Multifractal fingerprinting of fine resolution daily gridded rainfall of Kerala meteorological subdivision, India using detrended fluctuation analysis

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Multifractal Fingerprinting of Fine Resolution Daily Gridded Rainfall of Kerala Meteorological Subdivision, India Using Detrended Fluctuation Analysis

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Abstract. This paper performs the Multiracial Detrended Fluctuation Analysis (MFDFA) of fine resolution (0.25°x0.25°) daily gridded rainfall of Kerala Meteorological subdivision, India. First the MFDFA method is applied for long term rainfall datasets of different grid points for 1901-2013 period. The results show that rainfall time series of majority of the grid points (~66 %) exhibits short term persistence with strong multifractal characteristics. Except at three locations, the asymmetry index of rainfall time series displays right skewed spectra indicating local high fluctuations and fine structured series. Further, MFDF analysis was performed after splitting the time series into two with respect to the global climatic shift of 1976/77. The results of pre and post climatic shift period shows that 34 grids (out of 65) exhibited an increase multifractal spectral width while 41 grids exhibited a increase in persistence after the shift. The study further showed that the persistence property changed from short to long term in 23 % grids, which also indicated a change in pattern of rainfall within the subdivision. The results showed that a strong correlation 0.994 exists between Hurst exponent and Holder exponent, reinforcing the universal association between the two multifractal exponents.

INTRODUCTION

Investigating the multifractality of the time series is a classical complexity description problem in time series analysis. Harold Edwin Hurst [1] is perhaps one of the first contributors in this field and the Rescaled Range (R/S) analysis might be the first quantitative information on the persistence of time series. The concept of 'fractal' theory evolved in 1970s paved the way for the better understanding on the characteristic analysis of complex time series in different scientific disciplines. The fractality can be referred as the property of a fragmental geometrical object that can be partitioned into parts, each of which is a reduced size copy of the whole [2]. Fractal properties are considered as the identity of the time series and researchers have widely applied this concept in biomedical, financial, geophysical, and environmental time series in the past few decades [3]. In-depth understanding of the characteristics will help in improving the predictability efforts of complex time series like hydrologic time series.

For the detection of fractality or multifractality, a large number of methods were proposed in the past. The classical box counting algorithm [2], universal multifractal models (UMM)[4], extended self- similarity (ESS) method [5], wavelet transform modulus maxima (WTMM) [6], arbitrary order Hilbert spectral analysis (AOHSA) [7] are some among them. Peng et al., [8] proposed Detrended Fluctuation Analysis (DFA) rooted in a detrending operation to examine the fractal properties of time series. Kantelhardt et al., [9] extended the procedure to multiple moment orders to propose a modified DFA procedure namely multifractal DFA (MFDFA). The description of multifractality can be considered as the '*fingerprinting*' of the series, as it can be used as a benchmark for evaluating the

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performance of rainfall-runoff models in hydrologic studies [10]. Therefore in the past, DFA and MFDFA methods were popularly used for the characteristic analysis of different types of hydrological and meteorological time series. Multifractal description of streamflow is perhaps most popular among application [10-14].

The development of MFDFA method was a major breakthrough in the multifractal characterization of rainfall time series. Kantelhardt et al., [6] examined the multifractality of global streamflow and rainfall data of different temporal scales using MFDFA and the results were found to be in good agreement with that by WTMM technique. Kantelhardt et al., [10], investigated the multifractality of 99 rainfall and 43 runoff time series at daily time scale collected from stations located at different parts of the world. They reported short term persistence (STP) in rainfall series and long term persistence (LTP) in runoff series with an average scaling exponent of ~0.53 and ~0.73 respectively. Yu et al., [15] examined the multifractality of rainfall time series of Pearl River basin of China having length even up to 45 years. The results by MFDFA and UMMs detected the multifractality, but in different bands of time scales. Baranowski et al., [16] investigated the scaling characteristics of air temperature, relative humidity, radiation, wind speed, and rainfall datasets with more than 11300 points collected from four European countries. The multifractality of precipitation was found to be due to broadness of probability distribution, while that of remaining time series were found to be due to correlations prevailing for longer time spells. Tan and Gan [13] applied MFDFA for the description of multifractality of 145 river flow and 100 rainfall records of Canada. They found that the rainfall time series exhibited LTP in diverse time scales, while flow records exhibited LTP only at larger scales. Krzyszczak et al., [17] used MFDFA to analyze the multifractality of different meteorological signals recorded at 4 stations in Bulgaria and Poland. Daily time series comprising 11,323 data points of precipitation (mm), wind speed (ms^{-1}), air temperature (°C), and relative air humidity (%) were considered in the study. It was reported that the multifractal property of precipitation differs considerably from that of other analyzed variables. Each series was split into two with respect to the climatic shift of 2001/2002 and multifractality was analysed. The singularity spectra were found to be susceptible to climatic shift and it was evident for asymmetry, which switched from right- to left-skewed, implied the frequent occurrence of extremes in the regions in recent past. Some recent studies investigated the multifractality of precipitation and the Standardized Precipitation Index (SPI) [18-20].
Even though many studies performed fractal analysis employing MFDFA procedure worldwide, there is dearth of attempts to investigate multifractality of fine resolution rainfall time series from India and their spatio-temporal variability. The specific objectives of this paper includes :

1. To apply MFDFA for fine resolution rainfall of the state of Kerala, India.
2. To investigate spatio-temporal variability of multifractal characteristics of rainfall data of Kerala

MULTIFRACTAL DETRENDED FLUCTUATION ANALYSIS

The MFDFA algorithm involves the (i) generation of profile of the time series; (ii) splitting of profile into different segments and fitting polynomial for each of the segments; (iii) computation of fluctuation function (FF) etc. The slope of log-linear association FF vs scale for different moment orders provides the generalized Hurst exponent ($h(q)$) values. If GHE values are q-dependent, the time series will be multifractal in nature. From the GHE values, the mass exponent plot and multifractal spectrum can be developed. The base width of the multifractal spectrum and spread of GHE plots give information on degree of multifractality of the time series. The asymmetry of the spectrum gives the knowledge of the complexity of the time series. The different steps of MFDFA are presented in Figure 1 and more theoretical details on the procedure can be found elsewhere [6, 12, 21].

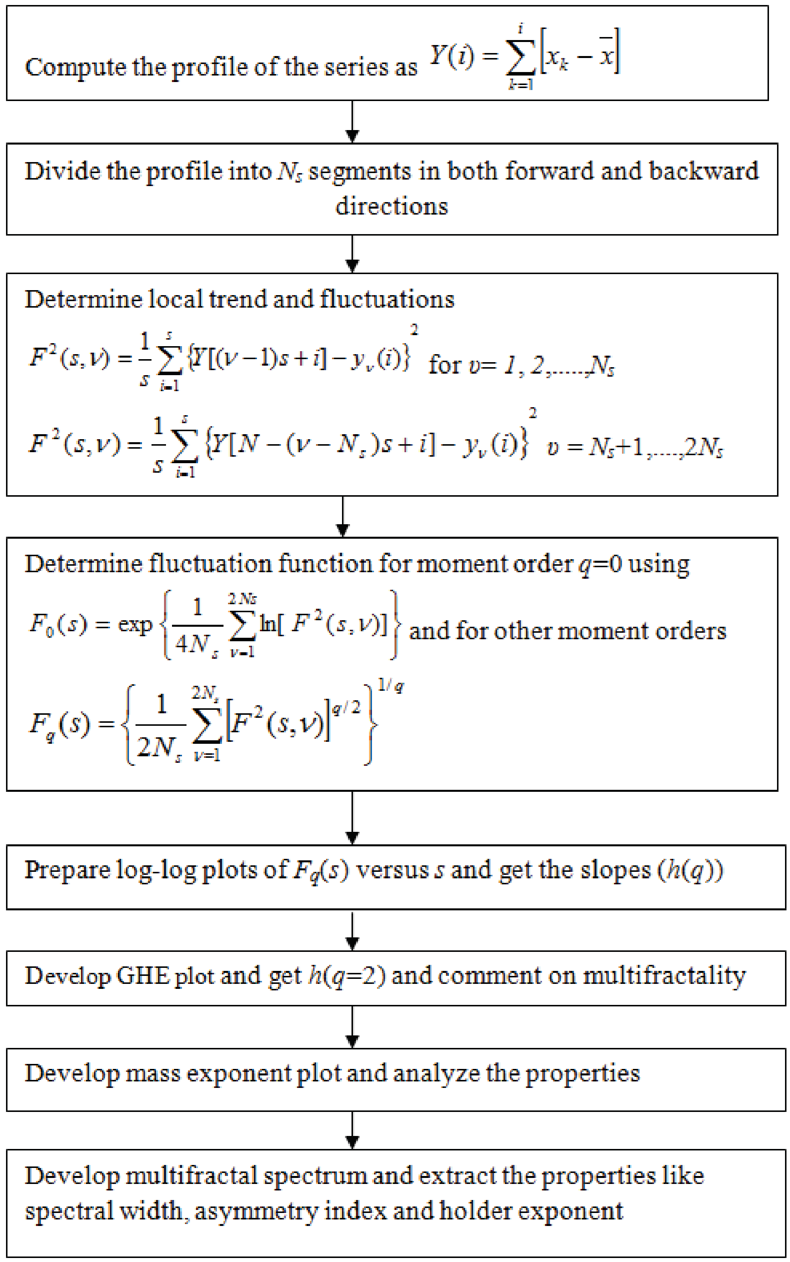

FIGURE 1. Flowchart of MFDFA algorithm

STUDY AREA AND DATABASE

The State of Kerala, considered as the 'gateway of Indian monsoon', bounded by the Arabian sea, is located in the south -west coast of India. The agro based economy of the State mainly depends on the availability of south west monsoon and post monsoon rainfall. The state receives an average annual rainfall of ~300 cm. The gridded data at a resolution of 0.25°x0.25° is one of the finest scale rainfall information provided by the India Meteorological Department (IMD) at daily scale. The gridded rainfall data product was prepared by Pai et al. [22] based on the observations at 6955 rain gauging stations. This fine resolution data for long period of 1901-2013 (length over 43000) is used in this study. Sixty five grid points are identified in the region and on an average, 54 % non-rainy days are there in different time series.

RESULTS AND DISCUSSIONS

In this section, results of MFDFA of different rainfall time series are presented in two sub-sections. In the first sub-section, the spatial variability of multifractal properties is presented and in the second sub-section, the temporal variability of multifractal properties is analyzed.

Spatial Variability of Multifractal Properties

In this study, first the MFDFA method is employed for the characteristic analysis of daily rainfall time series of all the 65 grid points of Kerala from 1901 to 2013 period. The analysis is performed by considering a moment order of -4 to 4 to avoid any possible bias on considering the long data [23]. The characteristics of the data show that the data comprises of long and continuous zero values, and to avoid plausible wrong conclusions on the persistence of the series, the minimum scale is kept more than the longest stretch of continuous zero values [23]. The multifractal properties like Hurst exponent (H), the spread of GHE plot ($\Delta h(q)$), spectral width, Holder exponent (α_0), asymmetry index (R), spread of singularity spectrum plot ($\Delta f(\alpha)$) etc. are computed. The spatial distributions of different multifractal properties of rainfall data are presented in Figure 2.

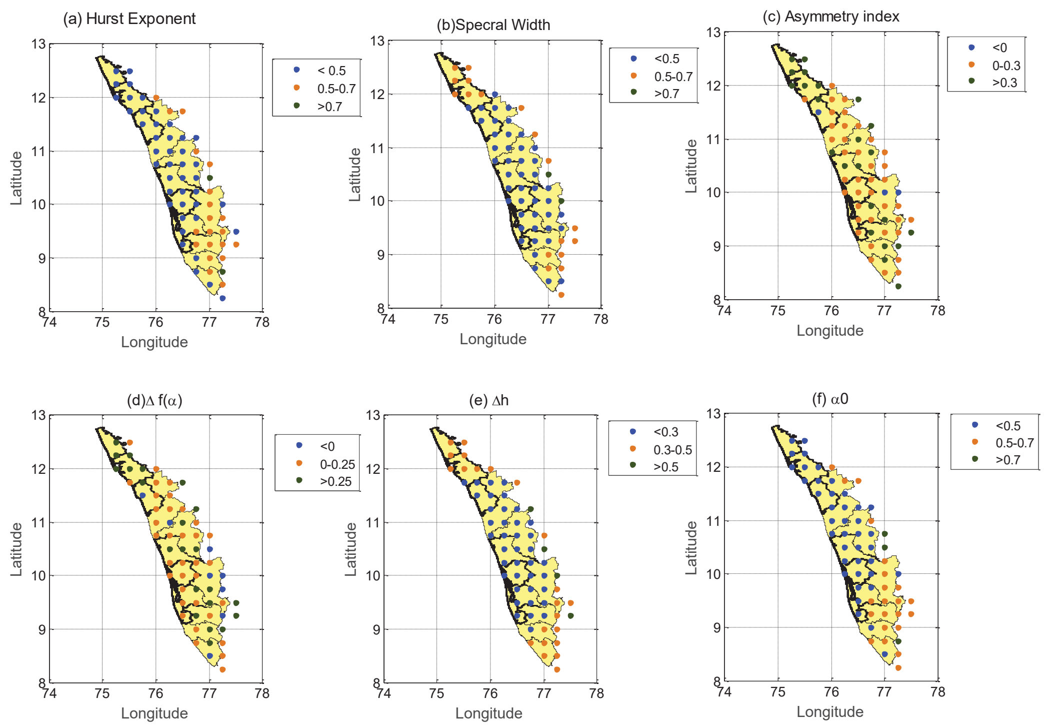

FIGURE 2. Spatial distribution of multifractal properties of rainfall data of Kerala (a) Hurst exponent; (b) spectral width; (c) asymmetry index; (d) spread of singularity spectrum; (e) spread of GHE plot; (f) Holder exponent

From Figure 2 it is clear that rainfall of majority of the grid points (43 out of 65) displays short term persistence (STP). The Hurst exponent ranges between 0.217 and 0.843, with an average value of 0.443 (with a standard deviation of 0.145), which is also in the range of STP. From Figure 2, it is noted that most of the grids showing LTP are concentrated in the eastern Hilly terrain and regions of southern Kerala. The spread of GHE plot and spectral width conveys similar information on the multifractality of the series, the mean values are found to be 0.25 and 0.39 respectively. The distribution of Holder exponent (Figure 2(f)) is similar to that of Hurst exponent. A presented plot between the two exponents is prepared and presented in Figure 3. There exists a strong association between the two with a correlation of 0.993, which confirms the close association between the two parameters reported by Burgueño et al., [24] considering the daily temperature time series of Catalonia region, Spain is also applicable for rainfall series. The mean value of Holder exponent is 0.462 (with a standard deviation of 0.16) which is quite close to that of Hurst exponent (0.44). It is further noticed that except at three grid points (of hilly terrains of Idukki and Calicut districts), the asymmetry index is positive indicating a right skewed spectrum showing relatively strongly weighted high fractal exponents [24]. This might be because of the localized high fluctuations. The spatial distribution of spread of singularity spectrum is also found to be displaying a fair degree of similarity with that of asymmetry index. Within the different grid points, the variability (based on coefficient of variation of values) noted are 32.6 % for H, 43.78 % for the spectral width and 32.2 % for the Holder exponent.

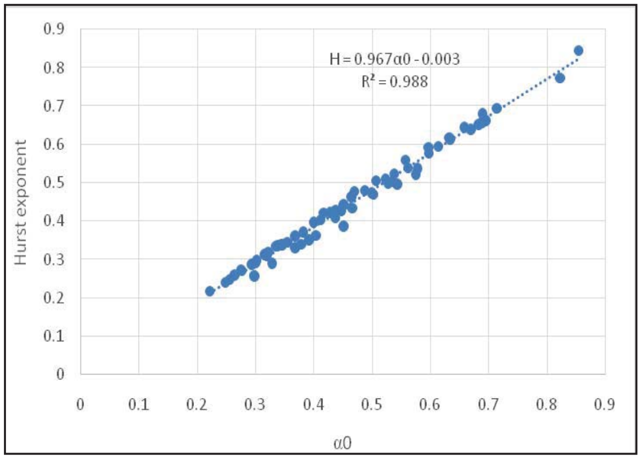

FIGURE 3. Relation between Hurst exponent and Holder exponent of rainfall time series of Kerala

Temporal Variability of Multifractal Properties

To evaluate the temporal variability of multifractal properties, the complete data can be partitioned into sub-series and the MFDFA of each sub-series can be performed. It is well evident that a Global climate shift occurred during 1976/77 period and some researchers have proved that the climate shift affected the pattern of Indian Summer Monsoon [25, 26]. Therefore the rainfall time series of multifractal properties of pre and post 1976/77 climate shift are examined for their multifractality. The CDFs of different multifractal parameters of rainfall time series for pre and post 1977 Pacific climatic shift prepared based on the non-parametric kernel density estimator [27] are portrayed in Figure 4.

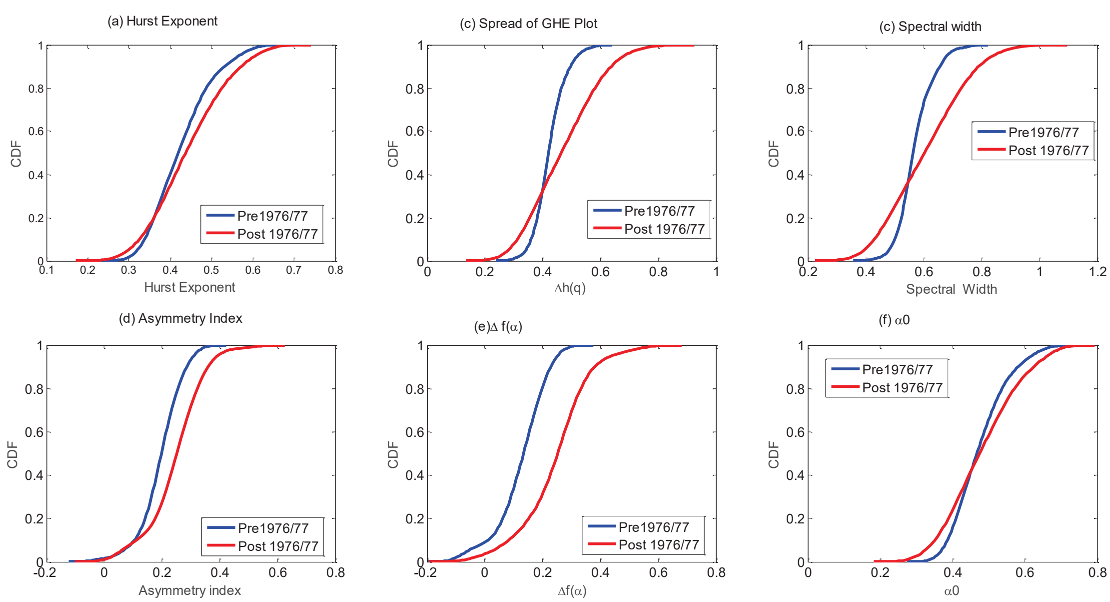

FIGURE 4. CDFs of multifractal characters of rainfall records of pre and post 1976/77 climate shift (a) Hurst exponent; (b) spread of GHE plot; (c) spectral width; (d) asymmetry index; (e) spread of singularity spectrum; and (f) Holder exponent.

From Figure 3, it is clear that there is domininancy of increase in multifractality of the series, persistenace and complexity of the series after the climate shift of 1977. This could also be linked with the changes indictated in the standardized precipitataion index (SPI) series of post 1976/77 period [19]. The asymmetry index (R) and spread of multifractal spectrum ($\Delta f(\alpha)$) are found to be increased for the time series of post-1977 period when comapred to the time series of pre-1977 period. On quantifying the increase in H, spectral width and complexity, it is noticed that there is an increase in these properties respectively at 41, 34 and 42 points.i.e., majority of grid points displayed increase in the values of these properties. It is further noticed ithat in 15 grids (23 % of grids), there is a swtichover in persistance from short term to long term and in four grid points, the change was in the contrasting way. A change from positive to negative asymmetry was noted in five grid points while at one grid point, a change from negative to positive asymmetry was noted. Overall analysis shows that the reduction in persistence, complexity and multifractality is the less in the region of Kerala.

The multifractal properties of rainfall could also be associated with the physical mechanisms resulting in rainfall. Kerala is bordered by Arabian Sea in the west and Indian Ocean in the south. The proximity to oceans has a dominant role in the rainfall of India in general, and the region in particular. It was established that the large scale climatic oscillations from oceans play a major role on Indian monsoon system [28]. Hence the role of these circulations on the multifractal properties of the rainfall also cannot be ignored [15]. Apart from the global parameters like terrestrial radiations and temperature, the local factors like the latitude, topography and local processes along with the oceanic and atmospheric circulations may influence the multifractality of the rainfall series. However it will be hard to find a general pattern in the changes in exponents with altitude, latitude or ocean proximity [15]. In short, the multifractality of rainfall over India may also be influenced by many local effects like terrain, moisture and vegetation conditions. As relatively lesser reduction in the properties was noted in the region for pre and post 1976/77 series, one can attribute it to the increased urbanization. The increased urbanization might have changed the precipitation pattern more heterogeneous and irregular in the region, which might have lead to relatively lesser reduction in the multifractal properties.

Understanding the multifractal properties may help in multifractal modeling, rainfall simulations, generation of rainfall data, de-noising of hydrological signals, developing Intensity-Duration-Frequency curves, dis-aggregation of rainfall etc. [29-33]. Any drastic change in the long-range power law dependencies or multifractality may lead to incorrect estimates the situation is fairly similar to the use of a stationarity assumption in non-stationary conditions. In this context, the spatio-temporal changes in the multifractal properties are to be monitored vigilantly particularly in a changing climate scenario.

CONCLUSIONS

This paper investigated the multifractality of fine resolution (0.25^ox0.25^o) daily gridded rainfall (1901-2013 period) of Kerala meteorological subdivision, India using Multiracial Detrended Fluctuation Analysis (MFDFA) method. The MFDFA application showed that rainfall time series of majority of the grid points (~66 %) are short term persistent with strong multifractal characteristics. Except at three locations, the asymmetry index of rainfall time series displayed right skewed spectra indicating fine structured series with local high fluctuations. Further, MFDF analysis was performed after splitting the time series into two with respect to the global climate shift of 1976/77. The results of pre and post climatic shift period showed that 52 % of grids exhibited an increase in multifractal spectral width while 63 % grids exhibited an increase in persistence and complexity after the shift. The study further showed that the persistence property changed from short to long term in 23 % grids. The results showed that a strong correlation 0.994 exists between Hurst exponent and Holder exponent, reinforcing the universality in the association between the two multifractal exponents.

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