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Research Article

Nonlinearity and Fractal Properties of Climate Change during the Past 500 Years in Northwestern China

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By using detrended fluctuation analysis (DFA), the present paper analyzed the nonlinearity and fractal properties of tree-ring records from two types of trees in northwestern China, and then we disclosed climate change characteristics during the past 500 years in this area. The results indicate that climate change in northwestern China displayed a long-range correlation (LRC), which can exist over time span of 100 years or longer. This conclusion provides a theoretical basis for long-term climate predictions. Combining the DFA results obtained from daily temperatures records at the Xi'an meteorological observation station, which is near the southern peak of the Huashan Mountains, self-similarities widely existed in climate change on monthly, seasonal, annual, and decadal timescales during the past 500 years in northwestern China, and this change was a typical nonlinear process.

1. Introduction

The climate system exhibits a long-term memory. However, no one knows how long this memory is. The memory plays an important role in climate prediction, and thus the study of this memory is crucial. The short-term memory of a dynamic system is usually present on a timescale of certain duration and it is accompanied by the exponential decay of an autocorrelation function. The diverging timescale existed in a time series with long-term memory which exhibits the scaling properties of the autocorrelation function. However, this long timescale does not mean that the system has a memory of infinitely long duration [1–3]. Many natural and social-economical phenomena display a scale distribution, such as price changes in the economic market, fluctuations in human's heart rate, electrical signals, water levels of the Nile River, and DNA sequences. By studying fluctuations in financial market indices with different timescales, the scaling of their distributions shows long persistence in the volatility [4], and the cumulative distribution of the volatility is consistent with a power-law asymptotic behavior [5]. The heartbeat time series also have fractal scaling properties, which fluctuate in an irregular and complex manner, even under resting conditions. The fractal analysis may provide a new approach to recognize deceased states by studying changes in the scaling properties [6]. Long-range correlations are present only in the REM phase [7]. An application of detrended fluctuation analyses on the electric signals shows that its power-law exponents are related with the non-Markovian character, which are consistent with the existence of long-range correlations [8]. The return intervals of extremes above some threshold also exhibit long-range correlation [9]. A similar phenomenon was also founded in the temperature and heavy rainfall records [10–14]. Based on the values of an autocorrelation function of a time series, these phenomena can be divided into three categories: an autocorrelated sequence, an anticorrelated sequence, and a noncorrelated sequence. The essential difference between price fluctuation and a temperature record is that price fluctuation contains a white-noise spectrum lacking intrinsic correlation, whereas a temperature record exhibits a long-range correlation.

The study of global climate change is a crucial scientific field of the International Geosphere-Biosphere Programme, and a great deal of information on past climate changes is contained in various types of proxy data. For example, ice cores, stalagmites, lake sediments, and tree rings all recorded some information of temperatures and rainfall amounts to some extent. Because the existing observational data span a relatively short time period and are scarce, proxy climate data are particularly important for the research of long-term climate change. The growth of tree rings is significantly affected by local climatic condition, and tree-ring data have several advantages, including being accurately dated and continuous and having high resolution. The measurements of tree-ring growth possess relatively higher precision than other proxy data and the identical tree-ring chronologies are easy to acquire in different time-instants. Therefore, tree rings can be used to extract a great deal of information regarding climate and environmental changes, which are more than that in other types of proxy data, and it is true for the reliability of the tree-ring data. In a technical report of the International Climate Dendrochronology Academic Conference in 1982, it was noted that, among the proxy data related to the change of various climate factors in most areas on the Earth, the tree-ring data are far more reliable than any other proxy data measured in terms of years [15].

These proxy data usually display complex evolutionary trends. We often know little about their underlying dynamic processes, and it is very difficult to distinguish the dynamic processes of a system from any superimposed external disturbances in the proxy data. Therefore, linear or nonlinear features of potential dynamic processes represented by the proxy data are important in developing time-sequence models, which can simulate the characteristics of climate change in these data. Consequently, there is an urgent need to qualitatively classify the properties of proxy data. It remains an opening question on the definition of nonlinearity. For example, some researchers define nonlinearity based on the response of a system to an external disturbance: if the response of a system to a disturbance is linear (nonlinear), the system is thus linear (nonlinear). Others distinguish linearity from nonlinearity based on the equation representing the dynamics of the system: if this equation contains linear (nonlinear) terms, the system is classified as linear (nonlinear). In order to deal with this problem, Ashkenazy et al. [1] proposed the following definition of a nonlinear time series: if the incremental sequence of a time series displays a long-range correlation, the time series is nonlinear; otherwise, it is linear. Because there is often no correlation between the incremental sequences of a linear time series, this definition is widely applied. In this study, we first conducted a scaling analysis of an incremental sequence in a tree-ring width chronology of Huashan pines on the southern peak of the Huashan Mountains based on the definition of nonlinearity presented by Ashkenazy et al. A clear scaling region is found and the scale exponent is greater than 0.5, which indicates that the original time series of the incremental sequence is nonlinear. Because the radial growth of trees is primarily affected by climatic and environmental factors, their growth rings display a significant response to temperatures and precipitation and may be expected to exhibit a long-range correlation with variations in temperature and precipitation. By analyzing tree-ring data from northwestern China, we studied climate change during the past 500 years in this region. The results indicate that there was long-range persistence in climate change over the past 500 years in northwestern China, and it was a typical nonlinear process with fractal behaviors. Further analysis indicates that the persistence of climate change in northwestern China can span a period of 100 years and even possibly longer.

2. Data and Methods

The tree-ring width chronologies used in this study were obtained from the Tree-Ring Data Center of China. We analyzed tree-ring data from two common types of trees at three locations in northwestern China: Huashan pines on the southern peak (elevation 2020 m) and western peak (elevation 2030 m) of the Huashan Mountains (110°05′E, 34°29′N), Shaanxi Province, with the tree rings during the periods of 1515–1992 A.D. and 1359–1992 A.D., respectively, and Qilian junipers in the De Halin area of Qinghai (97°56′E, 37°27′N, elevation 3500–3900 m) with the tree-ring chronology during the period of 980–2001 A.D. The records of daily average maximum temperatures were obtained from the National Meteorological Information Center, Chinese Meteorological Administration.

The incremental sequence $\{v_i,\ i = 2, \dots, N\}$ of a tree-ring sequence $\{x_i,\ i = 1, \dots, N\}$, where N is the sample size, is defined as the absolute value of the difference between the neighboring tree-ring index values in the sequence:

$$v_i = \left| x_i - x_{i-1} \right|. \tag{1}$$

To a nonlinear time series, if the incremental sequence of a time series (namely, the volatility of the sequence) displays a scaling feature, the original time series is nonlinear [1]. In this study, we analyzed the incremental records of the tree-ring sequences.

The persistence of a time series can usually be determined by calculating the autocorrelation function of the sequence:

$$C(l) = \langle \Delta x_i \Delta x_{i+l} \rangle = \frac{1}{N-l} \sum_{i=1}^{N-l} \Delta x_i \Delta x_{i+l}, \tag{2}$$

where $\Delta x_i = x_i - \overline{x}$ and $\overline{x}$ is the average of the sequence $\{x_i,\ i = 1, \dots, N\}$. If there is no persistence in the sequence $\{x_i\}$, there is no correlation in Δx_i, and the autocorrelation function is $C(l) = 0$. If there is persistence in the scale of l, the autocorrelation function is greater than 0 when it is smaller than a critical scale l_p, and when the scale exceeds the critical scale l_p, this persistence disappears. However, there is nonstationary variation in most of observational data, such as noises and various trends, which often affect the reliability of calculations of the correlation function using (2).

Detrended fluctuation analysis (DFA) is a scaling analysis method which was designed to investigate the long-range fluctuation correlation in a given time interval, where it is typically assumed that the type of correlation is unknown.

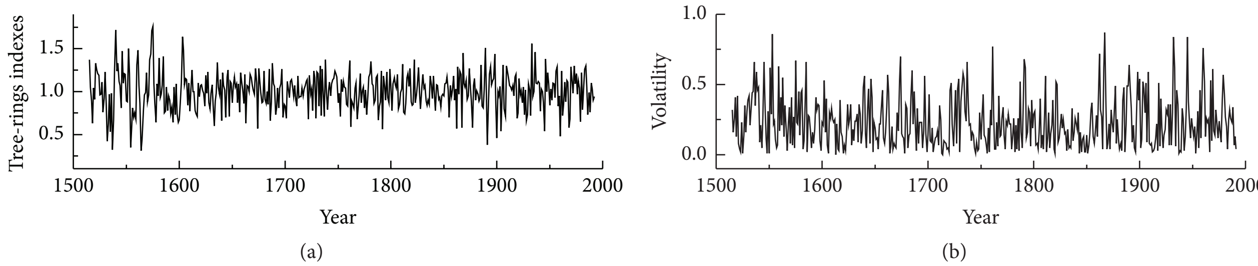

Figure 1: Tree-ring time series, (a) tree-ring width chronology for the pines on the southern peak of the Huashan Mountains, and (b) tree-ring incremental sequence.

Here, we briefly introduced the DFA algorithm [16, 17]. Considering a time series, $x(i)$ $(i = 1, 2, \dots, N)$, firstly, we integrate the time series $x(i)$,

$$y(k) = \sum_{i=1}^{k} [x(i) - \langle x \rangle], \quad k = 1, 2, \dots, N, \tag{3}$$

where

$$\langle x \rangle = \frac{1}{N} \sum_{i=1}^{N} x(i), \tag{4}$$

which is the average of $x(i)$. Next, the integrated time series is divided into nonoverlapping boxes of equal length n. In each box of length n, we fit the integrated time series by using a polynomial function, $y_n(k)$, which is called the local trend. For order l of DFA (DFA1 if $l = 1$, DFA2 if $l = 2$, etc.), the l-order polynomial function should be applied for the fitting. In the third step, we detrend the integrated time series, $y(k)$, by subtracting the local trend $y_n(k)$ in each box, and the root-mean-square fluctuation of this integrated and detrended time series is calculated by

$$F(n) = \sqrt{\frac{1}{N} \sum_{k=1}^{N} [y(k) - y_n(k)]^2}. \tag{5}$$

This computation is repeated over all timescales (box sizes n) to characterize the relationship between $F(n)$, the average fluctuation, and the box size n. Typically, $F(n)$ will increase with box size. A linear relationship on a log-log plot indicates the presence of power law. Under such conditions, the fluctuations can be characterized by a scaling exponent γ, the slope of the line relating $\log F(n)$ to $\log n$. If $\gamma = 0.5$, there is no correlation and time series behaves as a random series (Brownian noise), $0 < \gamma < 0.5$ indicates anticorrelations, and $0.5 < \gamma < 1.0$ indicates long-range correlations.

3. Results

Figure 1(a) shows the tree-ring width chronology for the Huashan pines on the southern peak of the Huashan Mountains, which spans the 478 years from 1515 A.D. to 1992 A.D. The corresponding incremental sequence is shown in Figure 1(b).

Based on the DFA results, there is a small difference between the two values of γ derived using DFA1 and DFA2. This difference indicates that the trend term is not completely eliminated in the sequence when using DFA1, and there remains a higher-order trend in the detrended time series. However, there is no essential difference in the calculating uncertainty by using DFA2, DFA3, DFA4, and other higher-order DFA, which indicates that the DFA2 is capable of eliminating the trend term in the original sequence. So this paper used the DFA2 method to estimate the scale exponent γ of a time series, and the range of the scale exponent calculation is $[6, \langle n/2 \rangle]$ years, where $\langle n/2 \rangle$ is the integer smaller than or equal to $n/2$. The fitted region of the scale exponent is selected based on the actual situation. In the fitted region range of the scale exponent, $[6, \langle n/2 \rangle]$, we noted an optimum linear fit range, and then we derived the approximate value of the scale exponent γ by calculating the slope of the straight fitted line.

To determine the properties of the tree-ring width chronology of the Huashan pines on the southern peak, we analyzed the incremental sequence of the chronology by using DFA2. The double-logarithmic curve of the fluctuation function $F_2(l)$ versus the window size l is shown in Figure 2(a), and the fitted range is approximately $\log_{10}(l) \in [0.8451, 2.38917]$. Based on Figure 2(a), there is a clear scaling range of $\log_{10}(l) \in [0.8451, 1.72428]$. When $\log_{10}(l)$ exceeds 1.72428 (namely, when l exceeds about 53 years) the scaling behavior vanishes. The calculated scale exponent γ is approximately 0.65754, which is greater than 0.5. Therefore, there is a long-range correlation in the incremental sequence, which indicates that one large increment is extremely likely to be followed by another large increment, and vice versa. According to the definition [1] for a linear sequence, the original sequence of the incremental sequence, namely, the tree-ring width chronology of the Huashan pines on the southern peak, is a typical nonlinear sequence. The magnitude of the scale exponent γ of the incremental sequence indicates the nonlinearity (weak or strong) in the record of the tree-ring width.

Figure 2(b) shows the DFA2 results of the tree-ring width chronology from the southern peak of the Huashan Mountains. Similar to the incremental sequence, when $\log_{10}(l)$ of the tree-ring sequence is less than or equal to 1.72428, the double-logarithmic curve of the fluctuation function $F_2(l)$ versus the window size l approximates a straight line with

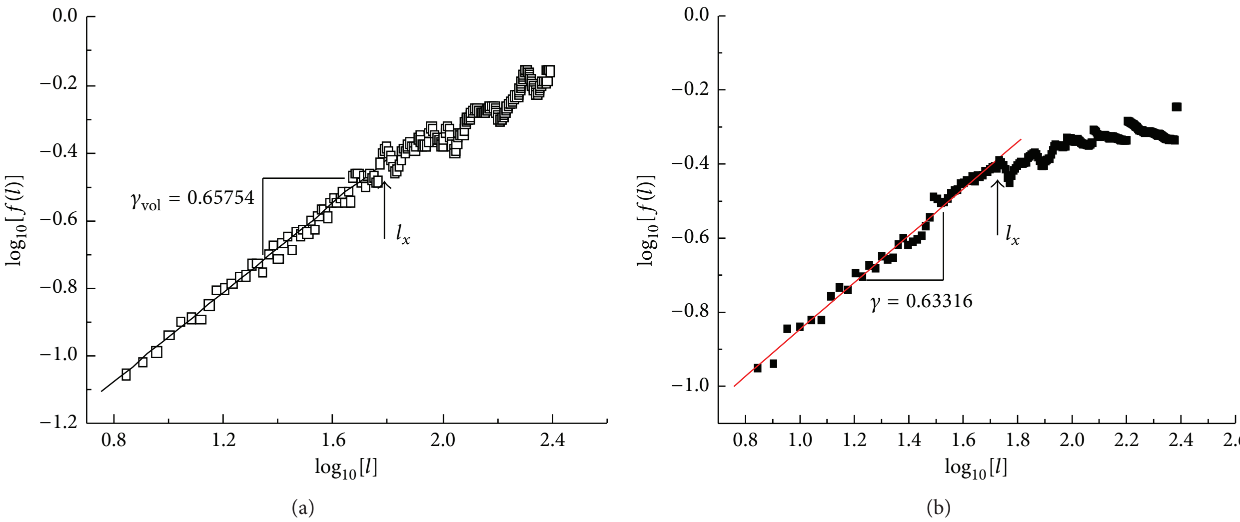

FIGURE 2: The DFA2 results of the tree-ring width chronology of the Huashan pines on the southern peak of the Huashan Mountains: (a) incremental sequence (□) and (b) original sequence (■). The straight lines represent the linear fits.

a slope of 0.63316 (greater than 0.5). This indicates that the tree-ring sequence had a long-range correlation, although this long-range correlation does not mean a memory of unlimited duration. As shown in Figure 2(a), when $\log_{10}(l)$ increases to 1.72428, namely, after approximately 53 years, this long-range correlation disappears. The presence of scaling behavior in the tree-ring sequence indicates that the tree-ring growth displays a "clustered" pattern, namely, some persistent feature in tree-ring growth. Rapid growth of a tree-ring width in one year was extremely likely to be followed by rapid growth in the following year. Usually, the persistence of tree growth can be divided to one of two categories. The first category is unique to individual trees. This persistence is caused by the highly localized environment around the trees at a sampling site, such as the competition for sunlight between two adjacent trees. The second category is common to the tree community and is caused by large-scale changes in the climate factors and other aspects of the environment in and around the sampling site, including forest pests, fire, atmospheric pollution, deforestation over a large area, and changes in temperature and rainfall [18]. Because any persistence unique to individual trees has been eliminated from the tree-ring width chronology of the Huashan pines on the southern peak [18], the analytical results shown in Figure 2 represent the persistence common to the tree community. In other words, this persistence represents large-scale changes in the environment and climate and is one type of response to past changes in the climate and other environmental factors of the area where the trees grew.

Based on the results, we obtained some preliminary conclusions. As one important set of proxy data for investigating global climate change, the tree-ring data display a long-range correlation. The analysis of its incremental sequence indicates that the tree-ring data is strongly nonlinear and has fractal properties. This finding suggests that there are self-similarities in the tree-ring data on various timescales, including interannual, decadal, and longer timescales. As proxy data that reflect changes in past local temperatures and precipitation, the fractal properties of the tree-ring data time series indicate that local climate change is a nonlinear process with a long-range correlation. If this conclusion is universal, there may be similar features in the record of climate change on even shorter timescales, such as monthly and seasonal scales. To verify this conclusion, we conducted a DFA2 analysis for the daily average high temperatures during the period of 1960–2005 at the Xi'an meteorological observation station (108°93′E, 34°30′N; elevation 397.5 m) near the Huashan Mountains. The results are shown in Figure 3.

In the detrended analysis of daily average maximum temperatures at Xi'an Station, the calculation range for the scaling exponent is $\log_{10}(l) \in [0.60206, 3.64207]$, and it exhibits a well linear fit in the region [1.5, 2.8]. Figure 3 shows that the double-logarithmic curve approximately obeys a scale distribution for $\log_{10}(l) < 1.5$ (about 31 days), which corresponds to the short-term correlation in the daily temperature data. (Because we primarily studied long-term variation in the climate system, we had no further discussion on the short-term correlation in the daily temperature data.) In the range of $\log_{10}(l) \in [1.5, 2.8]$, the corresponding window size l increases from 32 days to 631 days, namely, from monthly to interannual scales, and we found that the double-logarithmic curve of daily average maxima temperatures meets a good linear fit. The calculated scaling exponent of γ is approximately 0.63798, which indicates that the temperature fluctuations in this range display a long-range correlation. Based on the observational data, we concluded that this long-range correlation could last for 631 days, beyond which there was no long-range correlation. This limit was mainly probably caused by the sensitivity of the method to the span of the data time series; in other words, the existing observational data time series is too short. However, we have reason to believe that the long-range correlation may actually last longer. In 2003, using a global coupled model, Fraedrich

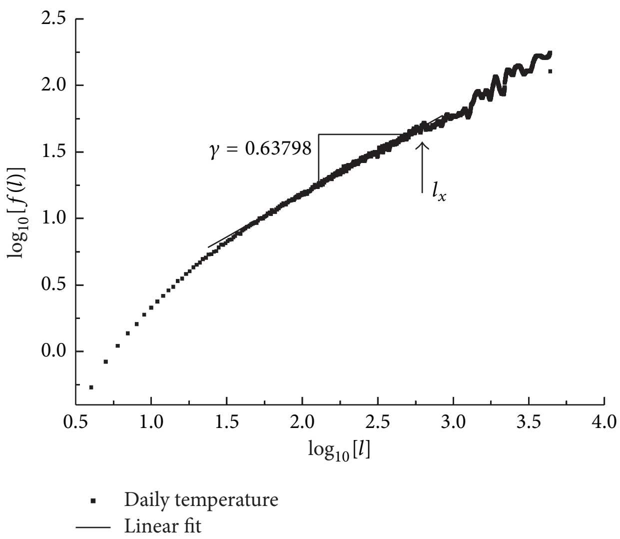

Figure 3: DFA2 curve of daily average maximum temperatures at Xi'an Station during the period of 1960–2005.

and Blender [19] concluded that the scale region was limited; namely, the long-range correlation did not mean an unlimited duration of memory. They also found that the long-range correlation in continental areas disappeared beyond a time span of approximately 150 years. The long-range correlation (0.63798) from the analysis of the temperature data at Xi'an Station is close to the value of 0.65754 in the tree-ring fluctuation sequence on the southern peak of the Huashan Mountains, which indicates that the tree-ring data indeed reflect the variation in temperature to a certain extent.

Based on the DFA results of the daily temperature records at Xi'an Station and the tree-ring proxy data from the Huashan Mountains, climate change during the past 500 years in northwestern China involved a nonlinear process, and there was a long-term memory. This memory had duration of approximately 53 years or longer. Because the scale exponents reflecting climate change on monthly, seasonally, annual, and decadal timescales are approximately similar, the climate change during the past 500 years in northwestern China displays fractal features, and the variations on various timescales display self-similarity.

To determine whether the nonlinearity and fractal properties of the tree-ring width chronology for the Huashan southern peak are present throughout the tree-ring proxy data, we conducted a DFA for the width sequence of the Huashan pines on the western peak of the Huashan Mountains and the width chronology of Qilian junipers in the De Halin area of Qinghai Province in China [20]. Figure 4 shows the DFA2 results for the two sets of data.

Figure 4 shows a distinct scaling region in both double-logarithmic curves, which indicates there was a long-range correlation in the ring width data of the two types of trees. It indicates that this scaling behavior is generally present in the tree-ring proxy data and is not related to the type of tree or the geographic location. Instead, it is a widespread behavior reflecting a response of tree-ring growth to past climate changes in some areas. This conclusion can be confirmed by analyzing tree-ring data from other regions of northwestern China. The range with a linear fit in both Figures 4(a) and 4(b) is $\log_{10}(l) \in [0.8451, 2.0]$. The double-logarithmic curves from the two datasets in this range can fit linearly, and this scaled region in the data corresponds to $\log_{10}(l) > 2.0$ (i.e., the time window l exceeds 100 years). The scaling property is no longer present in the data, which indicates that the persistence times of the long-range correlation of the tree-ring width chronology are almost the same (approximately 100 years) for the Huashan pines on the western peak of the Huashan Mountains and the Qilian junipers in the De Halin area. This is not consistent with the lasting time for the long-range correlation resulting from the analysis of the Huashan pines on the southern peak of the Huashan Mountains. One possible explanation for this finding is that the long-range correlation associated with climate change is relatively long, whereas the present observational data have not a sufficiently long time period to accurately analyze the duration of a longer-range correlation. However, the analysis result is sufficient to indicate that climate change over the past 500 years in northwestern China had nonlinear and fractal features and a clear long-range correlation. The scaling exponents derived from the calculations indicate that the observed climate change is of regional extent; namely, the tree rings were affected by changes in regional climate in addition to those of larger-scale global background.

4. Conclusions

In this paper, we first performed a scale analysis of the incremental sequence in the tree-ring width chronology of the Huashan pines on the southern peak of the Huashan Mountains in Shaanxi Province in China. We noted that the chronology displays a long-range correlation, which indicates that it is a typical nonlinear time series. Then, we conducted a DFA of the original time series and found that there was clear scaling behavior in the data on certain timescales, which means that the tree-ring width chronology displays a long-range correlation that may last 100 years or possibly longer. The proxy data primarily reflect variations in temperature and rainfall, and thus, the scaling features of the tree-ring data indicate that there was a long-range correlation in the climate change that could last 100 years or longer. The tree-ring width chronologies of two types of trees, that is, Huashan pines on the western peak of the Huashan Mountains and Qilian junipers in the De Halin area of Qinghai, also have been analyzed by DFA2 and the results confirm that this scaling is a widespread pattern in the tree-ring data. The scaling behavior is no observed connection with the type of tree or its geographic location, and the chronology is a response of the tree rings to changes in local climate and environment factors. The similar scaling behavior in the two types of data at different resolutions in response to climate change, namely, the daily temperature records and the tree-ring width chronologies, indicates that climate change during the past 500 years in northwestern China displayed nonlinear

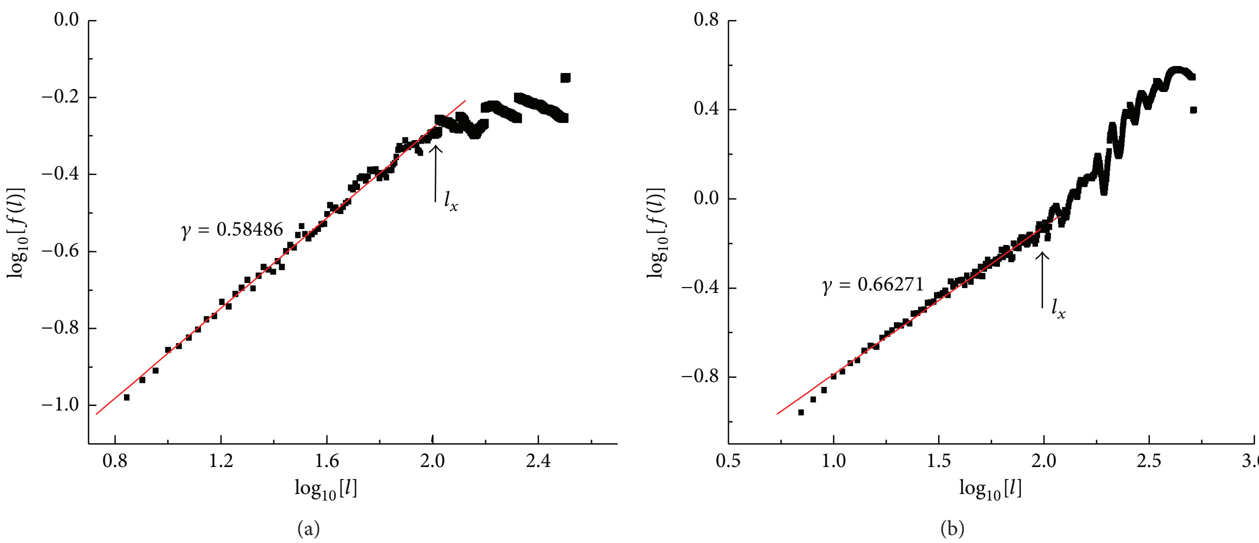

FIGURE 4: DFA2 curves for two tree-ring width chronologies: (a) Huashan pines on the western peak of the Huashan Mountains and (b) Qilian junipers in the De Halin area.

and fractal properties and that there were self-similarities on monthly, seasonally, annual, and decadal timescales.

This long-term persistence and self-similarity of the climate system have important implications for climate predictions and simulations. For example, by combining paleoclimate data, we can predict general trends in future climate changes on various timescales (namely, the application of self-similarity). Moreover, there are many climate models, and it is difficult to select a (good) model for simulating scenarios of future climate change and to verify the reliability of the model. According to the findings in this study, we may be able to solve this problem by using the type of scaling analysis used in this study to conduct a scale test of the model output. The model with output that displays the features of a scaling law will yield a scale exponent that better approximates the actual situation and be more reliable than that model which violates the scale behavior in climate system.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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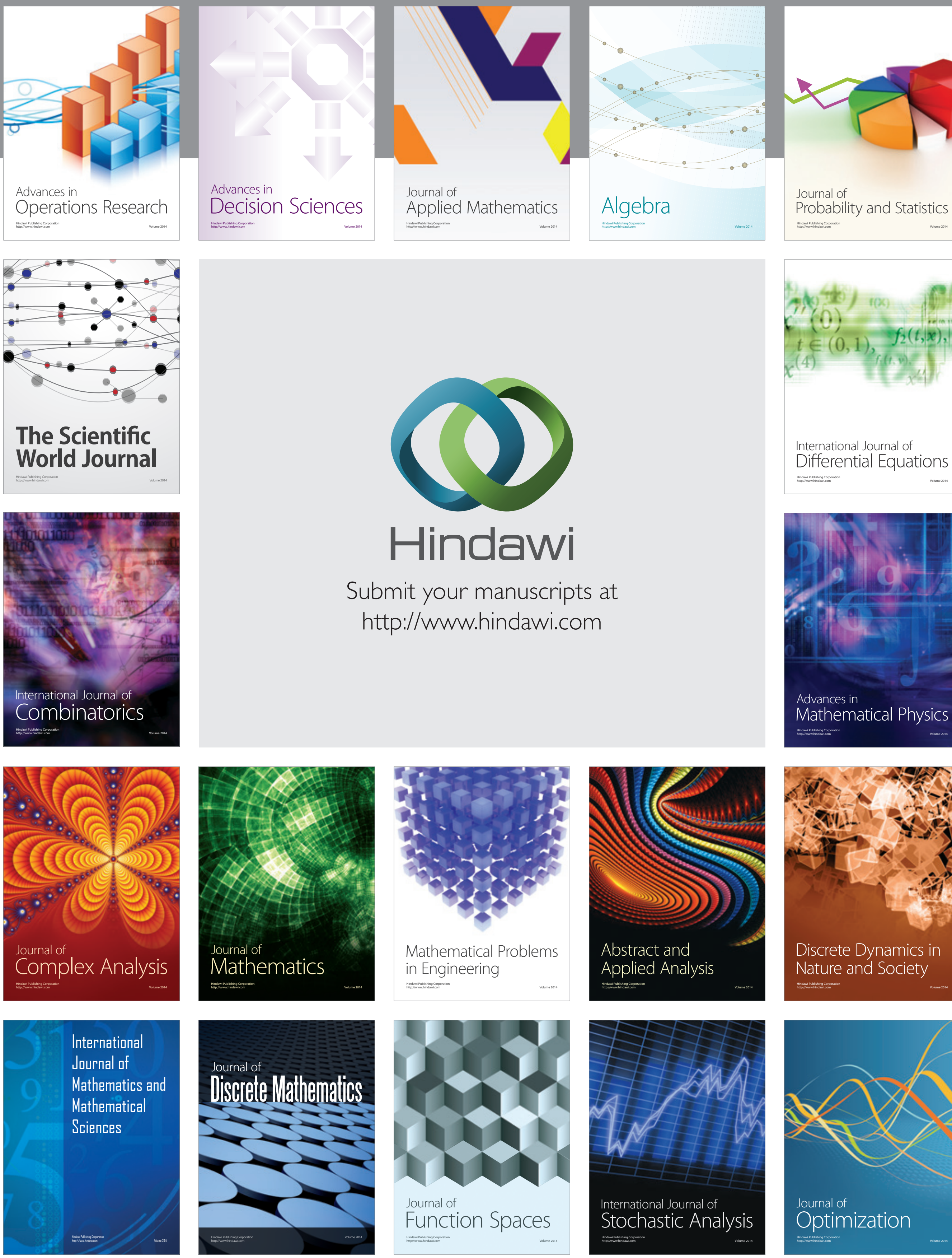
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