Chin. Geogra. Sci. 2009 19(4) 306–313
DOI: 10.1007/s11769-009-0306-7
www.springerlink.com

Wavelet Analysis and Nonparametric Test for Climate Change in Tarim River Basin of Xinjiang During 1959–2006

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Abstract: Using wavelet analysis, regression analysis and the Mann-Kendall test, this paper analyzed time-series (1959–2006) weather data from 23 meteorological stations in an attempt to characterize the climate change in the Tarim River Basin of Xinjiang Uygur Autonomous Region, China. Major findings are as follows: 1) In the 48-year study period, average annual temperature, annual precipitation and average annual relative humidity all presented nonlinear trends. 2) At the 16-year time scale, all three climate indices unanimously showed a rather flat before 1964 and a detectable pickup thereafter. At the 8-year time scale, an S-shaped nonlinear and uprising trend was revealed with slight fluctuations in the entire process for all three indices. Incidentally, they all showed similar pattern of a slight increase before 1980 and a noticeable up-swing afterwards. The 4-year time scale provided a highly fluctuating pattern of periodical oscillations and spiral increases. 3) Average annual relative humidity presented a negative correlation with average annual temperature and a positive correlation with annual precipitation at each time scale, which revealed a close dynamic relationship among them at the confidence level of 0.001. 4) The Mann-Kendall test at the 0.05 confidence level demonstrated that the climate warming trend, as represented by the rising average annual temperature, was remarkable, but the climate wetting trend, as indicated by the rising annual precipitation and average annual relative humidity, was not obvious.
Keywords: climate change; nonlinear trend; wavelet analysis; Mann-Kendall test; Tarim River Basin

1 Introduction

Under the general background of global warming, the climate in Xinjiang Uygur Autonomous Region of China has been undergoing significant changes (Yang and Wei, 2004; Xu and Wei, 2004). These changes, especially obvious in the Tarim River Basin, include evidences such as temperature rising, precipitation increasing, glaciers melting acceleration, river runoff increasing, lake water-level rising and its area expansion (Mansuer and Chu, 2007; Yang and He, 2003). These large scale climate changes have aroused a widespread concern in the climatic research community in China (Chen and Xu, 2005; Chen et al., 2006; Deng, 2006; Zhang et al., 2004). Whether these temperature and humidity changes over a century are a result of global climate warming has become an important issue for research.

Climate factors, as typical regional variables, have been used to reveal large-scale spatial zonal distribution for the planetary wind belt and pressure belt. Studies with these factors usually suffer from significant spatial uncertainty since they are influenced by natural conditions and human activities at smaller scales, such as terrain and physiognomy (Yue et al., 2003). Numerous studies have been published in the recent years regarding to the global climate change and its corresponding regional response (Ramanathan and Carmichael, 2008; Khon et al., 2007; Lenderink et al., 2007). Many case studies conducted in China as well as other countries indicated that the regional climate is a huge and com-

Received date: 2008-12-09; accepted date: 2009-07-06
Foundation item: Under the auspices of the Second-stage Knowledge Innovation Programs of Chinese Academy of Sciences (No. KZCX2-XB2-03, KZCX2-YW-127), National Natural Science Foundation of China (No. 40671014), Shanghai Academic Discipline Project (Human Geography) (No. B410)
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plex system (Zhao et al., 2007; Feng et al., 2005; Rial, 2004; Shackley et al., 1998), and its complexity is mainly represented as follows: 1) The system is so sensitive to the initial condition that a slight variation could lead to huge differences in system behavior. 2) Both the functional mechanism and the system process are nonlinear. And 3) it is difficult to precisely forecast the occurrence of outbursts and emergence (Xu et al., 2009).

To reveal the complex nature of regional climate processes, therefore, multiple spatial-temporal scales must be considered, and diverse methods must be investigated. A time-series dataset (1959–2006) from 23 meteorological stations was obtained, and average annual temperature, annual precipitation and average annual relative humidity were used as three measurable indexes in this study. Methodogically, a wavelet analysis was conducted to illustrate the nonlinear tendency of the data at different time scales. Then regression analysis was used to show the relationship among the three factors. Finally, a nonparametric method, i.e. the Mann-Kendall test, was chosen to test the statistic significance of this tendency.

2 Materials and Methods

2.1 Study area and data source

The Tarim River Basin (34º20'–43º39'N, 71º39'–93º45'E) was chosen as the study area (Fig. 1). It has an area of 1.02×10^6km^2, with over 97% of the area belonging to a drainage basin internal to China. This area covers almost the entire southern part of Xinjiang, including 42 cities or counties and 55 collective farms managed by Xinjiang Production and Construction Corporation, with a total population of over 9×10^6.

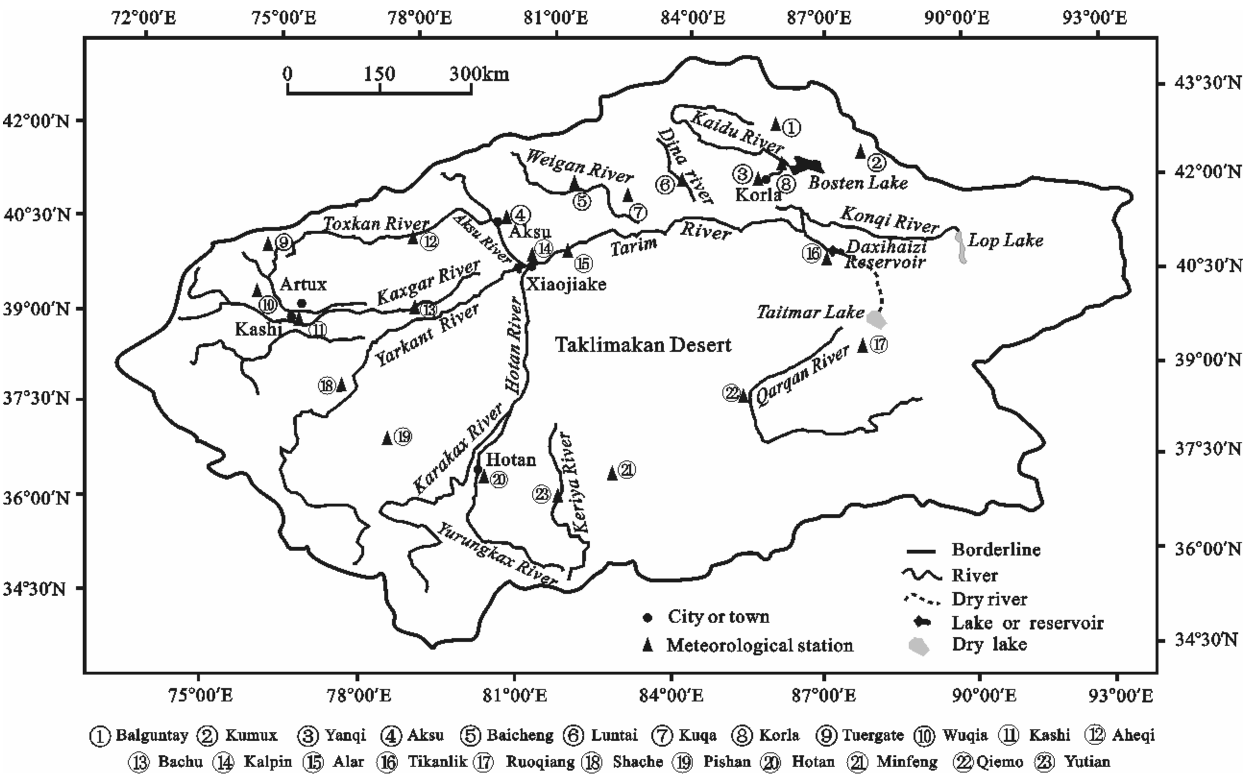

Fig. 1 Location of meteorological station in Tarim River Basin

This area has a typical desert climate with an average annual temperature of 10.6–11.5℃. Monthly mean temperature ranges from 20℃ to 30℃ in July and –10℃ to –20℃ in January. The highest and lowest temperature is 43.6℃ and –27.5℃, respectively. The accumulative temperature of >10℃ ranges from 4,100℃ to 4,300℃. Average annual precipitation is 116.8mm in the basin, ranging from 200mm to 500mm in the mountainous area, 50mm to 80mm in the edges of the basin, and only 17.4mm to 25.0mm in the central area of the basin. There is greatly uneven distribution of precipitation within any single year. More than 80% of the total annual precipitation falls between May and September, while less than 20% from October to next April.

Data used in this study included average annual temperature, annual precipitation and average annual relative humidity spanning from 1959 to 2006 from 23 meteorological stations in Tarim River Basin (Fig. 1). These data all came from the Information Center of Meteorological Office in Xinjiang Uygur Autonomous Region, so the accuracy and precision of the data can be ensured.

2.2 Methodology

2.2.1 Wavelet analysis

Wavelet analysis is a multi-resolution analytical approach to analyze the time scales of signals, and it can provide a new insight into the periodicity of runoff and climate processes (Han et al., 2007; Smith et al., 1998; Xu et al., 2008a; 2008b). One major interest of this paper is to approximate the nonlinear trends of the climate process based on wavelet decomposition and reconstruction at different time scales.

The principle of wavelet decomposition and reconstruction is as follows. Considering a time series $X(t)$, such as temperature, precipitation, humidity, etc., which can be built up as a sequence of projections onto father and mother wavelets indexed by both k $\{k=1, 2, \ldots\}$ and s $\{s=2^j, j=1, 2, \ldots, J\}$.

The coefficients in the expansion are given by the projections:

$$s_{J,k} = \int X(t)\Phi_{J,k}(t)\mathrm{d}t \tag{1}$$

$$d_{j,k} = \int X(t)\Psi_{j,k}(t)\mathrm{d}t, j = 1, 2, ..., J \tag{2}$$

where J is the maximum scale sustainable by the number of data points, $\Phi_{j,k} = 2^{-j/2}\Phi(\frac{t-2^j k}{2^j})$ is a father wavelet, and $\Psi_{j,k} = 2^{-j/2}\Psi(\frac{t-2^j k}{2^j})$ is a mother wavelet. Generally, father wavelet is used for the lowest-frequency smooth components, which requires a wavelet with the widest support; mother wavelet is used for the higher-frequency detailed components. In other words, father wavelet is used for the major trend components, and mother wavelet is used for all deviations from the trend.

The representation of the signal $X(t)$ now can be given by:

$$X(t) = S_J + D_J + D_{J-1} + \ldots D_j + \ldots + D_1 \tag{3}$$

where $S_J = \sum_k s_{J,k}\Phi_{J,k}(t)$ and $D_j = \sum_k d_{j,k}\Psi_{j,k}(t)$, $j=1, 2, \ldots, J$.

In general, we have

$$S_{j-1} = S_j + D_j \tag{4}$$

where $\{S_J, S_{J-1}, ..., S_1\}$ is a sequence of multi-resolution approximations of the function $X(t)$ at ever-increasing levels of refinement.

Using the Symmlet as the base wavelet, a number of scaling functions were experimented to determine the most suitable wavelet for this dataset. It was found that 'Sym8' produced the most robust qualitative results. Therefore, 'Sym8' was used for approximating the trends of the climate process in this paper, and S4, S3 and S2 were chosen to represent a series of time scales in the analysis.

2.2.2 Regression analysis

Although regional climate is a huge and complex system, the statistical relationship of humidity, temperature and precipitation can still be established, as it has commonly done in many other researches (Hastenrath, 1990; Xu, 2002; Lee and Chung, 2007). For the purpose of comparison, this paper also conducted a regression analysis to examine the effect of temperature and precipitation on relative humidity based on the results of wavelet analyses at each time scale.

2.2.3 Mann-Kendall test

A nonparametric statistical test, Mann-Kendall (MK) is generally used in examining the significance of temporal trends from time series data. The MK test has the characteristic of no need to hypothesize the statistical distribution of data samples in advance. It has been widely used to assess the significance of trend in hydrological and climate time series, such as runoff, temperature, precipitation, etc. (Yue et al., 2002; Xu and Zhang, 2006; He and Xu, 2006).

The statistic of the Mann-Kendall statistical test, Z_c, is expressed as:

$$Z_c = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{var}(S)}}, & S < 0 \end{cases} \tag{5}$$

where,

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \operatorname{sgn}(x_k - x_i), \tag{6}$$

$$\operatorname{sgn}(\theta) = \begin{cases} 1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases} \tag{7}$$

$$\operatorname{var}(S) = n(n-1)(2n+5)/18 \tag{8}$$

where x_k and x_i are the sequential data values, and n is length of the data.

The index for measurement of trend, i.e., the inclination is expressed as follows:

$$\beta = \operatorname{Median}\left(\frac{x_i - x_j}{i - j}\right) \tag{9}$$

where, $1<j<i<n$, and a positive β denotes a rising trend, while a negative β means a decreasing trend.

The Mann-Kendall test can be used in the following manner: for the null hypothesis of H_0, β=0, if $|Z_c| > Z_{(1-\alpha)/2}$, then the null hypothesis is refused, where, $Z_{(1-\alpha)/2}$ is the standard normal variance, and α is the significance level for the test.

3 Results and Discussion

3.1 Nonlinear trend of climate change

3.1.1 Average annual temperature

As mentioned above, the time-series (1959–2006) climatic data collected from 23 meteorological stations in the Tarim River Basin were analyzed using 'Sym8' as the operational wavelet function for the decomposition and reconstruction of the average annual temperature time series at three time scales, i.e. 16-year (S4), 8-year (S3) and 4-year (S2). The simulation results provide a characterization of nonlinear changes in these climatic factors (Fig. 2).

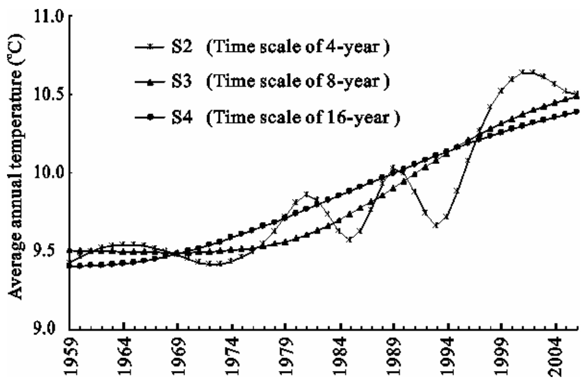

Fig. 2 Nonlinear trends of average annual temperature at different time scales

Wavelet analysis of the Tarim River Basin dataset seemed to characterize the nonlinear trends of average annual temperature differently at different time intervals. At the time scale of 16-year (S4), the year of 1964 seemed to serve as an inflexion point, with a rather flat process before the year and a rather linear and significant increase thereafter. As the time scale was set to 8-year (S3), however, the average annual temperature started to fluctuate, although still retaining the basic tendency as seen at S4. At this time scale, the fluctuation seemed to dominate the entire period, with a rather flat transition from 1959 to 1980, then starting to rise significantly until 1993, when the rising trend began to decelerate. In the case of a 4-year time scale, the average annual temperature fluctuated more frequently, with an average cycle of 12 years or so. In addition, the magnitude of fluctuation increased along the time span of the data, signifying a rising trend of temporal variation in regional temperature.

3.1.2 Annual precipitation

Similarly, the wavelet-based decomposition and reconstruction of the annual precipitation time series data reveal some nonlinear trends at the three different time scales. The simulation results are illustrated in Fig. 3.

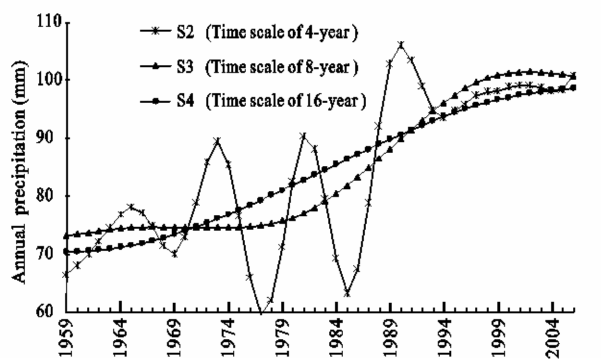

Fig. 3 Nonlinear trends of annual precipitation at different time scales

According to Fig. 3, there existed a generic rising trend in the annual precipitation at the time scale of 16-year, still with 1964 as the turning point. The analysis at the time scale of 8-year yields a slight fluctuation, with small amplitude before 1980 and a significant rise thereafter. When the time scale was further reduced to 4-year, the temporal variation of annual precipitation became more significant. It reached the highest point in 1990 for the entire study period, and the lowest record after that year was still higher than any of the highest annual precipitation before 1990.

3.1.3 Average annual relative humidity

The decomposition and reconstruction of the annual relative humidity time series also reveal some nonlinear characteristics at the selected three time scales, as shown in Fig. 4.

The analytic results indicate no obvious rising trend in the average annual relative humidity until 1964 when using the 16-year time scale (S4). At the time scale of 8-year (S3), this humidity index fluctuated slightly while as a whole still keeping the basic tendency as at S4. At this scale, the humidity change before 1980 was rather small, but picking up rapidly afterwards till 1999 with a maximum increase of 5%, then starting to oscillate in the rest of the study period. The analysis at the 4-year time scale (S2) added more characteristic details to the humidity index. The fluctuation seemed more salient and revealing. It showed that, for instance, the historical high value within the study period took place in 1993 and historical low one in 1985.

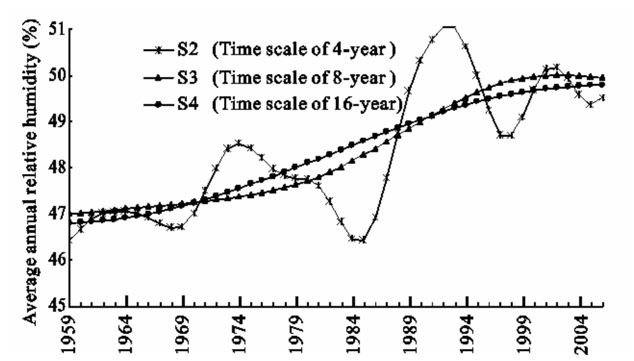

Fig. 4 Nonlinear trends of average annual relative humidity at different time scales

3.2 Relationships of three climate indices

In order to show the relationship of average annual relative humidity, average annual temperature and annual precipitation, we used the multiple linear regression analysis to fit the regression equations at different time scales (Table 1).

Table 1 Regression analysis for relationship among different climate factors at three time scales

Time scale	Regression equation	R^2	F	Significant level
S2	$AARH = -0.0189AAT + 0.0878AP + 41.1078$	0.69789	51.98	0.001
S3	$AARH = -0.2581AAT + 0.1104AP + 41.5687$	0.98456	1434.69	0.001
S4	$AARH = -1.1102AAT + 0.1439AP + 47.1428$	0.99999	7377758.44	0.001

Notes: *AARH* represents average annual relative humidity; *AAT*, average annual temperature; and *AP*, annual precipitation

Table 1 shows that the accuracy of regression equations rises with the increase of time scale, and all three equations are significant at the confidence level of 0.001. In all three models, average annual relative humidity presents a negative correlation with average annual temperature, and a positive correlation with annual precipitation. The results reveal a close dynamic relationship among them.

3.3 Results of Mann-Kendall tests

3.3.1 Average annual temperature

The Mann-Kendall method was applied to testing the significance of average annual temperature change from 1959 to 2006 for each of the 23 meteorological stations in the Tarim River Basin. The results are listed in Table 2.

The results indicate that average annual temperature of the entire basin rose significantly, with a variation of 0.1–0.4℃/10yr at the 0.05 confidence level. Most part of the Tarim River Basin displayed an amplitude of 0.13–0.32℃/10yr. Luntai and Aksu experienced the largest increase of about 0.4℃/10yr, followed by Minfeng, Yanqi, Hotan, Wuqia, Qiemo and Balguntay (0.30–0.37℃/10yr). The temperature increases at Tuergate, Baicheng, Tikanlik, Bachu, Kumux, Pishan, Korla, Kashi, Aheqi, Ruoqiang, Shache and Kalpin were rather moderate (0.13–0.29℃/10yr), and Yutian and Alar had the least increase (<0.10℃/10yr). This observation was basically in agreement with the outcome from Mansuer and Chu (2007) and Yang and He (2003).

One noticeable station is Kuqa, whose temperature records displayed the opposite trend by a decrease of 0.05℃/10yr. The reason for this is still an open question now. Some scientists suspected that it was caused by accidental alternation of the data due to the change of station management or measurement methodology, but this assumption still can not be confirmed today (Li, 2003).

3.3.2 Annual precipitation

The Mann-Kendall test was also performed on the annual precipitation time series data for the period of 1959–2006 for each of the 23 meteorological stations in

Table 2 Mann-Kendall test for trend of average annual temperature

Station	Inclination (β)	Z_c	$Z_{(1-\alpha)/2}$	Significance (α=0.05)
Luntai	0.0400	5.4395	0.6051	Significant
Aksu	0.0389	5.5906	0.4767	Significant
Minfeng	0.0365	5.2173	0.4928	Significant
Yanqi	0.0333	5.1728	0.4187	Significant
Hotan	0.0318	4.0974	0.4679	Significant
Wuqia	0.0314	4.0263	0.6238	Significant
Qiemo	0.0307	4.7107	0.3957	Significant
Balguntay	0.0302	3.6174	0.5552	Significant
Tuergate	0.0286	4.3996	0.4021	Significant
Baicheng	0.0286	4.1241	0.4136	Significant
Tikanlik	0.0271	5.3773	0.2893	Significant
Bachu	0.0267	4.6662	0.3051	Significant
Kumux	0.0263	4.3640	0.3804	Significant
Pishan	0.0262	3.4308	0.4133	Significant
Korla	0.0250	4.2929	0.3092	Significant
Kashi	0.0240	3.0042	0.4596	Significant
Aheqi	0.0236	3.7330	0.3554	Significant
Ruoqiang	0.0227	3.9285	0.2769	Significant
Shache	0.0221	4.0796	0.2742	Significant
Kalpin	0.0133	2.5509	0.2330	Significant
Yutian	0.0066	1.0666	0.2625	Significant
Alar	0.0063	1.5910	0.1442	Significant
Kuqa	–0.0054	–1.3243	0.1816	Significant

the Tarim River Basin. The test results at the 0.05 significance level (Table 3) indicate that, even though inclinations were all positive, which means the annual precipitation at each station presented a rising trend to some degree in the study period, such an increase could not be regarded as significant.

3.3.3 Average annual relative humidity

The test results for the average annual relative humidity (Table 4) also demonstrate a pattern similar to those for annual precipitation. While positive inclinations suggest a rising trend within the 48 years of the study period, none of the stations could pass the Mann-Kendall statistical test at the 0.05 confidence level. Therefore, the rising trend of average annual relative humidity at each station was not significant, either.

4 Conclusions

The analytic results from the application of the wavelet analysis and Mann-Kendall test provide some insights into the regional climatic change of the Tarim River Basin in the period of 1959–2006. A few points can be

Table 3 Mann-Kendall test for trend of annual precipitation

Station	Inclination (β)	Z_c	$Z_{(1-\alpha)/2}$	Significance (α=0.05)
Aheqi	2.1427	2.8975	5216.50	Insignificant
Wuqia	1.5417	1.9643	5038.30	Insignificant
Baicheng	1.4971	3.4752	1682.60	Insignificant
Balguntay	1.4252	2.1420	3827.10	Insignificant
Kalpin	1.2357	2.9508	1863.70	Insignificant
Luntai	1.0634	3.6174	936.62	Insignificant
Aksu	0.8308	2.4175	1114.40	Insignificant
Kuqa	0.8063	3.2619	553.11	Insignificant
Bachu	0.7375	2.1865	1141.00	Insignificant
Tuergate	0.6350	1.1466	3411.40	Insignificant
Ruoqiang	0.5225	3.4486	501.73	Insignificant
Yanqi	0.5024	1.5821	901.18	Insignificant
Shache	0.4000	1.0221	1356.80	Insignificant
Minfeng	0.3561	1.9109	597.01	Insignificant
Kumux	0.3327	1.5199	487.42	Insignificant
Qiemo	0.2600	1.6354	178.04	Insignificant
Kashi	0.2596	0.7733	1107.90	Insignificant
Alar	0.2549	1.3865	495.93	Insignificant
Pishan	0.2294	0.7910	837.31	Insignificant
Korla	0.1766	0.8799	502.89	Insignificant
Hotan	0.1702	0.8977	494.34	Insignificant
Yutian	0.1691	0.5422	770.37	Insignificant
Tikanlik	0.0575	0.3644	364.68	Insignificant

Table 4 Mann-Kendall test for trend of average annual relative humidity

Station	Inclination (β)	Z_c	$Z_{(1-\alpha)/2}$	Significance (α=0.05)
Kuqa	0.2667	6.4438	20.15	Insignificant
Alar	0.2432	6.7371	15.32	Insignificant
Yutian	0.2076	4.9240	18.71	Insignificant
Aheqi	0.1765	5.1462	13.11	Insignificant
Kalpin	0.1579	4.1241	14.41	Insignificant
Yanqi	0.1076	3.6708	8.38	Insignificant
Ruoqiang	0.1000	3.8219	6.33	Insignificant
Baicheng	0.0909	3.0219	9.19	Insignificant
Qiemo	0.0857	2.8175	9.29	Insignificant
Kumux	0.0769	2.7464	7.30	Insignificant
Korla	0.0702	2.7731	6.04	Insignificant
Tuergate	0.0667	2.4175	8.41	Insignificant
Kashi	0.0556	1.5998	10.48	Insignificant
Tikanlik	0.0513	2.1509	4.29	Insignificant
Shache	0.0513	2.4175	5.27	Insignificant
Pishan	0.0482	1.3332	10.25	Insignificant
Minfeng	0.0000	−0.4622	7.25	Insignificant
Hotan	0.0000	0.5511	8.61	Insignificant
Bachu	0.0000	−0.2666	6.96	Insignificant
Wuqia	0.0000	0.0089	13.59	Insignificant
Aksu	0.0000	0.4888	4.72	Insignificant
Luntai	−0.0370	−1.3510	7.15	Insignificant
Balguntay	−0.0435	−1.4488	6.64	Insignificant

made by summarizing the aforementioned observations.

(1) The processes of the climate change, observed as time series data for average annual temperature, annual precipitation and average annual relative humidity, in the Tarim River Basin all presented some nonlinear trends in the period of 1959–2006.

(2) In the wavelet analysis, using different time scales result in different levels of trend patterns and details. For instance, the 16-year time scale characterized the average annual temperature as a nonlinear curve with a flat period before 1964 and a noticeable rise thereafter. The 8-year time scale revealed some slight fluctuation in the data, while basic tendency was still visible as shown at the 16-year scale. It became apparent that the process began with a rather flat transition in 1959–1980, and then started to rise significantly until 1993, when the rising trend started to decelerate. More fluctuations and their details were seen for the analysis at the 4-year time scale, revealing the minima and maxima of the index as well as the spiral pattern of the rising trend. Similar conclusions for the other two meteorological indices were also drawn.

(3) More information can be revealed about these three meteorological indices in this particular spatio-temporal setting by cross-examining. The three indices seem to synchronize rather well. For instance, they all started to rise in the year of 1964 at the time scale of 16-year, and they all had a common breaking point in 1980 to divide the nonlinear trend at the time scale of 8-year. At the 4-year time scale, the peak humidity coincided with the biggest dip of temperature in 1993, when precipitation just fell into a local minimum from its all-time record high for the study period. All these features that were revealed at different time scales shall be valuable in providing some useful handlers for climate scientists to poke into the physical mechanism that drives the dynamics of climate changes in the region.

(4) At the significant level of 0.001, a statistical regression model of humidity, temperature and precipitation was established at each time scale, in which average annual relative humidity presents negative correlation with average annual temperature, and positive correlation with annual precipitation. The results reveal a close dynamic relationship among them.

(5) At the 0.05 confidence level, results from the Mann-Kendall nonparametric tests demonstrated that the rising trend of average annual temperature was significant in the period of 1959–2006, but the rising trends of annual precipitation and average annual relative humidity were not. That is to say, the warming trend, implied by the rising average annual temperature, was remarkable, whereas the wetting trend, represented by the rising annual precipitation and average annual relative humidity, was not significant. Although all three climatic indices interact with each other in a predictable pattern, as indicated in the results of wavelet analysis and regression analysis, the influence of temperature on the wetness of the region was rather limited.

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