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Changes in the characteristics of dry-wet periods in Xinjiang, China based on the SPEI index

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RESUMEN

El índice estandarizado de precipitación y evapotranspiración (SPEI), calculado a partir de 55 estaciones durante el período 1961-2015, se utilizó para analizar la variabilidad espacial y temporal del clima seco y húmedo en Xinjiang en una escala de tiempo de tres y seis meses, a fin de mitigar los efectos negativos del cambio climático y reducir las pérdidas por desastres. Los resultados obtenidos muestran que la precipitación y la temperatura en Xinjiang tienen una tendencia creciente, con tasas de 8.90 mm y 0.39 ºC por década, respectivamente. SPEI-3 y SPEI-6 muestran la misma tendencia de cambio lineal, con una tasa de cambio de 0.005 y 0.007 por década, respectivamente. Sequías severas ocurrieron en 1997 y 2008, y particularmente en 2008 el número de estaciones meteorológicas con sequía moderada y sequía extrema representó el 60 % del total de estaciones considerando SPEI-6. El análisis de funciones empíricas ortogonales (EOF) indica que SPEI-3 y SPEI-6 tienen una distribución espacial similar en los tres modos EOF. EOF1 refleja que los cambios secos y húmedos generales en el área de estudio se debilitan y hay una tendencia a la sequía; EOF2 indica un cambio inverso en el norte y el sur de Xinjiang; EOF3 muestra que en el este de Tianshan hay tendencia a la sequía, mientras que en la parte occidental del sur de Xinjiang tiende a disminuir la sequía. Los espectros de coherencia de ondeletas y transformada de ondeletas cruzadas mostraron que los valores SPEI en Xinjiang tienen períodos de resonancia de diferentes escalas de tiempo con la Oscilación Multidecadal (AMO) del Atlántico, El Niño y la Oscilación del Sur (ENOS), la Oscilación del Atlántico Norte (NAO) y la Oscilación Decadal del Pacífico (PDO), pero con ciertas diferencias en diferentes dominios temporales de correlación. Entre ellos, la AMO es el principal factor de circulación atmosférica que afecta al SPEI en la región.

ABSTRACT

The standardized precipitation evapotranspiration index (SPEI), calculated from 55 stations over the period 1961-2015, was used to analyze the spatial and temporal variability of the dry and wet climate in Xinjiang on a three and six-month time scale, so as to help to actively deal with the negative effects of climate change and reduce disaster losses. The obtained results show that precipitation and temperature in Xinjiang have an increasing trend, with rates of 8.90 mm and 0.39 ºC per decade, respectively. SPEI-3 and SPEI-6 show the same linear change trend, with a change rate of 0.005 and 0.007 per decade, respectively. Severe droughts occurred in 1997 and 2008, and particularly in 2008 considering SPEI-6, the number of meteorological stations with moderate drought and extreme drought accounted for 60 % of all stations. Analysis of Empirical Orthogonal Function (EOF) indicates that SPEI-3 and SPEI-6 have similar spatial distribution in the three EOF modes. EOF1 reflects that the overall dry and wet changes in the study area were weakening, and there was a drying trend; EOF2 was a reverse change in the northern and Southern Xinjiang; EOF3 shows that the East Tianshan had a drying trend, while the western part of Southern

Xinjiang had a moistening trend. The spectra of wavelet coherence and cross wavelet transform showed that the SPEI values in Xinjiang have resonance periods of different time scales with the Atlantic Multidecadal Oscillation (AMO), El Nino Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Pacific Decadal oscillation (PDO), but shows differences in different time-domain correlations. Among them, AMO is the main atmospheric circulation factor that affects SPEI in the region.

Keywords: Wet and dry change characteristics, Empirical orthogonal function, Standardized precipitation evapotranspiration index, Cross wavelet transform.

1. Introduction

Drought is a natural disaster caused by scarce rainfall and uneven surface water budget over a period. It affects a wide range of areas and usually lasts for months or even years (Shi et al. 2015; Xuan et al. 2016). Drought leads to the decrease of ecosystem productivity, which is one of the most serious meteorological disasters threatening China's food security and economic development (Shen et al. 2017; Li et al. 2017). In recent years, the global drought problem is worsening with the intensification of global warming (Guo et al. 2018).

In order to quantify drought monitoring and development trends, many scholars have put forward different indicators, such as the standardized precipitation index (SPI), the Palmer drought Index (PDSI), and the standardized precipitation evapotranspiration index (SPEI), which have different advantages and disadvantages (Wang et al. 2018; He et al. 2017). The standardized precipitation evapotranspiration index (SPEI) proposed by Vicente- Serrano et al., 2010) fully considers temperature and precipitation factors. It is an appropriate tool to monitor changes in meteorological drought, by using the SPI calculation method and multiple time scales characteristics and combines with the advantages of the PDSI on evapotranspiration (Vicente-Serrano et al. 2010; Liang et al. 2017).

Xinjiang in China is a typical arid and semi-arid region, and recent studies have focused on the change of its drought conditions (Xie et al. 2017). Many scholars have indicated a trend in climate transition from warm and dry to warm and wet, involving different spatial variability and strength in the transition trend (Shi et al. 2002; Xuan et al. 2016; Yao et al. 2018). The scope of the drought and the area affected are expanding year by year, and losses due to the drought are increasing in Xinjiang (Sun et al. 2014). Studies on drought change in different regions of Xinjiang have used different drought indexes, but few studies have concentrated on dryness and wetness changes (Pu et al. 2011; Tao et al. 2014; Luo et al. 2016). The 3-month time scale (SPEI-3) can indicate seasonal changes in dryness and wetness representing meteorological drought (Potop et al. 2012).

This study considers SPEI-3 (3-months) and SPEI-6 (6-months) as the main indicators of changes in dryness and wetness in Xinjiang analyzed by statistical techniques (EOF and cross-wavelet transform), for an in-depth characterization of the temporal and spatial distribution and changes of dryness and wetness in Xinjiang and insight into the underlying mechanisms, with a view to prevent and mitigate drought losses in Xinjiang.

2. Data sources and study area

2.1. Overview of the study area

Xinjiang is surrounded by high mountains that prevent the arrival of moist air currents, resulting in a temperate continental climate. The land area is 1.66 million km^2, accounting for 1/6 of China's land area (Fan et al. 2018). The average temperature in Xinjiang is 8.1 ºC and the annual precipitation is about 150mm. However, the spatial distribution of precipitation is very uneven, with large evaporation and potential evapotranspiration (PET) of about 3000mm (Zhang et al. 2019). Xinjiang has diverse landforms, including the Altai Mountains in the north, the Kunlun Mountains and A-erh-chin Mountains in the south, and the Tianshan 3 Mountains across the central part of Xinjiang. The three major mountain ranges surround the Junggar Basin and the Tarim Basin (Fig. 1).

2.2. Data sources

The monthly mean temperature and precipitation data of 55 representative stations in Xinjiang from

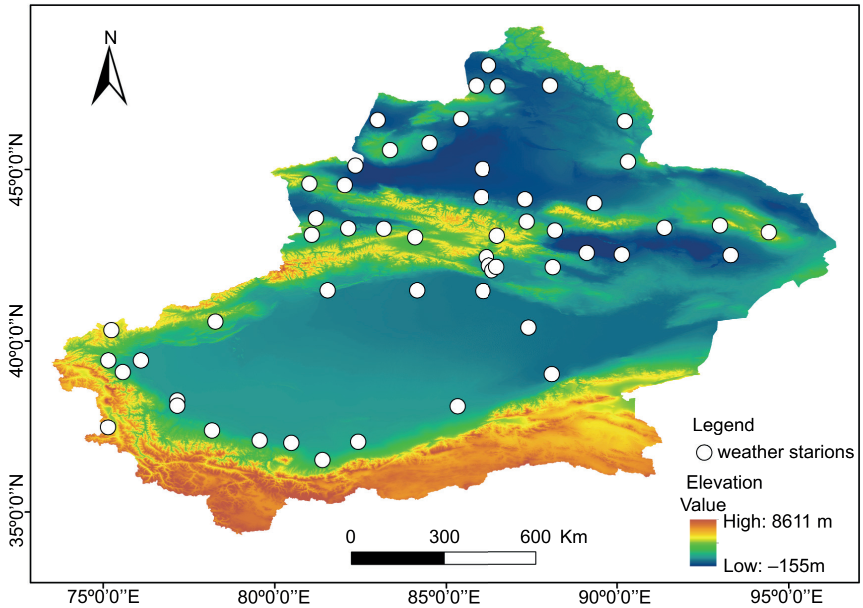

Fig. 1. Distribution of meteorological stations in Xinjiang.

1961 to 2015, as well as the geographic information data such as longitude, latitude, and altitude of each station, were analyzed. Their location is also shown in Figure 1. These data are provided by the Xinjiang Meteorological Information Center, and after strict data quality control, they can be used in climate change analyses. The SPEI index in each station was estimated for the past 55 years, to study the characteristics of dryness and wetness changes.

3. Research Methods

3.1. Calculation method of SPEI index

The standardized precipitation evapotranspiration index SPEI takes monthly average temperature and monthly precipitation as input data, calculates the difference between monthly precipitation and potential evapotranspiration and fits the corresponding probability distribution function, and finally obtains it through normal standardization (Zhang et al. 2018). There are three methods for calculating potential evapotranspiration: Thornthwaite, Hargreavea, and Penman-Monteith. The Thornthwaite method was relatively simple and only needs temperature data to obtain potential evapotranspiration, while the Penman-Monteith method requires more meteorological parameters resulting in a more accurate estimate. Mavromatis (2007) show that similar results are found using simple or complex methods to calculate the potential evapotranspiration in drought indicators. Vicente-Serrano et al. (2010) also show that the choice of potential evapotranspiration method has little influence on the calculation results of SPEI. Since an appropriate calculation method can be chosen according to the availability of meteorological data (Xuan et al. 2016), the Thornthwaite method is used here to calculate the monthly potential evapotranspiration of meteorological stations in Xinjiang over the recent 55 years. The calculation process is detailed in Zhang et al. (2018) and then the SPEI index at each station is calculated. The SPEI index's dryness and wetness rating criteria (Table I) is used to determine the extent to which a site experienced a change in drought conditions in each month.

3.2. Empirical orthogonal function analysis method

Empirical orthogonal functions (EOF) are a common method used in climatology to analyze the spatiotemporal variation characteristics of research areas (Guo et al. 2018). The basic principle is to transform the meteorological data matrix formed by n observations in m space points by principal component analysis, decompose it into a linear combination of space eigenvector matrix and corresponding time coefficient

Table I. Dryness and wetness degrees based on SPEI index.

project	Extreme drought	Moderate drought	Mild drought	Normal	Mild moist	Moderately moist	Extremely wet
SPEI	≤ –2.0	–2.0 ~ –1.0	–1.0 ~ –0.5	–0.5 ~ 0.5	0.5 ~ 1.0	1.0 ~ 2.0	≥2.0

matrix, and estimate and interpret the original field by using the value of space vector eigenmatrix and corresponding time coefficient function. The n observations in the SPEI series for the m space points are used here as input for the EOF analysis. The EOF decomposition method can accurately express the temporal variation and spatial mode of drought and is an important means to decompose the drought characteristics. Therefore, the drought analyzed by this method has strong regularity and consistency (Wang et al. 2016).

3.3. Cross Wavelet Transform

Cross wavelet is a signal analysis method which combines wavelet transformation and cross-spectrum analysis. This method provides the energy resonance and covariance distribution of two time series in the time-frequency space. It is used to study the relationship between two time series in the time-frequency domain from multiple time scales (Ge et al. 2020). The annual average values of SPEI and AMO, ENSO, NAO and PDO, are used here as input to the cross wavelet transform. This method can reveal the correlation and consistency of the two sequences at different time scales and reproduce the phase relationship in time-frequency space. The cross wavelet transform can reveal the high energy region and phase relationship of the two series, but when there is a strong peak in the energy spectrum, the Cross Wavelet may produce misleading results. Therefore, it is necessary to standardize the wavelet energy in the cross wavelet transform to obtain the wavelet coherence spectrum, which can measure the correlation between the two variables (Wang et al. 2019; Qi et al. 2018).

4. Results and analysis

4.1. Changes in precipitation and temperature in Xinjiang

Figure 2 shows that precipitation in Xinjiang has an obvious increasing trend in the recent 55 years, with a change rate of 8.90 mm per decade ($P<0.01$). Note the variability over the period 1961-1985 and

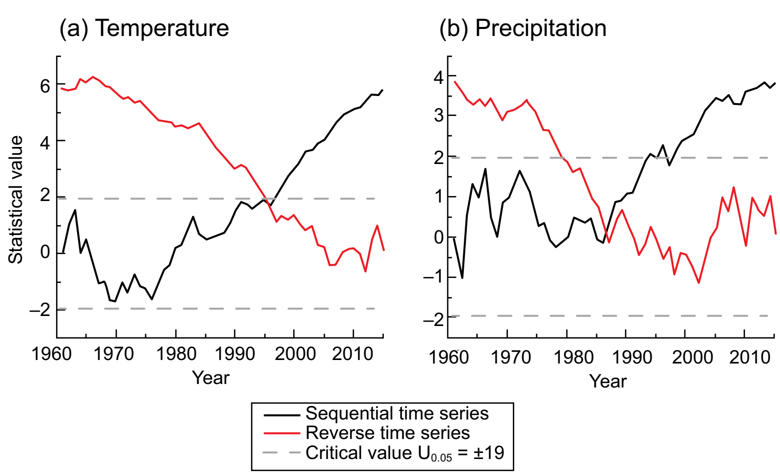

Fig. 2. Mann-Kendall tests for mean annual precipitation and mean annual temperature in Xinjiang.

the sudden change in precipitation that occurred in 1986, significant at the 95 % reliability test. From 1986 to 2015, the precipitation increased by 3.35 mm per decade (which failed the significance test) and the average precipitation increased by 31.07 mm. Overall, the average annual temperature in Xinjiang showed a first a decreasing trend and then increased significantly, with a change rate of 0.39 ºC per decade ($P<0.01$). An obvious abrupt change in temperature occurred in 1994, which passed the 95 % reliability test, over the period 1961-2015. The temperature increased by 0.68 ºC per decade ($P<0.05$) from 1994 to 2015, and the average temperature increased by 1.21 ºC.

4.2. Characteristics of climate change in Xinjiang

Figure 3 shows annual averaged of SPEI-3 and SPEI-6 at 55 meteorological stations in Xinjiang from 1961 to 2015; note that changes in trends are similar for annual averages of SPEI-3 and SPEI-6. The rate of change of SPEI-3 and SPEI-6 was 0.005 and 0.007 per decade, respectively. From 1961 to 1987, the SPEI index was alternately positive and negative, while from 1987 to 1996, the SPEI index was mainly positive, and Xinjiang was in a period of drought relief. After 1997, the SPEI index alternated between positive and negative, but from 2005 to 2015, the negative value of SPEI increased. The SPEI values of SPEI-3 in April 1997, October 2006, and July 2008 were relatively small, being -1.99, -1.69, and -1.79 respectively; SPEI-6 was SPEI in January 2007 and June 2008 the values are relatively small, respectively -1.70 and -1.69, indicating that severe drought in those years.

4.3. Dryness and wetness distribution characteristics of different climate grades in Xinjiang

The SPEI-3 and SPEI-6 values at each station in Xinjiang from 1961 to 2015 were divided into degrees of dryness and wetness. The number of stations with different levels of dryness and wetness observed each year was counted, to indicate the inter-annual variability of the different levels. Figure 4 shows that the overall variation pattern of SPEI-3 and SPEI-6 was similar. SPEI-6 has more wet years than SPEI-3, and SPEI-3 has more normal wet years than SPEI-6. The wettest years were 1987 and 1988, 1992, and 1993. Particularly in 1993 SPEI-6, the number of

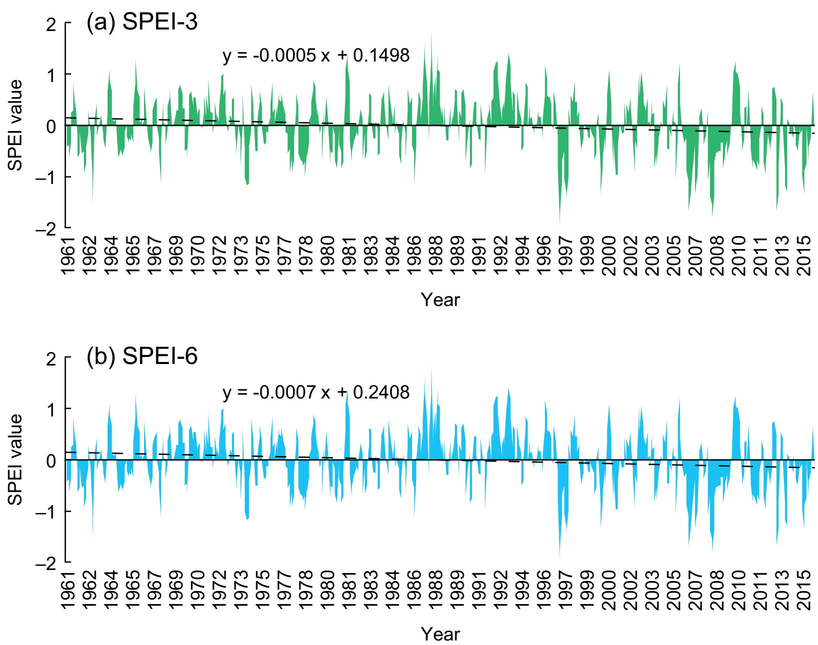

Fig. 3. The annual average SPEI-3 and SPEI-6 time series of 55 stations in Xinjiang from 1961 to 2015.

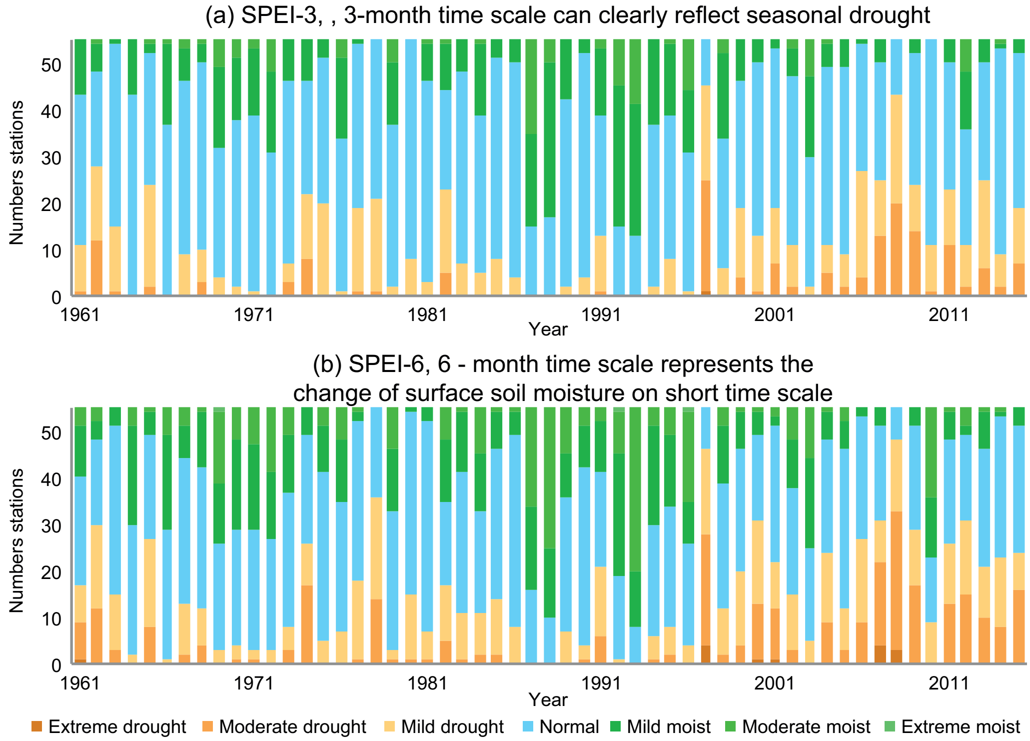

Fig. 4. Number of sites with different levels of wet and dry events in Xinjiang SPEI-3 and SPEI-6 from 1961 to 2015.

moderately humid stations reached 63.64 % of all stations; in 1987 SPEI-3, the number of moderately humid meteorological stations reached 36.36 % of all stations. The number of stations experiencing drought was relatively large in 1997 and 2008. In 1997, the number of meteorological stations with moderate drought and extreme drought reached 45.45 % of all stations, while in 2008 the number of moderate and extreme drought stations reaching 60.00 % of all stations in SPEI-3.

4.4. Temporal and spatial patterns of dry and wet changes in Xinjiang

In order to further study the spatial and temporal distribution climate characteristics in Xinjiang, empirical orthogonal function analysis was carried out on SPEI values of three-month time scale (EOF_3) and six-month scale (EOF_6). Table II shows that the cumulative contribution to the variance of the first three eigenvectors reaches 66.04 % and 60.77 % in three-month time scale and six-month time scale,

Table II. Variance contribution based on the first three modes of EOF_3 and EOF_6.

Mode	EOF_3		EOF_6	
	Variance contribution (%)	Cumulative variance contribution (%)	Variance contribution (%)	Cumulative variance contribution (%)
1	37.32	37.32	34.59	34.59
2	18.59	55.91	16.75	51.34
3	10.13	66.04	9.43	60.77

respectively, which relate to the main spatial-temporal distribution of dryness and wetness changes in Xinjiang.

Figure 5 shows that the contribution to the variance of the first eigenvectors of EOF_3 and EOF_6 were 37.32 % and 34.59 %, respectively. The eigenvector values of the first mode were all positive, indicating that the distribution of climate changes in Xinjiang were consistent throughout the region, e.g. the whole region was either wetter or drier. The high-value centers of the first modes of EOF_3 and EOF_6 are located in Turpan, Hami Basin, and the southwestern part of the Jungar Basin. The range of the first mode of EOF_6 is larger than that of the first mode of EOF_3. In the first mode, the low value of the range EOF_3 is greater than in EOF_6. The time coefficient of the first mode corresponds to the time-varying trend. From 1961 to 1986, the time coefficient showed an upward trend, which indicated that Xinjiang had experience increasing humidity.

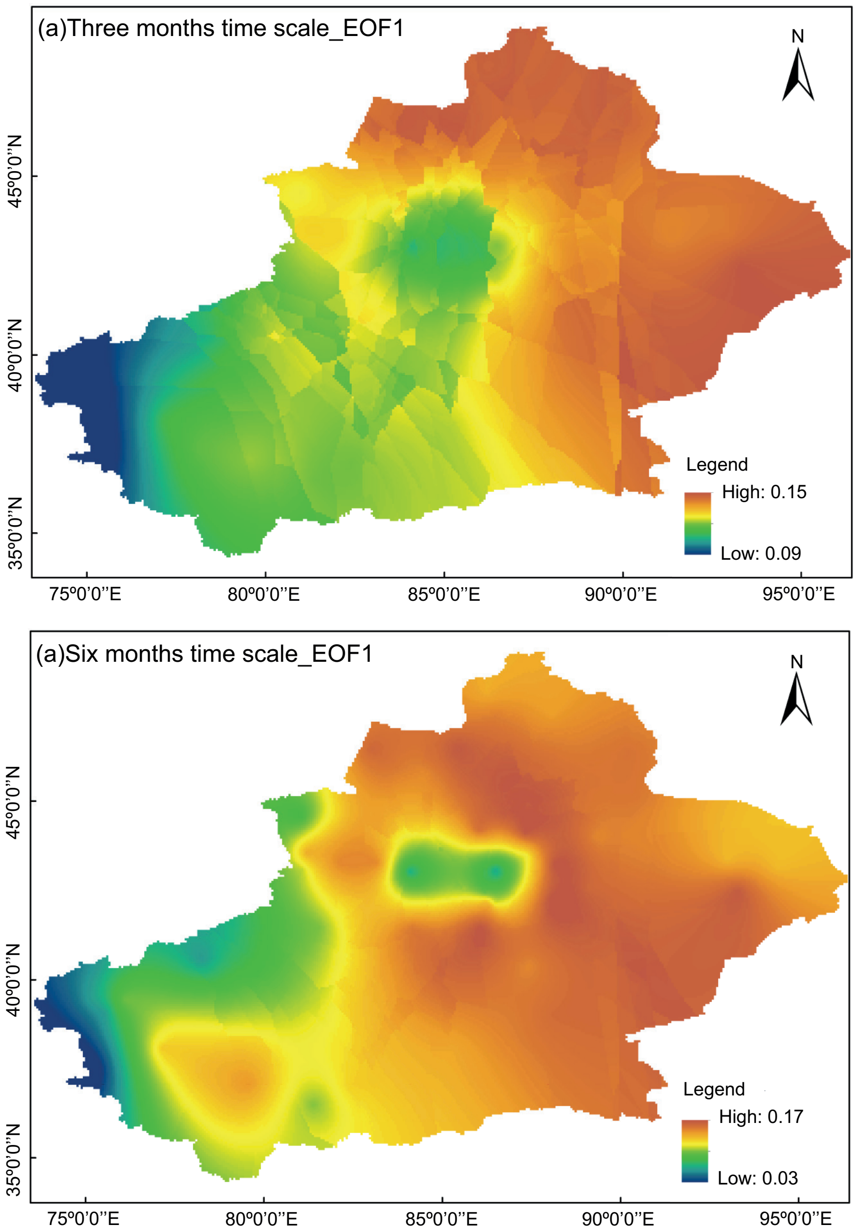

Fig. 5. Spatial distribution of the first mode of the (a) three-month time scale and (b) the six-month time scale in Xinjiang.

From 1987 to 1996, it fluctuated with positive values, indicating that Xinjiang was in a relatively humid period, reaching peak values in 1987 and 1993. However, there was an obvious downward trend after 1996, indicating that the consistency of changes in dryness and wetness in Xinjiang was weakening, and there was an obvious drying trend. In terms of spatial distribution, the change characteristics in northern Xinjiang were more obvious than in southern Xinjiang.

The contribution to the variance of the second eigenvectors of EOF_3 and EOF_6 were 18.59 % and 16.75 %, respectively. The spatial distribution of the second mode was obviously different from the first mode (Fig. 6). Considering the Tianshan Mountains as the boundary, it shows a North-South opposite

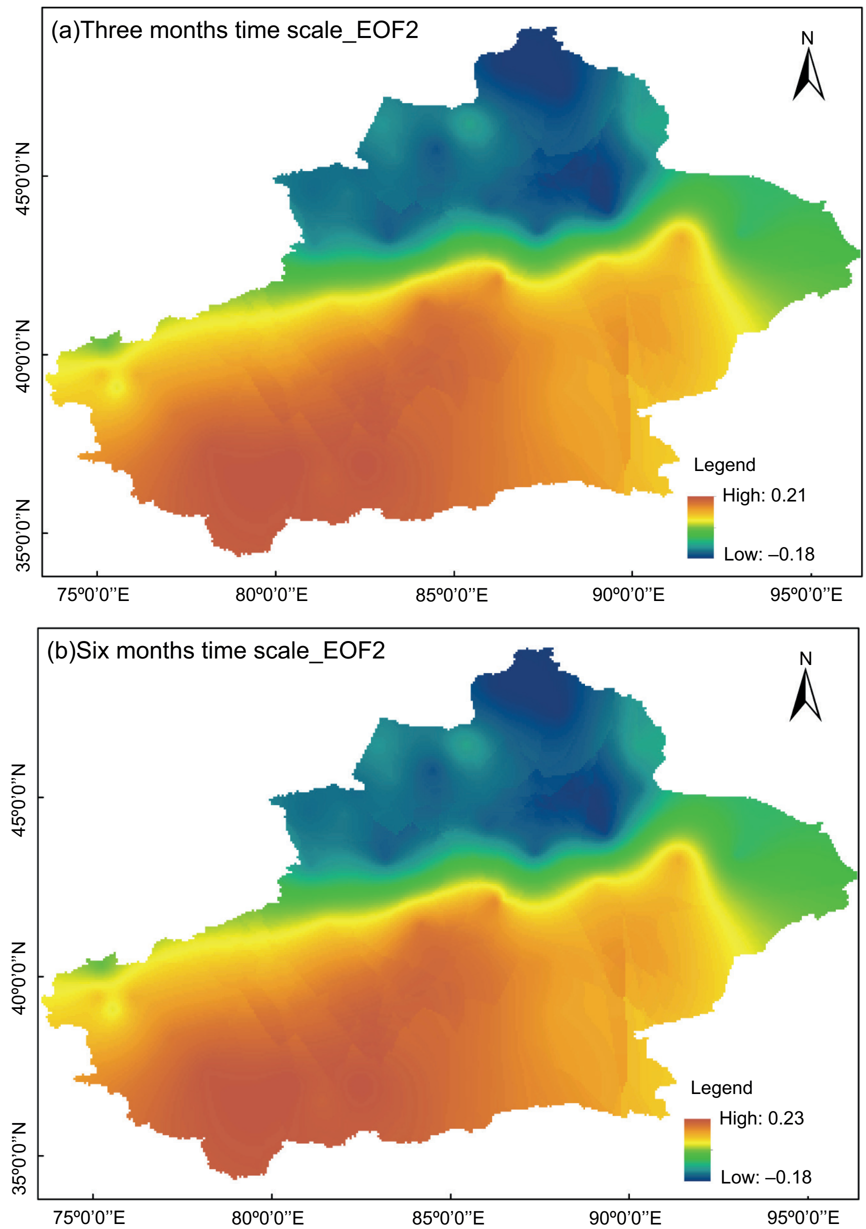

Fig. 6. Spatial distribution of the second mode of the (a) three-month time scale and (b) the six-month time scale in Xinjiang.

pattern of Xinjiang, with a wet northern part and a dry southern part. The spatial distribution of the second mode from SPEI-3 and SPEI-6 was similar but with differences in the local range, the lowest value range was -0.18, and the highest difference was 0.23. The time coefficient of the second mode, indicates that from 1961 to 1997, Xinjiang experienced a relatively humid period. Considering 1997 as the turning point, the regional drying trend becomes more obvious, especially in northern Xinjiang, with drought years in 2007, 2009, and 2011. The linear trend indicates that the aridity in northern Xinjiang was intensified, while it weakened in southern Xinjiang.

Figure 7 shows that the contribution to the variance of the third eigenvectors of EOF_3 and EOF_6 were 10.13 % and 9.43 % respectively, showing the opposite pattern in eastern and western Xinjiang, but with a complex distribution. Moist centers were

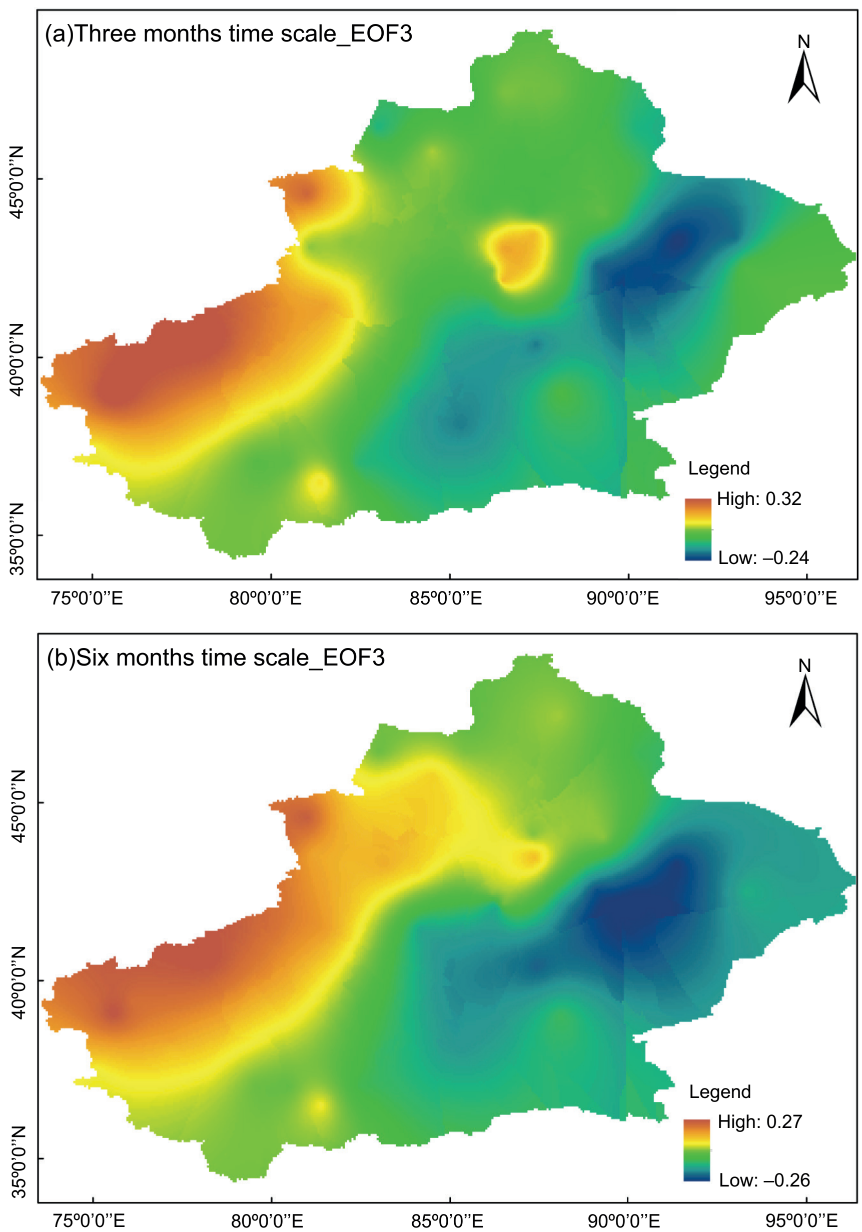

Fig. 7. Spatial distribution of the third mode of the (a) three-month time scale and (b) the six-month time scale in Xinjiang.

mainly located in the western part of southern Xinjiang, the Yili River Valley, and the Middle Tianshan region, while eastern Tianshan experienced a drying trend. In the wettest year of the western region, the eastern region was relatively dry. The time coefficient corresponding to the third mode indicates that 2012 is a typical wet year in the west and dry in the east; in contrast, 1970, 1973, and 1979 were dry years in the west and wet years in the east. The growth rate of the linear change indicates that the dry-wet spatial distribution of this mode increased, with moisture increasing in the western part of southern Xinjiang, also confirmed for example, by stable or expanding glaciers in the Karakorum mountain area in the recent ten years (Asad et al. 2017).

4.5. Relationships between SPEI and atmospheric circulation indexes

Wavelet coherence transform (WTC) and Cross Wavelet Transform (XWT) were used to analyze the multi-time scale correlation between annual SPEI and AMO, ENSO, NAO, and PDO. Coherent wavelet transforms mainly reveal the relationship between annual SPEI value and low energy of climatic factors in the time-frequency domain, while the cross wavelet transform highlights the relationship between the change in SPEI and the high energy region of atmospheric circulation index in the time-frequency domain.

Figure 8 shows that in the power spectrum of wavelet coherence transform and cross wavelet transform, the range surrounded by thick black line has passed the test of a standard spectrum of red noise at the significance level of $\alpha = 0.05$; power spectrum outside the thin black line was not considered due to the influence of boundary effects. The arrow indicates the relative phase difference: arrow from left to right indicates change in the same phase, from right to left indicates the reverse phase change; arrow upward indicates that the change phase of SPEI was 90º earlier than that of AMO, ENSO, NAO, and PDO; arrow downward indicates that the change phase of SPEI was 90º behind that of AMO, ENSO, NAO, and PDO. The cross wavelet transform (XWT) indicates there was a resonance period of 0-3 years between SPEI and AMO and coherent wavelet power spectrum from 1994 to 1999. Moreover, the two directions were downward, which indicates that the phase lag between the two was 90º. There are regions of high-energy of SPEI and ENSO in the coherent wavelet power spectrum in 1963-1965, 1971-1975 and 1983-1992 for period of 1-2 years, 3-4 years, and 4-6 years, respectively. There were 1-3 years resonance period between SPEI and high-energy region of NAO in the coherent wavelet power spectrum from 1963 to 1968, and their direction was upward, which indicates that the change phase between the two was ahead 90º. In 1975-1976, 1989-1992 and 1996-2003, the high energy region of the wavelet power spectrum of SPEI and PDO coherence had resonance periods of 3-4 years, 5-6 years, 1-2 years, and 9-10 years, respectively.

From the perspective of wavelet coherence transform (WTC), there were resonance periods of 0-3 years, 2-4 years, and 7-8 years respectively between SPEI and AMO coherent wavelet power spectrum from 1992 to 2011, and downward in the direction of 2-4 years, indicating that the change phase of SPEI and ENSO coherent wavelet power spectrum was backward by 90º. The low-energy region of SPEI and ENSO coherent wavelet power spectrum has a resonance period of 2-4 years and 4-6 years in 1987-2000. From 1964 to 1968 and 1978 to 1990, there were resonance periods of 0-2 years and 6-7 years between SPEI and NAO in the low-energy region of the coherent wavelet power spectrum, and their direction was upward, with a 90º change phase. SPEI and PDO coherent wavelet power spectrum low-energy region in 1964-1966, 1985-1991, and 1994-2011 have resonance periods of 0-2 years, 6-7 years, and 10-11 years, respectively.

5. Discussion

The results show that the warm and moist trend in the western part of Northwest China has been confirmed by many observational data since the 1980s (Shi et al. 2002; Ma et al. 2006). Liu and Jiang (2015) pointed out that this trend could not be detected by using the Thornthwaite formula. This paper, based on SPEI value with the potential evapotranspiration calculated by the Thornthwaite formula, shows that there was a moist trend in the western part of Southern Xinjiang. Results of the EOF analysis show that the aridity in Northern Xinjiang was more severe and that is was alleviated in southern Xinjiang, consistent

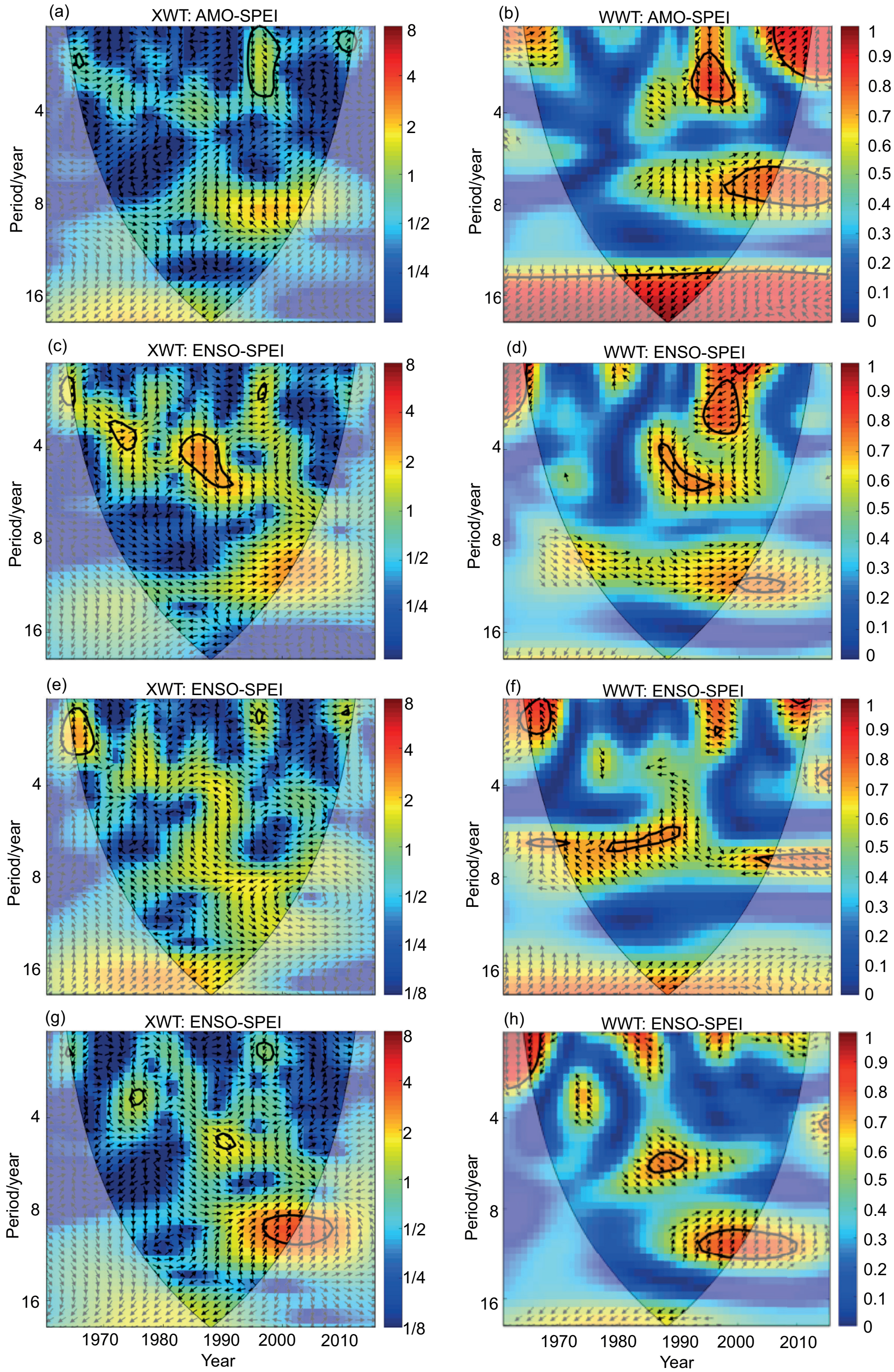

Fig. 8. Coherent wavelet power spectrum (WTC, right column) and cross wavelet power spectrum (XWT, left column) of SPEI and AMO, ENSO, NAO, and PDO in Xinjiang.

with Xuan et al. (2016) using the Penman Monteith formula. The SPEI index allowed to identify severe drought in 1997, 2006, and 2008 in Xinjiang. Bai et al. (2012) had previously pointed out that severe drought occurred in Xinjiang in those years, confirming that SPEI-3 has good applicability in the analysis of dryness/wetness trend in Xinjiang. The SPEI index indicates spatially opposite patterns, with the western region in drought relief and the eastern region relatively dry. This is consistent with results by Shi and Liu (2012) that the largest area of drought variability appears in eastern Northwest Xinjiang. Four spatial modes of dryness/wetness in Xinjiang were characterized by drought change in the whole region and heterogeneity in some parts. The aridity trend in Northern Xinjiang was intensified, while it was alleviated in Southern Xinjiang, and in eastern Tianshan was becoming dry.

Using SPEI to predict the changes in dryness and wetness, to better analyze changes and the duration of drought in Xinjiang, will help actively respond to the negative effects of drought and reduce disaster losses. However, due to the complex terrain of Xinjiang, the diversity of weather and climate systems present, and the scarcity of monitoring stations in the mountainous and desert hinterland, it cannot fully represent the whole extent of dryness and wetness changes in Xinjiang. In the context of global change, climate warming intensifies the water cycle and has a more obvious impact on dry and wet climate in arid areas. Therefore, there are still uncertainties in future climate changes in arid areas, which need to be studied through observational data and models.

6. Conclusions

(1) Both precipitation and temperature in Xinjiang have an increasing trend over the last 55 years, at a rate of 8.90 mm and 0.39 ºC per decade, respectively. Linear trends using SPEI-3 and SPEI-6 are similar, at a rate of 0.005 and 0.007 per decade, respectively.

(2) Drought years were identified in 1997 and 2008. In 2008, 60 % of all sites had SPEI-6 classified as medium drought and extreme drought. In 1997, 45.45 % of all sites had SPEI-3 the medium drought and extreme drought levels. In contrast, wet years were identified in 1987 and 1988, 1992 and 1993.

(3) Three main EOF modes of dry vs. wet climate were identified in Xinjiang, with SPEI-3 and SPEI-6 indicating similar spatial distributions. The first mode of EOF, the most important, reflects the regional consistency of dry and wet climate distribution in Xinjiang. The high-value center was observed in the Turpan, Hami basin, and the southwest of Jungar basin. The second mode reveals a North-South dipole pattern in Xinjiang; after 1997, the drought in Northern Xinjiang intensified and the drought in southern Xinjiang eased. The third mode reveals and East-West dipole pattern, which has an obvious increasing trend. The moist center was mainly located in the western part of Southern Xinjiang, the Yili River Valley, and the Middle Tianshan Mountain area, while the eastern Tianshan Mountain tends to become dry.

(4) The coherent wavelet transform and cross wavelet transform analysis shows that there were resonance periods in different time scales between the SPEI in Xinjiang and the Atlantic Multidecadal Oscillation (AMO), El Nino Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO), but there were some differences in the correlation in different time domains. The correlation between the low-energy regions of the power spectrum was obviously higher than that of the high-energy regions. The resonant periods of the cross wavelet transform were 1- 2 years and 3- 4 years, while for the coherent wavelet transform were 0- 2 years and 2- 4 years.

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