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Multifractal Detrended Cross-Correlation Analysis of sunspot numbers and river flow fluctuations

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ABSTRACT

We use the Detrended Cross-Correlation Analysis (DCCA) to investigate the influence of sun activity represented by sunspot numbers on one of the climate indicators, specifically rivers, represented by river flow fluctuation for Daugava, Holston, Nolichucky and French Broad rivers. The Multifractal Detrended Cross-Correlation Analysis (MF-DXA) shows that there exist some crossovers in the cross-correlation fluctuation function versus time scale of the river flow and sunspot series. One of these crossovers corresponds to the well-known cycle of solar activity demonstrating a universal property of the mentioned rivers. The scaling exponent given by DCCA for original series at intermediate time scale, $(12–24) \leq s \leq 130$ months, is $\lambda = 1.17 \pm 0.04$ which is almost similar for all underlying rivers at 1σ confidence interval showing the second universal behavior of river runoffs. To remove the sinusoidal trends embedded in data sets, we apply the Singular Value Decomposition (SVD) method. Our results show that there exists a long-range cross-correlation between the sunspot numbers and the underlying streamflow records. The magnitude of the scaling exponent and the corresponding cross-correlation exponent are $\lambda \in (0.76, 0.85)$ and $\gamma_\times \in (0.30, 0.48)$, respectively. Different values for scaling and cross-correlation exponents may be related to local and external factors such as topography, drainage network morphology, human activity and so on. Multifractal cross-correlation analysis demonstrates that all underlying fluctuations have almost weak multifractal nature which is also a universal property for data series. In addition the empirical relation between scaling exponent derived by DCCA and Detrended Fluctuation Analysis (DFA), $\lambda \approx (h_{\rm sun} + h_{\rm river})/2$ is confirmed.

1. Introduction

Recently, due to the developments in the area of complex systems as well as data measurements and data analysis, one can find many opportunities for examination and interpretation of climate change which exhibit irregular systems [1–8]. It is well shown that the climate system is enforced by the well-defined seasonal periodicity, however the existence of unpredictable perturbation and chaotic functioning lead to extreme climate events. Indeed the climate is a dynamical system affected by tremendous factors and variables, such as solar activity which is represented by Sunspot numbers in this research [4–10]. All factors that control the trajectory of such mentioned systems have enormously large phase space and evolve as non-stationary processes, consequently we should explore it with stochastic tools to achieve reliable results.

Nowadays, it has been clarified that a remarkably wide variety of natural systems can be characterized by long-range power-law cross-correlation behavior [9,10]. Such cross-correlations address scientists toward fractal geometry of the underlying dynamical systems and can hopefully help us to predict future events. Existence and determination of power-law

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cross-correlations would help to promote our understanding of the corresponding dynamics and their future evolutions [11–14]. Beside, many events which controls earths climate, water runoff records assigned by rivers and sun activity play a crucial and survival roles for human life. The runoff water fluctuations are excellent climate criteria because they integrate evapotranspiration (output) and precipitations (input) over large areas. It is well accepted that the prediction of water runoff is fundamental for different aspects of social and economical reasons, ranging from the prediction of floods and droughts to planning of agricultural conditions. As a result of the periodicity in precipitation, river flow has also strong seasonal periodicity [12]. It is worth to note that unlike other climate components, water runoff may be directly influenced by human activity, like agriculture, drainage network morphology and so on, consequently makes it hard to distinguish the artificial and natural effects on the river flow data. Finding some or at least a universal behavior for different streamflow fluctuations as well as quantifying the impact of sun activity on various temporal and spatial scales of water runoff fluctuations can improve the recent hydrological models [15].

To this end, the statistical and multifractal analysis of river flows as well as influence of sun activity due to the interior and exterior chemical and physical properties of sun should be an important issue in the geophysical and hydrological systems.

The streamflow of rivers and sun activity have been studied from various point of views such as: the probability distribution [16,17], correlation and fractal behaviors [18–23], connection between volatility and nonlinearity of fluctuations [11,12,24,25], scale invariance for distribution function [26]. In addition, sun activity have been investigated by some methods in chaos theory [27] and also multifractal analysis [28,29], wavelet analysis [30], cross-correlation functions between monthly mean sunspot areas and sunspot numbers [31,32], the relation between sunspot numbers fluctuation and number of flares, their evolution step [33,34], principal components and neural network methods to predict sunspots [35,36], sunspot areas time series and solar irradiance reconstructions [37], magnetic and dynamic properties of sunspots at the photospheric level [85] and the hydraulic–geometric similarity of river [38–40].

More recently, Pablo J. D. Mauas et al., have investigated the solar forcing on climate, using the quantification of cross-correlation between the yearly sunspot numbers, irradiance reconstruction and streamflow of Paraná river [9,10]. On the other hand, the mechanisms for solar influence on the earth's climate has been clarified in detailed from various point of views in Ref. [41]. Q. Zhang et al., have investigated the universal behavior of streamflow records of the Pearl river [15].

After innovation of Hurst to propose the self-similar processes and its criteria, namely "Hurst exponent" [18–23], long-range correlated fluctuation behavior has also been reported for vast category of sciences, specifically the geophysical records (for more discussion see Refs. [18–23,42–45]). In the last decade, the modification prescription which is required for a full characterization of many data sets such as the runoff records, the various moments of the so-called fluctuation functions, have been introduced [18–23]. The effect of non-stationarity on the detrended fluctuation analysis has been investigated in Refs. [46,47].

Here we take a new approach and rely on the state-of-the-art algorithm to investigate the contribution of sinusoidal trends embedded in the data set as well as non-stationarity properties of the underlying series. We implement robust methods to explore the multifractal nature of cross-correlation between two important climate variables, the monthly streamflow of some rivers and sun activity represented by sunspot numbers (see Fig. 1), by using the novel approach in the fractal analysis, Detrended Cross-Correlation Analysis (DCCA) and its multifractal modification, the Multifractal Detrended Cross-Correlation Analysis (MF-DXA) [48,49]. We restrict this article to use the sunspot numbers as the solar activity indicator, since there are many large and reliable data sets which can be considered as solar influence on the climate. Due to the presence of the sinusoidal trends in both sunspot numbers and the runoff river fluctuations and based on previous researches, one cannot expect to find a unique scaling behavior for fluctuation functions in all time scales (see Section 3), consequently, we have been motivated to use the well-known method, namely Singular Value Decomposition (SVD) method to exclude dominant trends in data set (see Section 2 for more details). So after, clean data set will be used in the DCCA and MF-DXA methods.

This paper is organized as follows: in Section 2, we describe the methods which are used to determine the cross-correlation of two non-stationary time series, the Detrended Cross-Correlation Analysis (DCCA), and investigate the corresponding multifractal properties by using the Multifractal Detrended Cross-Correlation Analysis (MF-DXA). Section 2 will be continued by introducing a method to eliminate trends from the original data set, the Singular Value Decomposition (SVD), and describing data used in this paper. In Section 3, the multifractal cross-correlation of the underlying data sets will be examined. Section 4, will be devoted to the results and summary.

2. Analysis techniques and data description

Time series measured in the nature are usually affected by non-stationarities such as trends and artificial noises which must be well distinguished from the intrinsic fluctuations of the series. In many cases also, intrinsic fluctuations behave as non-stationary processes. Consequently, common methods in data analysis will be encountered with spurious or at least unreliable results. One of the most famous and well-known approach used in many studies is Multifractal Detrended Fluctuations Analysis (MF-DFA) [50,51]. This method has been applied to various areas, such as economical time series [52–55], river flow [13] and sunspot fluctuations [56,57], cosmic microwave background radiations [58], music [59,60], plasma fluctuations [61].

For many reasons, we are interested in studying the mutual influence of two series in the presence of non-stationarities. Obviously, traditional methods for this investigation become inaccurate procedures. Recently Jun et al. have proposed