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Climate Change and Its Effects on Runoff of Kaidu River, Xinjiang, China: A Multiple Time-scale Analysis

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Abstract: This paper applied an integrated method combining grey relation analysis, wavelet analysis and statistical analysis to study climate change and its effects on runoff of the Kaidu River at multi-time scales. Major findings are as follows: 1) Climatic factors were ranked in the order of importance to annual runoff as average annual temperature, average temperature in autumn, average temperature in winter, annual precipitation, precipitation in flood season, average temperature in summer, and average temperature in spring. The average annual temperature and annual precipitation were selected as the two representative factors that impact the annual runoff. 2) From the 32-year time scale, the annual runoff and the average annual temperature presented a significantly rising trend, whereas the annual precipitation showed little increase over the period of 1957–2002. By changing the time scale from 32-year to 4-year, we observed nonlinear trends with increasingly obvious oscillations for annual runoff, average annual temperature, and annual precipitation. 3) The changes of the runoff and the regional climate are closely related, indicating that the runoff change is the result of the regional climate changes. With time scales ranging from 32-year, 16-year, 8-year and to 4-year, there are highly significant linear correlations between the annual runoff and the average annual temperature and the annual precipitation.

Keywords: runoff; temperature; precipitation; nonlinear trend; time scale; Kaidu River

1 Introduction

Glaciers are the largest freshwater storages that feed many major rivers in the world. The incremental retreat of glaciers due to global warming has directly affected the water supply of the rivers that mainly depend on glacier melts (Aziz and Burn, 2006; Barnett et al., 2005; Seidel et al., 1998). In China, such rivers are mainly located in the northwestern arid region (Shi and Zhang, 2005), where mountain snowmelt is an important source of water supply and vital to the local people's livelihood and socioeconomic development. On the other hand, the river systems there often are prone to flooding when there is heavy rain during the snow melting season (Zhang et al., 2007). It is, therefore, important to gain a deep and thorough understanding of the runoff mechanism in order to establish proper water management strategies for sustainable development and flood controls in those regions.

This study specifically targets the Kaidu River originating from the central part of the Tianshan Mountains, Xinjiang, China. This river is primarily supplied by the mixed water from snowmelt and rain, with a runoff approximately accounting for 85% of the current capacity of its outlet, Bosten Lake (Wang et al., 2003). Located in the south of the Tianshan Mountains, Bosten Lake is the sole water source for the Kongque River and provides multiple functions, including water resources regulation in the Kaidu River Basin, field irrigation in the Kongque River Basin, industrial, municipal and rural water supplies, basin ecological environmental protection, and water diver-

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sion to the middle and lower reaches of the Tarim River. The water management of Kaidu River Basin has been facing increasingly severe challenge due to global warming and drastic climate change (Christensen and Lettenmaier, 2007; Shi et al., 2007; Chen and Xu, 2005; Labat et al., 2004). Our primary interest lies in the hydrological process of the Kaidu River under the inevitable impact from the climate change.

Although many studies have contributed to the understanding of the Kaidu River in the climate change and its effects on runoff in recent years, majority of them are of the single-time scale analysis. In view of the fact that the process of climate change and its effects on runoff are complex, the authors believed that using a selected set of methods to conduct a multiple time-scale analysis is essential and meaningful. Based on the observed data series from a hydrologic station and a meteorological station, this paper presents a multiple time-scale analysis, which employed an integrated methodology combining a grey relation analysis, a wavelet analysis and a statistical analysis, to study the effects of the climate change on the temporal variation in the annual runoff of the Kaidu River, Xinjiang, China.

2 Materials and Methods

2.1 Study area

The Kaidu River is situated at the north fringe of Yanqi Basin on the south slope of the Tianshan Mountains in Xinjiang, and is enclosed between 42°14′–43°21′N and 82°58′–86°05′E (Fig. 1). The river starts from the Hargat Valley and the Jacsta Valley in Sarming Mountain with a maximum altitude of 5000m (the middle part of the Tianshan Mountains), and ends in Bosten Lake, which is located in the Bohu County of Xinjiang. This lake is the biggest lake in Xinjiang (also once the biggest interior freshwater lake in China) and immediately starts another river, the Kongque River. The catchment area of the Kaidu River above Dashankou, is 18,827km^2, with an average elevation of 3100m (Tao et al., 2007). In the basin the average annual temperature is only 4.6℃ and the extreme minimum temperature is –48.1℃. The annual snow-cover days are as many as 139.3d and the largest average annual snow depth is 12cm.

Bayanbuluke wetland, which is in the Kaidu River Basin, is the largest wetland in the Tianshan Mountains area. The large areas of grasslands and marshes in Bayanbuluke wetland have provided favorable conditions for swan survival and reproduction. For this reason, it becomes only state-level swan nature reserve in China. Due to the unique high alpine cold climate and topography, there are various alpine grassland and meadow ecosystems, having abundant aquatic plants, animals and good grassland resources. It is the birthplace and the headwater protection area of the Kaidu River and plays a crucial role in regulating, reserving water and maintaining water balance. It also plays the utmost important role in protecting the Bosten Lake and its surrounding wetlands and protecting the ecological environment and green corridor of the lower reaches of the Tarim River.

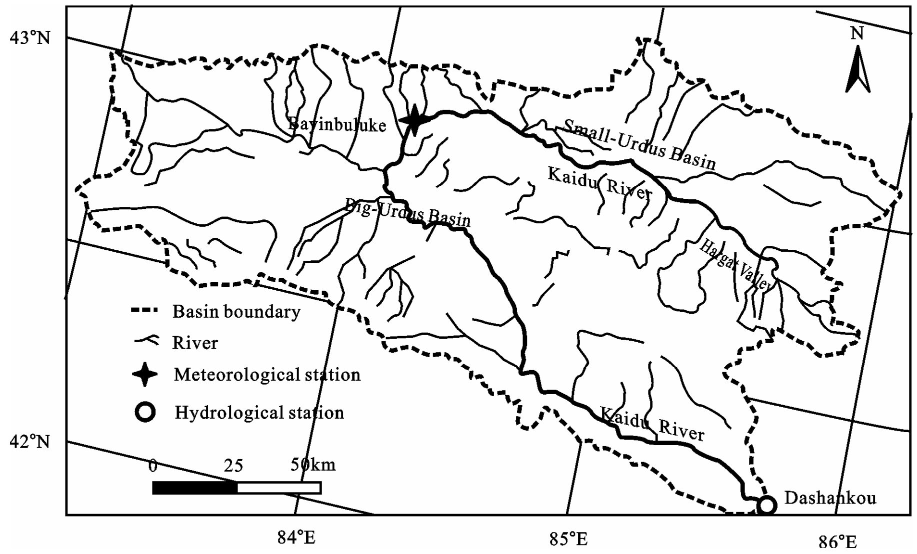

Fig. 1 Sketch map of Kaidu River Basin

2.2 Data

The Kaidu River is a typical inland river, and its surface runoff mainly occurs in the Tianshan mountainous area. The Dashankou hydrological station functions as the basin control station and has generated the longest observation data sequence for hydrological studies. Due to the non-inhabitant nature of the area, the monthly runoff observed is basically the natural amount of runoff, with very little human disturbance.

In the study of the annual runoff of the Kaidu River and the effects of the climate changes, we used the annual runoff data from the Dashankou hydrologic station and the annual precipitation, precipitation in flood season and the monthly, quarter and annual temperature data from the Bayanbuluke meteorological station spanning from 1957 to 2002. Those data were statistically summarized from the measured data, with a high accuracy and confidence level.

2.3 Methodology

In this study, an integrated method combining a grey relation analysis, a wavelet analysis, and a statistical analysis was used to investigate the effects of climate change on the annual runoff of the Kaidu River at multiple time scales.

2.3.1 Grey relation analysis

It is impossible to establish models showing the relationship between runoff and all climate factors. Therefore, a grey relation analysis was used to select most important factors for our study. In a grey relation analysis, variables of time series are represented as reference series and influence series. The grey relation is the indefinite relationship among the two types of time series data, and the aim here is to compute the affecting degree of influence series on reference series. A parameter called grey relation degree is used to represent propinquities of two series. If the relation degree of one series is higher than that of others, this particular series is deemed to place a greater influence on the reference series, and will be chosen for modeling (Deng, 1985; 1989).

The principle of grey relation analysis is as follows. For reference series $\{X_1(t),\ t = 1, 2 \ldots\}$, i.e. runoff, and influence series $\{X_i(t),\ i=1, 2 \ldots;\ t = 1, 2 \ldots\}$, i.e. annual precipitation, precipitation in flood season, average annual temperature, etc., the following formula is used to calculate relation parameters ($\xi_{1i}(t)$) of two series:

$$\xi_{1i}(t)=\frac{\min\limits_{i}\min\limits_{t}\left|X_1(t)-X_i(t)\right|+k\max\limits_{i}\max\limits_{t}\left|X_1(t)-X_i(t)\right|}{\left|X_1(t)-X_i(t)\right|+k\max\limits_{i}\max\limits_{t}\left|X_1(t)-X_i(t)\right|} \tag{1}$$

where k is a grey parameter with a value range between 0 and 1, and often assigned a value of 0.5 for calculation.

With the computed relation parameters, we can calculate the grey relation degree (γ_{1i}) of each influence series ($X_i(t)$) with reference series ($X_1(t)$):

$$\gamma_{1i}=\frac{1}{n}\sum_{t=1}^{n}\xi_{1i}(t) \tag{2}$$

It needs to be pointed out that the data of each series should be normalized before conducting the grey relation analysis. There are several methods for normalizing the data, and this paper uses one as follows:

$$x_i(t)=\frac{X_i(t)-\min\limits_{t}X_i(t)}{\max X_i(t)-\min\limits_{t}X_i(t)} \qquad i=1, 2 \ldots, m \tag{3}$$

That is to say, $x_i(t)$, instead of $X_i(t)$, should be used in Equation (1) for computation.

2.3.2 Wavelet analysis

Wavelet analysis is a multi-resolution analytical approach to analyzing the time scales of signals (Xu et al., 2004), and it provides us a new insight into the periodicity of a runoff process (Han et al., 2007; Smith et al., 1998; Xu et al., 2008). One of the main interests in this paper is to approximate the nonlinear trends of the runoff and 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 runoff, temperature, precipitation, etc., which can be built up as a sequence of projections onto Father and Mother wavelet indexed by both k $\{k=1, 2 \ldots\}$ and s $\{s=2^j, j=1, 2 \ldots\}$.

The coefficients in the expansion are given by the projections:

$$s_{J,k}=\int X(t)\Phi_{J,k}(t)\mathrm{d}t \tag{4}$$

$$d_{j,k}=\int X(t)\Psi_{j,k}(t)\mathrm{d}t \qquad j=1, 2 \ldots, J \tag{5}$$

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 father wavelet, and $\Psi_{j,k}=2^{-j/2}\Psi(\frac{t-2^j k}{2^j})$ is mother wavelet.

Generally, father wavelet is used for the lowest-frequency smooth components, which requires wavelet with the widest support; mother wavelet is used for the detailed highest-frequency 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:

$$X(t) = S_J + D_J + D_{J-1} + \ldots + D_j + \ldots + D_1 \tag{6}$$

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

$$S_{j-1} = S_j + D_j \tag{7}$$

where $\{S_J, S_{J-1} \ldots, S_1\}$ is a sequence of multi-resolution approximations of the function $X(t)$ at ever-increasing levels of refinement. The corresponding multi-resolution decomposition of $X(t)$ is given by $\{S_J, D_J, D_{J-1} \ldots, D_j \ldots, D_1\}$.

Choosing the Symmlet as the basic wavelet, we experimented with alternative choices of scaling functions, and found that the qualitative results from 'Sym8' were very robust. Therefore, 'Sym8' were used for approximating the trends of the runoff and climate process in this paper, and S5, S4, S3, and S2 were chosen to represent a series of time scales in the analysis.

2.3.3 Statistical analysis

Although climate change and its effects on runoff can be very complex studies, the statistical relationship between runoff and influencing climatic factors can still be established, as it was commonly done in many other researches (Hastenrath, 1990; Xu, 2002; Chen et al., 2007; Lee and Chung, 2007). For the purpose of comparison, this paper also conducted correlation and regression analyses to examine the effect of temperature and precipitation on runoff at each time scale, with reference to the results from the grey relation analysis and the wavelet analysis.

3 Results and Discussion

3.1 Ranking of climate factors in order of importance

As one of the headwaters of the Tarim River basin, the Kaidu River is supplied primarily by the mixed water of snowmelt and rain. Therefore, there are conceivably close relationships between runoff and a set of regional climate factors, especially precipitation and temperature. This perception is supported by the results of some previous studies for the headwaters of the Tarim River Basin (Chen et al., 2006; Tao et al 2007; Yang et al., 2007). As part of this study, we checked the importance of each climate factor by calculating the grey relation degree for annual runoff (AR) with each of the influencing climate factors, including annual precipitation (AP), precipitation in flood season (PFS), average annual temperature (AAT), average temperature in spring (ATSP), average temperature in summer (ATSU), average temperature in autumn (ATA), and average temperature in winter (ATW). The results are shown in Table 1.

Table 1 Grey relation degree between annual runoff and climate factors

	AP	PFS	AAT	ATSP	ATSU	ATA	ATW
AR	0.7507	0.7171	0.7961	0.5989	0.6375	0.7952	0.7834
Order of grey relation degree	4	5	1	7	6	2	3

Table 1 also provides a rank order of those climatic factors with respect to their relative importance in predicting the runoff process. The average annual temperature seems to have the highest rank, followed by the average temperature in autumn and then in winter. The annual precipitation and the precipitation in flood season take the fourth and fifth places, with the average temperature in the other two seasons being the last. When grouped, there is an obvious pattern showing that the average annual temperature and the annual precipitation are the leading climate factors that affect the annual runoff in this region. Those two climate factors, therefore, were chosen as the representative factors in this study to be involved in the subsequent analyses.

3.2 Nonlinear trends of runoff and climate factors at different time scales

The nonlinear trends of runoff and its associated climate factors at different time scales were detected through a series of wavelet analyses. We chose Symmlet as the base wavelet function and applied Sym8 as the operational wavelet function for the decomposition and reconstruction of the time series data at different time levels. The simulation results revealed the tendency of changes of the annual runoff, the average annual temperature and the annual precipitation, as shown respectively in Figs. 2–4.

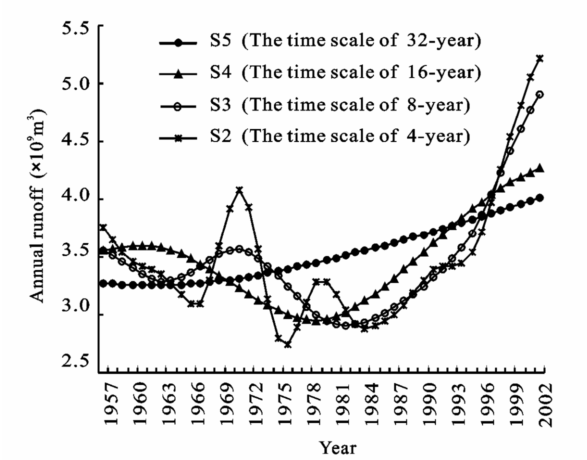

Fig. 2 Wavelet approximations for annual runoff at different time scales

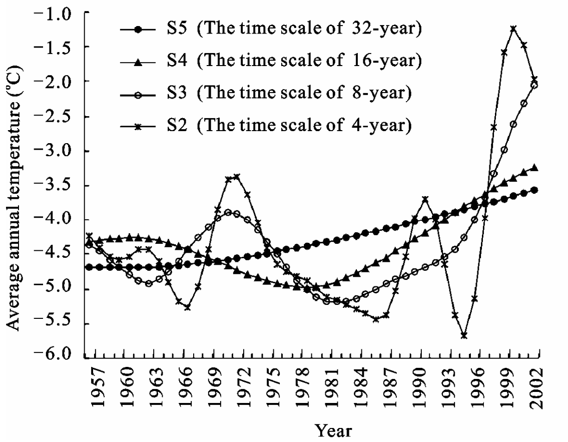

Fig. 3 Wavelet approximations for average annual temperature at different time scales

As we can see from Figs. 2–4, temporal trends were revealed for different time-series variables and at different time scales. At the scale of S5, namely the 32 (2^5) year time interval, the annual runoff and the average annual temperature present an obvious trend of escalation, whereas the trend of annual precipitation show a slightly increase. The tendencies of changes for these variables seem to match well with the physiological characteristics of this region, i.e., the Kaidu River is a snowmelt river of high elevation and high latitude (Collins, 2006). Moreover, they seem to reflect the effects of the accelerated global warming within the time frame of this study (Hanna et al., 2008; Cao et al., 2007, Ghan and Shippert, 2006). Similar trends have been found in the USA. For example, Muttiah and Wurbs (2002) found that the average annual temperature in the USA increased by about 0.6℃ and annual precipitation by about 5%–10% during the 20th century.

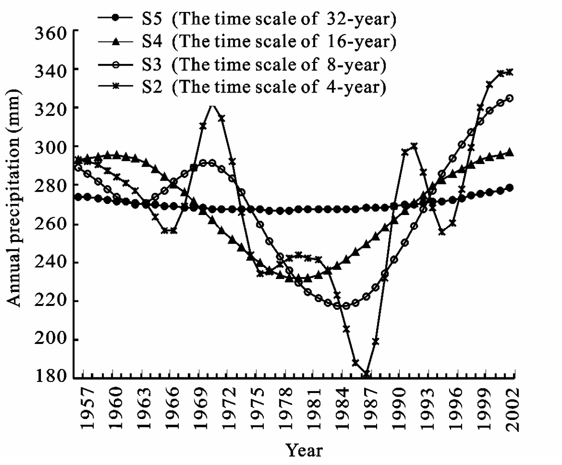

Fig. 4 Wavelet approximations for annual precipitation at different time scales

At the S4 scale, i.e. 16 (2^4) year time interval, all three time-series variables present basic tendency of first slightly rising, then dropping, and finally rising again (Figs. 2–4). Morphologically, all three curves of this time scale appear to synchronize very well, with the maximum and minimum taking place in the same years. This observation is perfectly explainable since runoff varies monotonically with the two chosen climate factors in this particular physiological setting. By examining the data table more carefully, we found that the max and min points (i.e. 1960 and 1980) for the annual precipitation was in fact either one year ahead or behind their counterparts (i.e. 1961 and 1979) in the other two time-series variables. Such slight differences, however, did not affect our interpretation of the overall patterns.

The wavelet analysis at the S3 scale, namely 8 (2^3) year time interval, revealed more local fluctuations along the time series of all three variables. The curves retained the basic trends shown at S4, yet they appeared to provide more and different details on the variability of those variables over time. First, the curves of all three time-series variables shared the same time spots for most maximums

(1971) and minimums (1963 and 1982), except the last minimum (1985) for the annual precipitation. Second, the min and max at this time scale did not occur in the same years (or even the neighboring years) as those revealed using the time-scale of S4. The first minimum of S3 curves, for instance, was located in approximately the same year when the maximum of S4 took place.

The S2-scale (i.e., the 4 (2^2) year time interval) analysis yielded a set of curves that retained the general trends being revealed when using the larger time interval steps but offered a significant increase of morphological details. In general, each curve presented a different number of min and max points from the other curves, and there were more cases in which the location of a point was different among the three curves (Table 2). Based on the tabulated data, it seems that the temperature in the early years of the time series exercised little impact on the annual runoff. The temperature drop in 1960, for instance, did not create a local minimum on the runoff of the same year, and the temperature rise in 1963 still could not reverse the runoff's descending trend. On the other hand, the global minima for the three time-series variables did not coincide in the same period. While the peak runoff took place in 1976, the highest temperature and precipitation were separately recorded in the next two decades (Table 2). In comparison, the local maxima of those three curves appeared approximately in the same year (i.e. 1971–1972). Incidentally, the local minima of the three curves also appeared within a two-year period (i.e., 1966–1967). A final observation is that after entering the 1990s, the runoff had continued to rise with no min or max along its curve, no matter how the two climate factors fluctuated. Compared to the wavelet analyses at the larger time scales, the temperature curve is more out of sync with the other two time-series variables at the S2 scale.

Table 2 Annum of minimum and maximum values for runoff, temperature, and precipitation as output from the wavelet analysis at a 4-year time scale for Kaidu River

Curve	Year of minimum					Year of maximum				
Annual runoff	↓	1966	1976	1984	–	↓	1971	1980	↑	↑
Average annual temperature	1960	1967	↓	1986	1995	1963	1972	↓	1991	2000
Annual precipitation	↓	1967	1976	1987	1995	↓	1971	1980	1992	↑

Notes: Symbols represent the moving trend when no peak value recorded in those years (↓ = descending; ↑ = ascending; and – = flat)

In summary, the result of wavelet approximation indicated that during the period 1957–2002, the annual runoff, the average annual temperature, and the annual precipitation of the Kaidu River presented a nonlinear process. This nonlinear tendency became more obvious when reducing the time scales in the wavelet analysis. With more details being revealed and more non-sync cases recovered from the time series data at smaller time scales, further studies of those cases are needed to provide appropriate explanations.

3.3 Relation between runoff and climate factors

The study of the relationship between the annual runoff and two climate factors at different time scales was performed through statistical correlation and regression analyses. The results were documented in Table 3 and Table 4.

Table 3 shows the regressive relation between the annual runoff and the annual precipitation at the four different time scales. The linear correlation of regression (R^2) for each time scale was in the medium range, with the lowest (0.2515) for the time scale of S5, the longest scale in all steps. The runoff-to-precipitation regression also presented an interesting phenomenon, i.e., along with the increase of the time step, the regression coefficient of independent variable AP decreases progressively. This suggested that at a larger time scale, we may expect

Table 3 Unitary regression analysis between annual runoff and annual precipitation at different time scales

Time scale	Regression equation	R^2	F	Significant level α
S5	$AR = 0.4056AP – 74.3750$	0.2515	14.7856	0.001
S4	$AR = 0.1382AP – 2.3011$	0.7069	106.1056	0.001
S3	$AR = 0.1372AP – 2.1150$	0.7798	155.8494	0.001
S2	$AR = 0.1236AP + 1.6090$	0.6785	92.8569	0.001

Notes: *AR* represents annual runoff, and *AP* represents annual precipitation

Table 4 Unitary regression analysis between annual runoff and average annual temperature at different time scales

Time scale	Regression equation	R^2	F	Significant level α
S5	$AR = 6.8044AAT + 64.351$	0.9994	6.8006e+004	0.001
S4	$AR = 7.8394AAT + 68.880$	0.9935	6.7762e+003	0.001
S3	$AR = 6.2678AAT + 62.089$	0.9415	708.7368	0.001
S2	$AR = 4.5947AAT + 54.688$	0.7485	130.9721	0.001

Notes: *AR* represents annual runoff, and *AAT* represents average annual temperature

a lower rate of contribution from the change of the annual precipitation to the annual runoff change, and vise versa.

Table 4 summarizes the regressive relation between the annual runoff and the average annual temperature. There was a high correlation of regression at the individual time scale, and these values were all higher than their counterparts in Table 3. Moreover, we may see from Table 4 that the regression coefficient of independent variable AAT decreases progressively along with the decrease of the time scale. This might imply that the rate of the contribution from the average annual temperature change reduces gradually when the time scale changes from large to small.

In order to further reveal the relation between runoff and the two selected climate factors, a three-dimensional scatter diagram was employed to visualize the raw data (Fig. 5). Its three axes represent the annual precipitation, the average annual temperature, and the annual runoff, respectively. Figure 5 illustrates that, along with the increase of annual precipitation and average annual temperature, the annual runoff presents an increasing tendency. Also the results of a multivariate regression analysis using the raw data indicate that the annual runoff is more sensitive to the average temperature than to the annual precipitation. This preliminary conclusion corresponds with the result from Tao et al. (2007).

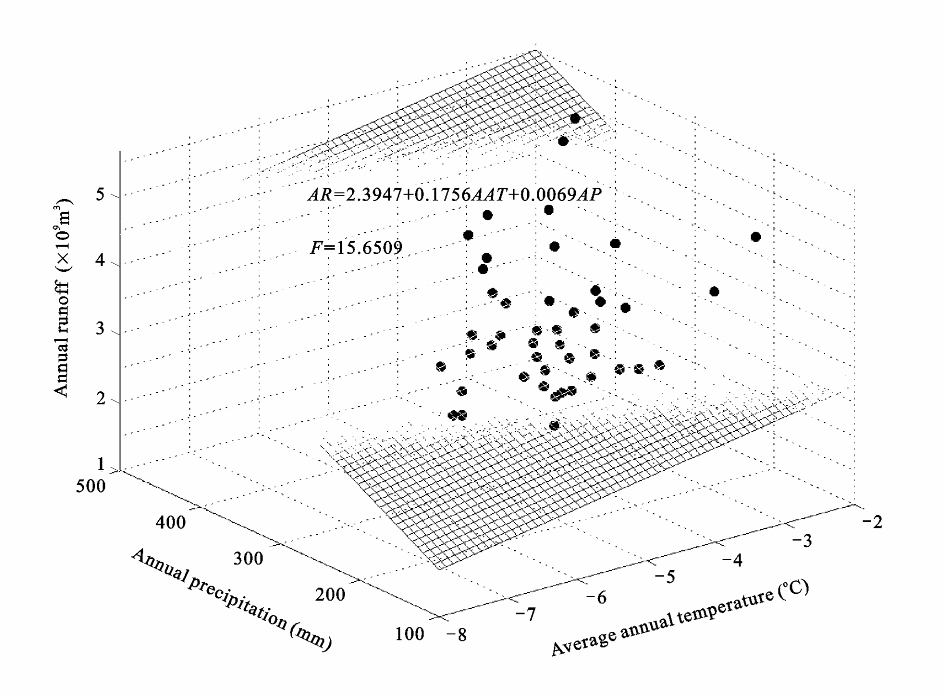

Fig. 5 3D scatter graph for annual precipitation, average annual temperature and annual runoff

Multivariate regression analyses were also applied to the data output from the wavelet analysis at different time scales. With the average annual temperature and the annual precipitation as independent variables and the annual runoff as the dependent variable, the regression model results were summarized in Table 5.

We can see from Table 5 that all four regression models are significant at the level of α=0.001, and the corre-

Table 5 Multivariate linear regression results between annual runoff and two climate factors

Time scale	Regression equation	R^2	F	Significant level α
S5	$AR = 58.6650 + 0.0198AP + 6.7421AAT$	0.9765	892.7686	0.001
S4	$AR = 60.4386 + 0.0194AP + 7.0955AAT$	0.8279	103.4064	0.001
S3	$AR = 48.4187 + 0.0323AP + 5.1239AAT$	0.6726	44.1594	0.001
S2	$AR = 32.7973 + 0.0563AP + 3.0270AAT$	0.4654	18.7176	0.001

Notes: *AR* is annual runoff, *AP* is annual precipitation, and *AAT* is average annual temperature

lation of regression ranges from 0.46 to 0.98 from small time scale to large time scale. This pattern indicated that the impact of the climate factors on the runoff in this study area showed up more significant in a long run than in a short time. This is especially true for the fact that the big dip of average annual temperature and annual precipitation in 1995 did not even place a dent on the runoff curve (Figs. 2, 3, 4, and Table 2), but the overall trend of rising after the 1980s was revealed at the longer time steps well enough to smooth out the valley of 1995 in both climate factors. Another latent point revealed in Table 5 is that the influencing power of precipitation was much smaller than that of temperature. The reason for this seems that although the Kaidu River is supplied mixedly by both snowmelt and precipitation, the increase of the temperature causes the meltwater exceed land vaporization, thus causing the increasing tendency of runoff. Therefore, in the time period of this study, the snowmelt had played a major role in driving the dynamics of the runoff of the Kaidu River. Along with the increasing reduction of the glacier reserves and the retreating of the snow area, we can expect that this kind of controlling role will be downplayed.

4 Conclusions

The integrated approach combining grey relation analysis, wavelet analysis, and conventional statistical analysis was proven effective to reveal important relationship between runoff and its influencing climate factors for the Kaidu River. Major findings from this study include the following.

(1) According to the level of their impact on the annual runoff, all climatic factors under examination through the grey relation analysis were ordered as follows (from high to low): average annual temperature, average temperature in autumn, average temperature in winter, annual precipitation, precipitation in flood season, average temperature in summer, and average temperature in spring. Average annual temperature and annual precipitation were selected as the representative factors that affect the annual runoff.

(2) At the time scale of S5 (i.e. the 32-year time interval), the annual runoff and the average annual temperature presented an obvious trend of escalation, whereas the annual precipitation showed little increase over the period 1957–2002. As the time scale for wavelet analysis to be reduced to 4 years (i.e. S2), all three time series variables manifest inherent high levels of nonlinearity, with an increasing number of peaks and valleys along the temporal dimension. At this finest time-scale of all in this study, the variation of runoff could not be explained by the variation of the climate factors in several particular years; therefore, further studies were necessary to seek other driving forces.

(3) The statistical analysis of this study indicated that the variability of the Kaidu River runoff was closely related to the change of the regional climate, which in turn might be more affected by the recent global climate change. By using results of wavelet analyses for multivariate regression modeling, correlations of regression for all four time scales (i.e. 32 (2^5), 16 (2^4), 8 (2^3), and 4 (2^2) years) were found significant. However, the correlation strength generally decreased with the time scale from large to small, indicating that the effect of climate change on the runoff should be viewed from a long-term perspective. Also the fact that partial coefficients of the average annual temperature are much larger than those of the annual precipitation suggested that the runoff of the kaidu River was more sensitive to temperature change than to precipitation change. This was also readily revealed in the wavelet curves for all three time series variables at the time scale of S5.

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