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Power spectrum and multifractal detrended fluctuation analysis of high-frequency wind measurements in mountainous regions

Luciano Telesca [a,*], Michele Lovallo [b], Mikhail Kanevski [c]

[a] Consiglio Nazionale delle Ricerche, Istituto di Metodologie per l'Analisi Ambientale, C.da S.Loja, 85050 Tito, PZ, Italy
[b] ARPAB, 85100 Potenza, Italy
[c] IDYST, University of Lausanne, Switzerland

HIGHLIGHTS

- High-frequency records of wind speed measured in Switzerland are investigated.
- Daily and half-daily periods are linked with temperature and pressure variation.
- Higher harmonics of 8 h and 6 h are not negligible.
- Two timescale ranges, with crossover at about 7 days characterize all the series.
- Persistence and multifractality feature the wind speed at large timescales.

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ABSTRACT

The main objective of the study was to investigate the temporal features of the wind speed in complex mountainous terrains that are important for the assessment and development of wind energy. Six high-frequency records of 10-min averages of wind speed measured in Switzerland are investigated in order to better characterize their inner time dynamics. All the wind speed time series are modulated by components periods of 1 day and 12 h, linked with the temperature and pressure daily variation due to the sunset and sunrise. Furthermore the time dynamics of the wind speed is characterized by the presence of two different timescale ranges, separated by a crossover at about 7 days: persistent and multifractal at larger timescales and antipersistent and monofractal (or weakly multifractal) at smaller ones. The found features do not seem to depend on the altitude, because all the wind speed series share the same dynamical characteristics. The results of this comprehensive study can be utilized to better understand the mechanisms governing the time dynamics of wind speed and to perform a better wind energy assessment and management.

1. Introduction

Demand of clean and sustainable energy is continuously growing, stimulating research studies for developing clean energy technologies [1], and more and more innovating sustainable future energy systems [2]. Among renewable energy sources, wind energy has been becoming the most promising energy source for its very competitive cost of production, and, more importantly, for its capability to overcome efficiently the well-know environmental problems linked with the use of more traditional energy sources [3]. Wind speed strongly influences wind energy; in fact, wind power is a function of the cube of wind speed. Thus, investigating the time structure of wind speed time series is important not only to design more properly and efficiently wind power plants, but also to better understand the dynamical mechanisms governing its variability. For instance, it should be noted that wind speed studies besides their importance to the renewable energy topics have a fundamental relationships to the study of the boundary layer, especially to the understanding of atmospheric turbulence [4].

A deep statistical analysis of wind speed in terms of averages and distributions would be generally required to evaluate wind power potential [5], but its intermittent nature in a wide range of time and space scales represents the most crucial issue to address in order to reduce as much as possible the effects of wind variability on power systems. This implies that the analysis of the inner structure of wind speed time series could furnish information about the underlying dynamical mechanisms governing the

* Corresponding author.
E-mail address: luciano.telesca@imaa.cnr.it (L. Telesca).

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variability of wind speed, and, thus, contribute to a better designing of wind power plant by means of assessment of more reliable predictive models [6].

The time series of wind speed has been generally investigated in terms of estimation of parameters of a Weibull distribution function that is commonly used in wind energy applications. However, Chang [7] showed that wind data actually observed do not necessarily follow a Weibull distribution, and suggested several methods to evaluate Weibull parameters, concluding that the maximum likelihood method provides more accurate estimation in case wind speed does not fit well a Weibull distribution. On the other side, the veracity of the Weibull distribution model to describe offshore wind data measured by three meteorological stations located in Hong Kong was investigated by Shu et al. [8], who concluded that the Weibull model furnishes an adequate representation of the frequencies of actual wind speed. Astolfi et al. [9] analyzed wind speed series by proposing data mining models to evaluate the performance of onshore wind farms and using indexes that capture and describe mainly the mechanical characteristics of wind speed. In the context of forecasting methods, recently a great attention was paid to the application to wind speed series of nonlinear data driven models based on machine learning algorithms [10–12].

A different approach to investigate time series of wind speed at several spatial and temporal scales is based on the concept of fractal. The fractal dimension has been recently proposed to investigate the inner time structure of wind speed. Chang et al. [13] analyzed the wind speed time series observed at three wind farms in Taiwan with different climatic conditions by means of the fractal dimension D calculated by using the box-counting method. Their findings were the existence of an inverse correlation between the mean wind speed and the fractal dimension. The box-counting method, however, describes the fractal properties of a time series in a geometrical sense. To quantify, instead, the long-term correlation properties of wind speed records, de Oliveira Santos et al. [14] applied the detrended fluctuation analysis (DFA) to average and maximum hourly wind speed time series measured at four weather stations in Brazil, and found that both these two observables are characterized by almost identical power-law behavior, with two different scaling regimes and two different DFA scaling exponents. From the value of the fractal dimension D, Fortuna et al. [15] derived the value of the Hurst exponent H ($D = 2 - H$). H is used to quantify the long memory in a time series; in particular, if H varies between 0 and 0.5, the time series is antipersistent (an increase/decrease of the series in one period is likely followed by a decrease/increase in the next period); if it varies between 0.5 and 1, the time series is persistent (an increase/decrease of the series in one period is likely followed by a increase/decrease in the next period); if $H = 0.5$, the time series is uncorrelated and no dependence can be found among its values. Fortuna et al. [15] found that the wind speed time series recorded in several weather stations in Italy and USA share the feature of persistence. They, furthermore, found that the daily and hourly wind speed time series are characterized by different shape of the power spectrum that, even if in both cases is a power-law, is featured by different spectral exponent, being 0.46 for the daily series and 1.37 for hourly series.

In all the cases mentioned above, the wind speed time series are modeled as mono-fractal series, thus indicating that only one scaling exponent (the fractal dimension D, the Hurst exponent, the spectral exponent, the DFA scaling exponent, or any other quantity that could be defined to describe the scaling characteristics of the series) is enough to get all the information concerning the dynamics of fluctuations of wind speed.

Monofractals are suited to model homogeneous series, meaning that the scaling properties do not change within the series and are characterized by a single singularity exponent [16]. More scaling exponents are, instead, necessary to describe the dynamics of series that are more complex and more heterogeneous than monofractals; and this happens when different scaling exponents have to be calculated for many interwoven fractal subsets into which the original series can be decomposed [17]. These time series are called multifractal, and are generally characterized by a spiky dynamics, with sudden and intense bursts of high frequency fluctuations [18].

Multifractality in wind speed has been becoming an important topic only recently; and, thus, not many studies have been performed so far. Up to our knowledge the first study that showed the presence of multifractal dynamics in wind speed was performed by Kavasseri and Nagarajan [19]; they investigated four time series of hourly means of wind speed in USA, finding that the binomial cascade multiplicative model could represent a close fit to the data. Telesca and Lovallo [20] analyzed the hourly wind speed time series at several heights from the ground, in the range between 50 m and 213 m, and in all the examined cases they found that the most of multifractality of the wind speed series is due to the different long-range correlations for small and large speed fluctuations. Fortuna et al. [15] applied the multifractal detrended fluctuation analysis (MFDFA) to several hourly wind speed series in Italy and USA and all of them were characterized by similar values of the multifractal width (width of the multifractal spectrum, measuring the degree of the multifractality) ranging between 0.39 and 0.59. de Figueirêdo et al. [6] applied the MFDFA to the mean and the maximum of four wind speed time series in Brazil and found that both the types of series are persistently correlated with a larger multifractality for the maximum than for the mean. Meteorological interpretation of the annual variation of some key multifractal parameters of wind speed was furnished by Piacquadio and de la Barra [21] suggesting their use as local indicator of climate change.

The most of the analyses that have been carried out on the wind speed series (especially those concerning the investigation of spectral and multifractal properties) were focused on, at most, hourly averages of wind speed, with obvious limitations in the range of investigated temporal scales. Using higher frequency sampled data would allow to explore the time dynamics of wind speed at timescales lower than those that have been generally investigated so far.

In the present study, in fact, we intend to analyze the spectral and multifractal fluctuations of 10-min averages of six wind speed time series recorded during 2013 in Switzerland by weather stations located in sites with different altitudes and geomorphologic conditions. The high-frequency sampling of the wind data and the different site locations of the wind sensors would enable to get a more complete picture of the complex time dynamics of wind speed in different ranges of timescales down to very small ones, at which the mechanisms governing its variability might be different from those at large timescales. In particular, the power spectrum and the multifractal analysis will be jointly used to study the temporal fluctuations of wind speed, pointing out its persistence properties the first, and its heterogeneity features the second. These properties, which were not deeply analyzed for high frequency wind speed time series so far, are of crucial importance because they are typical of atmospheric turbulence that has important impact on wind power generation performance, turbine loads, fatigue and wake effects [22].

Therefore, the study presented in this paper would contribute to enrich the background for a better understanding of atmospheric processes in a complex mountainous regions and for renewable energy assessments.

2. Preliminary data analysis

We analyzed the time series of 10 min averages of wind speed measured during 2013 at six stations in Switzerland