Atmospheric Research 171 (2016) 1–4

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Long-memory property in air pollutant concentrations

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ARTICLE INFO

Article history:
Received 2 September 2015
Received in revised form 4 December 2015
Accepted 14 December 2015
Available online 19 December 2015

Keywords:
Temporal evolution
Self-organized criticality
Self-cleansing of atmosphere

ABSTRACT

In the present paper, long-memory in air pollutant concentrations is reviewed and outcome of the past studies is analyzed to provide the possible mechanism behind temporal evolution of air pollutant concentrations. It is observed that almost all the studies show air pollutant concentrations over time possess persistence up to a certain limit. Self-organized criticality of air pollution, multiplicative process of pollutant concentrations, and uniformity in emission sources leading to self-organized criticality are few of the phenomena behind the persistent property of air pollutant concentrations. The self-organized criticality of air pollution is linked to atmosphere's self-cleansing mechanism. This demonstrates that inspite of increasing anthropogenic emissions, self-organized criticality of air pollution is sustained and has low influence of human interventions. In the future, this property may, however, be perturbed due to continuous air pollution emissions, which may influence the accuracy in predictions.

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1. Introduction

Fractal behavior exists in nature as tree structure, i.e. trunks and roots reflecting the similar behavior like trees and self-similar mountain ranges. A system where its part either when dilated, translated, or rotated imitates or represents it, is called self-similar or re-scaled or fractal. Due to the self-similarity property, various natural systems can be studied by only analyzing their parts. *Complex* problems in many natural systems have been shown to possess simple linear mechanisms and orderliness (May, 1976; Sugihara and May, 1990). According to Chira et al. (2010), 'Complex systems are situated at the delicate balanced edge between order and disorder.' In the disordered state, there are no correlations between events that are separated in time or space, and vice versa for the ordered state. It is of the notion that every sub-system in nature possesses the properties of its mother system, i.e. nature. Self-similarity, scale invariance, and fractal behavior are closely related concepts (Morales et al., 2012).

Complexity in the system is usually studied by fractal analysis. Scaling and fractal behavior are shown to be associated with long-memory process possessing characteristics of self-similarity and scale invariance (Mandelbrot and Ness, 1968; Musa and Ibrahim, 2012; Morales et al., 2012). The scale invariance implies the self-similar property of the system, suggesting the invariance of the process from one scale to another (Tsonis et al., 1999; Lee et al., 2006). Long-memory property is the presence of strong correlation between the past state and present state of the system. For such a system, statistical tools are applied differently than for identically and independently distributed systems (Beran, 1994). For a time series, short memory property is usually characterized by autocorrelation function which decays exponentially. For time series with long-memory property, autocorrelation function follows power law and decays gradually to zero. However, for long-memory time series, more rigorous methods such as Hurst exponent (Hurst, 1951) based on rescaled range analysis (R/S) and detrended fluctuation

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http://dx.doi.org/10.1016/j.atmosres.2015.12.007
0169-8095/

analysis (*DFA*) are developed in the past. For details on detrended fluctuation analysis and rescale range analysis, one may refer Peng et al. (1994) and Hurst (1951), respectively.

Atmosphere is a mixture of various gases and hidden forces, the composition of which is perturbed by air pollution. Although induced by human interventions, air pollution is a system which possesses the mechanisms like emission, dilution, dispersion, and transportation. Air pollution has been studied by analyzing air pollutant concentrations in ambient air. Several studies have confirmed the fractal behavior, scale invariance, self-similarity and long-memory property of air pollutant concentrations through various techniques. This study is an attempt to review those studies related to persistence or long-memory property in air pollutant concentrations over time. It is also attempted to provide possible explanation of long-memory property in the air pollution time series.

2. Long-memory in air pollutant concentrations: Literature review

Several studies have confirmed the fractal behavior of air pollutant concentrations through various techniques. The existence of persistence or long-range correlations in time series is helpful in making further projections as the measurements rely on the correlations with historical observations. This is usually done through studying the time series of air pollutant concentrations at a site. Liu et al. (2015) used detrended fluctuation analysis and multifractal method to characterize the temporal fluctuations of SO_2, NO_2, PM10, and air pollution indices in Shanghai. Weng et al. (2008) used *R*/*S* analysis and BDS test to ascertain nonlinearity in ground level peak ozone time series. Based on *R*/*S* analysis, ozone time series was identified as persistent and long-memory process which implied nonlinearity and fractality of ozone time series. Several approaches such as rescale-range analysis, spectral analysis, and detrended fluctuation analysis (DFA) have been used in the literature for persistence or long-range correlations analysis (Zhu and Liu, 2003; Shi et al., 2008; Chelani, 2009). Using DFA, persistence in air pollutant concentrations is studied (Varotsos et al., 2005; Lu and Wang, 2006; Varotsos and Kirk-Davidoff, 2006; Varotsos et al., 2006; Weng et al., 2008; Lau et al., 2009; Yuval and Broday, 2010; Perez et al., 2011; Chelani, 2012). Using *R*/*S* analysis, persistence in air pollutant concentrations is studied by Windsor and Toumi (2001) who used Hurst exponent to study the variations in hourly ozone and observed high persistence up to 400 days and Weng et al. (2008) who analyzed the ozone time series at two sites and observed the Hurst exponent of about 0.75 for the deseasonalized time series. Varotsos et al. (2005) observed persistent power–law correlations in deseasonalized ozone concentrations with lags of 1 week to 5 years. Lu and Wang (2006) studied evolving long-term trend in hourly ozone concentrations. The above studies with techniques used and outcomes are summarized in Table 1.

3. Description of long-memory in air pollutant concentrations

Long-memory property in air pollutant concentrations has been attributed to mechanisms such as self-organized criticality (Shi and Liu, 2009), nonlinear interactions, and aggregation or multiplication (Varotsos et al., 2005) and multiplicative cascade process (Anh et al., 2000; Lee, 2002; Lee et al., 2003; Lee et al., 2006). Sivakumar (2001) has explained the cascade process as eddies breaking up into smaller sub-eddies, each of which receives a part of the flux of its parent body. Multiplicative cascade process, which is the concept from turbulence theory, is closely related to multi-fractal process (Sivakumar, 2001; Lee, 2002). For rainfall data, multifractal characteristics have been explained as a large-scale flux successively broken into smaller and smaller cascades, each receiving an amount of the total flux specified by a multiplicative parameter (Olsson, 1996; Lee, 2002). For air pollutants emitted from a source, transportation and diffusion are considered major significant phenomena to state their presence in ambient air. Due to the stochastic behavior of air movement, air mass follows a random path or trajectory. Lee (2002) explained this phenomenon using the context of successive random dilution theory (Lee, 2002). The term self-organized criticality in systems indicates the presence of attractor which functions as a critical point to which the system organizes

Table 1
Studies carried out on long-memory of air pollutant concentration time series.

S No	Reference	Pollutant concentration	Duration (frequency)	Study area	Technique applied	Outcome
1	Windsor and Toumi (2001)	Ozone, PM10, PM2.5	1993–1999 (Hourly)	UK	Sigma-T, Hurst rescaled range and kurtosis	Persistence on time scales up to 416 days
2	Varotsos et al. (2005)	Ozone, NOx, PM	1987–2003 (Hourly)	Athens	DFA	Persistent power-law correlations in Ozone PM10 and NOx
3	Lee et al. (2006)	Ozone	1998 (Hourly)	Taipei, Taiwan	Box-Counting	Right-skewed frequency distribution, cyclic pattern, and long-term memory
4	Varotsos et al. (2006)	Aerosol Index	1979–2003 (Daily)	Global	DFA	Persistent long-range power-law correlations for time scales longer than about 4 days and shorter than about 2 years
5	Varotsos and Kirk-Davidoff (2006)	Global column ozone	1964–2004 (Daily)	Over the belt 25^0S–25^0N	DFA	Persistence at long time scales strongest in tropics, but weaker in mid-latitude
6	Lu and Wang (2006)	Ozone	1984–2002 (Hourly)	Central Hong-Kong	Fractal analysis	Strong self-similarity, ozone pollution has increasing trend
7	Shi et al. (2008)	SO_2, NO_2, PM10, air pollution indexes	July 2000 to July 2006 (Daily)	Shanghai	R/S, DFA, spectral analysis	Two different power laws in all; similar persistence corresponding to the annual cycle in short time scale. Different self-organized critical states in air pollutants
8	Shi and Liu (2009)	PM10, NO_2, SO_2	July 2000 to July 2006 (Daily)	Shanghai	Sand pile model	Air pollution—manifestation of self-organized criticality
9	Chelani (2009)	Ozone	2006 (Hourly)	Delhi, India	Hurst exponent (R/S analysis)	Persistence up to 5 days
10	Musa and Ibrahim (2012)	Ground ozone	1998–2006 (Daily)	Malaysia	Rescaled range and variance, dispersional, linear and bridge detrending	Long-memory in the ozone, persistence up to 150 days
11	Chelani (2012)	CO, NO_2 and O_3	2000–2009 (Daily)	Delhi, India	DFA	Persistence up to 1.5, 1, and 1.25 years, respectively, in CO, NO_2, and O_3
12	Chelani (2013a)	CO, NO_2, O_3	2000–2009 (Daily)	Delhi, India	DFA	Persistence in exceedance time series of only primary pollutants
13	Chelani (2013b)	PM2.5	2007–2009 (Daily)	Delhi, India	DFA	Strong persistence in original and exceeded PM2.5