Predicting Wind Fluctuations at Horns Rev

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DTU Risø DTU
National Laboratory for Sustainable Energy

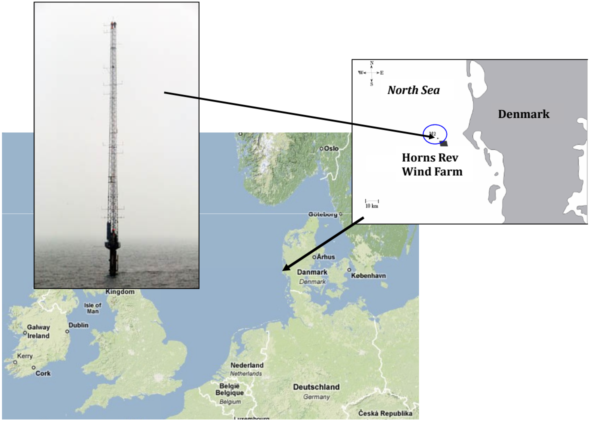
Overview

Introduction

- This work has been done at the Risø-DTU National Laboratory for Sustainable Energy, as part of my PhD
- My background:
- Mech. Engineering and Applied Mathematics (The University of Melbourne)
- Meteorologist at the Australian Bureau of Meteorology - operations and research assistant
- PhD student at Risø-DTU since January 2008

Background and Motivation

The Horns Rev offshore wind farm, with capacity 160 MW, is situated in the Danish North Sea



Background and Motivation

- Large fluctuations in wind speed on time scales of minutes to hours are experienced at Horns Rev
- Large wind fluctuations result in large power fluctuations
- The fluctuations can cause problems for:
  - Transmission system operators, who need to manage the electricity in the grid
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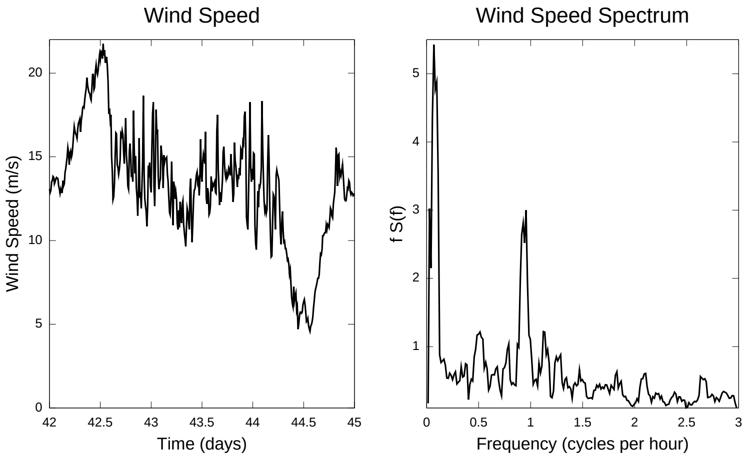
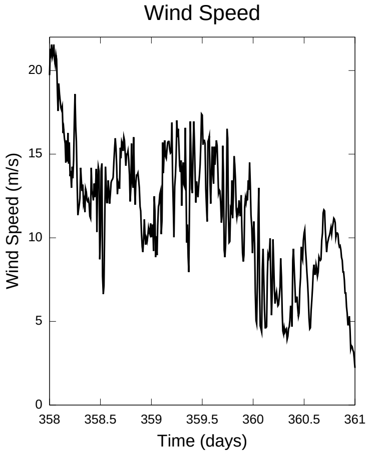
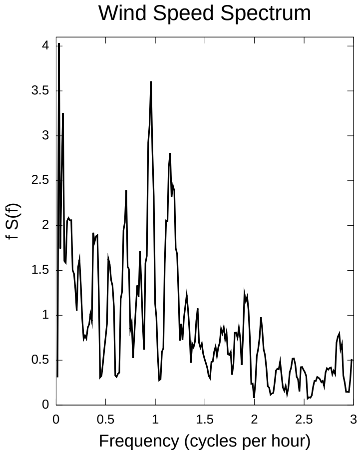
  - Wind farm operators, who need to maximize the economic value of their produced wind power
- Deficit in predicted power needs to be filled with expensive reserve power

The spectrum of fluctuations: 2000021200 to 2000021500

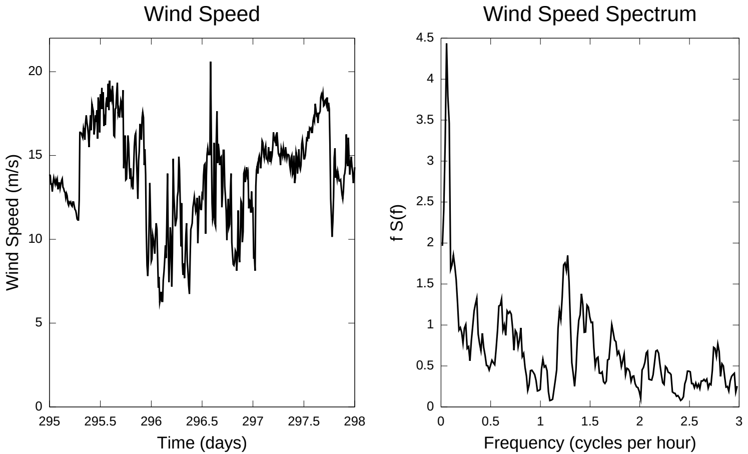


The spectrum of fluctuations: 2001122500 to 2001122800

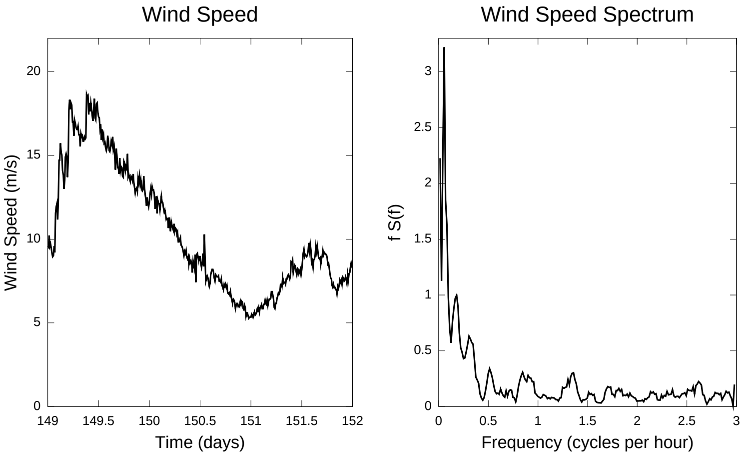




The spectrum of fluctuations: 2002102300 to 2002102600



A calm example: 2000052900 to 2000060100



Spectral Analysis of Wind Fluctuations

- The Fourier spectrum of wind speed time series shows very different characteristics at different times
- There often seems to be a peak close to 1 hour during episodes of severe wind fluctuations
- At other times, there is very little variance on time scales of minutes to hours

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- The Fourier spectrum of wind speed time series shows very different characteristics at different times
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- At other times, there is very little variance on time scales of minutes to hours
- To properly characterize wind fluctuations, we should find an adaptive spectral method, which can describe the time evolving fluctuations
- We have used the 'Hilbert-Huang Transform' [2, 1]

Brief introduction to the Hilbert-Huang Transform (HHT)

The HHT consists of:

- An ‘Empirical Mode Decomposition’ (EMD) of the time series in to ‘Intrinsic Mode Functions’ (IMFs)
- Normalization of components
- Hilbert transformation of the components and calculation of instantaneous frequency

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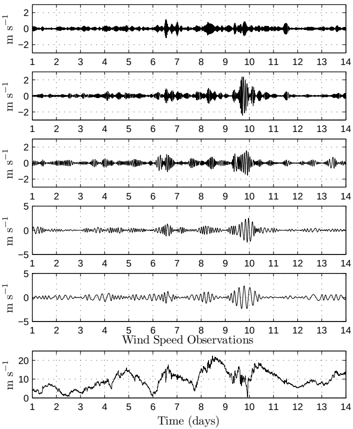
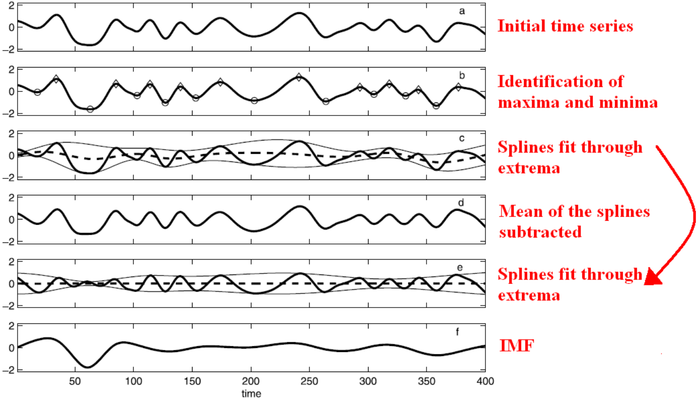
The empirical decomposition



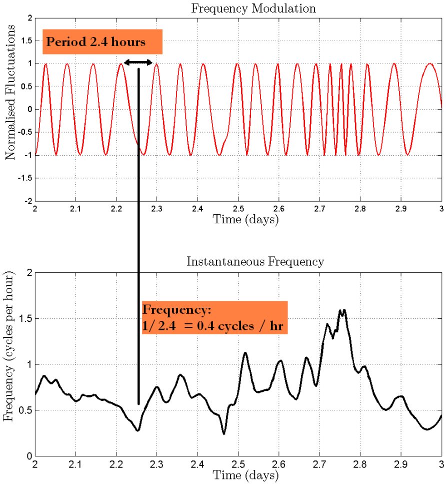
Empirical Mode Decomposition

The time series is 'sifted' by fitting cubic splines through the extrema:

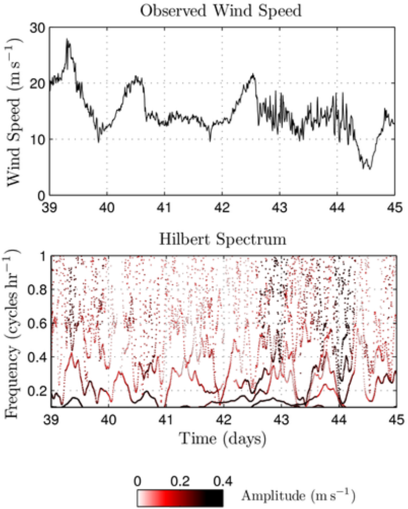


(graphic from Huang and Wu (2008))

Instantaneous Frequency



The Hilbert spectrum



Benefits and Draw-backs of the method

- ✗ Empirical decomposition: Lack of mathematical formulation
- ✗ Orthogonality and uniqueness of decomposition
- ✗ Mode mixing: Different frequencies in the same IMF
- ✗ Need $4\Delta t$ to resolve variance (compare with $2\Delta t$ for Fourier transform)

- ✔ Local, non-parametric decomposition with no *a priori* decision about shape of basis functions
- ✔ Time evolving spectrum which responds quickly to non-stationarity
- ✔ Can create conditional spectra from non-consecutive parts of the time series

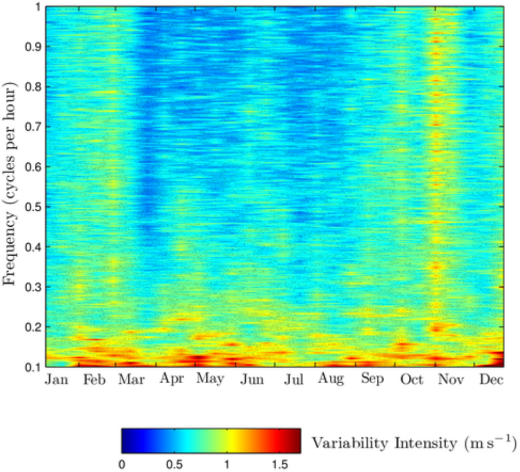
How have we used the HHT?

- To build up a climatology of wind fluctuations [6, 5]
- For forecast verification: Scale separation, verification of particular scales in the model [4]

Building a climatology of wind fluctuations: Methodology

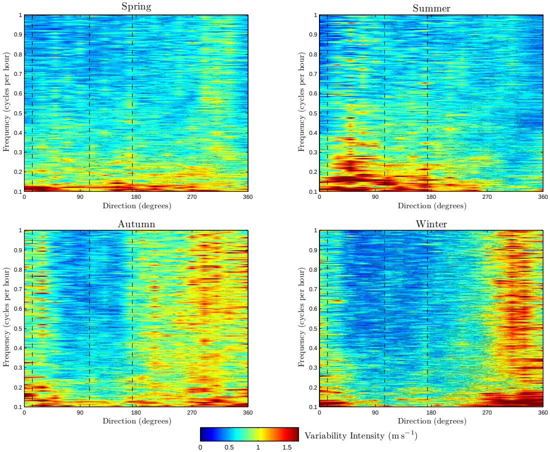
- The Hilbert-Huang transform was applied to 4 years of wind speed measurements, from a cup anemometer mounted at 62 m in the North Sea.
- Time-averaged spectra were calculated *conditional* on observed atmospheric conditions including time of year, wind direction and rain rate.
- Conditional spectra were combined to show patterns in the occurrence of wind fluctuations.
- Wind fluctuations on time scales of 1 to 10 hours are considered

Result 1: Wind fluctuations as a function of time of year



Result 2: Wind fluctuations as a function of wind direction

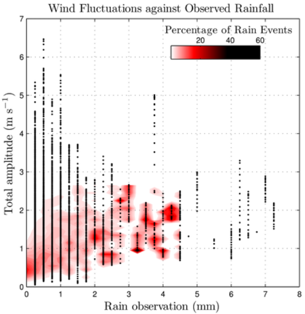
Westerly sector: flow from the sea. Easterly sector: flow from the land



Result 3: Wind fluctuations as a function of rain rate

'Rain observation' is maximum 10 min rainfall amount within 180 minute time window

'Total amplitude' is the sum of amplitudes for frequencies between 1 and 3 hours



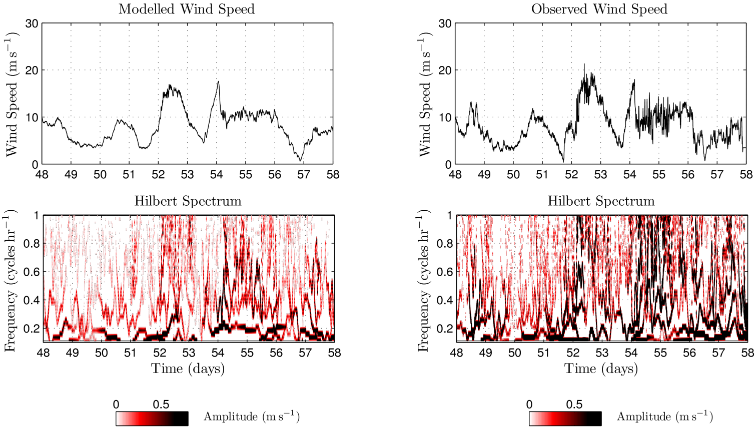
Summary

These results (and others not shown here) suggest that:

- intense episodes of wind fluctuations usually occur in flow from the sea
- the most intense episodes of wind fluctuations occur in the winter and autumn seasons
- there is a positive correlation between observed rain rate and severity of wind fluctuations
- wind fluctuations are slightly more intense when the pressure tendency is rising - post frontal conditions
- wind fluctuations are more intense in unstable and neutral conditions than in stable conditions

The Hilbert spectrum as a verification tool

Comparing the Hilbert spectrum for forecast and observed time series. Dark colours = larger amplitude of variance



The model

We used the Hilbert spectrum to verify different scales in a 75 member multi-scheme ensemble prediction system (MSEPS)

- Model run by Danish company WEPROG ApS, successfully used for probabilistic wind power forecasting in many locations around the world [3]
- Model wind speeds at Horns Rev were saved at every model time step (close to 30 seconds) for this experiment
- Special 'Warm-Run': continuously updated boundary conditions but no new initial conditions
- The warm-run avoided spectral discontinuities . . .

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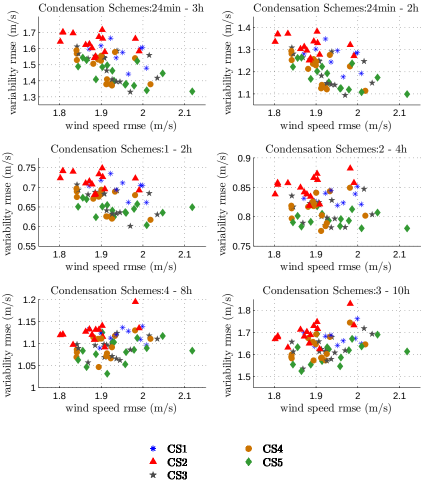
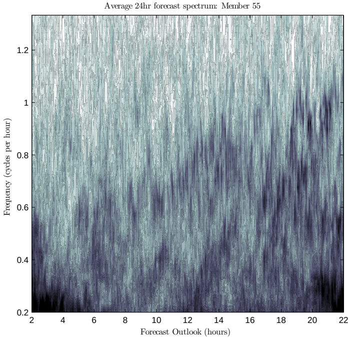
- Special 'Warm-Run': continuously updated boundary conditions but no new initial conditions
- The warm-run avoided spectral discontinuities . . .
- . . . but may have introduced errors due to no reinitialisation. Still expect large scale timing to be correctly controlled from the boundaries.

Variability skill versus Mean wind skill



Average variance

Hilbert spectrum, averaged over many different forecasts



On average, the amplitude of variance on shorter time scales increases with forecast outlook.

Ensemble Empirical Mode Decomposition (EEMD)

- Problems with the EMD include lack of uniqueness, mode mixing and sensitivity to the number of siftings
- Addressing these problems, Wu and Huang (2009) propose the **Ensemble EMD**.

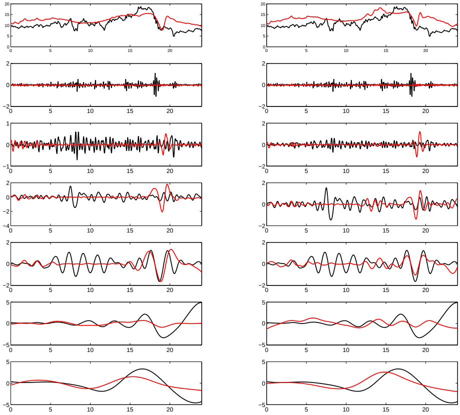
Ensemble Empirical Mode Decomposition (EEMD)

- Time series is pre-whitened with N different realisations of white noise with a fixed standard deviation.
- The N pre-whitened time series are decomposed using EMD
- The average of the IMFs is considered the ‘true’ decomposition

With the problems of mode mixing and uniqueness alleviated, is it possible to directly compare the components of the model and forecast?

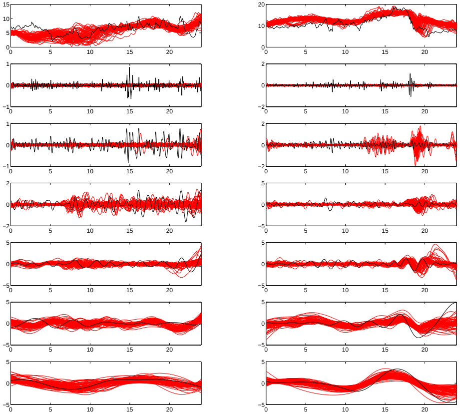
EEMD of forecast and observed time series

Examples of two ensemble members on 2004011218



Ensemble of Ensemble Empirical Mode Decompositions

Examples on 2004011500 and 2004011218



Conclusions

- Wind speed time series are non-stationary, and an adaptive spectral method is needed to describe them properly
- A climatological study of wind fluctuations near the Horns Rev wind farm showed that wind fluctuations are most pronounced:
    - in winter and autumn seasons,
    - in flow from the sea,
    - in unstable atmospheric conditions,
    - in the temporal vicinity of precipitation events, and,
    - in post-frontal conditions

Conclusions

- The empirical decomposition, and the Hilbert spectrum, have interesting applications for forecast verification
- We found that there was an inverse relationship between skill in predicting mean wind, and skill in predicting fluctuations on time scales of 1 to 3 hours.
- We showed that the variance on time scales of 1 to 10 hours tended to grow, on average, throughout the 24 hours of the model run
- Direct use of Ensemble Empirical Mode Decomposition may be a better way of verifying particular time scales than the Hilbert spectrum
- Questions? . . .

Acknowledgments

Part of this work was done within the Danish project ‘HRENSEMBLE - High Resolution ENSEMBLEs for Horns Rev’, under contract PSO-6392, and data for Horns Rev Mast 2 data was provided by Vattenfall as part of this project. The work was also partly supported by the Danish project ‘Mesoscale atmospheric variability and the variation of wind and production of offshore wind farms’ (under contract PSO-7141).

Additional sonic anemometer observations of wind speed at the met mast were downloaded from the Danish database http://www.winddata.com.

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MSEPS model data was kindly provided by WEPROG ApS.

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I am grateful to all involved

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