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Publication date:
2016

Document Version
Peer reviewed version

The model chain and the full scale spectrum of the boundary layer wind

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INTRODUCTION

In the European Union project: "The New European Wind Atlas [1, 2]" *the model chain* is a central research area. In a recent study [3] we looked into the resolution issue of linking the mesoscale models with the turbulence models by performing spectral analysis on extensive mean meteorological data and high frequency sonic anemometer data from the 100m meteorological mast at Danish test station Høvsøre. Datasets from the offshore wind farm Horns Rev were also analyzed. The conclusions from the analysis are given below. In the present study we complement and extend the analysis using a new dataset from the test station Østerild.

APPROACH

Some more or less unresolved questions remain from the Høvsøre and Horns Rev analysis and we are therefore analyzing an exceptional dataset measured at a 245 meter high mast at the Danish National Test Centre for Large Wind Turbines "Østerild". The dataset consist of one year (February 2015 to February 2016) of sonic anemometer wind measurements at 20 Hz obtained at 5 heights: 7 m, 37 m, 103 m, 175 m and 241 m. Included in the dataset are also measurements from traditional cup anemometers and wind vanes. The dataset allows us to investigate one of the most crucial issues in the concept of the model chain namely that of linking the two-dimensional mesoscale flow models to the three-dimensional microscale turbulence models.

THEORY AND ANALYSIS

A first result of the analysis is shown on the two figures depicting the spectra of the horizontal wind speed from 10 Hz to 10^{-7} Hz (period of one year) at the 5 measuring heights. The frequency range of most interest for the linking issue is centered on periods between 10 minutes to one hour. This is the range where the discussion on the "spectral gap" has been going on since the 1950ties (especially credited to Van der Hoven [5]). The gap discussion has been hampered by the lack of appropriate data and it has been necessary to patch different measured series together which basically conflicts with the underlying assumptions of spectral analysis such as ergodicity and stationarity. The range has also been named "the terra incognita" [6] explaining that in this range both mesoscale models and microscale models such as LES models have severe problems. For the mesoscale part, because of the requirement for high resolution, a very small grid length in the numerical scheme conflicts with the possible subgrid parameterization of the turbulence. For the high frequency part, the problems of the microscale models, such as LES models, are that in order to cover the full range of the turbulence down to the gap-frequencies, the size of the area necessary to model renders it apparently computational impossible. The current analysis is a follow-up of the recent analysis made by the authors on similar data from Høvsøre and Horns Rev [3]. In this study we attempted to answer or shed light on some of the outstanding model chain questions:

- Is there a gap between microscale and mesoscale, centered on 1 hr^{-1}?
- How do microscale and mesoscale motions interact? Can these motions be considered correlated, uncorrelated, or just weakly correlated?
- In the mesoscale range, how do the spectra vary with height, how do the spectra and cross-spectra of the three wind components (the longitudinal, the transverse and the vertical) vary with height and stability?

The conclusions of the study [3] were:

- The spectral gap in the horizontal wind component power spectrum exists and can be modeled. The linear composite of the wind variations from the mesoscale and microscale give the observed power spectrum in the gap range. This suggests that the turbulence from the two frequency regions is weakly correlated.

- Depending on the relative contribution to the variation from the microscale and mesoscale, the gap may be visible or invisible. The depth of the gap decreases with height, in general. The disappearance of the gap could also be caused by structured features such as “Open Cells”, which can contribute significant fluctuations in this frequency range. The spectral structure around the gap could be used for defining “natural” time windows for turbulence characteristics.

- For spatial scales larger than the gap, in the range from about 10^{-5} Hz to about 10^{-3} Hz, the turbulence is two-dimensional. The power spectra S(f) of the wind speed and its two components u and v increase with decreasing frequency, following a −5/3 dependence on frequency on a log–log scale. In this scale range, S(f) increases upward from the ground and levels off at a height ≈50m at the Høvsøre site, but <15m at the Horns Rev site. Our study indicated that, on average, it is possible to describe the boundary-layer turbulence as being limited by a f^{+1} behavior at low frequency, and being statistically stationary and ergodic, at least within the surface layer. Above this layer the assumption is more uncertain, and depends on how one understands and models the “invisible gap”. However, also in surface-layer situations, stationarity cannot always be assumed, as is well-known.

- Winds in the mesoscale frequency range seem more spatially coherent than winds in the 3D turbulence range.

CONCLUSION

The current study from the Østerild mast will further add to our knowledge on the variation with height of the mesoscale and turbulence flows as we extend the analysis from 100 m to 241 m. Of a special interest is the variation with height of the spectral gap, the turbulence quantities and the daily variation of the horizontal wind speed. The Østerild study also complements the Horns Rev (off-shore) and the Høvsøre (coastal) study in the sense that Østerild shows clearly land based properties, such as a non-disappearing diurnal peak in the spectra for all the heights as depicted by the figures. Further we are replacing the Kaimal formulation of the turbulence spectrum with a climatological high-frequency spectrum based on a longitudinal velocity wave-number spectrum [4] and the Weibull description of the mean wind speed.

LEARNING OBJECTIVES

The analysis of long-term mean wind and turbulence data from the 7 to 241m at the Østerild Test Station in Denmark, will further improve our understanding of the full-scale boundary-layer wind spectrum in mid-latitudes. The findings will provide guidelines for numerical modelling, turbulence analysis and wind engineering applications.

The establishment of the mesoscale spectrum will make it possible for us to demonstrate the gap even more quantitatively than in our first study [3]. It will also been useful for validating mesoscale modelling [7]. It can further be applied for extreme wind estimation by introducing expected wind variability to the modelled time series that suffers from numerical smoothing effects [8]. This application so far is limited to the mesoscale. The description of the spectrum covering the mesoscale, the gap region and the microscale, as shown herein, provides a possibility for extending such an application for extreme winds to higher frequencies. Wyngaard [6] argues that neither the ensemble mean models nor large-eddy simulation is appropriate in reproducing the significant fluxes and energy transfer in the so-called Terra Incognita between the inertial subrange and the mesoscale range. The results from our study illustrating spectral aspects of Wyngaard's Terra Incognita might possibly guide modelers in a productive direction.

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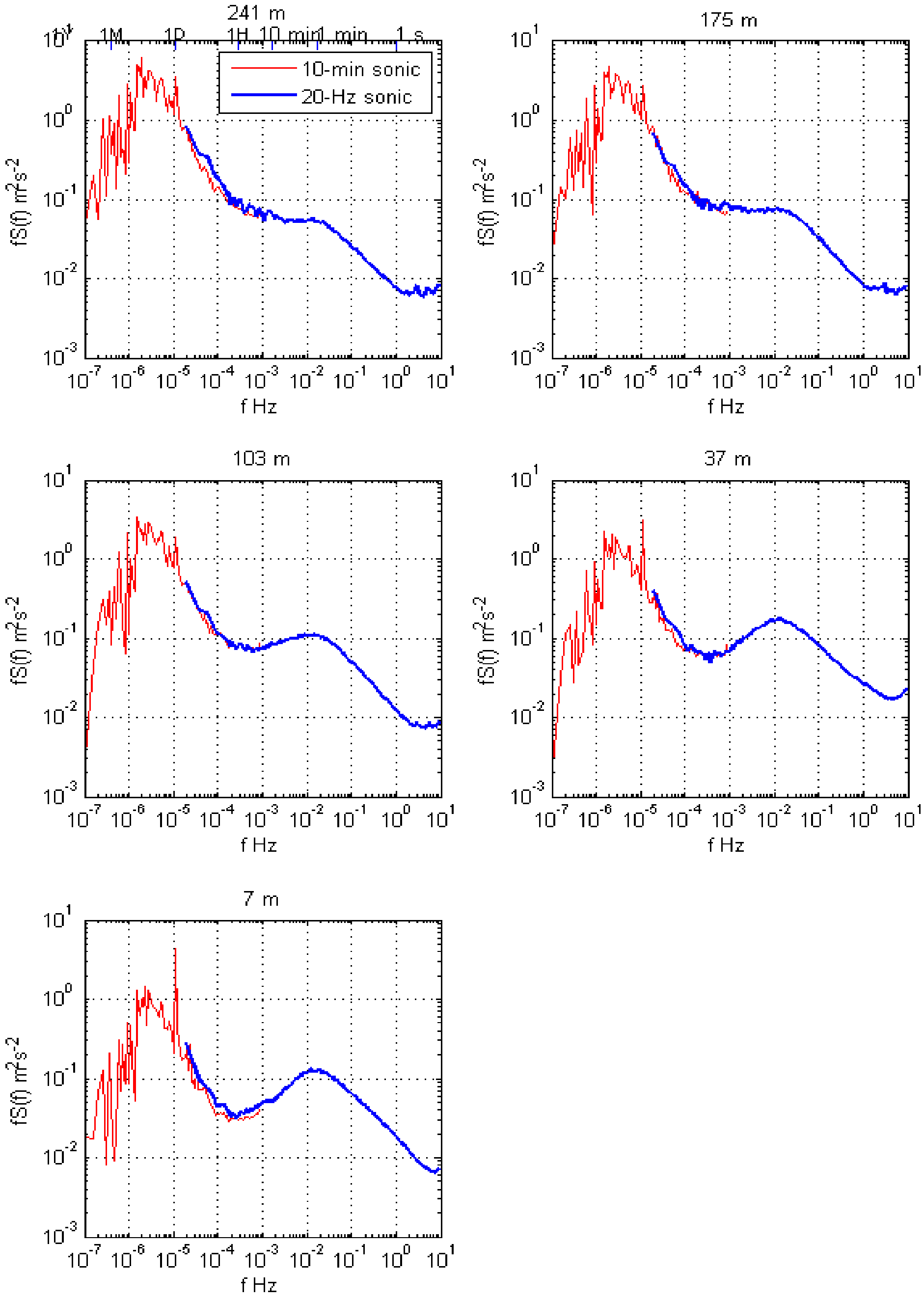

Figure 1. Spectra of wind speed at 5 heights at Østerild, from 1 year 10-min mean value time series and from day-long 20 Hz time series.

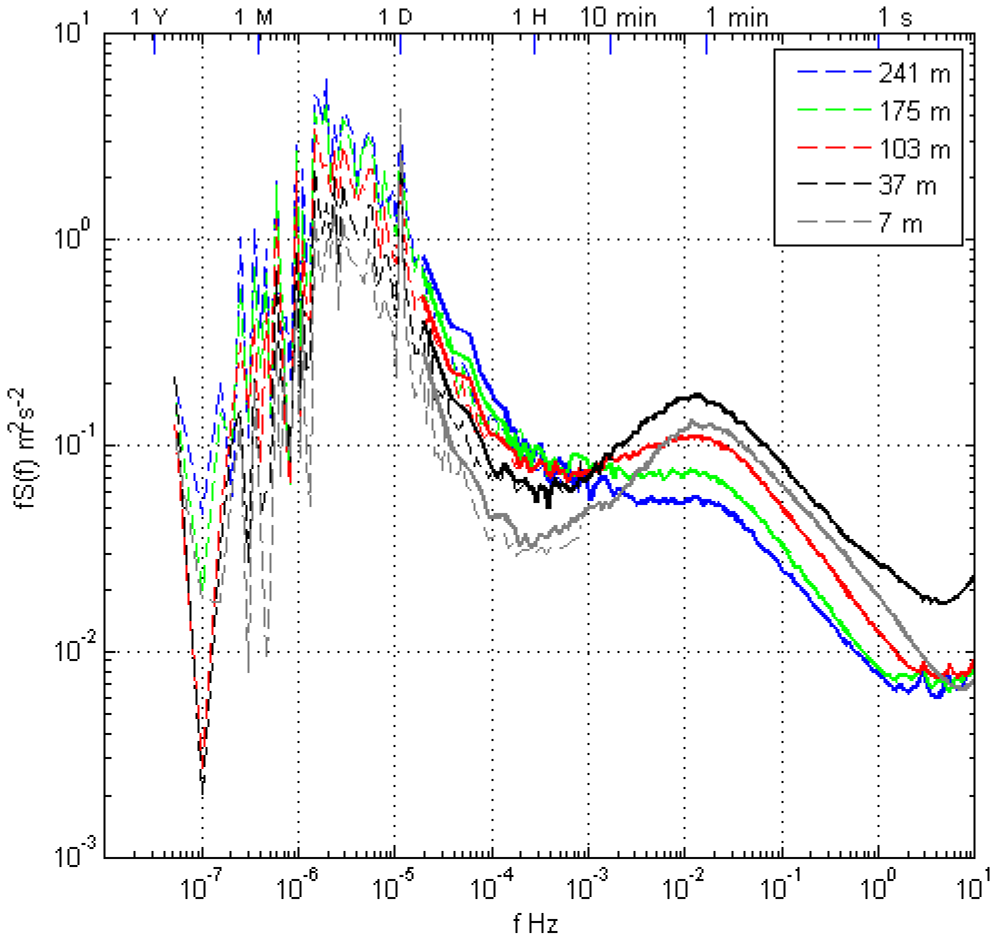

Figure 2. Spectra of wind speed at 5 heights at Østerild, from 1 year 10-min sonic data time series (dashed curves) and from day-long 20 Hz sonic time series (solid curves). Note 7 m is most likely sheltered by a surrounding forest.