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Autocorrelation in ultraviolet radiation measured at ground level using detrended fluctuation analysis

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HIGHLIGHTS

- We applied detrended fluctuation analysis (DFA) to ultraviolet (UV) radiation data.
- We detected long range correlations and clear fractality in the data.
- **DFA** requires detrending by a high polynomial due to the complex solar radiation curve.
- **DFA** index of UV radiation resembles other climate records, but not solar activity.

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ABSTRACT

In this study, we analyzed the autocorrelation among four ultraviolet (UV) radiation data sets obtained at 305 nm, 320 nm, 340 nm, and 380 nm. The data were recorded at ground level at the INPE climate station in Natal, RN, Brazil, which is a site close to the equator. The autocorrelations were computed by detrended fluctuation analysis (**DFA**) to estimate the index α. We found that the fluctuations in the UV radiation data were fractal, with scale-free behavior at a **DFA** index $\alpha \simeq 0.7$. In addition, we performed a power law spectral analysis, which showed that the power spectrum exhibited a power law behavior with an exponent of $\beta \simeq 0.45$. Given that the theoretical result is $\beta = 2\alpha - 1$, these two results are in good agreement. Moreover, the application of the **DFA** method to the UV radiation data required detrending using a polynomial with an order of at least eight, which was related to the complex daily solar radiation curve obtained at ground level in a tropical region. The results indicated that the α exponent of UV radiation is similar to other climatic records such as air temperature, wind, or rain, but not solar activity.

1. Introduction

In recent decades, great efforts have been made to understand autocorrelations in climatic data [1,2]. Long-range autocorrelation or persistence has been detected in climate records for temperature [3–5], river flows [6,7], rain [8,9], and wind [10]. Indeed, weather persistence is a well known aspect of our daily life, where if one day is sunny and warm, then we might also expect the next day to be sunny and warm. The persistence of weather over short time scales is also present over

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long time scales according to analyses of climate [1,4]. In this study, we explore the behavior of the solar ultraviolet (UV) radiation that reaches the earth surface. Similar to air humidity, river flow, air pressure, wind, or temperature, UV radiation is affected by atmospheric dynamics and it exhibits autocorrelation.

The study of signal persistence and autocorrelation is a key point to understand climate time series [3,11]. The autocorrelation function is the traditional tool used for investigating autocorrelations in data, where this function computes the correlation between a signal and itself when shifted by a time lag. However, evaluating autocorrelations in a time series is not a simple task, where the autocorrelation function as well as Fourier analysis may produce incorrect or imprecise results [12,13]. To address this problem, we employed detrended fluctuation analysis DFA as a robust tool to estimate an index that characterizes scale-free fluctuations in a time series. Using **technique**DFA, we can obtain a confident estimate of the index α to calculate long-range correlations in a time series [13,14].

We hypothesized that the fluctuating patterns in UV radiation would follow similar dynamics to solar activity and the corresponding solar radiation. Several studies of solar activity have used the global radiation data obtained from satellites or by measuring sun spots and flares [15–17]. However, our data were obtained at ground level and not at the top of atmosphere. Indeed, the fluctuations in UV radiation or daily radiation are determined greatly by atmospheric dynamics. In fact, the UV radiation measured at ground level is related mainly to the presence of clouds and aerosols in the atmosphere, which are climatic variables [18].

In this study, we analyzed the long-range correlations in a time series of UV radiation, which mainly reflect autocorrelations in climate. To the best of our knowledge, this is the first attempt to apply the **DFA** method to a ground level time series of UV radiation. In Section 2, we describe the acquisition of the UV data, the theoretical fitting of the data, which is important for understanding the detrending of the signal by a higher polynomial, and finally the **DFA** method. In Section 3, we explain the application of the **DFA** technique to the data and the estimation of the Fourier power spectrum, as well as comparing the results obtained using these two methods. In Section 4, we present our main results, discuss the higher order detrending, and compare our findings with other climate records and solar activity results from previous studies.

2. Methodology

2.1. UV radiation data

We analyzed four UV radiation data sets, which corresponded to filters of 305 nm, 320 nm, 340 nm, and 380 nm. The observations were made between 2002 and 2007 by the Solar Radiometric Station at INPE in Natal, RN, Brazil (southern hemisphere; latitude −5°45′54″, longitude −34°12′34″). Natal is a coastal city with a typical tropical climate, which comprises alternating wet and dry seasons. The temperatures varies with a mean maximum of 31 °C and minimum of 24 °C, and the humidity is high throughout the year because of the proximity to the sea. The data were acquired using a ground-based multispectral UV radiometer (model 511-C), where the instrument was designed to measure spectral irradiance in the following wavelength windows: 305 − 1 nm, 320 − 2 nm, 340 − 2 nm, and 380 − 2 nm [19]. The default unit used for measuring the spectral irradiance by the is employed throughout this study. The UV radiation time recordings obtained by INPE included gaps due to occasional experimental problems with the equipment. Thus, to apply the **DFA** algorithm, we completed the time series by inserting data using standard Legendre interpolation [20]. We consider that this procedure did not change the results significantly because missing data comprised less than 6% of the total.

2.2. Modeling UV data as daily solar radiation

We used the estimated solar radiation at ground level to analyze the dynamic fluctuations in UV radiation, which also facilitated the analysis using the **DFA** technique, as described later. It is well established that the instant solar radiation depends on the hour of the day, the latitude of the site, and the day of the year (the solar declination) [21,22]. In our rough model, we considered the daily radiation, which is a measure of the instantaneous solar radiation integrated over the total hours in a day. The UV radiation is a fraction of the solar radiation, i.e., the solar radiation filtered in a wavelength window. In our theoretical model, we fitted the theoretic solar radiation to our data. We are aware that our fitting is a rather raw model, but it is helpful for discussing our results.

The solar radiation and the total daily solar radiation are introduced as follows, where we use the notation given in [22]. The instantaneous amount of solar radiation S is related to the solar constant S_o and the zenith angle z according to the relation:

$$S = S_o \cos z, \tag{1}$$

which states that S is the projection of the solar constant on the earth's surface for an observer at any place or time. In addition, S_o depends only on the solar activity. However, in Eq. (1), it is necessary to apply a correction to introduce variations in solar intensity due to the ellipticity of the earth's trajectory. Thus, we add the term $(\frac{\bar{d}}{d})^2$ to the sequence, where d is the distance between the earth and the sun throughout the year, and $\bar{d}$ is the mean distance value. Moreover, we use spherical