	3400	2.59	18	0.89	27.76/9.52%	261.5	1.74

Dynamic variation of drought on different time scales was presented in Fig. 4. Figure 4a shows the precipitation variation from January 1979 to December 2014, it is evident that precipitation more focused on July and August. Monthly precipitation characteristics are more clearly demonstrated in Fig. 4b. The observed precipitation is significantly greater than the threshold in January (15%), February (22%) and December (19%), it also presents a higher value in July (11%) and August (10%), while other months shows a slightly precipitation increment, or even a negative. Over the past 36 years, 21-year present the observed precipitation lower than threshold in September, which probably indicates the increased drought conditions in September. Fig. 4c presents the statistics of droughts with its duration and severity. 2-month duration was considered as the dominant drought duration, and 7-month duration was the longest drought duration. Analysis of the calculated drought properties at each site indicated regional scale has its different period of recording, and regional drought analysis is need as an efficient method.

3.2 Cluster Analysis

The regionalization of Xinjiang was conducted via K-Means cluster method, and resulted in three main clusters, as shown in Table 2 and Fig. 5. The three main clusters are possibly

homogeneous regions, which were tested through heterogeneity measures (Table 1). Fig. 5 shows the distribution of stations with lines according to the cluster results, cluster 1, 2 and 3, correspond roughly to southern Xinjiang, northern Xinjiang and mountainous area (Tianshan mountain, Altai mountain and Pamirs), respectively.

3.2.1 Historical Drought and Precipitation Characterized by Clusters

In Table 2, we calculated various basic descriptive statistics of duration and severity (e.g., mean, maximum value, and skewness) as well as the number of drought events, during historical periods at each site. Both the duration and severity present the extreme drought in cluster 1, and the mild drought in cluster 3. To explain this phenomenon, altitude might be a determining factor.

Table 3 indicates the historical precipitation in Xinjiang characterized by three clusters: cluster 1 is the driest with lower precipitation. Cluster 2 has a clear increasing tendency (9.1 mm/10a), and precipitation increased about 25.52% after the mutation year. The significance trend test presents precipitation increased significantly in cluster 2 through the Mann-Kendall method and Spearman's Rho test. Cluster 3 was detected with abundant precipitation, the mean annual precipitation approximates to 300 mm.

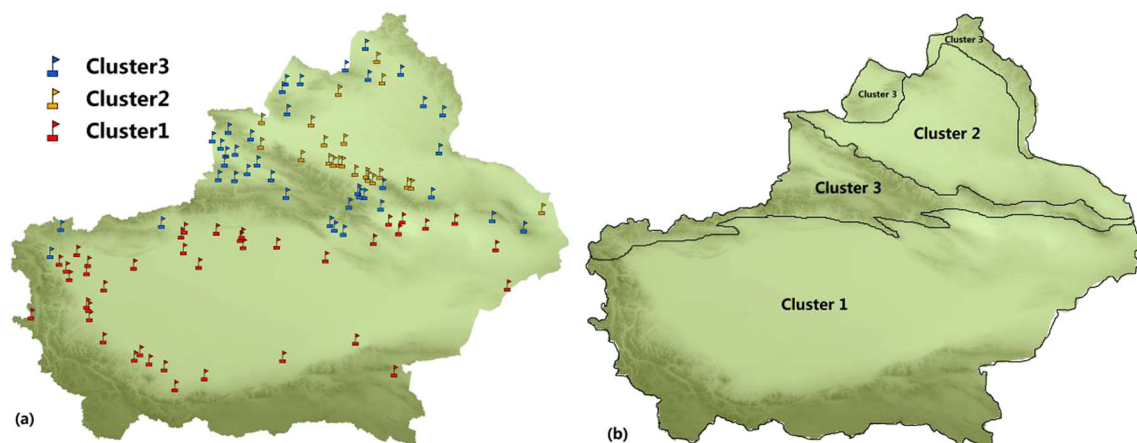
**Fig. 5** Regionalization of meteorological station

Table 3 The descriptive statistics of precipitation in each cluster

Name	Mean annual precipitation (mm)	Regression coefficients	Mutation year (year)	Z_S value	Q_{med} value	Z_{SR} value	Variation of precipitation (%)
Cluster 1	49.5	0.33	1990	1.1	↑ (0.305)	1.092	14.06%
Cluster 2	131.7	0.91	1986	2.19 *	↑ (0.880)	2.290 *	25.52%
Cluster 3	291.6	0.80	1989	0.99	↑ (0.792)	1.331	6.88%
Xinjiang	163.1	0.67	1988	1.57	↑ (0.611)	1.845	10.87%

Instruction: (a) The variation of precipitation in column 8 is a relative amount of increase of precipitation around the mutation year; (b) Z_S : Mann-Kendall test, Q_{med} : Sen's slope estimator, and Z_{SR} : Spearman's Rho test; (c) * statistically significant trend at the 5% significance level.

3.2.2 Precipitation Concentration Associate with Clusters

Precipitation is important in water circulating process, and exerts a crucial impact on the occurrence of drought. PCI affected drought deeply, because the higher precipitation concentration indicates drought may happen in drier period. PCI was calculated as stipulated Oliver's (1980) classification: $PCI \leq 10$ denote a low precipitation concentration; whereas PCI range from 11 to 15 represents moderate precipitation concentration; and PCI between 16 and 20 represents irregular precipitation distribution. However, $PCI > 20$ denote a strong irregularity in precipitation distribution.

Figure 6 shows the PCI varies from 9 to 26, and the PCI in the whole Xinjiang presents a downward trend ($-0.27/10a$). Cluster 2 and 3 shows PCI range from 11 to 15, implying moderate precipitation concentration. While cluster 1 shows PCI in the most years ($n = 26$) range from 16 to 20, implying irregular precipitation distribution, and several years ($n = 7$) greater than 20, which indicated strong irregular precipitation distribution. Moreover, a decreasing trend of PCI was detected in each cluster from 1979 to 2014 (data not shown). PCI is closely related to seasonal precipitation, the result could be proved by the conclusion that precipitation present evident seasonal variation (Dai et al. 2013). This trend indicated a relative uniform precipitation is coming, the strong irregularity

of precipitation in cluster 1 is expected to weaken, and it may bring fewer droughts.

4 Discussion

PCI can better represent precipitation concentration during a year, as shown in section 3.2.2, but it unable to point out the specific change explicitly (Michiels et al. 1992). In this part, warm-season and cool-season were partitioned to perform the precipitation distribution according to Huang et al. (2012).

Figure 7 shows the seasonal precipitation variation based on the three clusters. The precipitation anomaly presents the linearly increasing trend both in warm-season and cool-season. Mutation analysis of seasonal precipitation presented in the pie chart indicated the proportion of the precipitation in cool-season increased obviously than warm-season, precipitation concentration tend to be reduce, which explain the fluctuating downward tendency of PCI in section 3.2.2. The significance test presents precipitation increased significantly in cluster 2 both in warm-season and cool-season, which indicated there is no evident seasonal variation. While cluster 2 and cluster 3 show a higher level of precipitation increased in cool-season, especially for cluster 1.

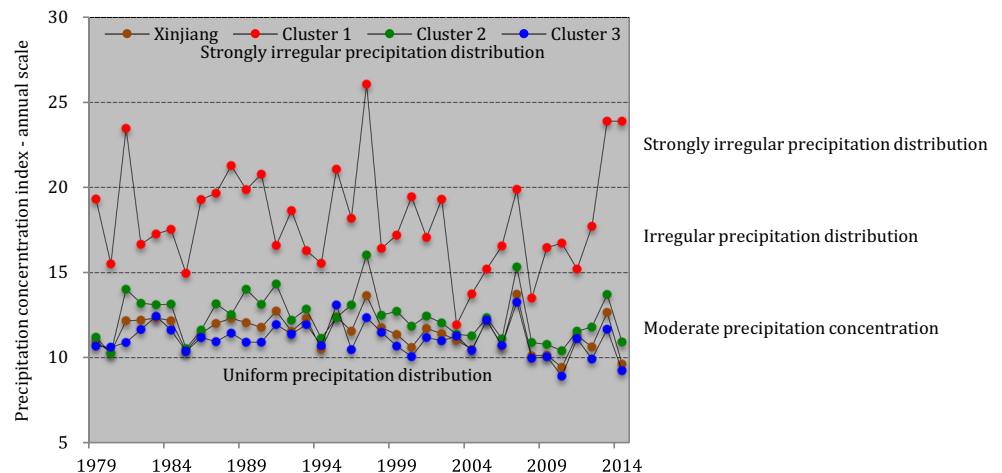
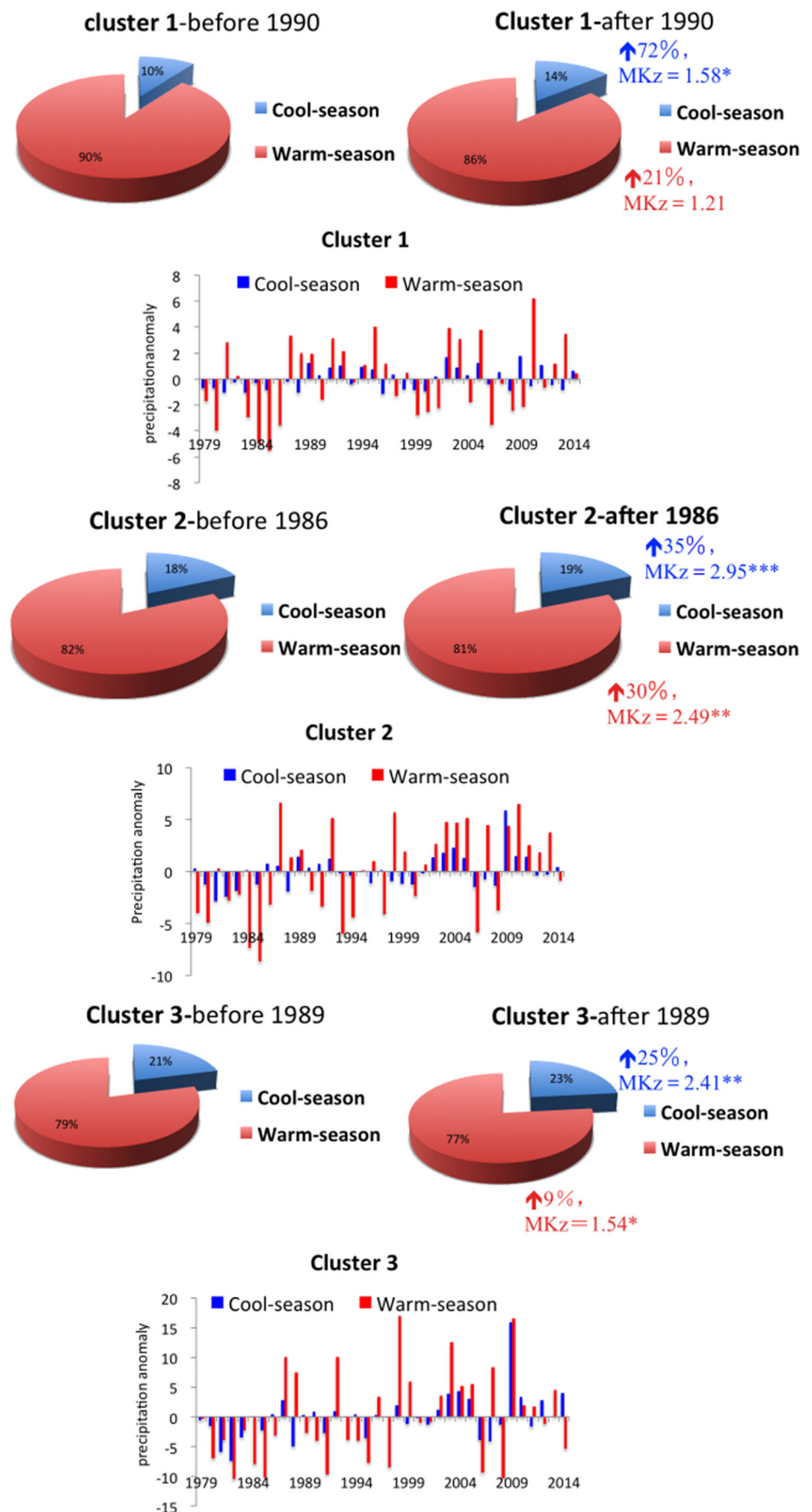
Fig. 6 Temporal variation of precipitation concentration index

Fig. 7 Seasonal precipitation variation and its significance test before and after the mutation year at three clusters. (Instructions: warm-season: May–September; cool-season: November–March; The mutation year of the three clusters was detected through Mann-kendall test which can be viewed across Table 3)



In addition, an obvious increasing trend of temperature in cool-season ($0.6\text{ }^{\circ}\text{C}/10\text{a}$) has also been detected in Xinjiang. This result is in accordance with Huang et al. (2017) that an enhanced cool-season warming was detected in semi-arid regions. Correlation analysis shows a weak correlativity (0.14) between precipitation and temperature. Chen et al. (2015) indicated that the temperature and precipitation in the arid region of northwest China had a significant increasing trend in the past 50 years, and the frequency of climate and hydrological extreme events increased. These findings further support the conclusion by Zhou et al. (2008) that the total precipitation in most parts of China would increase with the number of precipitation become more frequent and extreme under the warmer climate.

5 Concluding Remarks

This study investigated precipitation and drought characteristics in Xinjiang Province and its sub-areas using MK test and cluster analysis. The results show that precipitation in Xinjiang area is generally becoming more, especially for cool-season, and there is non-uniform variation of seasonal precipitation in each cluster. In addition, drought was firstly defined by precipitation threshold in the study area. Some salient conclusions can be highlighted:

1. The abundant precipitation was detected in July and August, but precipitation in cool-season increased significantly. Precipitation in January, February and December significantly increased and exceeds the threshold about 15%, which provide further support for the downward trend of precipitation concentration.
2. Threshold based on local precipitation is suitable for drought investigated in this study. Drought in southern Xinjiang is serious, which well revealed by the numbers of droughts, drought severity and drought duration. Short-duration drought (2-month duration) occurs frequently in the whole Xinjiang, while the west part of southern Xinjiang was detected more easily to occur long-duration drought.
3. The historical drought situation in Xinjiang is better represented by three clusters rather than a homogeneous region. Cluster 1 is the driest with higher precipitation concentration, the precipitation in cool-season increased obviously. Cluster 2 shows precipitation increased clearly both in warm-season and cool-season, but there is no evident seasonal variation of precipitation. Cluster 3 is the wettest with moderate precipitation concentration, the mean annual precipitation approximates to 300 mm.

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Compliance with Ethical Standards

Conflict of Interests The authors declare that there is no conflict of interests.

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