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Analyses of relationship between Loess Plateau erosion and sunspots based on wavelet transform

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Abstract

Loess Plateau is one of the worst soil erosion regions in the world, which may resulted from various factors such as precipitation, land cover and land use, soil, vegetation, human intervention, as well as solar activities. The purpose of this study is to find the relationship between soil erosion and sunspot activity on the Loess Plateau, through analyses of the sunspot relative number and the long-term sediment discharge series in Longmen station in the Yellow River based on the Morlet wavelet method. In this paper, annual sediment discharge series from 1919–2008 in Longmen station and the sunspot relative number were decomposed with Complex Morlet wavelet. The results of real part, modulus and the second power of modulus showed an obvious periodic variability in sediment discharge, with 25–40 years, about 10 years, and less than 10 years scales. There are six centers of energy. From the wavelet variance, 6, 12, and 35 years periods were detected within 50-year scale, and the 35-year period is the most significant one. Similar analyses were conducted for the sunspot relative number during the same period of 1919–2008. The sunspot series showed an 11-year periodic variation, and two energy center. Then, the correlation analyses for 11-year scale were computed. From a long-term period (1919–2008) view, there is no significant correlation between the sediment discharge and the sunspot relative number; however, it is evident that the correlations exist in short-term periods. The results also indicate that the relationships between solar activities and the erosion of the Loess Plateau are complicated.

1 Introduction

Soil erosion is one of the world's most important environmental problems. And it is one of the major subjects under the International Geosphere-Biosphere Programme (IGBP) to investigate soil erosion on a global scale. International academic communities believe that, terrestrial and marine sediment records may become an important information base to reveal the global soil erosion processes (Gong and Xiong, 1979). It is estimated that loess covers 10% of the total land surface of the earth. In Northwest China, the ratio is ever higher, especially in the middle reaches of the Yellow River. The continuous distribution of the thick layer of loess shaped the spectacular Loess Plateau. Loess in the middle reaches of the Yellow River is the most typical in the world. Yellow River flowing through this region is famous for the large amounts of sediment. Researches have proved that the Loess Plateau is the main source of the Yellow River sediment and loess is the main material source of the Yellow River sediment. The volume of Loess Plateau erosion and river sediment load is nearly the same (Gong and Xiong, 1979; Mu and Meng, 1982), thus, the basic characteristics of the sediment-laden Yellow River on the Loess Plateau are closely dependent. The Yellow River sediment discharge changes basically represent the erosion intensity changes on the Loess Plateau, and the volume of the Yellow River sediment record reflects the occurrence of the Loess Plateau erosion conditions and the role of the law (Shi and Shao, 2000; Gao et al., 2010; Wang and Li, 2010).

Various solar activities such as flares, solar radiation bursts, and solar winds can lead to radiation enhancement and plasma movement. A number of researchers have focused on the sunspots' periodic variability (Han and Han, 2002; Krivova and Solanki, 2002; Yin et al., 2007; Balthasar, 2007). These studies demonstrated that solar periodical activities could affect global climatological changes in direct and/or indirect ways. Global climate fluctuations that occur with a regular frequency may have their origins associated with the solar activities. Moreover, the influences of solar activities on hydrological and meteorological processes possess significant regional features (Alexander, 2005; Thresher, 2002; Seleshi et al., 1994). Therefore, revealing the relationships between solar activities and hydrological and meteorological parameters (such as precipitation, runoff and sediment) is desired.

Previously, a number of studies were undertaken on the correlations existing between solar activities and runoff/precipitation. It has been known for some time that there is a statistical relation between solar activities (the sunspot number) and

precipitation (Wang et al., 1997; Dima et al., 2005). It is also clear that there are some relationships between solar activities and natural runoff (Labitzke and van Loon, 1993; Li et al., 2009). Hong et al. (1990) studied the relationship between the Loess Plateau erosion and sunspot activity; the study suggests that the intense loess erosion is closely consistent with the periodicity of sunspot activity.

In this paper, the objective is to analyze the long-term sediment discharge series in Longmen station in the Yellow River based on the Morlet wavelet method, and then to find the relationship between soil erosion and sunspots on the Loess Plateau. Firstly, a Morlet wavelet method was introduced to analyze the correlation between sediment discharge and sunspots. Then, sediment discharge in Longmen station during 1919–2008 and sunspots were decomposed and analyzed using the Morlet wavelet method, and their multi-scales variability and periodicity would be given in details. At last, the relationship between sediment discharge and sunspots was explored based on wavelet coefficients, and the possible effects of the sunspots on erosion of the Loess Plateau changes were discussed.

2 Study area and data sets

Longmen station is located at Xiayukou, Hancheng County, Shaanxi Province. It is one of the major hydrological control stations in the middle reaches and has high academic value in the main channel of the Yellow River (Fig. 1). On the Loess Plateau, the area Longmen station located has the most serious problems of soil erosion and sediment yield. The dramatic changes in sediment quantity and quality in the Longmen region represent the Yellow River sediment characteristics with multiple determinants. This region has also become a sensitive reflection of the erosion process in the Loess Plateau.

The long-term annual sediment discharge series (1919–2008) in Longmen hydrological station was analysed in this study (Fig. 1). The data were obtained from the Chinese River Streamflow and Sediment Communiques, and the Ministry of Water

Resources of PRC (MWR). The annual sunspot relative number during the period of 1919–2008, which is from NOAA's National Geophysical Data Center (NGDC) (ftp://ftp.ngdc.noaa.gov/stp/solar_data/sunspot_numbers/international/yearly/yearly), is applied for solar activities analyses. All data used in this study have been checked for quality control by corresponding agencies, and are of good quality.

3 Wavelet transform method

The Wavelet transform (WT) is a major development in the methods of data analysis in the last decade. It evolved from several fields including signal processing, physics, and mathematics. The application of the WT in analysing time based data, particularly those with non-stationary characteristics, has been found to be very successful (Nason and von Sachs, 1999; Percival and Walden, 2000). The WT is also an effective means in the field of hydrology and it is frequently encountered in hydroclimatic time series (e.g. Jay and Flinchem, 1997, 1999; Smith et al., 1998; Torrence and Compo, 1998; Gan, 2001; Labat et al., 2001). In this paper, the Morlet wavelet is used for examining the wavelet variation of sediment discharge and sunspots number series and for analyzing their linear correlation under different sunspots' periods.

The WT of a signal $x(t)$ is an example of a time-scale decomposition obtained by dilating and translating a chosen analyzing function (wavelet) along the time axis. The continuous wavelet transform is defined as follows:

$$W_f(a,b) =< f(t),\ \Psi_{a,b}(t) = |a|^{-1/2}\int_R^{f(t)} \overline{\Psi}(\frac{t-b}{a})dt \tag{1}$$

where $\overline{\Psi}(t)$ is the complex conjugate of the wavelet function $\Psi(t)$ (the mother wavelet), b is the parameter localizing the wavelet function in the time domain, a is the dilation parameter defining the analyzing window stretching and $f(t)$ is the complex conjugate of the basic wavelet function. The $W_f(a,b)$ represents the correlation between the signal

$x(t)$ and a scaled version of the function $\Psi(t)$, and the idea of the WT is to decompose a signal $x(t)$ into wavelet coefficients by using the basis of wavelet functions.

The mother wavelet function in this paper is one kind of Complex Morlet wavelets defined as

$$\Psi(t) = \frac{1}{\sqrt{\pi f_b}} e^{2i\pi f_c x} e^{-\frac{x^2}{f_b}} \tag{2}$$

where f_b is a bandwidth parameter; f_c is a wavelet center frequency. In this research, $f_b : f_c = 1.5:1$. The real-valued Morlet is the real part of the complex version of the Morlet wavelet. The difference between imaginary part and real part of the complex-valued Morlet is the phase shift of the imaginary part from the real part by a quarter periods.

The wavelet variance used to detect the main periods contributing to a signal can be expressed as:

$$\mathrm{Var}(a) = \sum (W_f)^2(a,b) \tag{3}$$

where Var(a) is the wavelet variance, $W_f(a,b)$ is the wavelet coefficient, a is the frequency/scale variable and b is the time variable. Since wavelet variance denotes the distribution of wavelet energy by scale (period), the domain predominant periods of one time series can be obtained from its extreme values.

4 Variations of sediment discharge and sunspot relative number

The annual sediment discharge in Longmen hydrological station from 1919–2008 had no clear periodic fluctuation (as shown in Fig. 2), and was highly non-linear and non-stationary. The variation of the sunspot relative number is shown in Fig. 3. Unlike the sediment discharge, the sunspot relative number indicated a clear period.

5 Wavelet analyses of sediment discharge

The 50-year scale is chosen, the wavelet coefficient contour map of the sediment discharge time series is plotted based on the above Morlet wavelet method. The wavelet map represents how closely the wavelet is related with each section of the signal. The wavelet variability can be analyzed through the modulus, the second power of modulus and the real part of wavelet. In general, the higher the scale used in the analysis, the more stretched the wavelet, the longer the part of the signal with which it is being compared, and thus the coarser the signal features being measured by the wavelet coefficients. That is, a high scale is used to reveal the long-term changes in the signal rather than rapidly changing details, and vice versa. The intensity at each x-y point represents the magnitude of the wavelet coefficients. The real part of Complex Morlet wavelet coefficient includes both the intensity and the phase of the signal variation, at particular scales and locations in wave domain (the time-frequency domain). In the sediment discharge wavelet coefficient, a positive real part coefficient means that the sediment discharge quantity is higher, and vice versa. From the real part periodic change, the sediment discharge variation structures with higher flow and lower flow phases are clearly shown on different scales, and they are different with the scales. The lower scale changes have more complex structures nested into the higher scales.

The real part of the annual sediment discharge in Longmen station in the Yellow River during the period 1919–2008 is plotted (as shown in Fig. 4). In the figure, the red regions represent higher sediment, blue regions mean lower and other colors show the middle sediment. From Fig. 4, it is seen that the sediment discharge has 25–45, about 10, and less than 10-year periodical characters within a 50-year scale. On a 25–45-year scale, there are more two-cycle oscillations. The periods of 1922–1940, 1958–1974 and 1992–2006 are the high-sediment periods, while 1941–1957 and 1975–1991 are the low-sediment periods. The sediment discharge would enter into a low-sediment period after 2007. Its real part coefficients changes on a 35-year scale are shown in Fig. 5. On 10-year scale, there are more cycle oscillations. The annual sediment

discharge shows obvious and stationary periodic variability. On less than 10-year scale, its oscillation frequency is very high and complicated.

The modulus of wavelet coefficient represents the power density, and it shows the periodic variability in time scales. The higher the modulus is, the more obvious the periodic variability is for its time and scale. The modulus of sediment discharge in Longmen station is plotted in Fig. 6, and it shows that there are obvious periodic variability with 30–50 years, about 10 years and less than 10-year.

The second power of modulus represents the energy spectrum, and it shows the energy variability in time scale. The higher the energy is, the stronger the periodic oscillation is. The second power of modulus of the sediment discharge (Fig. 7) shows that there are six centers of energy.

The wavelet variance of the sediment discharge in Longmen hydrological station was computed based on Eq. (3) (Fig. 8). And the main periods were obtained from its peak values. On a 50-year scale, there are 6, 12, 35-year periods and the 35-year period is significantly obvious.

6 Correlations between sunspot relative number and sediment discharge

Similarly to wavelet analyses of sediment discharge, the sunspot relative number series of 1919–2008 was also decomposed on a 50-year scale by the Complex Morlet, and its real part, modulus and second power of modulus of wavelet coefficient are shown in Figs. 9, 10, and 11. From them, the sunspot relative number shows remarkable periodic changes, especially on an 11-year scale; and there is two main energy center on about 11-year scale in the modulus map and power of modulus map. From its wavelet variance (Fig. 12), the 11-year period is the most important on a 50-year scale.

Compared to the basic statistics of sediment discharge and sunspot relative number, the appearance times of their minimum and maximum are different. From their 90-year change lines (Fig. 13), the high sediment discharge years corresponded with not only the peak of sunspot years, but also the valley or normal years; for example, both of sediment discharge and sunspot had a peak value in 1937 and a valley value in 1986; however, in 1947, sediment discharge had a peak value, while sunspot had a valley value; conversely, sediment discharge and sunspot had respectively a valley value and a peak value in 1980. It is difficult to find their clear relationships or how solar activities influence on sediment discharge (or Loess Plateau erosion).

As is known, sunspot relative number has an 11-year period; and a 12-year period has been further found in sediment discharge. The two periods are almost the same. Therefore, the possible impacts of solar activities on sediment discharge in Longmen station showed an 11-year feature. In this study, their real part coefficient series on 11-year scale were applied for analyzing the correlations and the correlation coefficients were computed as −0.007. They had no significant correlations from 1919–2008; however, they had different correlations within different time phases (Fig. 14, Table 1). From 1919–1955, they had a negative correlation with −0.613 at the 0.01 Sig. level. From 1956–1990, they had a positive correlation with 0.485 at the 0.01 Sig. level. From 1991–2008, they had a negative correlation with −0.557 at the 0.05 Sig. level. The time phase is about 35 years, which happens to be the first primary period of sediment discharge in Longmen station. These show that the impacts of solar activities on Loess Plateau erosion are changing with time and there are different impacts in different phases.

7 Discussions and conclusions

Based on the annual sediment discharge data (1919–2008) in Longmen station, sediment discharge and sunspot relative number have been decomposed using Complex Morlet. From the analyses of real part, modulus and power of modulus, the annual sediment discharge has obvious periodic variability with 25–45, about 10, and less than 10-year scales. On every scale, there would have different periodic characters. There are six centers of energy. From the wavelet variance, 6, 12, 35-year periods are detected within a 50-year scale, and the 35-year period is the most obvious. The

similar methods have been employed for the sunspot relative number during the same period of 1919–2008. The sunspot series shows an 11-year period variation, as well as two energy center.

During the period of 1919–2008, there is no notable correlation between sediment discharge and sunspot relative number; however, in some short phases, there are obvious correlations between these two factors. For example, on an 11-year scale, there is a negative correlation in 1919–1955 (−0.613) and 1991–2008 (−0.557), while there is a positive correlation in 1956–1990 (0.485). The results demonstrate that the effects of solar activities on Loess Plateau erosion are complicated.

Complex Morlet wavelet method is applied to analyze the wavelet structure of annual sediment discharge and sunspot relative number. In the present research, based on Complex Morlet wavelet coefficient, the possible impacts of solar activities on the Loess Plateau erosion are analyzed, and the important results are obtained, which are different with those before. However, the correlation between sunspot relative number and sediment discharge may be lower, because the Loess Plateau erosion progress is affected by kinds of factors such as precipitation, land cover and land use, soil, vegetation, human intervention, and others besides solar activities. Moreover, the effects of solar activities on Loess Plateau erosion are associated with a number of complex physical processes; more robust methods are thus desired to be advanced in the future studies.

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Table 1. Correlation coefficients of the WT real part coefficient series of 11-year scale between sunspot relative number and sediment discharge in Longmen station.

Time phase	Pearson correlation coefficients	Sig. level
1919–2008	−0.007	–
1919–1955	−0.613	0.01
1956–1990	0.485	0.01
1991–2008	−0.557	0.05

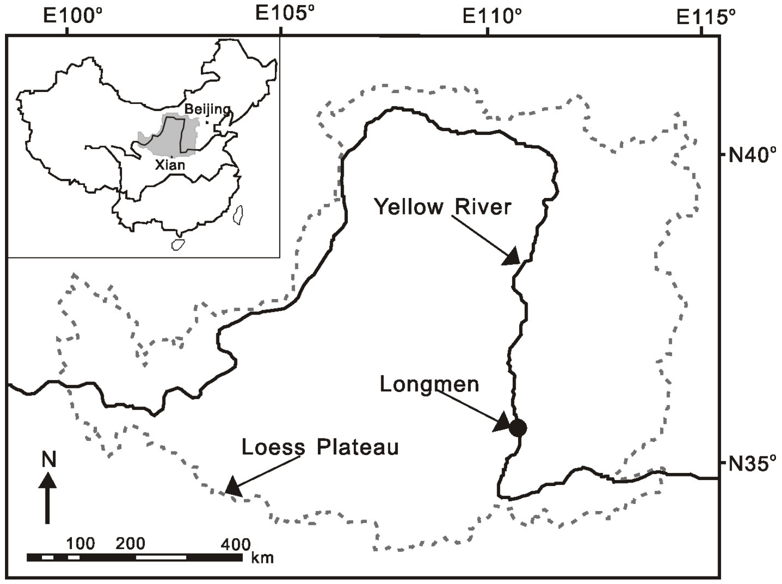

Fig. 1. Situation of Longmen station in the Yellow River Basin.

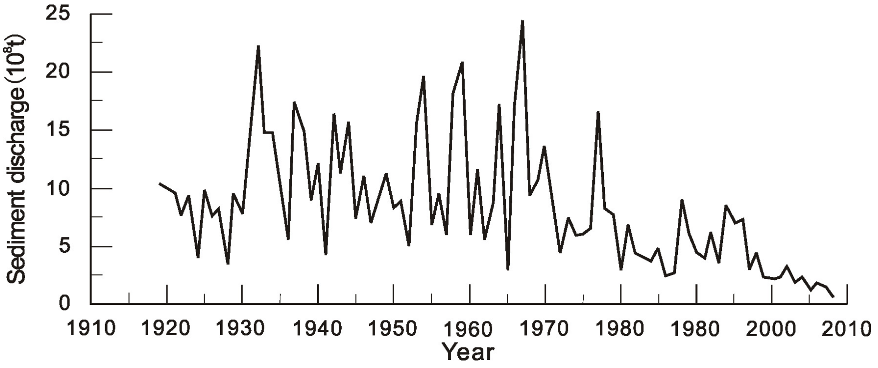

Fig. 2. Variation of annual sediment discharge in Longmen station.

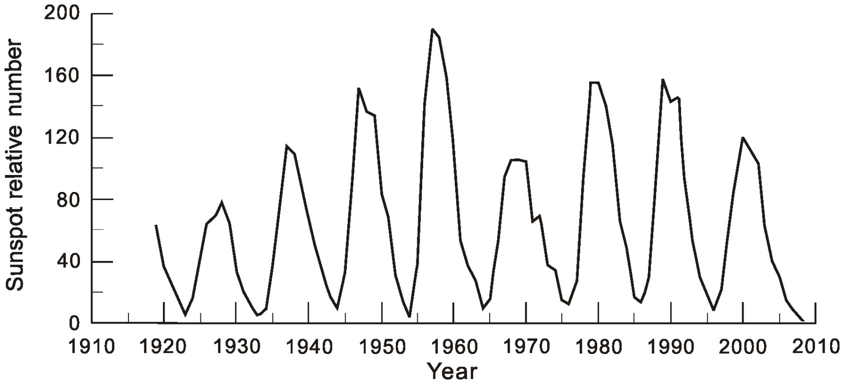

Fig. 3. Variation of the sunspot relative number.

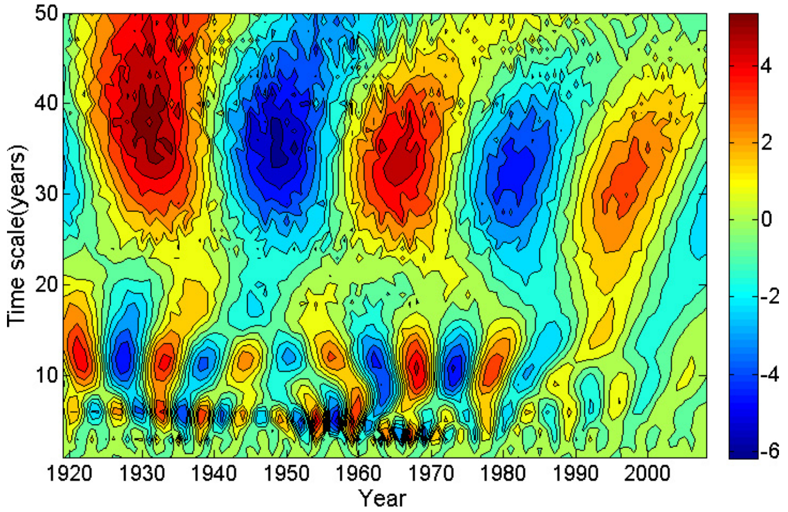

Fig. 4. Real part wavelet coefficient contour map of sediment.

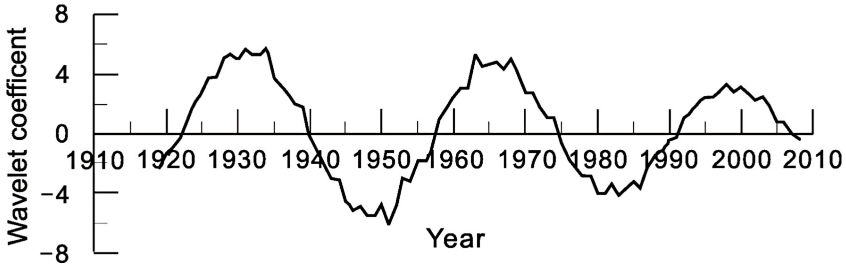

Fig. 5. Real part coefficients changes of sediment discharge on a 35-year scale.

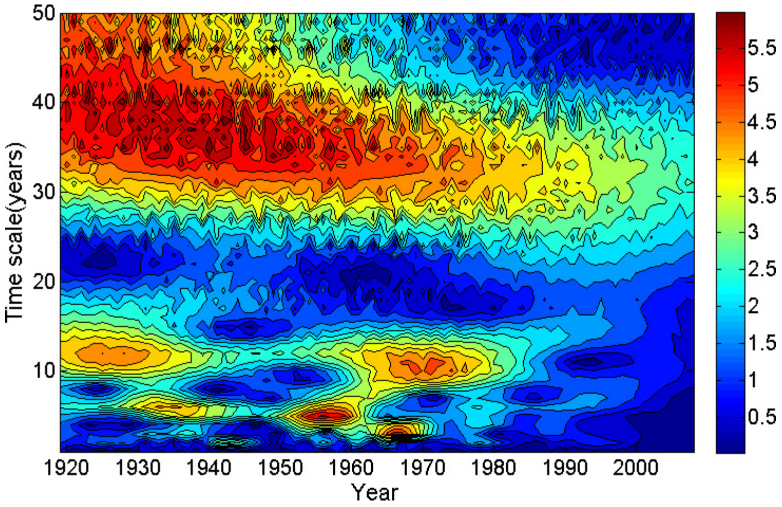

Fig. 6. Modulus of wavelet coefficient contour map of sediment discharge.

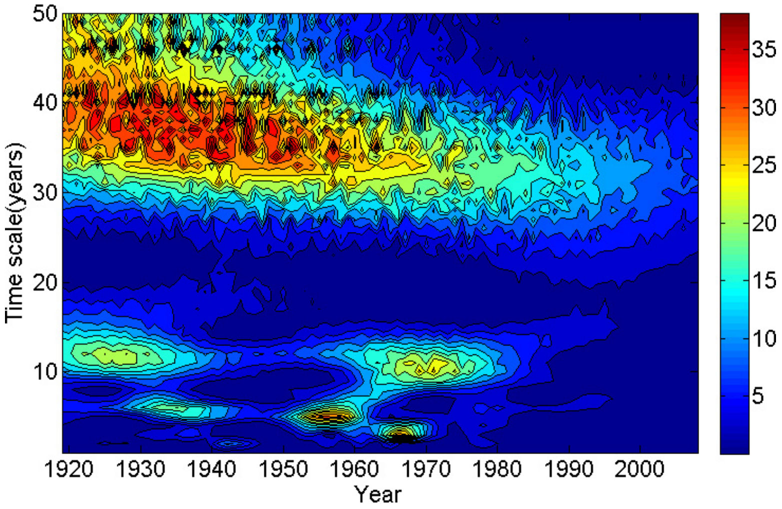

Fig. 7. The second power of modulus of wavelet coefficient contour map of sediment discharge.

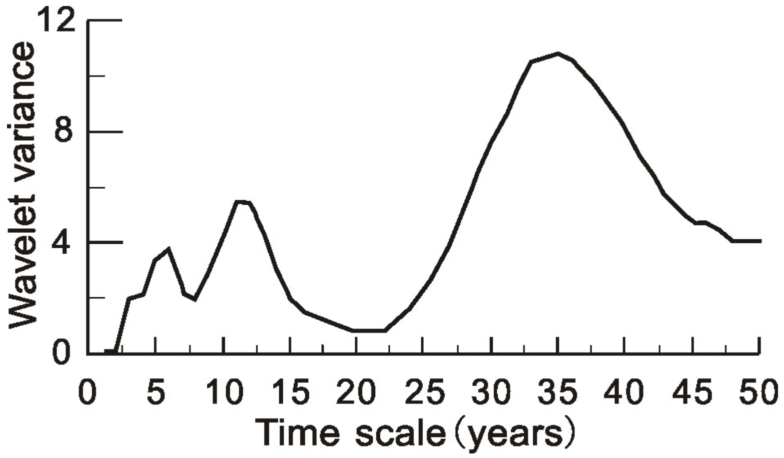

Fig. 8. Wavelet variance of the sediment discharge in Longmen station.

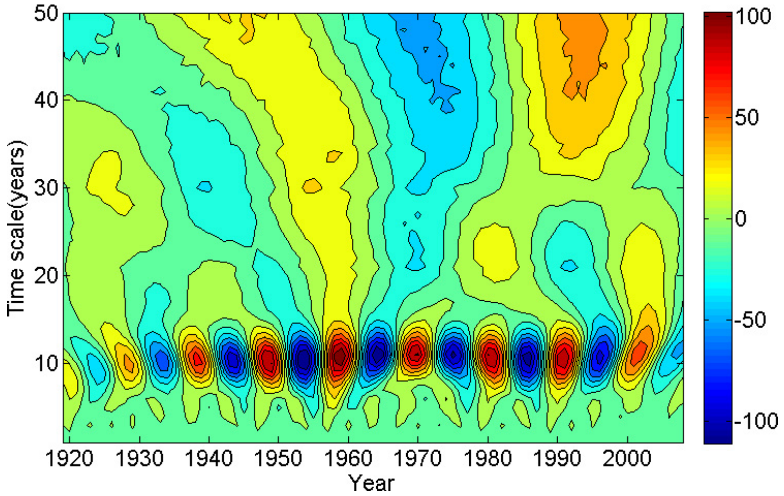

Fig. 9. Real part wavelet coefficient contour map of the sunspot relative number.

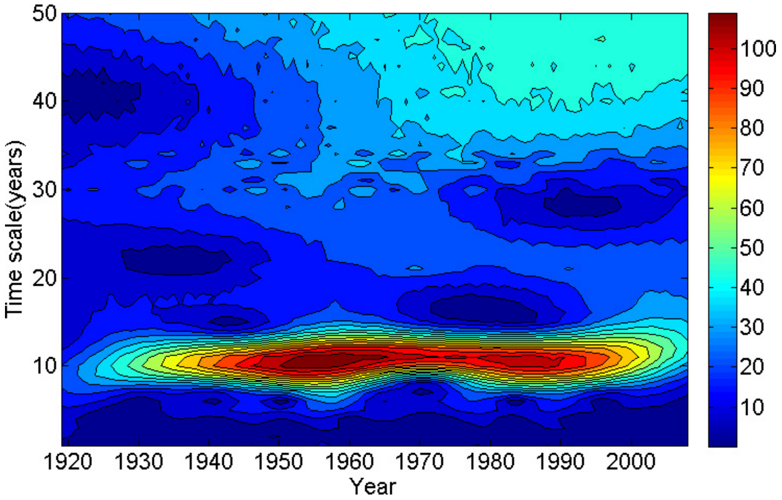

Fig. 10. Modulus of wavelet coefficient contour map of the sunspot relative number.

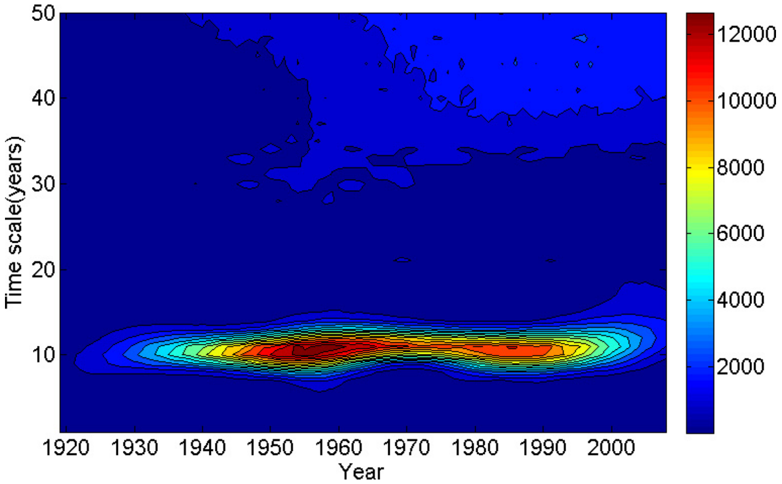

Fig. 11. The second power of modulus of wavelet coefficient contour map of the sunspot relative number.

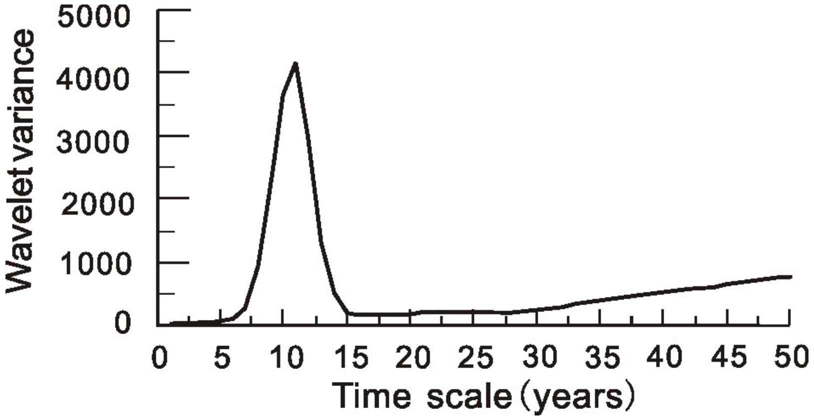

Fig. 12. Wavelet variance of the sunspot relative number.

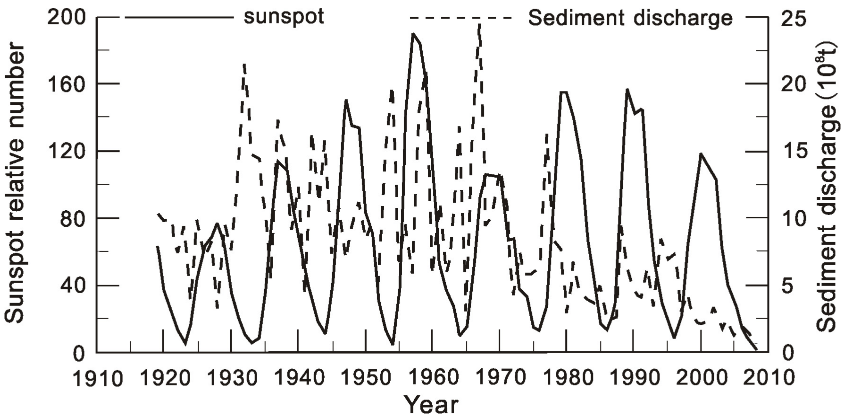

Fig. 13. Variation of sediment discharge in Longmen station and the sunspot relative number.

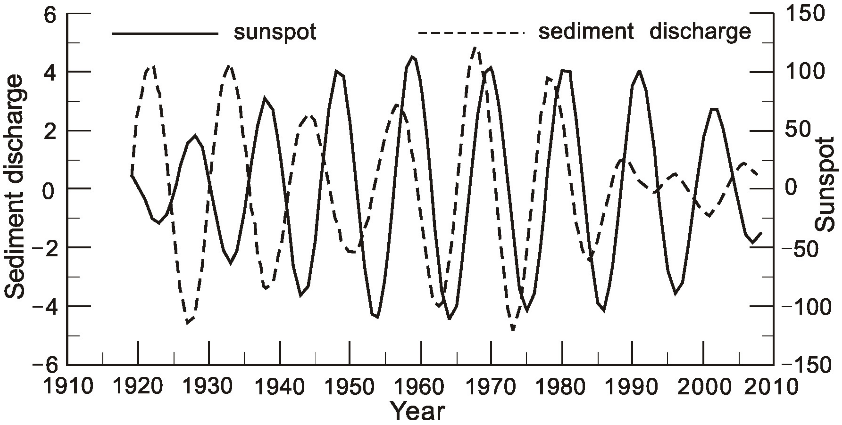

Fig. 14. Wavelet coefficient changes of sediment discharge in Longmen station and the sunspots from 1919–2008 on an 11-year scale.