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Multifractal characterization of air polluted time series in China

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HIGHLIGHTS

- Each AQI time series has multifractal rather than monofractal characteristics.
- There are two sources of multifractality.
- The coupled correlations of six air polluted series have multifractal features.
- SO_2, O_3 and NO_2 have different impacts on air quality in each of three cities.

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ABSTRACT

This paper adopts multifractal methods to analyze the multifractal characteristics of polluted time series in Beijing, Zhengzhou, and Jinan. The results of the multifractal detrended fluctuation analysis (MF-DFA) show that each of three air quality index (AQI) time series has multifractal characteristics, which provides evidence that the multifractal method but the traditional linear or monofractal method is feasible. The sources of multifractality in three AQI time series are all from long-range correlations and fat tail distributions, although the highlighted sources are different in three cities. The results of the coupling detrended fluctuation analysis (CDFA) show that SO_2 has a vital impact on air quality in each of three cities. O_3 has an important impact on air quality in Beijing and Jinan city and NO_2 has an important impact on air quality in Zhengzhou city. It is noted that $PM_{2.5}$ has not as large an impact as we imagine in three cities. It has a relatively large impact on air quality of Zhengzhou city, while it has a small impact on air quality of Beijing and Jinan city. The chi square (χ^2) test further confirms the above results.

1. Introduction

In recent years, with the development of urbanization and industrialization, air pollution is becoming more and more serious. The occurrence of these pollution incidents makes people gradually realize the importance of air environment. When the concentration of pollutants in the atmosphere is very high, it will not only seriously harm human health, but also destroy the human ecosystem. In consideration of the complexity of air pollution, nonlinear methods to study the evolution of air pollutant have been adopted in the researches at home and abroad. Of these methods, the multifractal method provides a powerful tool for people to deal with complex objects, which is also an important branch of nonlinear science. In recent years, more and more scholars have adopted this method to study environmental problems.

The multifractal detrended fluctuation analysis (MF-DFA) proposed by Kantelhardt et al. [1] has been widely adopted [2–8]. In the environmental pollution field, Lee et al. [9] find that there exist multifractal characteristics in the ozone

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concentration time series in Taipei. Diosdado et al. [10] provide evidence that the concentration time series of atmospheric pollutants have multifractal characteristics. And these series have long term correlations and strong persistence that reflect in its multifractal character. In addition, Liu et al., Dong et al. and Shen et al. on China mainland [11–13]; Varotsos et al. on Greece and Maryland also find that there exist multifractal characteristics [14].

Since Podobnik and Stanley [15] proposed the detrended cross-correlation (DCCA) method to investigate the cross-correlations between non-stationary time series, scholars in different fields begin to use this method to study multifractal characteristics of two time series [16–21]. Zhou [22] applies the DCCA method into the multifractal detrended fluctuation analysis, i.e. MF-DCCA method, to explore multifractal cross-correlations. This method has been widely adopted by many scholars [23–28]. However, there are relatively few researches in the field of environmental pollution. Zhang et al. [29] analyze the cross-correlations of PM2.5 and meteorological factors with the MF-DCCA method. The results show that the cross-correlations between PM2.5 concentration and four meteorological factors are multifractal and anti-persistent, and the strength of multifractality of Beijing is stronger than that of Hong Kong.

The development experience of the world shows that economic developments are often accompanied by increasingly serious environmental problems. During the past decades, China's provincial capitals, with the rapid economic developments, have been faster cities in the progress of urbanization than other ones. Accordingly, the pollutions in these cities are more serious than that of other cities. On the basis of the environmental air quality standard and the effects of various pollutants on human health, ecology and environment, the air quality index (AQI) transforms the concentrations of several common air pollutants into a numerical value, indicating the levels of air pollution. The greater the numerical value, the more serious the pollution is. The main pollutants affecting air quality are particulate matter ($PM_{2.5}$), respirable particulate matter (PM_{10}), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2) and ozone (O_3). According to the AQI, the top ten polluted cities in China are Shijiazhuang, Zhengzhou, Jinan, Beijing, Urumqi, Xian, Tianjin, Wuhan, Chengdu and Shenyang.

In this paper, we analyze the multifractal characteristics of polluted time series in Beijing, Zhengzhou and Jinan. Compared with the existing literatures, our main contributions are as follows. (1) Most scholars focus on long memory properties and multi-scale features of one or more polluted time series such as SO_2, CO, SO_2, O_3 in previous studies [10,30,31]. Only a few scholars are concerned about the AQI. The AQI can provide overviews of air quality across the major part of one city, and can enhance the public awareness of air pollution. This paper studies the multifractal characteristics of the AQI and the empirical results show that there are multifractal characteristics of AQI time series in three cities despite the existence of differences in these series.

(2) In addition to AQI, this paper also explores each pollutant's role in resulting in the air pollution. With the CDFA method and chi square $\left(\chi^2\right)$ test, we analyze the multifractal characteristics of $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2 and O_3 and further identify the sources of multifractality in these time series. By this way, we know that SO_2 is a very important factor in evaluating the air pollution of each city. O_3 is a vital factor in affecting air quality in both Beijing and Jinan city, while NO_2 is a significant factor in affecting air quality in Zhengzhou city. The importance of $PM_{2.5}$ to the air pollution is limited to Zhengzhou city and it has a minor role in the air pollution of Beijing and Jinan city. Understanding the source of pollution has an important significance to take specific measures to fight against pollution in different cities.

(3) Previous studies on the air pollution time series often use the method of the vector auto-regression (VAR) model or the Generalized AutoRegressive Conditional Heteroskedasticity (GARCH) model [32–37]. Few studies adopt the multifractal detrended analysis method. For some time series, they exhibit complicated statistical correlations and fractal or multifractal features in most commonly considered situations [38]. In addition to MF-DFA and MF-DCCA methods, the coupling detrended fluctuation analysis(CDFA) method has been adopted to explore multifractal features in a few researches [39,40]. In this paper, we adopt MF-DFA and CDFA methods to study Multifractal characterization of air polluted time series in three cities. Firstly, we perform the MF-DFA analysis to confirm the existence of multifractal characteristics and explore the sources of multifractality in each of three AQI time series. Secondly, we use the CDFA method to evaluate the coupled correlation among six polluted series in three cities. The purpose is to identify the sources of air pollution in three cities.

The remainder of this paper is organized as follows. Section 2 introduces the methodology. Section 3 describes air polluted data in three cities. Section 4 presents the empirical results and Section 5 provides the conclusions.

2. Methodology

There are two multifractal methods in this paper. In the first place, we introduce the MF-DFA method proposed by Kantelhardt et al. [1]. A brief description of MF-DFA method is as follows.

First, let x_t be a time series of length N. So the profile can be defined as $X(i) = \sum_{t=1}^{i}(x_t - \bar{x})$, where $i = 1, 2, \ldots, N$.$\bar{x}$ represents the mean value of the whole series.

Second, the entire profile series $X(i)$ is divided into $N_s = int(N/s)$ non-overlapping segments of equal length s. Since the length N of each series is often not a multiple of the considered time scale s, a short part at the end of the profile may remain. In order not to disregard this part of the series, the same procedure is repeated starting from the opposite end. Thereby, $2N_s$ segments are obtained altogether.

Third, the local linear trend $x_v(i)$ for each of the $2N_s$ segments is calculated using the least-square fitting model. Then, the detrended variance of each segment v for the first half is calculated as follows:

$$F_v^2(s) \equiv \frac{1}{s}\sum_{i=1}^{s}\{X[(v-1)s+i] - x_v(i)\}^2 \tag{1}$$