Intermittence and Scale Separation above the North Sea

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Abstract

A general better understanding of wind turbulences is of great interest for wind energy applications for both predictions of mechanical loads and power output. Many meteorological simulations, which are used as input for these predictions rely on the assumption that there is a so-called spectral gap, i.e. a separation of wind properties on large scales and small scales and that all the extreme fluctuations occur on time scales smaller 10 minutes. Using 10 minutes averages like in the the IEC standard 61400-12-1 for estimating power curves of wind turbines one tries to eliminate these extreme fluctuations, which enables for using faster and simpler models for flow properties on larger scales. While the 10 minutes have widely been used as a separation (averaging) scale there has been little support for this somehow arbitrary chosen scale in standard analysis, e.g. power spectra. In this paper we show an analysis that gives a good reason to select 10 minutes as separation scale allowing for simpler models on larger scales and more sophisticated models on smaller scales.

The statistics of wind speeds measured at several heights up to 100m above the North Sea have been analyzed by means of velocity increments (velocity changes within a certain amount of time). The continuous measurement for a period of 6 months with 0.85Hz allows for considering scales ranging from 1.18s to several days on a solid statistical basis. While the probability density functions (PDFs) of velocity increments on small scales are very intermittent, i.e. they are non-Gaussian and heavy-tailed corresponding to high risks for large gusts, they become only Gaussian on scales in the order of days. This scale dependence of the PDFs is known from isotropic, homogenous turbulence as realized in laboratory experiments, e.g. free-jets or wake flows and can be quantified by an easy to calculate shape parameter using superstatistics. However, while the shape parameter for laboratory flows is a monotonic decaying function of the scale the atmospheric data considered here show a local maximum in the shape parameter at a time scale of 600s, which corresponds to the length scale of the controversial discussed spectral gap. This special behavior is not apparent in the data's spectra. Thus this increment analysis can be used for a more detailed investigation of scale separation to distinguish between small scale turbulence and larger structures within atmospheric winds.

Intermittence

In many complex systems the statistics of some internal properties have found to deviate a lot from normal Gaussian behavior. The deviation is in that way, that extreme events occur much more often than they would do for a Gaussian process. Two famous examples for this so called intermittence are financial data, e.g. stock values or exchange rates [1] and turbulence [2]. In stationary, isotropic and homogenous turbulence as realized in laboratory flows like free-jets and wake flows, the intermittent behavior can be found especially on small scales, while the statistics on larger scales are close to pure Gaussian behavior. This can be seen by looking at probability density functions (PDFs) of increments

$$p(\delta_\tau),\ \ \delta_\tau = v(t+\tau) - v(t). \tag{1}$$

Here $v(t)$ denotes the time series of a stochastic process, e.g. the horizontal velocity, and τ a certain lag of time. For the above mentioned laboratory turbulent flows a continuous transition of the shape of the PDFs $p(\delta_\tau)$ from normal to intermittent behavior goes along with a decreasing time lag τ, see Fig. 1. To characterize the shape of the PDFs Castaing introduced a method to fit the PDFs with an equation that has only one parameter as function of the scale τ

$$\begin{aligned} p(\delta_\tau) &= \frac{1}{2\pi\lambda} \int \exp\left(\frac{-\ln^2(\sigma/\sigma_0)}{2\lambda^2} \right) \\ &\quad \times \exp\left(\frac{-\delta_\tau^2}{2\sigma^2}(1+\gamma) \right) \frac{d\ln\sigma}{\sigma}, \\ \gamma &= a_s \frac{\delta_\tau/\sigma}{\sqrt{1-(\delta_\tau/\sigma)^2}}. \end{aligned} \tag{2}$$

For the derivation of this equation we refer to [3]. Here γ represents the possible asymmetry of the PDFs with an empirically found skewness parameter a_s. The distributions of the different increments can therefore be seen as an superposition of Gaussian distributions with log-normal distributed variances.

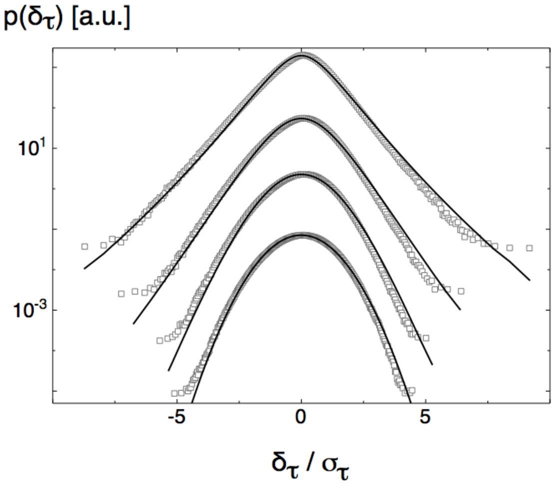

Figure 1: Symbols represent PDFs normalized by their scale dependent standard deviation from a laboratory free jet experiment. From top to bottom τ takes the values 0.01, 0.05, 0.2 and 1.0 T, where T denotes the integral time. Lines correspond to fits by Eq. (2). All graphs are shifted against each other in vertical direction for clarity of presentation.

Because one gets a parameter λ for each separation τ, $\lambda^2(\tau)$ can be used to describe the shape of the PDFs. For laboratory turbulent flows $\lambda^2(\tau)$ is a monotonic decaying function.
Another way to calculate the shape parameter $\lambda^2(\tau)$ is by using super statistics by Beck [4]

$$\lambda^2(\tau) = 0.25 \cdot \log\left(\frac{\langle \delta_\tau^4 \rangle}{3\langle \delta_\tau^2 \rangle^2}\right), \qquad (3)$$

where $\langle \; \rangle$ denotes ensemble averaging.

Analysis of Offshore Data

The analysis here is based on horizontal velocities measured on the FINO platform in the North Sea [5]. The velocities were measured with a cup anemometer at a height of 100m. The data were acquired from Jan 1st – Jun 30th 2006. Some basic properties of the data set are given in the table below.

mean velocity	9.65 m/s
standard deviation	4.40 m/s
min. velocity	0.22 m/s
max. velocity	30.18 m/s

In Fig. 2 the power spectrum of the data set is shown. No significant gap due to scale separation can be found.

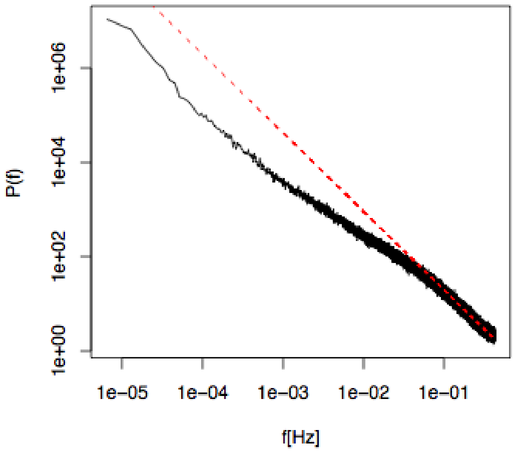

Figure 2: Power spectrum of the horizontal wind speed measured 100m above sea level at FINO.

As published in [6] the statistics of atmospheric turbulence and of isotropic homogenous and stationary turbulence deviate from each other. Here the PDFs show a strong intermittent behavior for a very large range of scales. As can be seen in Fig. 3 the PDFs of the FINO offshore data also show the intermittent non-Gaussian behavior for a broad range of scales.

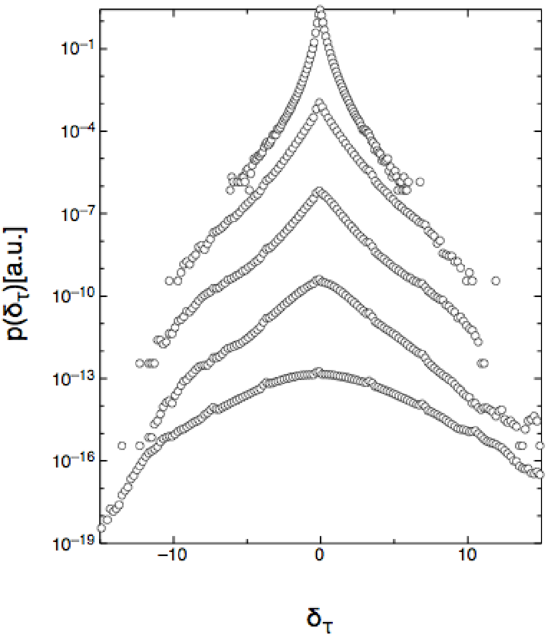

Figure 3: PDFs of horizontal velocity increments obtained from the FINO data. Time lags are from top to bottom τ = 1,18s, 1min, 10min, 1h, 6h. All graphs are shifted against each other in vertical direction for clarity of presentation.

To quantify the intermittence for the different time scales we calculated the shape parameter according to Eq. (3), see Fig. 4.

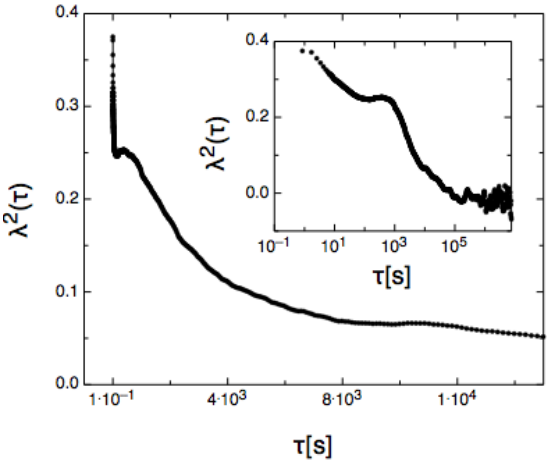

Figure 4: Shape parameter $\lambda(\tau)$ for horizontal velocities measured 100m above sea level. The inset shows $\lambda^2(\tau)$ in an log-lin plot.

Contrary to the $\lambda^2(\tau)$ for isotropic, steady and homogenous turbulent flows in laboratories the shape parameter for the offshore data is not a monotonic decaying function but has a local maximum at 600s. This local maximum can be interpreted as a separation between small scale turbulence and turbulence on larger scales. A characteristic that can be found in other heights above sea level measured at the FINO platform as well.

Because events in the tails of the PDFs correspond to very large increases or drops in velocity they can be directly connected to gusts, the knowledge of which is very important for wind energy applications but is not yet taken into account in the design process of wind turbines. Up to now commonly used numeric wind field generators have no intermittence included. The statistical information of the increments corresponds to the generalized higher order two-point correlations, this means that these correlations are not included correctly in actual wind field tools. Note, the power spectrum corresponds to the standard two-point correlation $\langle v(t+\tau)v(t)\rangle$, which corresponds to variance of the PDFs $p(\delta_\tau)$. This variance does not grasp the non-Gaussian shape of the PDFs! In Order to tackle this lack of correctness new methods have to be used to include these extreme statistics in future wind field generators, e.g. [7].

For offshore applications the here shown separation of scales has to be considered in addition.

Summary

It has been shown that a separation of scales can be found in atmospheric turbulence above the North Sea. This separation takes place for time scales of approximately 10 minutes giving support to the common procedure of using 10 minutes averaging in order to neglect small-scale turbulence. However, since the fluctuations on smaller time scales are responsible for extreme loads on wind turbines the here shown intermittent behavior should seriously be considered to be included in numeric wind field generators.

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