Cluster analysis of drought variation and its mutation characteristics in Xinjiang province, during 1961–2015

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ABSTRACT

The Xinjiang province of China is vulnerable to drought, but the occurrence of drought varies substantially among different sub-areas. This study investigated drought characteristics in Xinjiang province and its sub-area using the Mann–Kendall trend test, cluster analysis and Morlet wavelet analysis. The results show that drought in Xinjiang is generally becoming less severe, and there is a non-uniform spatial variation of drought, which is especially pronounced for stations in northern Xinjiang. There is a unique spatiotemporal distribution trend of drought in Xinjiang, and the inter-decadal variation of drought shows a gradual shift from the east to the west and then back to the east again over the past 55 years. Northern Xinjiang is becoming wetter at a faster rate compared with that of southern Xinjiang, and it also has a higher occurrence of change point sites (70%). The historical drought situation in Xinjiang is better characterized by three clusters. Cluster 1 is the driest, cluster 2 has a clear alleviating tendency of drought, while cluster 3 shows late occurrence of change point. A broader view of the accumulated variation of drought is formulated in this study, which may help to identify potential droughts to support drought disaster management and mitigation.

Key words | change point, cluster analysis, drought, Xinjiang

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INTRODUCTION

Drought is characterized by a negative water balance originating from a deficiency of precipitation or a lack of available water resources for an extended period of time (Wilhite & Glantz 1985). It has become an increasingly serious problem with detrimental environmental and socioeconomic consequences. However, drought patterns have become more complicated in recent years due to climate change, and thus there is a need to better understand drought patterns and characteristics.

The spatiotemporal variability of droughts has received considerable attention due to their serious detrimental impacts. The Intergovernmental Panel on Climate Change (IPCC) documented large uncertainties about the 'future vulnerability, exposure, and responses of interlinked human and natural systems' (IPCC 2014). China's IPCC indicated that the average warming rate in China (0.9–1.5 °C) was higher than the global average with an obvious regional difference in the annual precipitation over the last century (http://www.cma.gov.cn). An increase in frequency and severity of drought is expected in the future due to climate changes, and thus the spatiotemporal variability of drought at global and regional scales has become a topic of considerable research interest. Sheffield *et al.* (2002) conducted a global assessment of drought under the warming climate over the past 60 years. Numerous regional studies have also been conducted to analyze the spatiotemporal variability of drought (Lewis *et al.* 2011; Gosling 2014).

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The Xinjiang Uygur Autonomous Region (hereafter referred to as Xinjiang for short) is a key eco-environmental zone in China with a semi-arid climate and the hottest temperature nationwide. Yan *et al.* (2016) investigated the combined impacts of future climate and land use changes on the streamflow in Xinjiang. Zhang *et al.* (2015) also investigated the impacts of climate changes on spatiotemporal properties of drought extremes and local agriculture. Zhang *et al.* (2012c) found that northern Xinjiang was wetter than southern Xinjiang, and the whole region has exhibited a wetting tendency with a higher frequency of heavy precipitation extremes since 1980. Among the indexes used in monitoring drought (Zhang *et al.* 2012a; Wang *et al.* 2015), the Standardized Precipitation Index (SPI) is suitable for drought reconstruction in Xinjiang (Zhai & Feng 2011). Previous indexes can be classified into two groups: (1) indexes related to the physical processes of droughts, such as the Palmer Drought Severity Index (Palmer 1965) and Surface Water Supply Index (Shafer & Dezman 1982); (2) indexes based only on precipitation, such as Standard Precipitation Index SPI (McKee *et al.* 1993). The SPI has been commonly used in recent studies due to its simplicity and temporal flexibility (Li *et al.* 2012; Belayneh *et al.* 2014). However, the impacts of droughts appear to be multifaceted and often difficult to quantify over large areas and long time scales. Clearly, a better understanding of the spatiotemporal changes in droughts is essential in the development of drought contingency plans (Heim 2002).

This is especially important in Xinjiang with its towering mountains and large low-altitude plateaus or basins. In this study, we investigated the spatiotemporal variation of droughts in Xinjiang and its sub-areas over the past 55 years. We focused on regionalization using a clustering algorithm and drought properties for partitioning meteorology stations of interest. Subsequently, change point analysis was performed for homogeneous regions, and the relationship between SPI-based drought and its affecting factors discussed.

The rest of this paper is structured as follows: immediately below, the study area and data set are introduced, as well as the statistical technique used in the study. This is followed by the results for the whole of Xinjiang as well as for different geographic sub-areas. The next section discusses the temporal trend, especially the occurrence of change point in some stations and regions. Finally, the conclusions and recommendations for future research are presented.

DATA AND METHODS

Study area and dataset

Xinjiang (73°40′–96°18′E and 34°25′–48°10′N) is located in Central Asia with a total area of 1.6 million km^2 and an elevation of -158 m to 7,390 m. It plays an important strategic role in the 'One Belt and One Road Initiative', and shares borders with eight countries: India, Russia, Kazakhstan, Kyrgyzstan, Tajikistan, Pakistan, Mongolia, and Afghanistan (Figure 1). Xinjiang can be geographically divided into two regions 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. The daily meteorological data collected at 51 meteorological stations from 1 January 1961 to 31 December 2015 were used in this study, and were downloaded from the official Chinese meteorological website (http://data.cma.cn). The sea surface temperature (SST) data over the North Atlantic Ocean (20–70°N) with a resolution of $5^\circ \times 5^\circ$ were provided by the National Oceanic and Atmospheric Administration (NOAA). Data quality control and homogeneity assessment were attained using the RclimDex software package (Zhang & Yang 2004). The process consists of two steps: (1) missing records were interpolated using data of nearby stations in the same year; and (2) data quality control was performed and unreasonable data were handled in accordance with the missing data.

Drought indexes

The SPI is a meteorological drought index based solely on precipitation data (Mckee *et al.* 1993). Three main advantages may arise from the use of SPI: (1) the calculation is relatively easy as this index is based on precipitation alone; (2) it can characterize drought intensity and duration well; and (3) it has a multi-temporal scale application dimension. The SPI-12 is a good indicator of the long-term drought conditions, which is calculated based on the total precipitation amount of the past 12 months. In this paper, the gamma distribution function is found to fit the precipitation data well, because the precipitation does not follow a

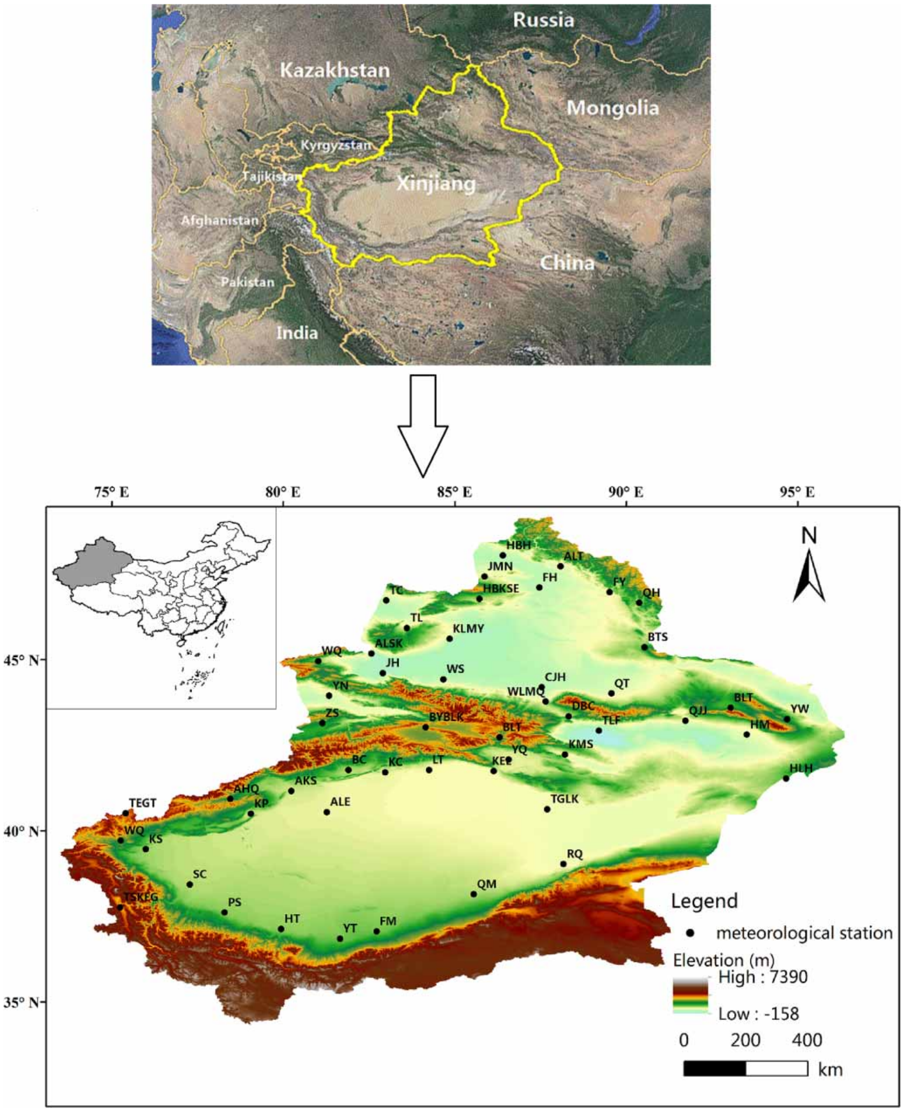

Figure 1 | Location of the study area and the meteorological stations for data collection.

normal distribution. Detailed computation of the SPI can be found in Cacciamani *et al.* (2007).

Proposed methodology

The variation of SPI-12 from the meteorological stations was first examined using k-means analysis, which would enable the grouping of stations with similar temporal trends. The Mann–Kendall (MK) method (Kendall 1975) and correlation analysis were used for trend and change point analysis. The Morlet wavelet (Weng & Lau 1994) was used to locate vital temporal statistics. The overall methodology is shown in Figure 2.

Statistical methods

The non-parametric statistical MK test (Kendall 1975) has wide applications in climate modeling, trend detection, environmental studies, and hydrology. It is a non-parametric test requiring no specific assumption of the joint distribution of the data, and thus is generally not affected by departures from normality.

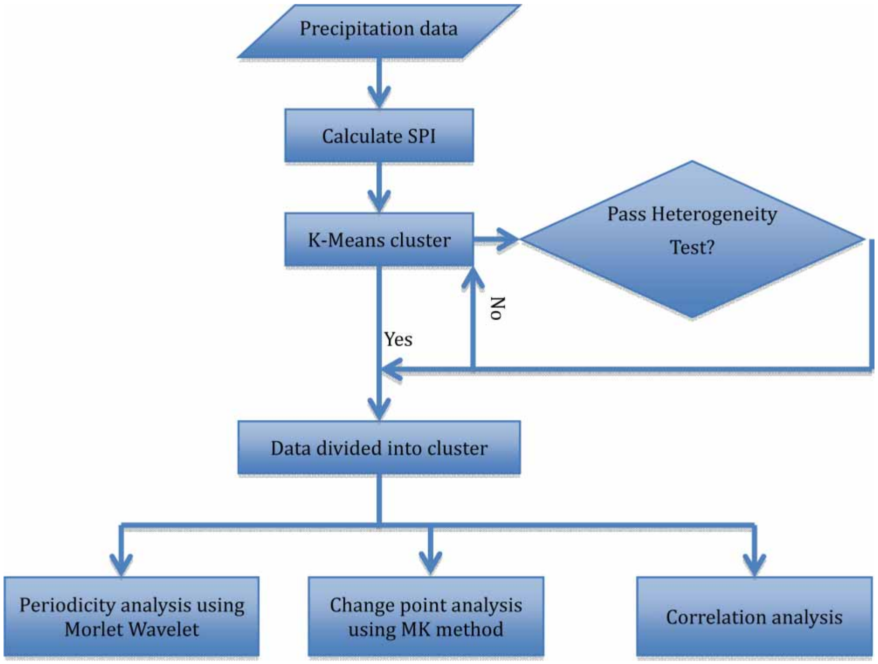

Figure 2 | The steps of the methodology.

The Morlet wavelet transform method converts the initial signal into a compact description (Weng & Lau 1994), which has two major advantages over other wavelet functions (i.e., Mexican hat wavelet, Daubechies wavelet, and Morlet wavelet) in hydrological analysis: (1) continuity of the results; and (2) arbitrary selection of time scales.

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

Table 1 | Heterogeneity test

	SPI-based drought		
Name	**H(1)**	**H(2)**	**H(3)**
Cluster 1	−0.7966	−0.8820	−1.2298
Cluster 2	1.4103	−0.5163	0.0101
Cluster 3	−0.6137	1.3984	1.2197

$$H = \frac{V - u_v}{\sigma_v} \tag{1}$$

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

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.

K-means method

Different basins and hydrological factors can have 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 vectors to the cluster whose centroid is the closest. The iterative steps involved in the K-means clustering include (Sönmez 2009):

(1) All samples are selected randomly into the k clusters, each of which is represented by a centroid.
(2) Computing the centroid of each cluster by averaging its sample vectors.
(3) All samples are redistributed to the nearest cluster according to the distance between the cluster centroid and sample, and then the centroid of the cluster is recalculated.

Steps 2 and 3 are repeated until the clusters become stable.

RESULTS

Cluster analysis

The frequency of droughts at different spatial scales changes, largely depending on geographical locations, basin size, and local hydrological factors. Three main clusters can be obtained using the K-means clustering based on drought, which are largely associated with the topography and climate of the region. The heterogeneity test in Table 1 shows that these three clusters are possibly homogeneous regions. Figure 3 shows the geographical location of the three clusters (cluster 1, 2, and 3), corresponding roughly to south Xinjiang, north Xinjiang, and mountainous area (Tianshan Mountain, Altai Mountain, and Pamirs), respectively.

Trend analysis of Xinjiang province

The inter-decadal variation (1961–2015) of drought shows an obvious decreasing tendency in 1961–2015 (Figure 4). Severe drought is observed in north Xinjiang in the period 1971–1980, which might be related to the most severe drought that occurred in 1974. However, further study is needed to fully elucidate the causes of this phenomenon. The inter-decadal variation of drought shows a gradual shift from the east to the west and then back to the east again over a period of 55 years. The most severe drought occurs in the period 1961–1970 and the more recent period 2001–2015 in the east region, whereas the period 1971–2000 shows the reverse phenomenon.

Figure 5(a) shows the inter-annual and inter-decadal variation of drought in the study area based on SPI-12, and Figure 5(b) shows the changing trend of drought obtained by the MK method. Figure 5(a) shows that this region experiences widespread drought from 1961 to the mid-1980s, and subsequently there is a relative humid period with higher SPI-12 values. The average SPI-12 value is −0.365, −0.312, −0.028, 0.211, 0.308, and 0.354 in the period 1961–1970, 1971–1980, 1981–1990, 1991–2000, 2001–2010, and 2010–2015, respectively, thereby indicating that this region becomes increasingly humid over time.

Figure 5(c) shows the changing trends of different drought grades. It shows that the number of sites with 'normal drought' shows an increasing trend (17%) since

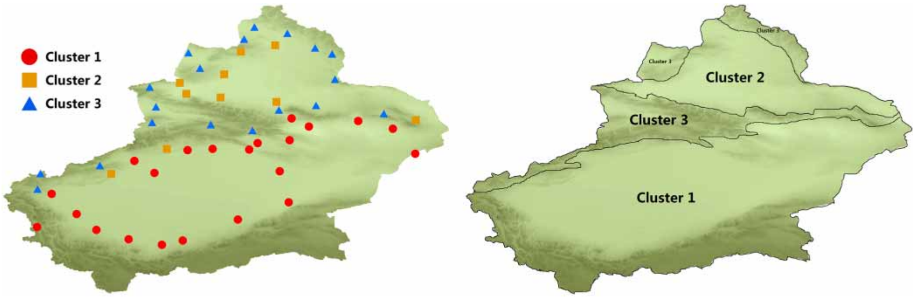

Figure 3 | Regionalization of meteorological stations for drought analysis.

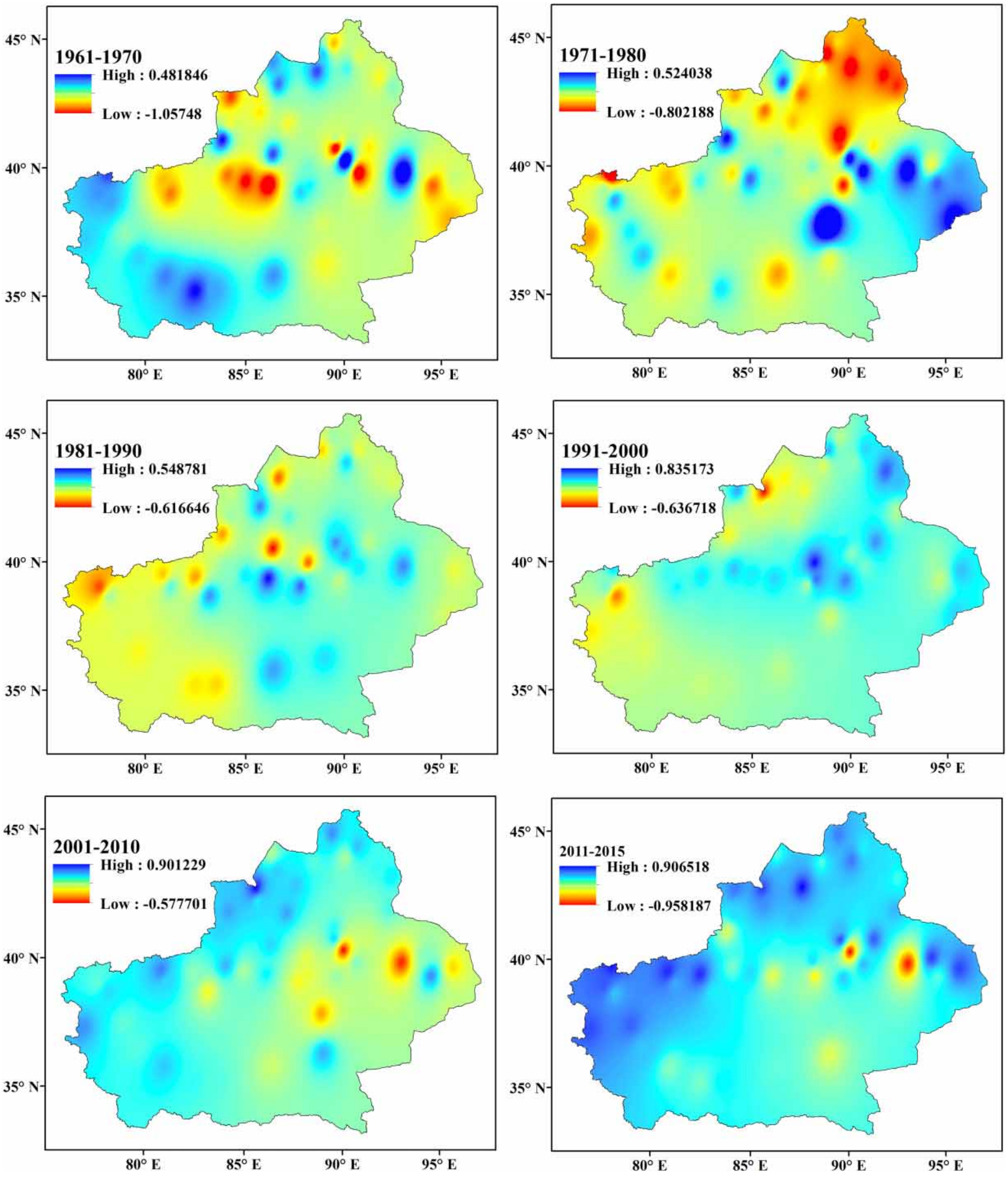

Figure 4 | Spatial distribution of drought in different periods (10 years in all plots except for the last one (5 years)).

the early 1990s, whereas that with 'special drought' decreases dramatically and approaches 0% over the last 4 years. The variation tendency of 'normal drought' shows an obvious increasing trend at the rate of 0.33/a, followed by that of 'medium drought', 'mild drought', 'special drought', and 'severe drought' with a rate of −0.09/a, −0.06/a, −0.05/a, and −0.04/a, respectively. These results are largely in agreement with those of Li *et al.* (2012), which also show a decreasing tendency of drought in Xinjiang with additional differentiation of drought grades.

Trend analysis of each cluster

Table 2 shows that the maximum and medium SPI-12 values reach a maximum in cluster 3, followed by those in cluster 2 and cluster 1, indicating the high vulnerability of cluster 1

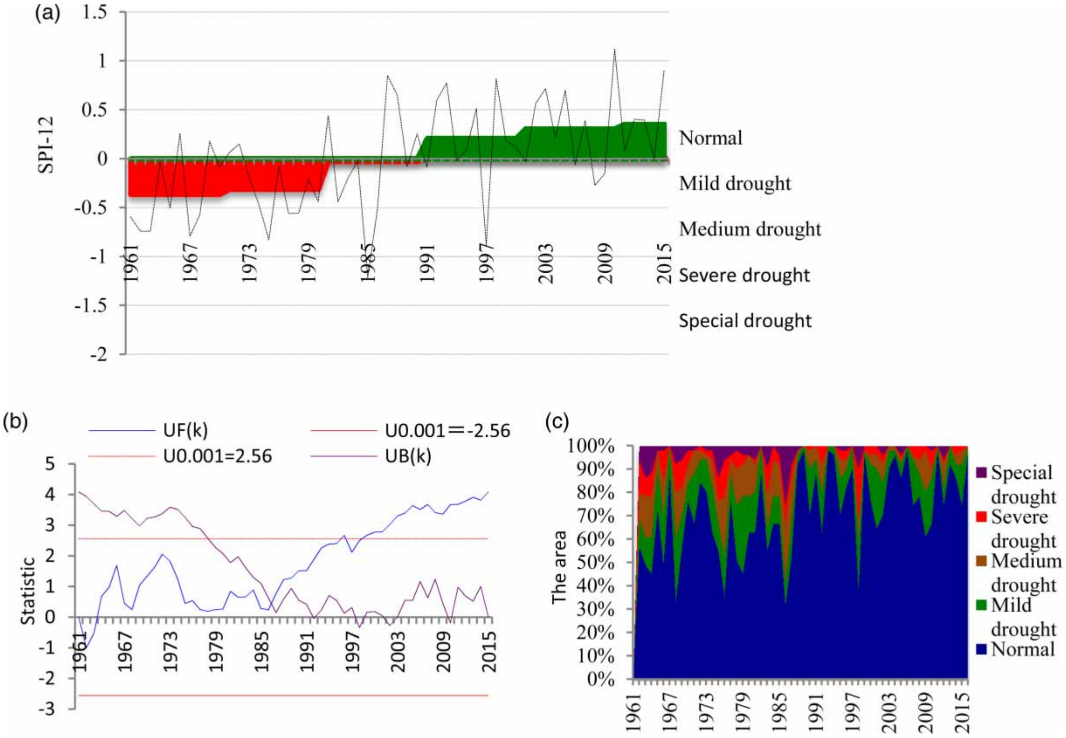

Figure 5 | Inter-annual and inter-decadal variations based on SPI-12 (a), changing trend obtained by the MK method (b), and changing trends of different drought grades (c) in Xinjiang during 1961–2015. In Figure 5(a) the portions in red and green represent the six periods of 1961–1970, 1971–1980, 1981–1990, 1991–2000, 2001–2010, and 2010–2015. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/nh.2018.105.

Table 2 | Basic statistics of regional droughts

			SPI-12 value	
Name	**Numbers of sites**	**Spatial distribution of sites**	**Medium**	**Max**
Cluster 1	23	Among them 17 sites located in South Xinjiang (74%)	−0.024	0.996
Cluster 2	18	Among them 14 sites located in North Xinjiang (78%)	0.019	1.176
Cluster 3	10	All of the sites with high altitude in mountainous area	0.033	1.296

where water scarcity is a tangible constraint. Figure 6 shows an obvious decreasing tendency of drought in all clusters. Both cluster 2 and cluster 3 show the same changing trend after the change point, and drought decreases significantly with few negative values. However, drought occurs for some time in cluster 1.

Presence of periodicity over time

The wavelet transform coefficients, which indicate how the energy of the strain signals is divided in the time-frequency domain (Darpe 2007), are shown in the left part of Figure 7, where the x-axis denotes the time parameter and the y-axis denotes the scale parameter that is inversely related to the frequency. The scalogram surface in the right part of Figure 7 shows the position of the dominant energy. The plots of wavelet power spectrum for the SPI-12 data illustrate the periodic oscillation of droughts. A periodicity of 1.5–3.5 year is clearly observed in the wavelet spectrum of cluster 1 and cluster 2 with a cycle of more than 30 years. However, the long-scale patterns (more than 30 years) are relatively weak. Cluster 3 shows a periodicity of 1.5–3.5 years, 5–7 years, 8–10 years and the cycle of more than 30 years. However, the

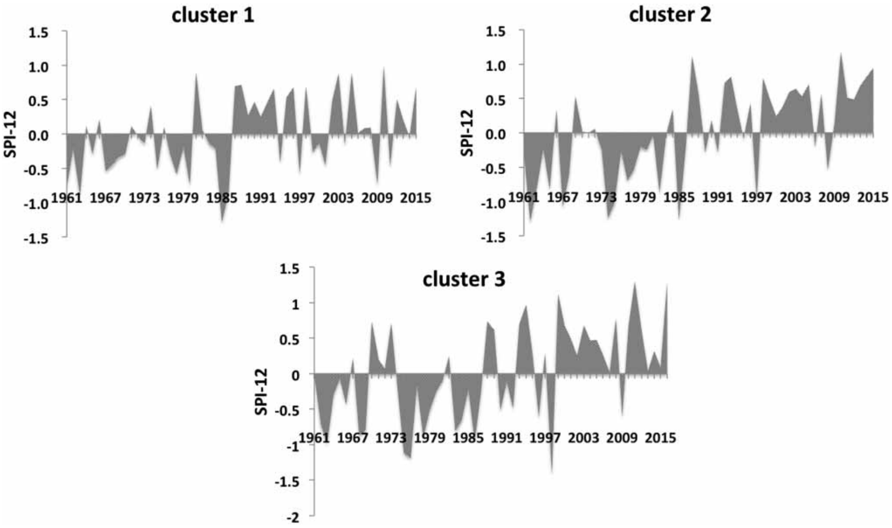

Figure 6 | Drought patterns in each cluster according to SPI-12 annual variations.

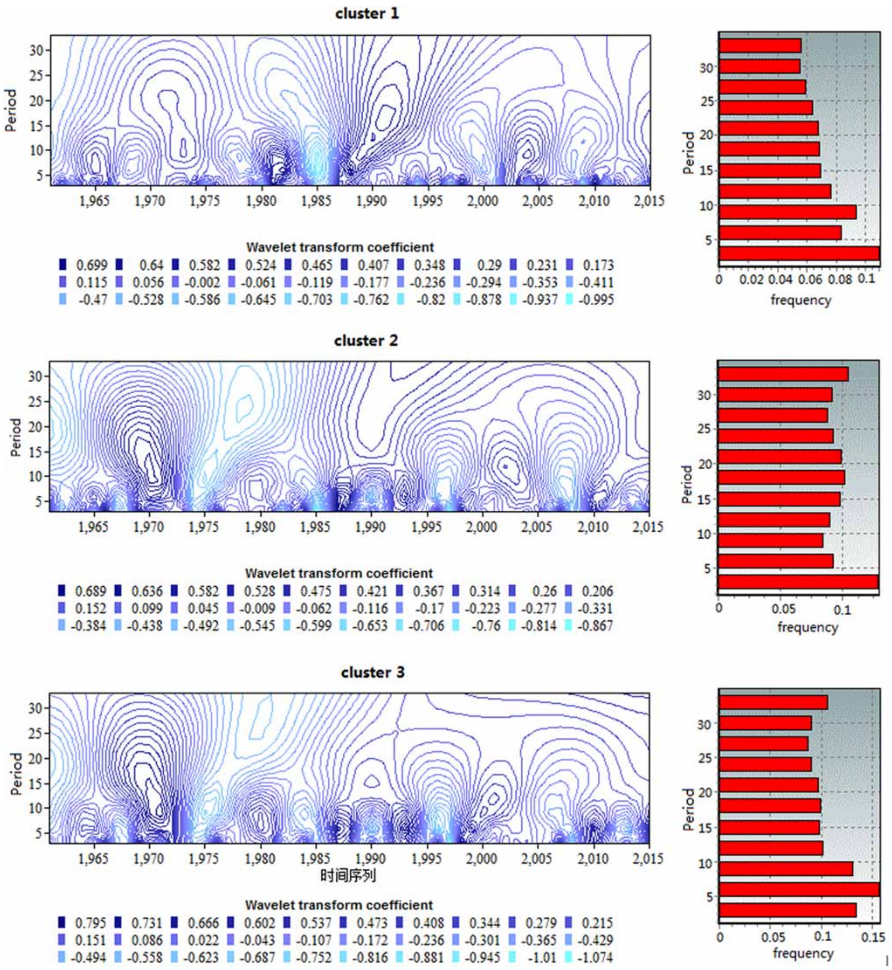

Figure 7 | Dominant periodicities of SPI-12 based drought by Morlet-wavelet analysis in each cluster.

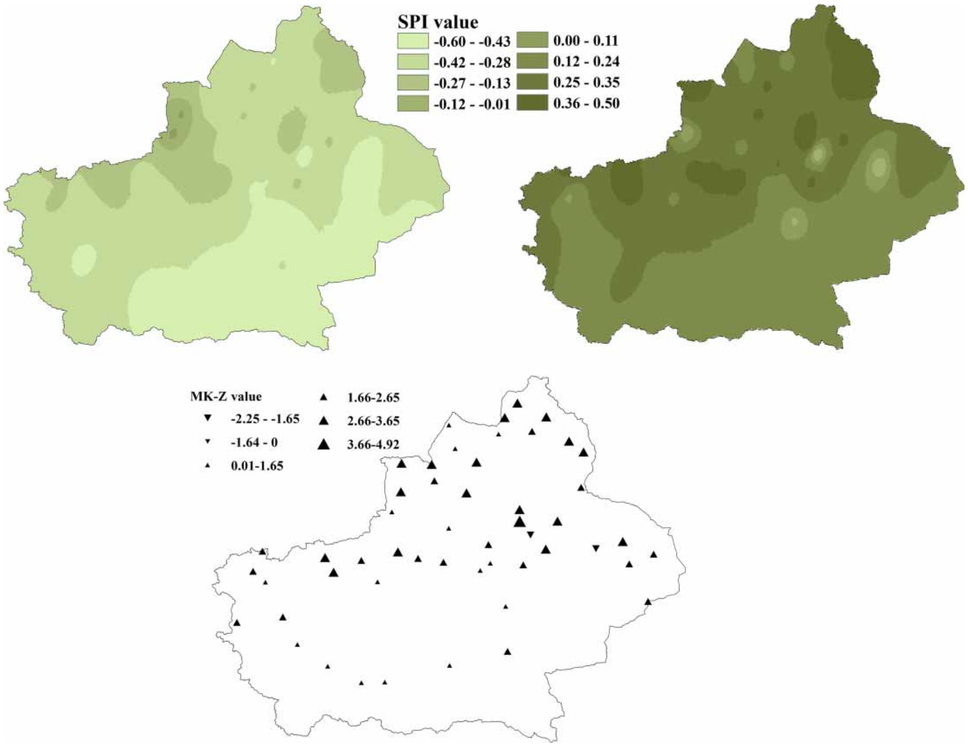

Figure 8 | Spatial patterns of droughts before (a) and after (b) the change point (shown in Figure 5); (c) the significance test represented by Z values.

5–7 year component is the strongest and can affect the entire study period. In summary, there is a strong short-scale periodicity (1.5–10 years) in Xinjiang, which may be related to the atmospheric circulation, one of the main factors affecting climate change. For example, Dai *et al.* (2012) found that precipitation was greatly affected by the North Atlantic Oscillation.

Change points

Drought shows an obvious decreasing tendency in the periods before and after the change point (Figures 8(a) and 8(b)), especially in northern Xinjiang, which is in good agreement with that of precipitation and precipitation extremes (Zhang *et al.* 2012b, 2012c). The significance is calculated by the MK method (Figure 8(c)). It shows that the changing trend is enhanced from the south to the north throughout the study area, and about 55% of sites have a significant alleviating tendency of drought at the 0.01 significance level (|Zs| greater than 2.32). However, droughts at some sites are more, yet not significantly, severe.

DISCUSSION

Occurrence of change points

Table 3 shows a summary of change point analysis of each site. Change point is detected in 65% of sites over the past 55 years. Of the 18 sites with no change point, 14 sites (78%) are located to the south of Tianshan Mountain; whereas of the 33 sites with a change point, 23 sites (70%) are distributed north of Tianshan Mountain. Table 3 also shows the number of change points in the period 1961–1970, 1971–1980, 1981–1990, 1991–2000, and 2001–2010, respectively. It shows that about 4% of change points occur in the period 1971–1980, 74% in the period 1981–1990, and 22% in the period 1990–2000, respectively. This is in line with the occurrence duration shown in Figure 8. However, some abnormal phenomena are also noted. For instance, 30% of sites south of Tianshan Mountain have drought change points in some years (detailed in the table). It can be concluded that the most significant change occurs in the 1980s where there is an

Table 3 | Change-point analysis of the whole of Xinjiang by MK test

Change point	**Numbers of sites**	**Distribution of sites**	**Period of change points (number of sites)**	**Significance**
Detected	33	North of Tianshan (23)	1971–1980 (1)	$Z \geq 2.32$
			1981–1990 (17)	$1.9 \leq Z \leq 4.92$
			1991–2000 (5)	$2.22 \leq Z \leq 3.22$
		South of Tianshan (10)	1971–1980 (4)	$2.44 \leq Z \leq 2.76$
			1981–1990 (2)	$2.03 \leq Z \leq 3.09$
			1991–2000 (2)	$2.56 \leq Z \leq 3.55$
			2000–2010 (2)	$1.47 \leq Z \leq 2,63$
Not detected	18	North of Tianshan (4)	–	–
		South of Tianshan (14)	–	–

abrupt change from warm-dry to warm-wet in northwest China.

Based on the cluster analysis, the diverse changing trends of droughts are presented in Figure 9. In cluster 1, the change point occurs over a period of time from 1974 to 1986, which differs from that in clusters 2 and 3 in which the change point is distinctly clear and later in time. Figure 9 shows the occurrence of change point in 1986 in cluster 2 and in 1991 in cluster 3, respectively. All clusters show a significant increasing trend at the 0.001 significance level, with a |Zs| value greater than 2.56 (3.48 in cluster 1, 4.78 in cluster 2, and 2.66 in cluster 3, respectively). Future studies are needed to account for the strongest variation in cluster 2, which may be due to the terrain and local microclimate identified during clustering. An example is that the movement of water vapor from the Arctic Ocean can be affected by local terrain and climate, thus causing an increase in precipitation in North Xinjiang. These findings are also supported by previous studies on the effect of climate change on precipitation in Xinjiang (Shi *et al.* 2002; Feng *et al.* 2006). It has been suggested that: (1) the global warming effect may result in greater circulation of water masses over the Tibetan plateau and consequently more precipitation in Xinjiang; and (2) the atmospheric humidity and water content increase significantly. Shi *et al.* (2002) found a significant change in snowmelt in the west Tianshan region since 1987. In addition, we also found a continuous alleviating tendency of drought since 2002, with an average changing rate of 0.016 per decade.

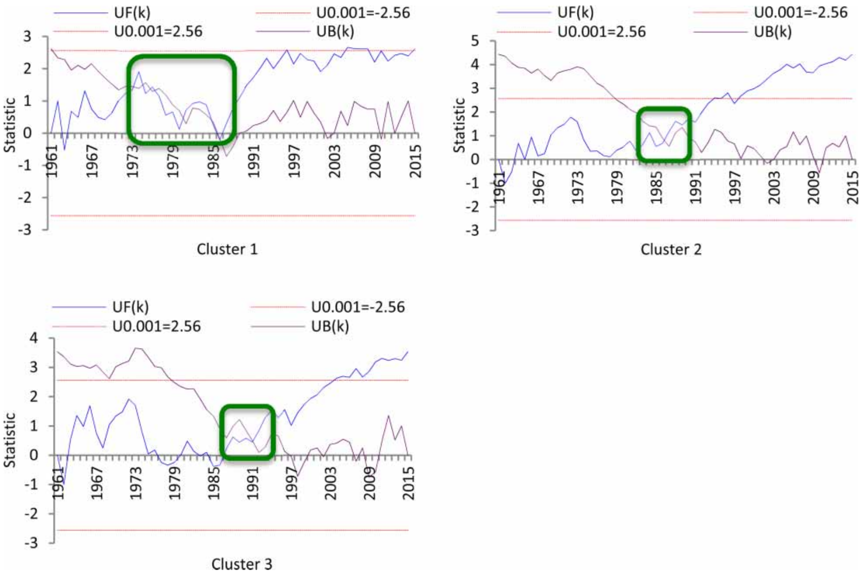

Figure 9 | Change point in each cluster.

Table 4 | Correlation analysis of drought-related factors during the earlier, middle and latter stage of change period

	Precipitation	Temperature	Sunshine	Relative humidity	SST
Earlier stage	0.97	−0.28	−0.18	0.76	0.13
Middle stage	0.95	0.08	−0.20	0.82	0.17
Latter stage	0.97	−0.17	−0.62	0.45	0.19

Possible factors affecting change point

The occurrence of meteorological drought of interest in this study depends mainly on changing climate, especially the precipitation. The regional variation of dry-wet climate is intimately linked with precipitation and evaporation, and thus climate factors, such as sunshine, temperature, and relative humidity, are potential factors affecting the change point. In addition, the variation of global SST patterns and large-scale atmospheric circulation is also associated with regional changes in precipitation and temperature due to tele-connections (Alexander *et al.* 2009). Thus, SST is also considered in this study. Correlation analysis was conducted for the early, middle, and latter stages of the change period (1981–1990) and shown in Table 4. The results show a significant relationship between precipitation and the SPI-12 value, and an increase in precipitation can result in a reduction in the severity of drought. However, the relationship between drought and relative humidity is not stable, with the maximum value observed in the middle stage. The SPI-12 value is negatively correlated with temperature, drought, and sunshine, probably because an increase in sunshine can result in high temperature and a large amount of evaporation, and consequently the aggravation of drought. However, SST shows a weak relationship probably due to the location of the study area, because Xinjiang is in the hinterland of China, and the moist air from the ocean can be affected by the Tibetan plateau with an average altitude of above 4,000 m.

CONCLUSIONS

This study investigated drought characteristics in Xinjiang province and its sub-areas using MK test, cluster analysis, and Morlet wavelet analysis. The results show that drought in the Xinjiang area is generally becoming less severe, and there is non-uniform spatial variation of drought, which is especially pronounced in northern Xinjiang. Change point analysis shows multiple change point incidents over the past 55 years. Some salient conclusions can be drawn from this study:

1. There is a unique spatiotemporal distribution trend of drought in Xinjiang, and the inter-decadal variation of drought shows a gradual spatial shift from the east to the west and then back to the east again in the period 1971–2015.
2. North Xinjiang is becoming wetter at a faster rate compared to south Xinjiang, and it has a higher occurrence of change point sites (70%) than south Xinjiang (30%).
3. The historical drought situation in Xinjiang is better represented by three clusters rather than a homogeneous region. The periodicity of drought in Xinjiang is stronger in short time scale. Cluster 1 is the driest, cluster 2 has a clear alleviating tendency of drought, and cluster 3 shows late occurrence of change point.

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