8

Correlation and Persistence in Global Solar Radiation

Isabel Tamara Pedron
Paraná Western State University
Brazil

1. Introduction

This work is focused on the investigation of correlations and memory effects in daily global solar radiation data series and in the capture of underlying multifractality. It is well known that the behaviour of the climatological variables affect directly crucial aspects of the people's daily lives. Typically measurements of these variables are a sequence of values that constitute a time series, and time series analysis tools can contribute effectively to the study of such variables. An interesting investigation that can be done on the series is to identify the occurrence of correlation in the records of the sequence and to detect an effect of long-term memory in this data set over time. One possible approach is to estimate how a particular measure of fluctuations in the series scales with the size s of the time window considered. A specific method for this analysis is the Detrended Fluctuation Analysis – DFA, a well-established method for the detection of long-range correlations. Usually, trends may mask the effect of correlations. DFA can systematically eliminate trends of polynomial of different orders. This method was proposed in (Peng et al., 1994) and has successfully been applied to many different fields, and particularly in the study of data series of variables associated with the weather and climate. The fluctuation function behaves as a power law with the values chosen for s. The exponent can be identified as the Hurst exponent (H). The DFA method gives the Hurst exponent, and estimating such exponent from a given data set is an effective way to determine the nature of correlation in it. Values of H in the range (0, 0.5) characterize anti-persistence, whereas those in the range (0.5,1) characterize persistence, long-range correlations. The value $H=0.5$ is associated with uncorrelated noise. Temperature and precipitation have characteristic values of H (Koscielny-Bunde *et al*., 1998; Bunde & Havlin, 2002) although some claim that the scaling exponent is not universal for temperature data (Király & Jánosi, 2005; Rybski *et al*. 2008). Relative humidity shows stronger persistence (Chen *et al*., 2007; Lin *et al*., 2007), and wind speed also exhibit behaviour with long-range correlation (Govindan & Kantz, 2004; Kavasseri & Nagarajan, 2005; Koçak, 2009; Feng *et al*., 2009). One can be sure of the universality of the correlations in climatological time series but its exponents can be related to local patterns.

The variation of the Hurst exponent in time for a given series indicates the existence of non-stationary fluctuations, pointing to a multi-fractal. Thus, when the series points to the existence of more than one exponent for its characterization we are dealing with multifractal behaviour. Multifractal signals are far more complex than monofractal signals and require more exponents (theoretically infinite) to characterize their scaling properties. In this work multifractality in time series data of global solar radiation is studied by applying the Multifractal Detrended Fluctuation Analysis (MF-DFA) proposed in (Kantelhardt *et al.*, 2002). It is a modified version of DFA to detect multifractal properties of time series and provides a systematic tool to identify and quantify the multiple scaling exponents in the data. This method was applied in several cases, in particular in climatological data series as presented in (Kantelhardt *et al.* 2003; Alvarez-Ramirez *et al.*, 2008; Pedron, 2010; Zhang, 2010).

2. Data set and method

Series of (daily) global solar radiation data were studied and all data set is within the period (Jul 97 – Apr 2011). Data were provided by Technological Institute SIMEPAR-Brazil from 18 meteorological stations in Paraná State (PR) (Fig. 1) located in Southern Brazil (Fig. 2). The coordinates of each station are in Table 1. Data cover a region with 199,314.9 km^2 and the climate is classified as subtropical. Mean temperature oscillates between 4 °C and 21 °C. The weather conditions in Paraná are usually associated with incursions of polar air toward the Equator and areas of convective clouds associated with extra tropical cold fronts. It also shows areas of local instability associated with mesoscale convective complexes, squall lines, convective clouds, heavy precipitation and lightning.

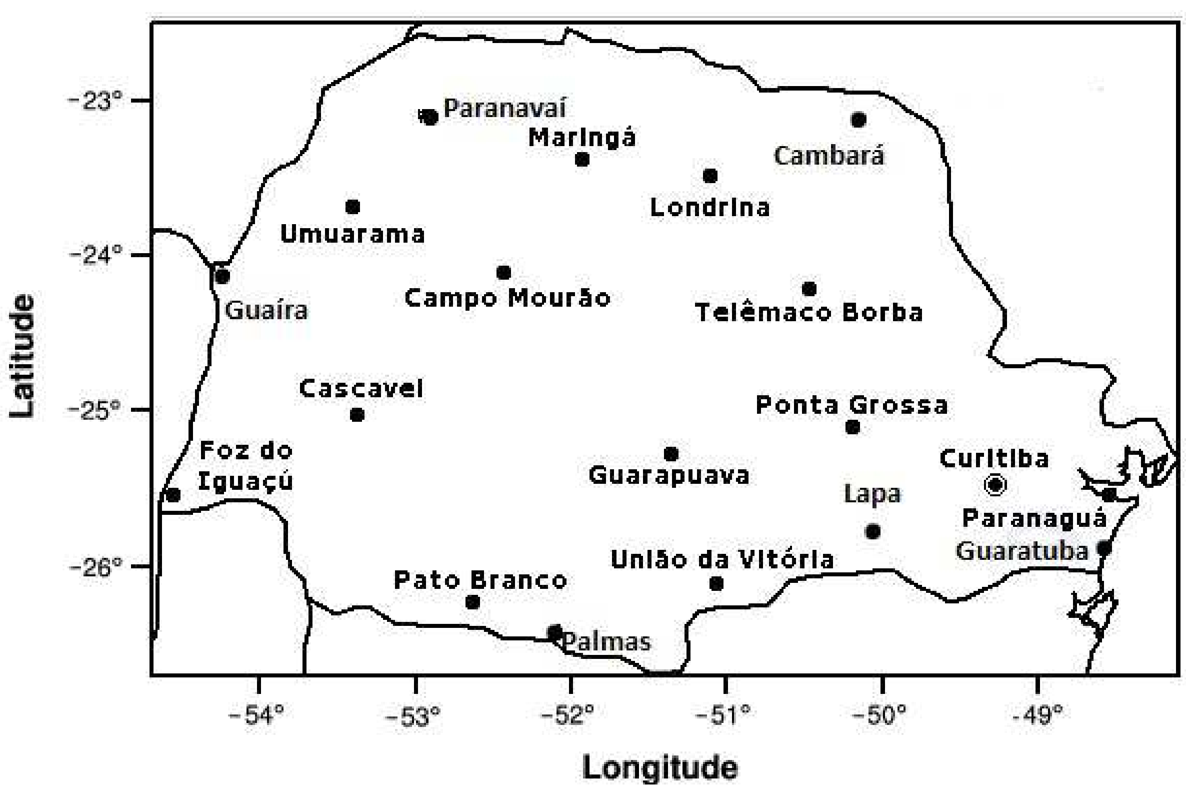

Fig. 1. Meteorological stations in Paraná state. Adapted from: <http://www.simepar.br>.

Fig. 2. The Paraná (PR) state location in Southern Brazil.

Data series provide the incidence of direct solar radiation measured on the surface. There is no correction carried out regarding the presence of clouds.

The MF-DFA method is a generalization of the standard DFA, being based on identification of the scaling of the *mth*-order moments of the time series which may be non-stationary. The modified MF-DFA procedure consists of a sequence of steps and detailed information about computation can be found in Kantelhardt et al. (2002). The steps are essentially identical to the conventional DFA procedure. First we construct the profile $X(i)$ as $X(i)=\sum_{k}^{i} x'_k$ .The index *i* counts the data points in the record, i.e., *i=1,2,..., N*. For eliminating the periodic seasonal trends daily differences $x'_i = x_i - \overline{x}_i$ were computed, where $\overline{x}_i$ represents the average value of radiation for each calendar date *i*. The profile is then divided into $N_s = int(N/s)$ non-overlapping segments of length *s*, where *s* represents time intervals measured in days. To accommodate the fact that some of the data points may be left out, the procedure is repeated from other end of the data set. The local trend is determined by using the least-squared fit to each segment v and we obtain the detrended time series $X_s(i) = X(i) - p_\nu(i)$ where $p_\nu(i)$ is the polynomial fit to the ν^{th} segment. In this work it is used as linear fit (DFA1). The variance of the detrended time series is calculated for each segment as

$$F^2(\nu,s) = \frac{1}{s}\left\{\sum_{i=1}^{s} X_s^2[(\nu\text{-}1)\mathrm{s}+\mathrm{i}]\right\}. \tag{1}$$

Averaging over all segments the *mth* order fluctuation can be obtained and

$$F_m(s) = \left\{ \frac{1}{2N_s} \sum_{\nu=1}^{2N_s} [\, F^2(\nu,s)\,]^{m/2} \right\}^{1/m} . \tag{2}$$

For *m*=2 the standard DFA procedure is retrieved. If the original series are long-range power-law correlated, the fluctuation function will vary as $F_m(s) \propto s^{h(m)}$ (for large values of *s*). Note that *h(m)* is the generalized Hurst exponent and *h(2)* is the usual exponent H previously mentioned. A multifractal description can also be obtained from considering partitions functions $Z_m(s) = \sum_{\nu=1}^{N_s} \left| X_{\nu s} - x_{(\nu-1)s} \right|^m \propto s^{\tau(m)}$ where $\tau(m)$ is the Renyi exponent (Barabasi & Vicsek, 1991). A linear scaling of $\tau(m)$ with *m* is characteristic of a monofractal data set, whereas a nonlinear scaling is indicative of multifractal behaviour. The exponent *h(m)* is related to the Renyi exponent $\tau(m)$ by

$$\tau(m) = m h(m) - 1 . \tag{3}$$

It is also possible to verify the multifractality degree by defining the ratio $H_< / H_>$ where $H_<$ is the slope of the function $\tau(m)$ *versus m* for $m < 0$ and $H_>$ is the equivalent for $m > 0$. By definition such relation is equal to unity in monofractal signals and a deviation from this value indicates multifractal properties.

3. Results and discussion

The mean global solar radiation at each station is showed in (Fig. 3).

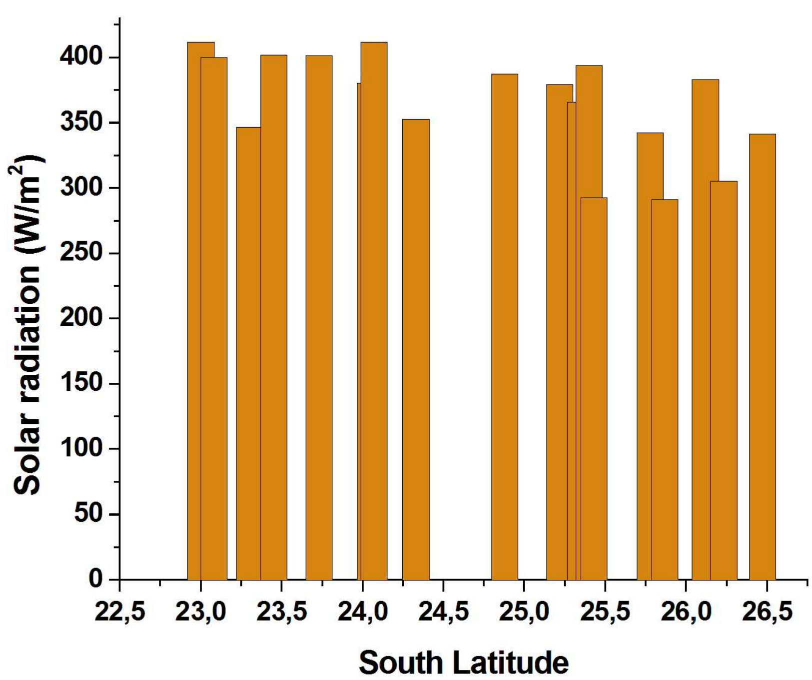

Fig. 3. Latitude dependence of the mean global solar radiation in the Paraná state.

In general, the mean intensity of solar radiation measured on the surface (global solar radiation) at each station decreases with increasing latitude, it is expected (Table 1). The lowest values were recorded for the stations closest to the coast, Curitiba and Guaratuba, not necessarily being of higher latitude. Local characteristics of clouds can affect actual radiation on the surface.

The typical distribution of radiation during the year is shown in Fig. 4. This seasonal behaviour implies a natural correlation, the consequent periodic trends are eliminated being the daily differences, previously discussed in the DFA method. On the other hand, the phenomena ElNiño/LaNiña affect the region, particularly in precipitation and temperatures. The radiation itself is not affected by the phenomenon, but a greater or lesser distribution of clouds would affect the radiation values measured directly on the surface. In a first approach, it is assumed that the presence of clouds have a random effect in the data stream and does not represent an actual correlation.

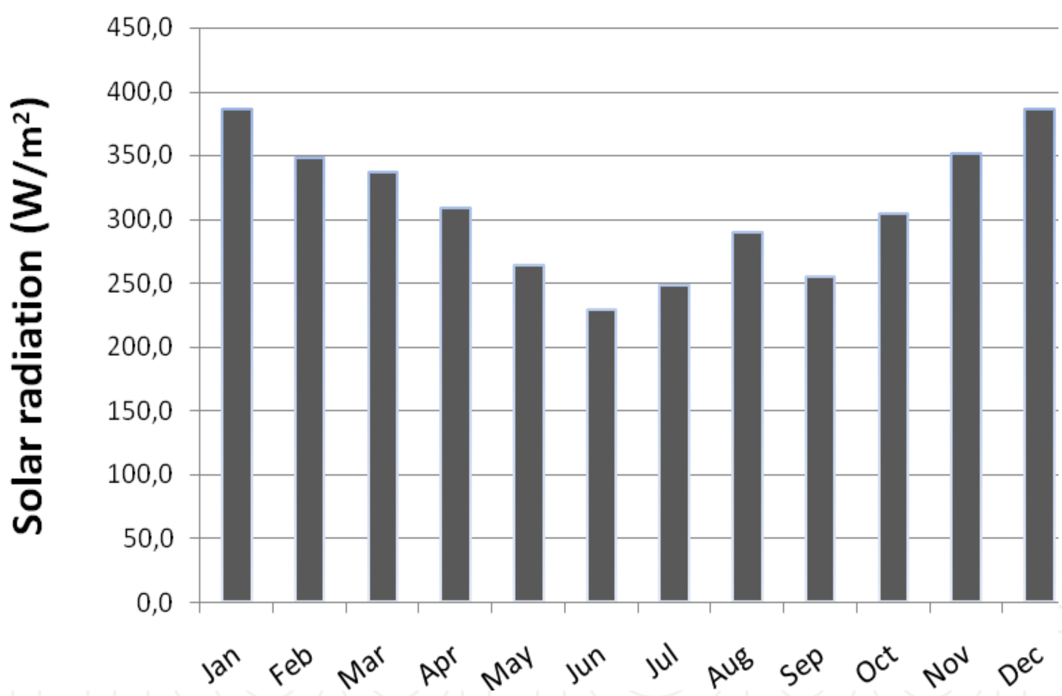

Fig. 4. Distribution of mean global solar radiation during the year, typical of the South Hemisphere.

Fig. 5 shows the global solar radiation series and the profile of cumulative series $X(i)$ for the Curitiba station. To perform the DFA method the lower and upper limits for s values for the time windows were chosen as 4 and $N/4$, where N corresponds to the number of records. The result for Hurst exponent is presented in Fig. 6 for both original and shuffled series. For randomic data series is expected $H=0.5$.

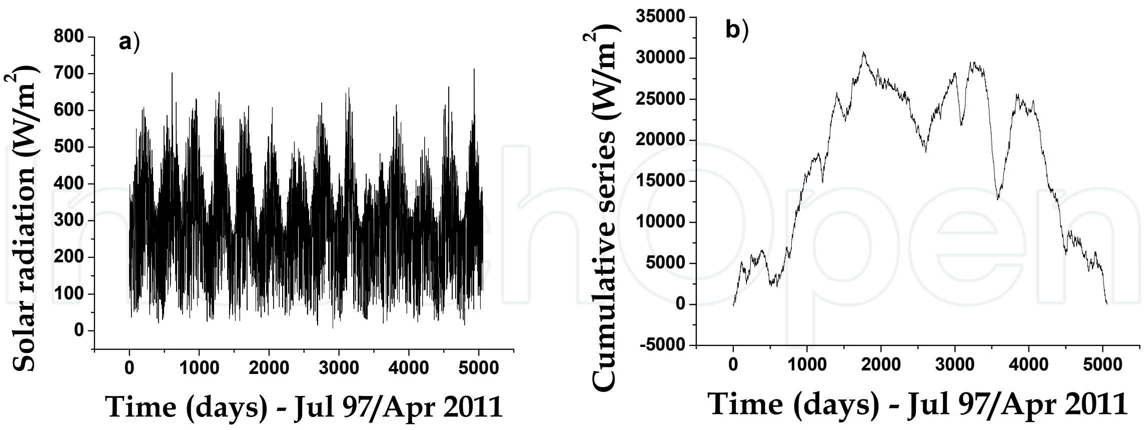

Fig. 5. a) Solar radiation measured on the surface at Curitiba station. b) Cumulative series of daily deviations for the same station.

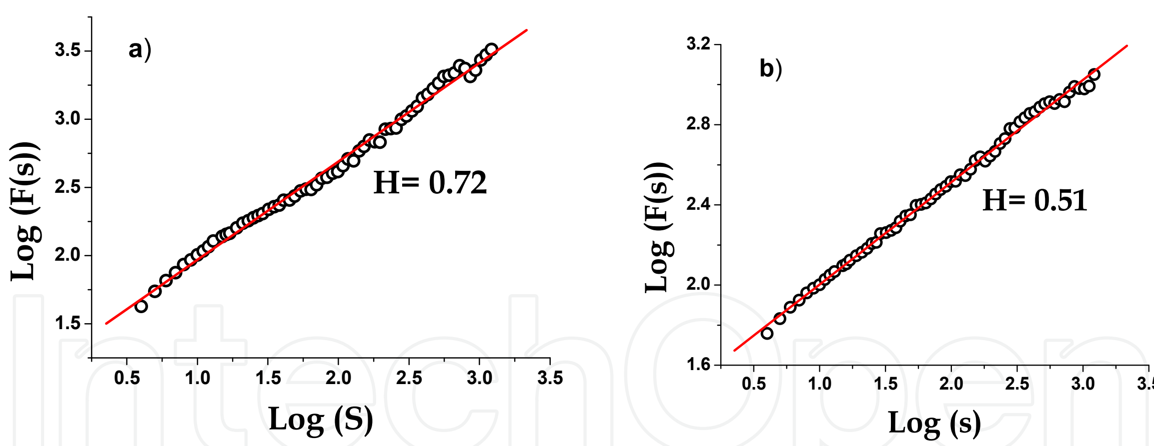

Fig. 6. a) Hurst exponent for Curitiba station. b) The exponent H for the shuffled series.

The H exponent for all studied data series presented value in the range 0.53 to 0.76 with mean value 0.65 (Table 1). Remembering that $H > 0.5$ is related with correlation and persistence the values for it in solar radiation is not surprising. It is reasonable to suppose that the incidence of solar radiation in the next day is not too different from the previous day. No correlation, in a statistical sense, it was found with the exponent H and latitude, altitude and average solar radiation, respectively.

Station	LAT (S)	LONG (W)	ALT (m)	Solar Rad (Wm-2)	H	$H_{<}/H_{>}$
Cambará	23º00′	50º02′	450	352.6	0.66	0.97
Campo Mourão	24º03′	52º22′	601	319	0.68	1.15
Cascavel	24º53′	53º33′	719	331.6	0.65	0.98
Curitiba	25º26′	49º16′	935	256.9	0.72	1.32
Foz do Iguaçu	25º24′	54º37′	232	327.3	0.64	1.38
Guarapuava	25º21′	51º30′	1070	347.8	0.64	1.14
Guaratuba	25º52′	48º34′	0	311.9	0.55	0.88
Guaíra	24º04′	54º15′	227	252.4	0.53	1.23
Lapa	25º46′	49º46′	909	296.8	0.57	0.94
Londrina	23º22′	51º10′	585	281.8	0.76	0.97
Maringá	23º25′	51º59′	570	332.5	0.63	1.24
Palmas	26º29′	51º59′	1100	314.1	0.73	0.80
Pato Branco	26º07′	52º41′	721	341.9	0.68	0.96
Paranavaí	23º04′	52º27′	480	327.9	0.63	1.48
Ponta Grossa	25º05′	50º09′	885	328.1	0.61	0.84
Telêmaco Borba	23º44′	53º17′	768	321.4	0.65	1.35
Umuarama	23º45′	53º19′	480	342.8	0.66	1.24
União da Vitória	26º14′	51º04′	756	255.4	0.76	0.80

Table 1. Location of the meteorological stations, mean value of global solar radiation, Hurst exponent H and the relation $H_{<}/H_{>}$, the multifractal degree.

The values grouped by frequency and intensity of Hurst exponent occurrences are presented in Fig. 7. Our results present contrasting value with those presented by (Harrouni &, Guessoum, 2009). They indicate high degree of anti-persistence. When the method is applied to temperature data series, the H value obtained is closer to a universal value, however this may depend of geographical position. It is expected that global solar radiation has similar performance regarding the persistence, in this case depending on the distribution of clouds or other elements in the local atmosphere.

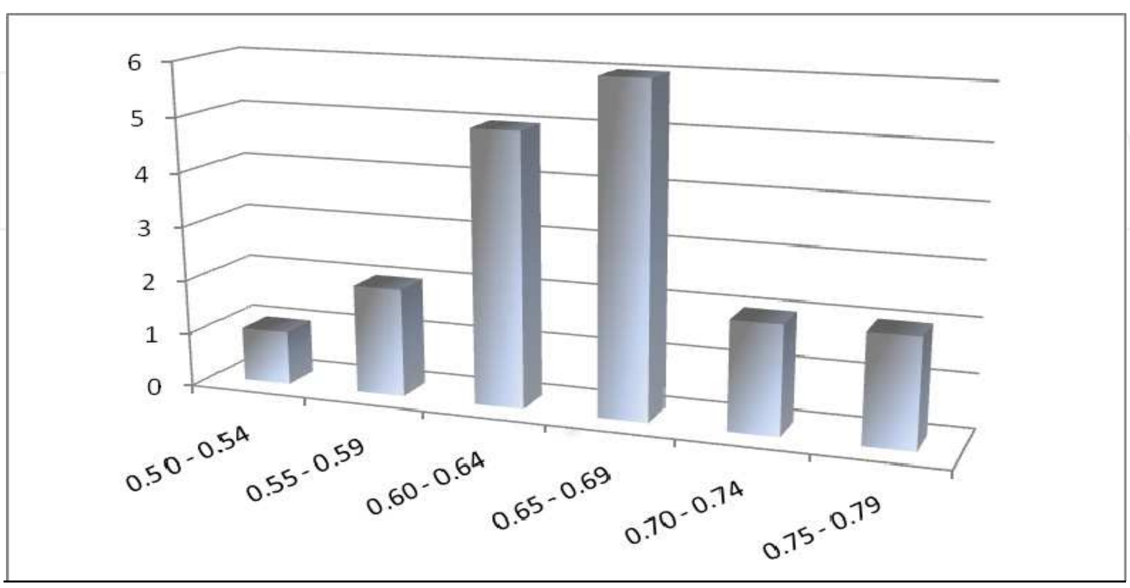

Fig. 7. Frequency of occurrence of Hurst exponents H.

In Table 1 it is also possible to observe the ratio $H_{<}/H_{>}$ which indicates the deviation from monofractal behaviour. Monofractal signals are characterized by unity in this relation. In this sense, a representative graphic is presented in Fig. 8 were the perfomance of the exponent $\tau(m)$ with different values of m is showed. In general the values for all stations indicate weak multifractality (Table 1). In this sense radiation time series present stationarity. Intrinsic correlations of time series represent the behavior of global solar radiation and, despite the presence of clouds, it does not demand the need for multiple Hurst exponents to describe the time series. Note that negative values of m emphasize on the parts with small fluctuations. For positive values of m the focus is on the parts with large fluctuations. Small deviations of the ratio above or below from unity are related with this characteristic.

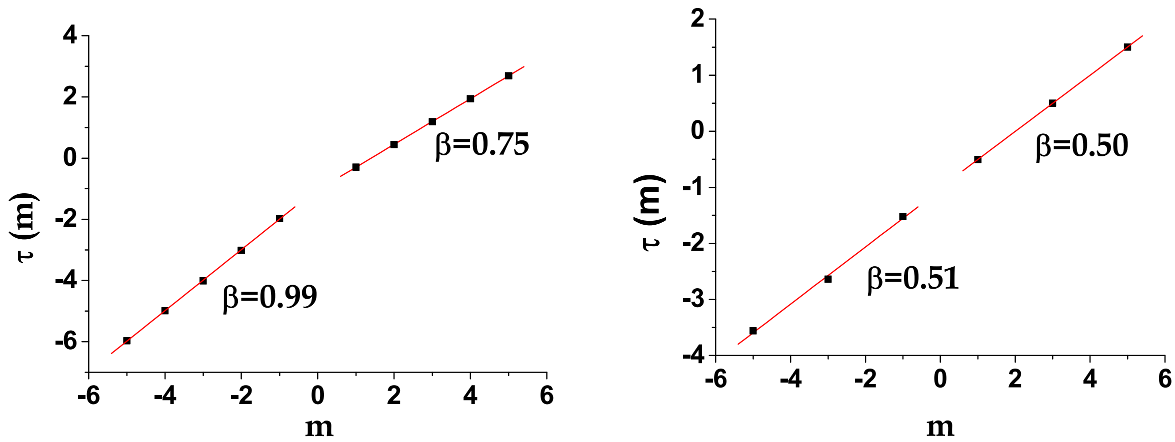

Fig. 8. The multifractal exponent versus several moments m. Different slopes indicate multifractality. At the left is the result for original series from Curitiba station. In the right is the result for the shuffled series.

As described in (Kantelhardt *et al.*, 2002) two different types of multifractality in time series can be identified. In the first case the multifractality of a time series which can be due to the shape of probability density function and the second case, the multifractality which can also be due to different long-range correlations for small and large fluctuations. It is possible to distinguish between these two types of multifractality. To achieve this the corresponding randomly shuffled series was analyzed. The correlations are destroyed by shuffling procedure but dependence of broad distribution function remains, and consequently the multiplicity of exponents is maintained.

Applying the method in the shuffled series of all stations, the ratio $H_{<}/H_{>}$ approaches unity, indicating a tendency toward monofractal nature. This demonstrates that the multifractality present in the series of solar radiation are due to different long-range correlations of the small and large fluctuations. In Fig. 8 the right graph presents the result for the shuffled series from Curitiba station.

It is interesting to note here the role of clouds or the presence of other particles or aerosols in the atmosphere. The method could be applied to time series related with solar radiation at the top of the atmosphere, for each location, and the series of solar radiation measured on the surface. In this case it would be possible to obtain information about the behaviour of clouds or other elements in the atmosphere at each location. On the other hand, variations of radiation incident on the planet due to periodic variations in solar activity could be detected in longer series.

4. Conclusion

In this work the DFA method was applied to detect long range correlation in data series of daily global solar radiation, measured on the surface, from 18 climatological stations, in Southern Brazil. The Hurst exponent presented mean value 0.65. Results indicate that series exhibit correlation of persistent character. The MF-DFA method was applied to the data set to analyze their scaling properties. Results indicate that the series are multifractal, but in a weak degree. These characteristics means that the processes may be governed by more than one scaling exponent to capture the complex dynamics inherent in the data. However, the low degree of multifractality of these series indicates small effect and points to a possible stationarity in the time series. Furthermore, the shuffled series present monofractal nature, indicating that the multifractal behaviour in the original ones arises from long-range (time) correlations. Both methods are powerful to analyze climatological time series from fluctuations and their statistical behaviour to obtain important information about the nature of the phenomena from its historical data.

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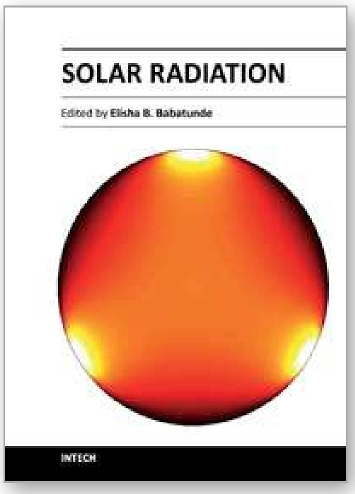

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The book contains fundamentals of solar radiation, its ecological impacts, applications, especially in agriculture, architecture, thermal and electric energy. Chapters are written by numerous experienced scientists in the field from various parts of the world. Apart from chapter one which is the introductory chapter of the book, that gives a general topic insight of the book, there are 24 more chapters that cover various fields of solar radiation. These fields include: Measurements and Analysis of Solar Radiation, Agricultural Application / Bio-effect, Architectural Application, Electricity Generation Application and Thermal Energy Application. This book aims to provide a clear scientific insight on Solar Radiation to scientist and students.