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Effects of non-stationarity on the magnitude and sign scaling in the multi-scale vertical velocity increment

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HIGHLIGHTS

- No significant scaling range for original stationary records.
- Nonlinear correlation is obvious in increment records for both cases.
- Two scaling ranges in both magnitude and sign fluctuations exist with larger lag.

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ABSTRACT

We study the scaling properties of multi-scale increment series from the stationary and non-stationary vertical velocity records by the detrended fluctuation analysis (DFA) and series decomposition methods, and show the impact of non-stationarity on the magnitude and sign scaling properties. Firstly, we show it is difficult to define a significant scaling range for stationary records themselves. Secondly, for increment series with lag one, the nonlinear correlation found in magnitude fluctuation (i.e. volatility fluctuation) is obvious for both cases. And over the smaller scale range, the linear correlation found usually in the sign series is the same for both cases. However, over the larger scale range, the difference is sharp and marked nonlinear correlation is also incorporated for the non-stationary sign series. Thirdly, with the lags in increment increasing, there exist two scaling ranges in both the magnitude and sign fluctuations. The nonlinear correlation in the magnitude series over both small and large scale ranges decreases with the lags increasing. For the sign series, the linear correlation is dominant over both small and large scale ranges for stationary case; however, the nonlinear correlation can be found over the large scale ranges for non-stationary case and will decrease with lags increasing. The nonlinear correlation found in the sign series over large-scale range is resulted from the modulation of the large scale structures found in the non-stationary data, which will incorporate parts of the magnitude information into the sign series.

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1. Introduction

A broad class of physical and geophysical systems exhibits complex dynamics, which is associated with the presence of many components interacting over a wide range of time or space scales. These often-competing interactions may generate an output signal with fluctuations that appear "noisy" and "erratic" but reveal scale-invariant structure [1]. To address this problem, one of the most commonly used methods, detrended fluctuation analysis (DFA) was developed to accurately

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quantify long-range correlations embedded in time series through their scaling exponents [2,3]. Long-range correlations are usually characterized by scaling laws where the scaling exponents quantify the strength of these correlations [4]. It has been successfully applied to diverse fields such as DNA sequences [5], heart rate dynamics [6], neuron spiking [7], human gait [8], long-time weather records [9–11], geology [12], cloud structure [13], ethnology [14], economic time series [15], and solid state physics [16].

Some previous studies [17–19] have investigated the correlation of wind velocity records collected within the atmospheric boundary layer. Carefully inspecting the results given by these authors, it can be easily found that there is no dominant scaling range from the original wind velocity records [17,18], so the fitted exponents over an insignificant scaling range are with great uncertainty. Actually, we cannot find a significant scaling range for stationary vertical wind velocity records. The significant scaling range exists in DFA results of the volatility series (i.e. magnitude series of one step ahead velocity increment) of wind velocity series collected in the atmospheric boundary layer [19]. Govindan and Kantz reported the volatility scaling results from volatility series and found that nonlinear correlation does not necessarily imply multi-fractality. However, there still exist two problems unresolved. The first one is how much the results will be changed when lags in the velocity increment increase, since the multi-scale lags have been often used in the structure function analysis of turbulent wind velocity. The second one is how to quantify the effect resulted from the non-stationarity found in the wind velocity series collected in the atmospheric boundary layer, especially its impact on the nonlinear correlation.

The motions within the atmospheric boundary layer are inherently non-stationary. Non-stationarity usually means the average, standard deviation, and higher moments or the correlation functions are not invariant under time translation [20]. As an important aspect of complex variability, it can often be associated with different trends in the record or heterogeneous segments (patches) with different local statistical properties [20]. Turbulence series collected in the atmospheric surface layer over land may often be non-stationary. It has been found that a stationarity test shows that about 40% of the turbulent heat fluxes at Summit, Greenland are classified as non-stationary [21]. Mahrt and Thomas examined the relationship of turbulence to the non-stationary wind and stratification, and found that the turbulence is simultaneously generated by different non-stationary mechanisms [22]. Using telegraph approximation [23,24]), we have found that non-stationary records possess different cluster and intermittency properties from those of its stationary counterparts [25]. Other techniques for detection of correlations like the autocorrelation function and the power spectrum are not suited for non-stationary time series. The effects of non-stationarity cannot be quantified by the probability density function (PDF) and the spectral analysis of the original series [25]. However, the PDF of the multi-scale wind velocity increments shows different features for stationary and non-stationary series and the differences can be quantified by multi-scale entropy analysis [26]. Since one advantage of the DFA method is to avoid spurious detection of correlations caused by the non-stationarity in the series, how to use DFA to quantify the effect that resulted from the non-stationarity found in the wind velocity series collected in the atmospheric boundary layer, especially its impact on the nonlinear correlation, deserves further studies.

Firstly, we use the space time-index method (STI) to classify different vertical velocity records as two kinds, stationary or non-stationary. The STI is a graphical method, and can be effectively used to detect dynamical non-stationarity in time series [27]. Detailed descriptions of the STI method can be found in Refs. [28,29] and are not repeated here. Secondly, since the observable variables in the output of natural systems at each moment are the product of its magnitude and sign [30,1,6,31–36], we focus on the sign and magnitude series of the velocity increment with lag one and obtain the correlations within significant scaling range for both stationary and non-stationary series. Thirdly, we confirm that different nonlinearity correlations exist in stationary and non-stationary series using the phase randomized surrogate method (PRS, [37]). Lastly, the magnitude and sign fluctuations of multi-scale increment from vertical velocity records are investigated to quantify the correlation variation with lags increasing.

The rest of the paper is organized as follows. In Section 2, we will make a short introduction of the analysis methods and the data sets used in this paper. Results for the magnitude and sign scaling from multi-scaled increment of stationary and non-stationary turbulent velocity series are provided in Section 3. In Section 4, we make a brief discussion and some conclusions are summarized.

2. Data and methodology

2.1. Data

In this paper, atmospheric boundary-layer turbulence records collected during the experiment in Huaihe River Basin (HUBEX) between June 5 and June 22 in 1998 are used in the analysis. Huaihe River basin is situated between Yangtze River and Yellow River with a total area of 270,000 km^2. It represents the typical climate condition in the East Asia monsoon region, and effects of human activity are relatively slight. The observation site was in the yard of the Shouxian Meteorological Observatory in Anhui province, People's Republic of China and is located on the western edge of a large rice field. The yard was about 200 m long in the north–south direction. The measurement height was set as 4 m above ground, a three-dimensional sonic anemometer (SAT-211/3 K, sample rate 20 Hz, sound path 0.15 m) was used to measure wind velocity components and temperature, and each hour sampling will be taken as one record (detailed information can be found in the Refs. [38,39]). And this data set has been applied to analyze the characteristics of turbulence in the atmospheric boundary-layer, and nonlinear features have been derived [40,38,39,41]. Typical parts of records can be found in Fig. 1,

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