Application of Wavelet Analysis to Correlation Between Sunspot Activity and Precipitation in Yunnan Province

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Abstract: Wavelet analysis is widely applied in the processing of time series such as climate and hydrology to extract the change characteristics and periodic relations. Based on wavelet analysis and time lag correlation analysis, this paper studies the correlation between sunspot numbers and precipitation at seven meteorological stations in Yunnan Province from year 1959 to 2019.The results show that the cross wavelet analysis and time lag correlation analysis are suitable for studying the periodic response and time delay relationship between solar activity and climate factors. These two methods can extend to other geographical locations. It is shown that the resonance period between sunspot numbers and the annual mean precipitation at the seven meteorological stations are mainly concentrated in the scale of 8-12a, and there are obvious time lag relationships between these time series from the phase angle. The time lag correlation analysis shows that there are different time delays between sunspot numbers and precipitation in different climatic regions.

1 INTRODUCTION

As a powerful statistical tool, wavelet analysis has been used in the field of mathematics for about a century. It is a development of the Fourier Transform, which can be used for time-frequency analysis of signals with non-stationary characteristics. The wavelet transform replaces the infinitely long trigonometric basis in the Fourier transform with a finite length decaying wavelet basis to obtain the frequency change and time information. At present, wavelet analysis is widely used in signal analysis, image processing, quantum mechanics, theoretical physics and other fields. Many scholars apply wavelet analysis to climate analysis to diagnose the internal hierarchy of climate change and analyze the evolution characteristics of time series at different scales. For example, Li and Gao et al. (2017) used wavelet analysis to study the influence of solar activity and El Nino on extreme precipitation in the Loess Plateau. They found that the maximum precipitation mainly occurred at or near the peak of sunspot numbers, and extreme precipitation often occurred in the year after El Nino event. Li and Wen et al. (2020) studied the time response to drought based on the wavelet transform method. They found that meteorological drought and hydrological drought had obvious periodicity on the scale of 2-4a, and hydrological drought was usually followed by meteorological drought for 1-2 months. Zhao and Luo (2021) applied wavelet analysis to the study of temperature and precipitation changes in Dabie Mountain in western Anhui Province. The results showed that temperature had an oscillation periodicity of 22a and 10a, and precipitation had an oscillation periodicity of 26a. We will get different conclusions by using wavelet analysis to study climate characteristics at different regions.

Climate changes have always been a hot issue of social concern. The frequent occurrence of extreme climates has caused huge losses to human life and property. It will greatly reduce and avoid the harm caused by climate changes if we understand the climate changes, improve the accuracy of predictions and take effective measures to cope with climate change actively. At present, many scholars improve the accuracy of climate prediction by data assimilation, such as Cheng and Argaud et al. (2021) use a flexible combination of existing covariance tuning algorithms to tackle the problem of a multivariate and spatially distributed hydrological model and gain a significantly more accurate and more robust flow forecast for the Tarn river. We can also increase climate factors in the prediction model to improve the accuracy. The climate changes are

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influenced by many factors, such as solar activity, atmospheric circulation, ENSO, land-sea distribution, global warming and anthropogenic factors. Sunspots are a symbol of solar activity. The sunspot numbers are related to the intensity of solar radiation. Therefore, this study uses sunspot numbers to represent the solar activity to investigate the correlation between solar activity and precipitation.

Based on the precipitation in Yunnan Province at seven meteorological stations and sunspot numbers, this paper adopts the method of wavelet analysis and correlation analysis to study the possible relationship between solar activity and precipitation. It helps for analyzing the mechanism of solar activity affecting climate change and predicting climate changes in Yunnan Province.

2 MATERIALS AND METHOD

2.1 Study Area

Yunnan Province is located in the Yunnan-Kweichow Plateau region, between latitudes within 21°8 ' N ~ 29°15' N and longitudes within 97°31 ' E~106°11 ' E, covering an area of 394100 km^2. Due to the influence of atmospheric circulation, there are different climate zones in the province. The main climatic zones including north tropical zone, South subtropical zone, middle subtropical zone, North subtropical zone, South humid zone, middle temperate zone and plateau climate zone. The paper selects the precipitation data of one meteorological station in each of the 7 climatic zones for research. The 7 meteorological stations are Kunming Station, Pu'er station, Mengla Station, Zhaotong Station, Gongshan Station, Lijiang Station and Shangri-La Station. Because of geographical complex topography and diverse climate zones, it is important to select precipitation data from different meteorological stations in Yunnan Province to study the correlation between solar activity and precipitation.

2.2 Data

The precipitation data of Yunnan Province are selected from the National Meteorological Science Data Center (https://data.cma.cn). The sunspots data are selected from Royal Observatory of Belgium, Brussels (https://www.sidc.be/silso/homes). The study covers the period from year 1959 to 2019 (61 years). Even though there are some abnormal, missing or invalid information exists in the original data, it will not bring much influence on the result of the research if these abnormal data are processed. In this study, missing values are filled in and outliers are replaced.

2.3 Method

2.3.1 Wavelet Analysis

Wavelet analysis is an effective method to reveal the temporal structure time series (Wang & Wang, 1996). Many time series show non-stationary in their statistics. Different from most classical signal analysis methods, wavelet analysis can be used to detect and analyze the non-stationary of signals (Chellali, Khellaf & Belouchrani, 2010). It can help us extract the change features with complex temporal patterns, such as periodic variation and response events. Wavelet transform is a powerful time-frequency analysis method, which has been applied in many studies (e.g., Chellali, Khellaf & Belouchrani, 2010; Alperovich, Zheludev & Hayakawa, 2016). These applications help to develop the wavelet analysis theory and practice (Torrence &Webster, 2010; Ge, 2007). In this paper, we use cross wavelet transform to analyze the respond periodicity of two time series. Cross wavelet transform is constructed by continuous wavelet transform to study their high-power region and phase relationship in the time-frequency interval. Continuous wavelet transform is an important method widely used in wavelet analysis. Here, Morlet wavelet is used as the wavelet basis function of continuous wavelet transform and it is defined as follow.

$$\psi_0(t) = \pi^{-1/4} e^{i\omega_0 t} e^{-t^2/2} \tag{1}$$

In equation (1), ω_0 is the frequency parameter. we often choose $\omega_0 = 6$ because it can make the balance between time and frequency. t is the time parameter.

The continuous wavelet is a band-pass filter which can be stretched and translated to get different wavelet basis. The continuous wavelet transform of wavelet ψ is defined as.

$$CWT = \psi(\tau, s) = \frac{1}{\sqrt{s}} \int x(t) \psi^* (\frac{t-\tau}{s}) dt \tag{2}$$

In equation (2), $x(t)$ is the input data. t is the time parameter. s is the scale parameters (inversely proportional to the spatial frequency). τ is the position offset. ψ^* represent the complex conjugate of the function ψ.

Cross wavelet transform is used to analyze the correlation between two time series in the time-frequency domain (Banerjee & Mitra, 2014). The cross wavelet transform can reveal the similarity or difference between time series, quantify the correlation and the lag relationship between two time series. The cross wavelet transform of two time series x_n and y_n is defined as.

$$W_n^{XY} = W_n^X . W_n^Y \tag{3}$$

In equation (3), W_n^X is the wavelet coefficient matrix of time series x_n. W_n^Y is the wavelet coefficient matrix of time series y_n. W_n^{Y*} is the complex conjugate matrix of wavelet coefficient matrix W_n^Y. The larger value of $|W_n^{XY}|$ is, the more significant the correlation is. It means that there is a common high energy region between two time series.

The cross wavelet transform uses the phase angle to estimate the phase difference of two time series. It can represent the lag relationship between two time series.

$$\arctan\left(\frac{i_{mag}\{W_n^{XY}(s)\}}{r_{eal}\{W_n^{XY}(s)\}}\right) \tag{4}$$

In equation (4), r_{eal} represents the real part of the cross wavelet coefficient. i_{mag} represents the imaginary part of the cross wavelet coefficient.

According to the relationship between phase angle and period, phase lead or lag can be obtained. In the cross wavelet transform power spectrum figure (as shown in figure 1). ← indicates that sunspots are negative correlated with precipitation. → indicates that they are positive correlated. ↓ indicates that sunspots lead precipitation by 90°. ↑ indicates that sunspots lag precipitation by 90°. In figure 1, red and blue colors represent the peak and valley values of energy density. It reflects the local and dynamic characteristics of the time-frequency transformation of the dominant fluctuation. The shades of color represent the relative change of energy density. Thick solid black line is the 5% significance level, which has passed the red noise test. Thin solid black line denotes the boundary of wavelet influence cone. This area is the edge effect of wavelet transform which cannot be ignored (Grinsted, Moore & Jevrejeva, 2004).

2.3.2 Time Lag Correlation Analysis

In the study of atmospheric, ocean and other scientific problems, the response of the process is often not immediate. It is necessary to carry out time lag correlation analysis on the time series. Time lag correlation analysis is to determine whether there is a certain correlation between two time series if one time series is lagged a period of time. The way to do that is letting the time series y_2 lags by the value from -n to n, and then calculate its Pearson coefficient with the other time series y_1. It is assumed that the correlation is strongest by the value of i. If $i > 0$ means that y_2 lags y_1 by the value of i. If $i < 0$, then y_2 is ahead of y_1 by i.

Pearson's correlation coefficient was developed by Carl Pearson. Pearson correlation analysis uses Pearson's formula to obtain the correlation coefficient r of two variables. The calculation formula of correlation coefficient is.

$$r_{X,Y} = \frac{COV(X,Y)}{S_X . S_Y} \tag{5}$$

In equation (5), $r_{X,Y}$ represents the correlation coefficient between series X and series Y. COV(X,Y) is the covariance between series X and series Y. S_X and S_Y are the sample variances of series X and series Y. The value of $r_{X,Y}$ ranges from -1 to 1, with a positive value indicating a positive correlation and a negative value indicating a negative correlation. The larger value of $|r_{X,Y}|$, the better the correlation between two time series.

3 RESULT AND DISCUSSION

3.1 Result of Cross Wavelet Analysis

In this study, cross wavelet transform is used to analyze the response relationship between sunspot numbers and the average annual precipitation of seven meteorological stations in Yunnan Province. The cross wavelet power spectrum of the time series are shown in Figure 1.

From the cross wavelet power spectrum, it can be seen that sunspot numbers and the precipitation of seven meteorological stations with different climates in Yunnan Province have different scale periodic response. They have significant characteristics in the high-power region. Figure 1(a) shows cross wavelet power spectrum of the sunspot numbers and average annual precipitation in kunming. We can see that there is a 9-12a resonance period between sunspot numbers and precipitation from year 1972 to 2007, which shows a high power. The phase difference indicates that the sunspot numbers and average annual precipitation are negative correlated in kunming. Figure 1(b) is the cross wavelet power spectrum of the sunspot numbers and the average annual precipitation of Pu'er. The resonance cycle of sunspot numbers and precipitation is concentrated in the scale of 8-12a from year 1973 to 2001, and high power is shown in this resonance period. The phase difference indicates that the sunspot numbers are negative correlated with the precipitation from year 1973 to 1991, and positive correlated from year 1991 to 2001, with an abrupt change around year 1991. Figure 1(c) is the cross wavelet power spectrum of sunspot numbers and average annual precipitation in Mengla. We can see that there is a resonance period of 8-12a between them from year 1972 to 2003, and high power is displayed in this resonance period. The phase difference indicates that there is a positive correlation between them in the resonance period. Figure 1(d) is the cross wavelet power spectrum of sunspot numbers and average annual precipitation in Zhaotong. The sunspot numbers and precipitation have an 8-10a resonance cycle from year 1980 to 1992, a 10-12a resonance cycle from year 1985 to 2006, and a 1a resonance cycle from year 1989 to 1991. Higher power is shown in the 8-10a and 10-12a resonance cycles, and lower power is shown in the 1a cycle. The phase difference indicates that the sunspot numbers are negative correlated with the variation of annual precipitation in Zhaotong during the resonance period. Figure 1(e) is the cross wavelet power spectrum of sunspot numbers and the annual average precipitation in Gongshan. There is a 9-12a response periodicity of sunspot numbers and annual precipitation from year 1983 to 2005. High power is displayed in this resonance period. The phase difference indicates that sunspots are positive correlated with the precipitation during the resonance period. Figure 1(f) is the cross wavelet power spectrum of sunspot numbers and annual average precipitation in Lijiang. We can see that sunspot numbers and average annual precipitation have an 8-12a resonance period from year 1974 to 2006. High power is shown in this resonance period. The phase

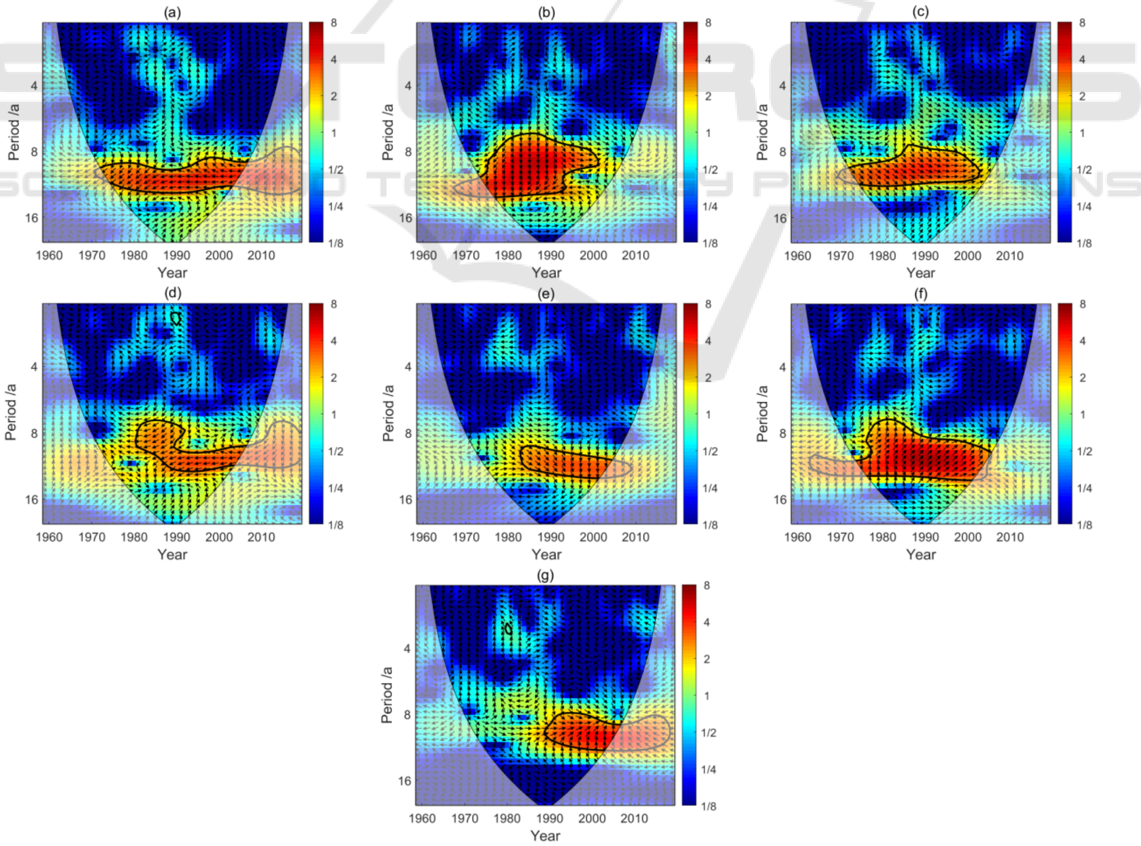

Figure.1 Cross wavelet power spectrum of sunspot numbers and precipitation at kunming (a), Pu'er (b), Mengla (c), and Zhaotong (d), Gongshan (e), Lijiang (f), Shangri-La (g) meteorological station.

difference indicates that sunspots are positive correlated with the variation of precipitation in Lijiang during the resonance period. Figure 1(g) is the cross wavelet power spectrum of sunspot numbers and average annual precipitation in Shangri-La. The sunspot numbers and precipitation have an 8-12a resonance cycle from year 1989 to 2007, and it shows high power in this resonance period. The phase difference indicates that sunspots are positive correlated with the annual precipitation in Shangri-La during the resonance period. In conclusion, the analysis shows that the periodic responses of sunspot activity and annual average precipitation mainly focus on 8-12a, and the corresponding response periods pass the significance test at 95% level. The cross-wavelet power spectrum of sunspot numbers and annual average precipitation of seven meteorological stations in Yunnan Province shows that their resonance periods are consistent. It indicates that the variation of annual average precipitation is related to solar activity. From the phase angle of arrows in figure 1, it can be seen that there is a time lag relationship between the average annual precipitation and the solar activity index.

3.2 Result of Time Lag Correlation Analysis

The response of time series often occurs lead or lag phenomenon. This paper uses this method to study whether there is a certain time lag relationship between the two series. Figure 2 is the result of time lag correlation analysis between sunspot numbers and precipitation in Yunnan Province. The time lag correlation analysis shows that the average annual precipitation of Kunming, Pu'er, Mengla and Gongshan meteorological stations lag the sunspot numbers. The lag time are 9 years, 3 years, 7 years and 8 years. The correlation coefficients are -0.22, 0.23, 0.2 and 0.12 respectively. The average annual precipitation of Zhaotong, Lijiang and Shangri-La are 6 years, 8 years and 9 years ahead of the sunspot numbers. The correlation coefficients are 0.22, 0.31 and 0.2 respectively. The results of the time lag

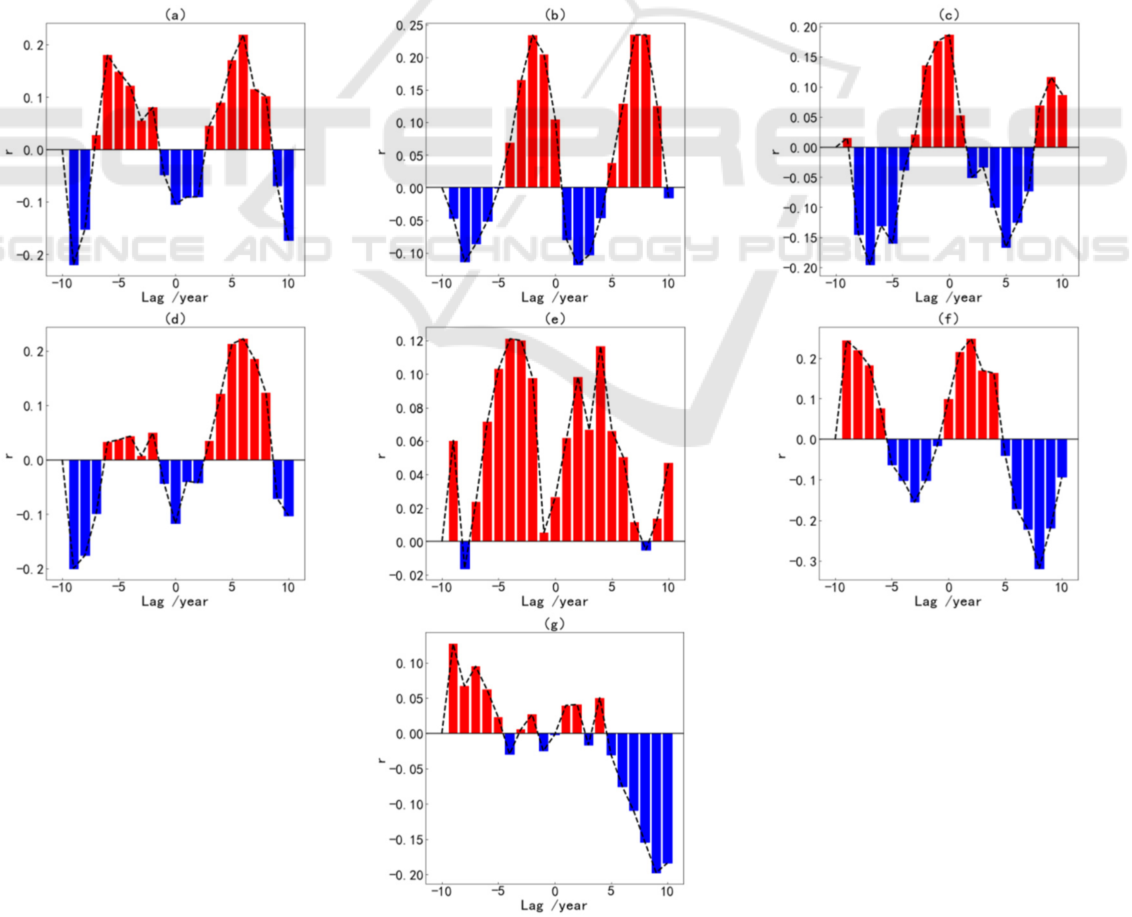

Figure.2 Time lag correlation analysis between sunspots and precipitation at kunming (a), Pu’er (b), Mengla (c), and Zhaotong (d), Gongshan (e), Lijiang (f), Shangri-La (g) meteorological station.

correlation analysis are basically consistent with the wavelet analysis except the Zhaotong meteorological station. It may be caused by the large number of missing values in the data of the Zhaotong meteorological station. The figure of the time lag correlation analysis at Shangri-La meteorological station is different from other meteorological station, this may be due to the fact that the Shangri-La region is part of the Three Rivers area, where the water distribution has a greater effect on precipitation than sunspot numbers. This method illustrates the correlation and time-lag characteristics between sunspot activity and precipitation.

4 CONCLUSIONS

This paper studies the periodic variation characteristics of solar activity and precipitation at seven meteorological stations in Yunnan Province and analyzes the correlation between time series based on wavelet analysis and time lag correlation analysis. The main conclusions are as follows.

- Based on the cross-wavelet analysis, we study the periodic responses of sunspot numbers and average annual precipitation at seven meteorological stations in Yunnan Province. The results show that the periodic responses of sunspot activity and average annual precipitation are mainly concentrated in 8-12a, and the response periodicity has significant characteristics in the high-power region. From the phase angle, we can see that there is a certain lead-lag relationship between sunspot numbers and average annual precipitation in Yunnan Province. The seven meteorological stations are selected from different climate zones, which indicates that solar activity greatly influences the annual precipitation in different climate zones, and there is a good correlation between them.
- Based on the time lag correlation analysis, we find that the average annual precipitation of Kunming, Pu'er, Mengla, and Gongshan meteorological stations all lag the changes in sunspot numbers. The average annual precipitation of Zhaotong, Lijiang, and Shangri-La meteorological stations is ahead of the changes in sunspot numbers. They are basically consistent with the results of the cross-wavelet analysis. However, the correlation coefficient between sunspots and the annual average precipitation in different meteorological stations is different, indicating that the response of annual average precipitation to solar activity in different regions is inconsistent.

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REFERENCES

Li, H, J., Gao, J, E., Zhang, H, C., et al. 2017. Response of Extreme Precipitation to Solar Activity and El Nino Events in Typical Regions of the Loess Plateau[J]. Advances in Meteorology, 2017:1-9.

Li, Y., Wen, Y., Lai, H., et al. 2020. Drought response analysis based on cross wavelet transform and mutual entropy[J]. AEJ - Alexandria Engineering Journal, 59: 1223-1231.

Zhao, Y., Luo, Y., 2021. Wavelet Analysis on Temperature and Precipitation Changes in Dabie Mountain of West Anhui[J]. Journal of Physics: Conference Series, 1732(1): 012105.

Cheng, S, B., Argaud, J, P., Iooss, B., et al. 2021. Error covariance tuning in variational data assimilation: application to an operating hydrological model[J]. Stochastic Environmental Research and Risk Assessment, 35: 1019-1038.

Wang, B., Wang, Y., 1996. Temporal Structure of the Southern Oscillation as Revealed by Waveform and Wavelet Analysis[J]. Journal of Climate, 9(9): 1586-1598.

Chellali, F., Khellaf, A., Belouchrani, A., 2010. Wavelet spectral analysis of the temperature and wind speed data at Adrar, Algeria[J]. Renewable Energy, 35(6): 1214-1219.

Alperovich, L., Zheludev, V., Hayakawa, M., 2016. Use of wavelet analysis for detection of seismogenic ULF emissions[J]. Radio Science, 38(6): 1-13.

Torrence, C., Webster, P, J., 2010. Interdecadal Changes in the ENSO–Monsoon System[J]. Journal of Climate, 12(8): 2679-2690.

Ge, Z., 2007. Significance tests for the wavelet power and the wavelet power spectrum[J]. Annales Geophysicae, 25(11): 2259-2269.

Banerjee, S., Mitra, M., 2014. Application of Cross Wavelet Transform for ECG Pattern Analysis and Classification[J]. IEEE Transactions on Instrumentation and Measurement, 63(2): 326-333.

Grinsted, A., Moore, J, C., Jevrejeva, S., 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series[J]. Nonlinear Processes in Geophysics, 11(5/6): 561-566.