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Research Article

Using Wavelet Analyses to Determine Drought Characteristics: A Cause Study of Western Jilin Province, China

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Abstract: Drought characteristics vary substantially among different climatic regions. Here in this study, wavelet analyses are used to characterize drought from monthly precipitation. The precipitation data are obtained from 6 fairly distributed stations across Western Jilin province (in China) for the period from 1957 to 2010. The calculated monthly Standardized Precipitation Index (SPI) is used as a drought index. Morlet wavelet analysis shows multiple time-scales and significant cycles of drought exist in the study area. The cross wavelet approach was applied to see if there was a connection between monthly SPI time series and large scale climate indices, such as NINO3. The result shows that drought occurrence in the region is mainly influenced by medium and long-time climatic factors. However, different factors have degrees of influence at different stations.

Keywords: Drought characteristics, multifractal analysis, standardized precipitation index, wavelet analysis, western Jilin province

INTRODUCTION

Droughts are among the world's costliest natural disasters, causing an estimated global damage of US$ 6-8 billion and affecting tens of millions of annually (Byun and Wilhite, 1999). Therefore, much focus has been put into drought scenarios in recent years (Mishra and Singh, 2010, 2011). The most common model used in statistical precipitation distribution analysis is the Standardized Precipitation Index (SPI). This model was developed by McKee *et al*. (1993) to categorize the standardized departure of observed precipitation in relation to its probability distribution function (Giddings *et al*., 2005). SPI not only nicely reflects drought intensity and duration, but also has a multi-temporal scale application dimension. In recent decades, SPI has been increasingly used in drought analysis (Bussay *et al*., 1999; Guttman, 1999; Bordi *et al*., 2001).

Hydrological time series are often generated by complex systems of which we know little. By time and frequency signal adjustments, wavelet analysis can be used to investigate detailed temporal patterns in frequency and time domains (Anctil and Coulibaly, 2004; Kang and Lin, 2007; Özger *et al*., 2009; Grinsted *et al*., 2004). Because wavelet analysis is suitable for investigations involving multi-time scales or variance trends (Torrence and Compo, 1998), it is widely used in drought analysis.

The objective of this study was to:

- Calculate monthly SPI for the semi-arid Western Jilin province using 1957-2010 precipitation data from 6 meteorology stations across the region.
- Use wavelet analysis to identify SPI time-series with significant multi-temporal scales/cycles.
- Use the cross wavelet transform to investigate the effect of large scale climate indices of El Ni˜no Events.

The results of this analysis could be critical in developing sustainable agronomic and water resources management strategies that are based on drought characteristics in the study area and beyond.

MATERIALS AND METHODS

Study area and acquired data: The Western Jilin province study area which is part of the giant fracture basin lying in the humid east and inland arid transition

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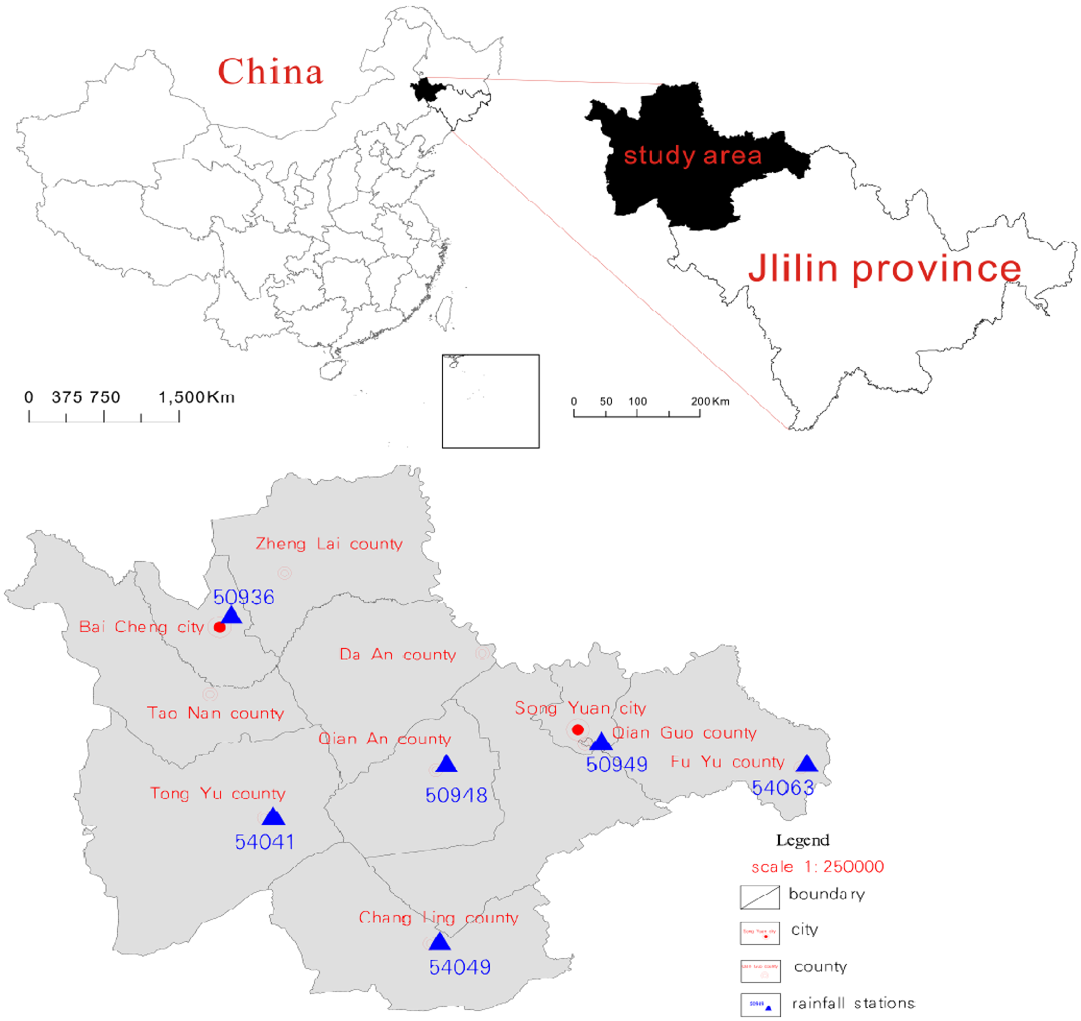

Fig. 1: A map of the study area showing the weather stations selected for precipitation data collection

Table 1: A list of weather stations used in the study along with the basic statistical properties of the precipitation

Station ID	Station name	Longitude (°E)	Latitude (°N)	Elevation (m)	Annual mean (mm)	S.D	Monthly mean (mm)	S.D
50936	BAI-CHENG	122.83	45.63	155.30	390.01	130.44	32.50	51.26
50948	QIAN-AN	124.02	45.00	146.30	407.21	101.48	33.93	49.55
50949	QIAN-GUO	124.87	45.08	136.20	423.94	88.07	35.33	48.26
54041	TONG-YU	123.07	44.78	149.50	384.69	97.00	32.06	47.21
54049	CHANG-LING	123.97	44.25	188.90	439.20	107.33	36.60	50.91
54063	FU-YU	126.00	44.97	196.80	505.90	127.20	42.16	56.25

zone. The study area has 43 779 km^2. The majority of the study area is located in the plains and a small portion is located in the hilly region. The climate of this region belongs to the semi-arid and semi-humid continental monsoons. The annual mean rainfall is 350-500 mm. Because of the skimp precipitation, the quantity of water is lacking and water resources exploitation keeps in higher level. Droughts are frequent in this region, with localized occurrences on nearly yearly basis (Wang *et al*., 1991).

Monthly precipitation data used in characterizing droughts were collected from 6 weather locations across the Western Jilin province study area for the period from 1957 to 2010. Locations of weather stations are shown in Fig. 1 and the characteristics of the stations (e.g., geographical coordinate, annual mean and standard devotion) are listed in Table 1.

Standardized precipitation index: The Standardized Precipitation Index (SPI) was developed by McKee *et al.* (1993) for identifying, monitoring simulating localized droughts. It identifies drought periods and determines the independence of droughts at multi-temporal scales. The calculating values of the SPI for different time scales can reflect the different sensitivity of precipitation.

The index is negative for dry and positive for wet conditions. With increasing severity of dry or wet conditions, the corresponding index also becomes more

Table 2: The McKee *et al*. (1993) Standard Precipitation Index (SPI) categories for drought

Category	SPI Value
Mild drought	(0) – (-0.99)
Moderate drought	(-1.0) – (-1.49)
Severe drought	(-1.5) – (-1.99)
Extreme drought	≤-2

negative or positive. Drought categories of SPI are defined in Table 2. In this study, SPI values of monthly time-scale are calculated and analyzed. Negative SPI values that represent meteorological drought are also emphasized.

Wavelet analysis: The wavelet transformation converts a function (or signal) into another form that either makes certain features of the original signal more amenable to study or enables the original dataset to be more succinctly described (Addison, 2002). The Morlet wavelet function φ(sometimes called the Gabor wavelet) is used in this study and is given as (Wang *et al*. 2005):

$$\varphi(t) = e^{i\omega_0 t} e^{\frac{-t^2}{2}} \quad (1)$$

where, ω_0 is the non-dimensional frequency. When $\omega_0 \geq 5$, the Morlet wavelet approximately satisfies the compatibility condition.

For a given Morlet wavelet and hydrological time-series *f*(t), the continuous wavelet transformation is given as:

$$W_f(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t) \overline{\varphi}\left(\frac{t-b}{a}\right) \mathrm{d}t \quad (2)$$

where,
$W_f(a, b)$ = The coefficient of the wavelet transform
$\varphi(t)$ = The global wavelet function
$\overline{\varphi}$ = The complex conjugate of φ

The parameter *a* is either a dilation (*a*>1) or contraction (*a*>1) observation factor that indicates the value of a time-scale. Also the parameter *b* is a temporal translation or shift of the function φ. As a time-series is usually discrete (e.g., $f(k\Delta t)$ where k = 1, 2, 3, …, N and Δt is equal time spacing) Eq. (2) becomes:

$$W_f(a,b) = \frac{1}{\sqrt{a}} \Delta t \sum_{k=1}^{N} f(k\Delta t) \overline{\varphi}\left(\frac{k\Delta t - b}{a}\right) \quad (3)$$

The wavelet spectral power is equal to the modulus square of the wavelet transform coefficient (Koirala *et al*., 2010). A plot of the spectral power is obtained by varying *a* and *b*. In Morlet wavelet, the quantitative relationship between the cycle with the parameter *a* is give as (Meyers *et al*., 1993):

$$T = \left[\frac{4\pi}{\left(\omega_0 + \sqrt{2 + \omega_0^{\,2}}\right)}\right] * a \quad (4)$$

when ω_0 = 6.2, T = 1.0006a. This implies that the parameter *a* and cycle T are considered to be identical. In other words, the Morlet wavelet can be used to analyze a cycle via parameter *a* with ω_0 = 6.2.

To further reflect the wave energy distribution with a scale, the wavelet variance is calculated by integrating the square of the wavelet transform coefficients in the entire time domain as (Deng *et al*., 1997):

$$var(a) = \int_{-\infty}^{+\infty} \left|W_f(a,b)\right|^2 \mathrm{d}b \quad (5)$$

where, $Var(a)$ is the wavelet variance in scale *a*. Based on the graph of the wavelet variance obtained by varying scale *a*, the significant time scale of the time-series (or significant cycle) is determined from the peak position.

Torrence and Compo (1998) defined the cross-wavelet spectrum of two time series *X* and *Y* with wavelet transform W_k^X and W_k^Y as:

$$\left|W_k^{XY}(a)\right| = \left|W_k^{X}(a) \cdot \overline{W}_k^{Y}(a)\right| \quad (6)$$

where, $\overline{W}_k^Y$ is the complex conjugate of W_k^Y. The complex argument of W_k^{XY} can be interpreted as the local relative phase between time series *X* and *Y*. Thus, the cross Wavelet Transform (XWT) can be constructed from two continuous wavelet transformations. XWT denotes their common power and relative phase in time–frequency space.

RESULTS AND DISCUSSION

SPI calculated results: The monthly SPI sequences are calculated for each of the six stations of precipitation data (for Jan. 1957 through Dec. 2010) using the edited program on VB (visual basic) platform. The resulting monthly SPI sequences for FU-YU station are shown in Fig. 2a. SPI is obtained by transforming the cumulative probability into standard normal distribution, which is a more stable form of calculation (Yuan and Zhou, 2004). As drought analysis is the focus of this study, only negative monthly values of monthly SPI are considered (Fig. 2b).

Wavelet analysis: To analyze multiple drought time-scales, continuous Morlet wavelet transforms of the station monthly SPI time-series are interpreted. Fig. 3 shows the power (absolute value squared) of the wavelet transform for the SPI data. It gives information on the relative power at a certain scale and time. Then Tong-Yu and Chang-Ling stations are used as proxies in the study area to analyze multiple drought time-scales. For Tong-Yu station (Fig. 3), the wavelet spectrum mainly highlights the 30, 15 and 2-year

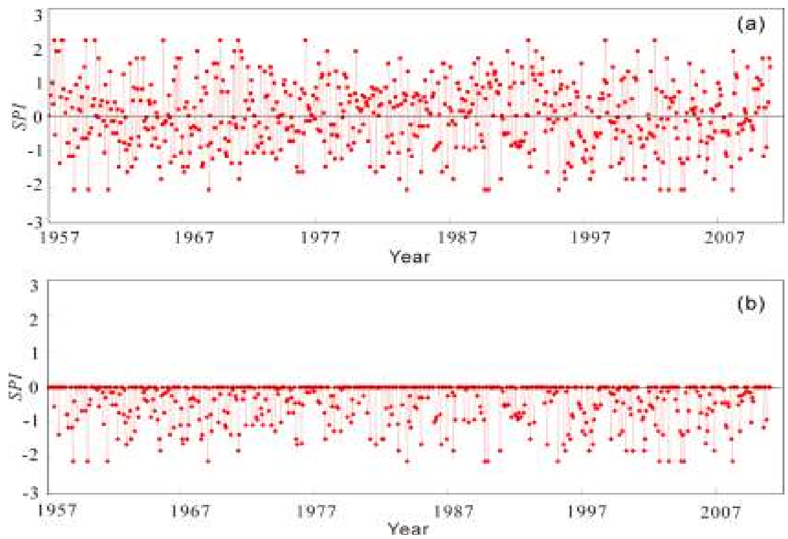

Fig. 2: Time-series of (a) monthly Standard Precipitation Index (SPI) for Fu-Yu station and (b) negative monthly Standard Precipitation Index (SPI) for the station

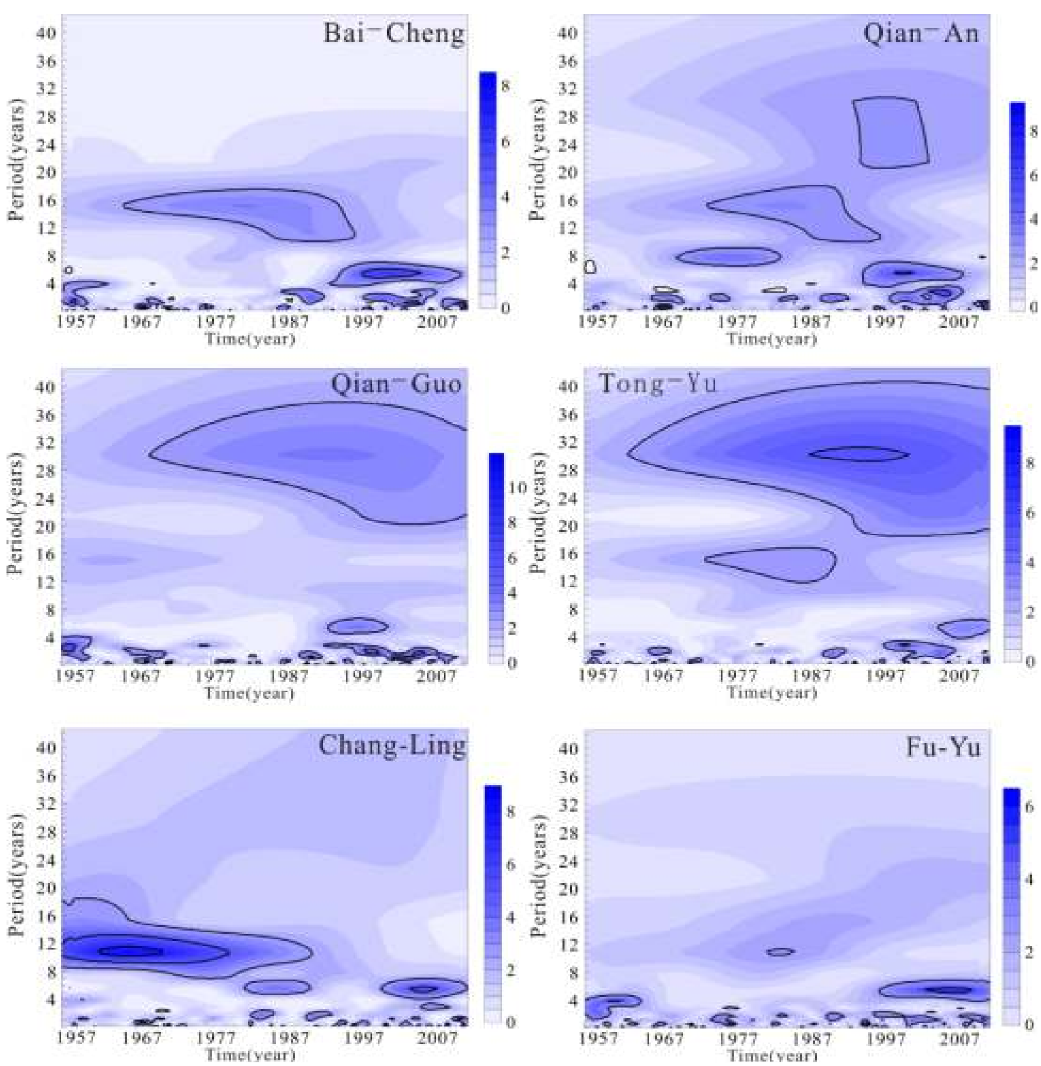

Fig.3: Plots of wavelet power spectrum of Standerd Precipitation Index (SPI) time-series for the six stations used in the study area

components, respectively. The 30-year component (with 1992 as the center of oscillation) expresses the strongest scale, occurring for the entire study period. The 2-year component expresses a relatively stronger scale that the 15-year component and occurs around 1967-1900 and 1997-2007. The 15-year component is expresses the lowest of the three and occurs between 1975-1990. The one-year component is highly variable and intermittent.

For Chang-Ling station (Fig. 3), the wavelet spectrum mainly highlights the 12 and 6-year components. The 12-year component (with 1967 as the center of oscillation) expresses the strongest trend, occurring in the 1957-1977 period. It then gradually decreases in intensity afterwards. The 6-year component also expresses a strong trend in the 1967-2005 period. The high frequency patterns of the one-year component for Chang-Ling station are less visible than those for Tong-Yu station. Map comparisons for the different stations much clearly show that the periods and intensities differ and change with time. For the six stations, the high-frequency or short-scale patterns are very similar. The one-year components are expressed in each station. But the low-frequency or long-scale patterns have very significant differences among the stations.

To explore at a further depth the main cycles of monthly SPI time-series, the wavelet coefficients are fed into the Eq. (5) and the wavelet variances of various time-scales are calculated. The resulting wavelet variance maps for the six stations are depicted in Fig. 4. The wavelet variances reflect energy fluctuant with scales in the weather stations. From Fig. 4, the peak wavelet variance is very noticeable and the shock cycles are strongest for Chang-Ling and Tong-Yu stations. While the main cycle for Chang-Ling station is 11 years that for Tong-Yu station is 30 years. These results are consistent with those from the wavelet spectrum analysis. The significant cycles for Qian-Guo and Bai-Cheng stations are 30 and 15 years, respectively. Fu-Yu and Qian-An stations have relatively weak cycle fluctuations and with no obvious major cycles. Through long-cycle comparisons, it is noted that drought occurrence in Western Jilin province is generally in accordance with medium-to-long-term climate patterns. There are, however, different driving

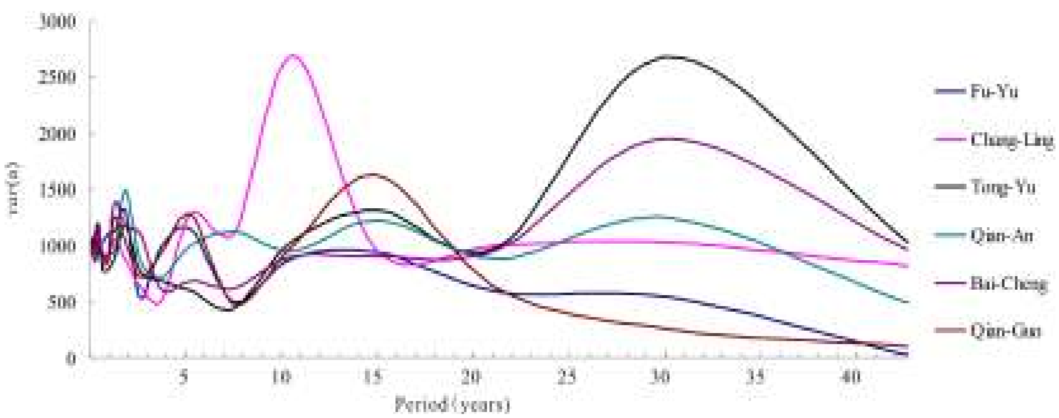

Fig. 4: Plots of wavelet variance of Standard Precipitation Index (SPI) time-series for the six stations used in the study area

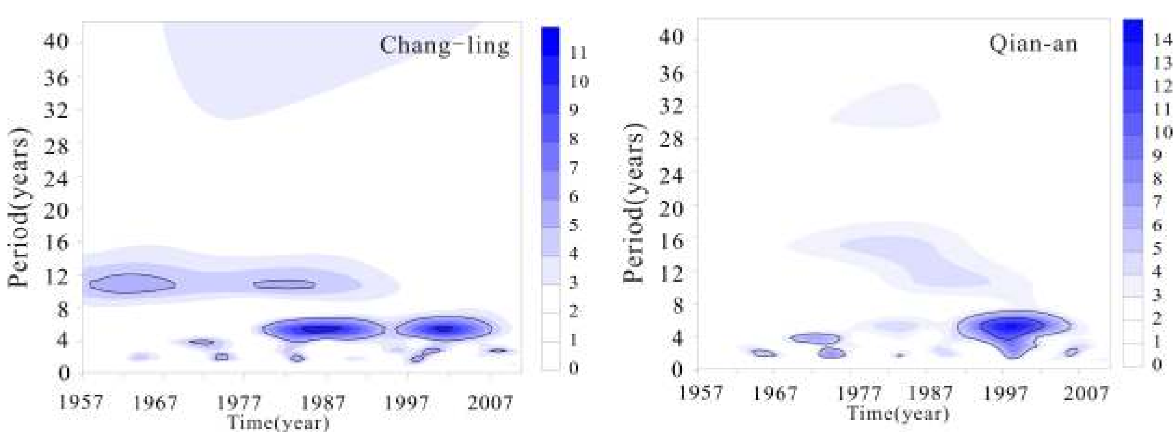

Fig. 5: Cross wavelet transforms of NINO3 versus Chang-Ling and Qian-An stations

factors in different regions of the study area. That is to say that each station has characteristic variations that are unique only to it.

In order to determine the relationship of droughts and the large scale climatology, the cross wavelet approach was applied to see if there was a connection between monthly SPI time series and large scale climate indices, such as NINO3, Southern Oscillation (SO) and Pacific Decadal Oscillation (PDO). NINO3 which represents deviations from the long term mean of sea surface temperatures at 90~160°W, 5°N~5°S has a possible impact on drought of the Northeast China (Liu, 2007). Here, NINO3 was used as a large scale climate index to seek its possible relation with scaling properties. The monthly data of the NINO3 from 1957 to 2010 is provided by National Centers for Environmental Prediction (NCEP). The cross wavelet plots of stations are shown in Fig. 5. In Chang-ling station, several markedly peaks appear at a period of between 8 to 12 years around 1962 and 1982 and at a period between 4 to 8 years around 1987 and 2003. There also exist several peaks, such as at a period between 4 to 8 years around 1997, for Qian-An station. All these peaks are associated with El Ni˜no Events. It proves that the drought occurrences in the region influenced by the medium and long-term climatic patterns.

Moreover, it is apparent from the figure (Fig. 5) that while the monthly SPI time series of Chang-ling station with drought characteristics tending to obvious cycle fluctuations has a common power at a 10-year band with NINO3 index, the common power is not obviously seen at the 10-year band for Qian-an station that has relatively weak cycle fluctuations. In time domain, it can be seen that the drought of Chang-ling station is influenced by El Ni˜no Events in all time, but the effect of Qian-an station only between 1992 and 2007 is obvious. This shows that enduringly influence of medium and long-term climatic patterns, such as El Ni˜no Events, may lead to the obvious cycle fluctuations of drought of some stations.

CONCLUSION

Monthly rainfall data from six weather stations across the Western Jilin province study area (spanning from 1957 to 2010) are used to calculate monthly SPI, which is the measure of the characteristics of drought. Morlet wavelet analysis is conducted to the monthly SPI time-series. Morlet wavelet spectrum and variance maps reveal multiple time-scales and significant cycles of drought in the region. Cross wavelet approach is used to determine the relationship of droughts and the large scale climatology.

Give the results of the study, the following conclusions are drawn: Wavelet spectrum and variance maps clearly reveal the nature of the power and distribution of various time-scales and significant cycles for all the weather stations. Comparisons among the stations show close similarities between multiple time-scales and significant cycles in terms of high-frequency or short-scale patterns. Also while one-year components are expressed in all stations, significant differences exist among the stations in terms of low-frequency or long-scale patterns. The occurrence of drought in Western Jilin province study area is mainly driven by the medium and long-term climate conditions. However, the degrees of influence of different factors in different stations are different. This implies that some variations exist among the stations. Cross wavelet analysis shows that for stations the drought occurrences in the region influenced by the medium and long-term climatic patterns, such as El Ni˜no Events. And enduringly influence of medium and long-term climatic patterns may lead to the obvious cycle fluctuations of drought of some stations.

Moreover, the results suggest that the method used in this study is an efficient too for analyzing drought characteristics. This could provide critical information for water resource management. Nevertheless, further research is recommended especially in the area dealing with the relationship between drought and large-scale climatic indices, such as Pacific Decadal Oscillation.

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