Realistic wind conditions for load assessment: alternatives to de-trending of time series

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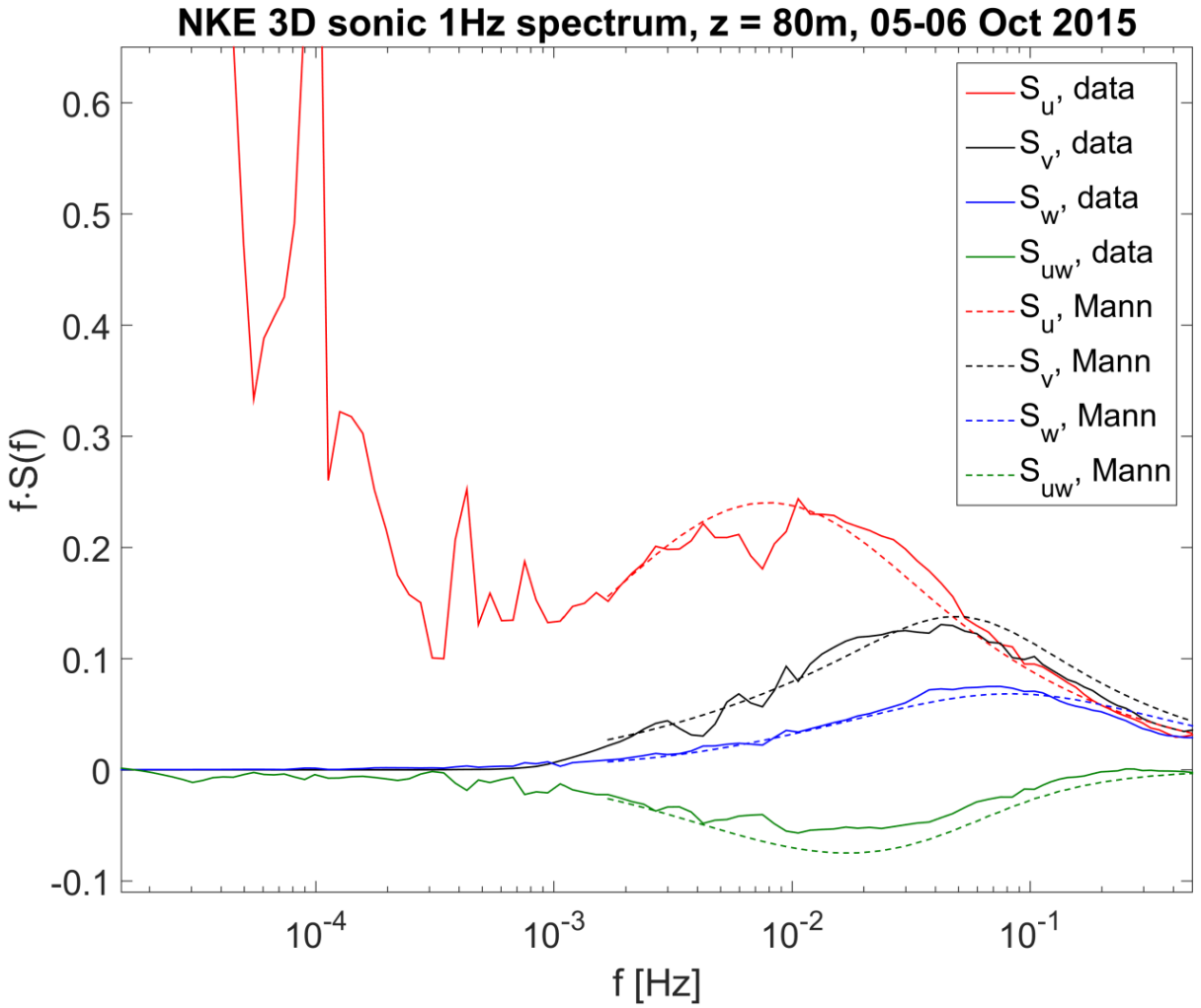
Presentation outline

- Introduction/Problem formulation
- Methods for identifying trends in the wind speed
- Load measurement campaign at Nørrekær Enge
- Load simulations setup
- One-to-one comparisons
- Conclusions

The problem:

- We would like to validate our turbine prototype design
- Measured loads are normally used to validate the design load simulations
- Simulations of normal operation use stationary turbulence realizations
- Due to weather patterns, the actual wind is rarely stationary
- Due to the trends (changes in mean), the variance of a 10-minute realization from a non-stationary process is higher.



How can we take non-stationarity into account?

1) Linear de-trending

2) Low-pass/high-pass filtering

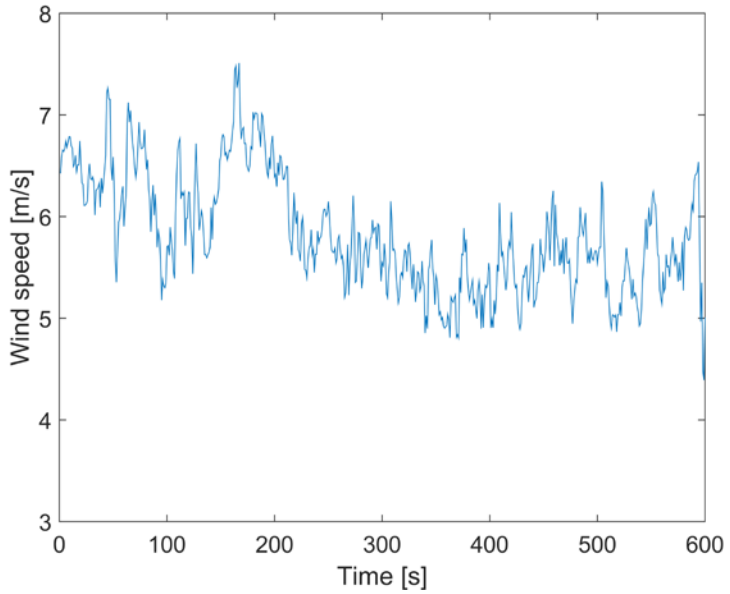
3) Constrained wind fields (including the trends in the simulations)

What do the standards say?

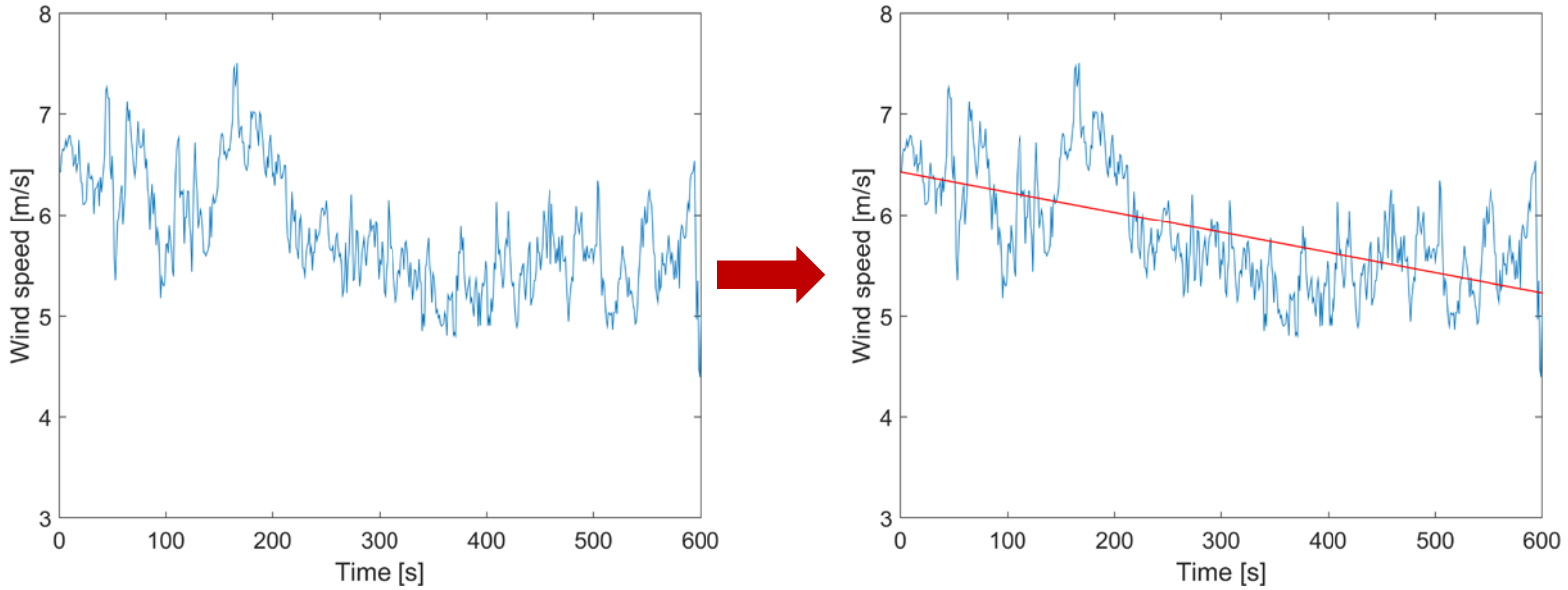
IEC61400-1, ed.3: linear de-trending is preferred (but not compulsory)

IEC61400-13, ed.1: data should not be de-trended, but trends should be identified for ensuring result validity

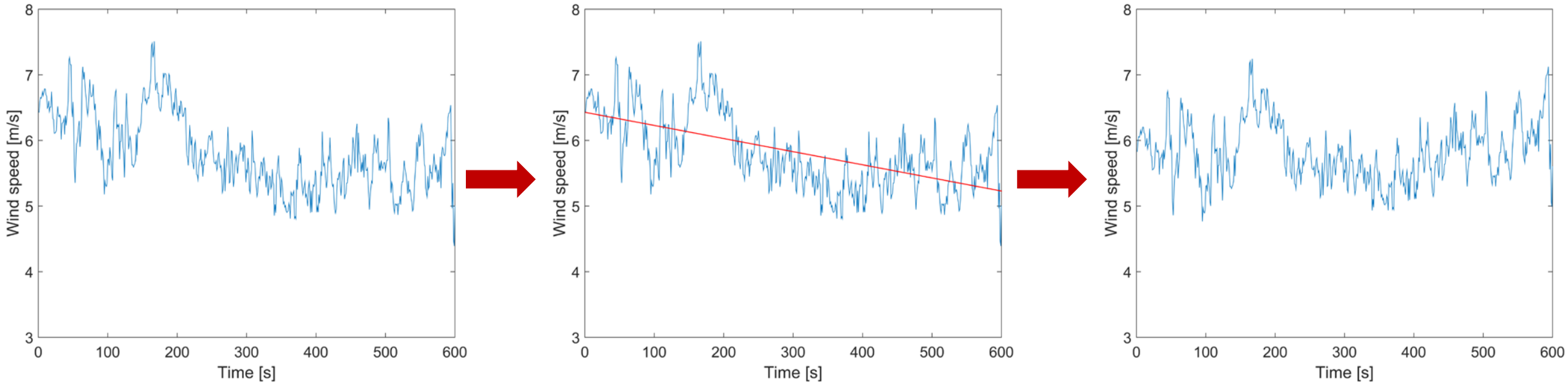
Linear de-trending



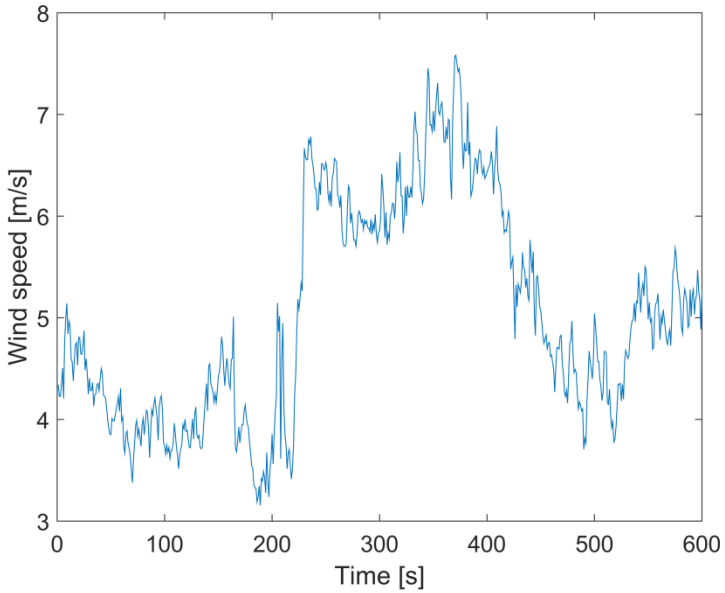
Linear de-trending



Linear de-trending



High-pass and low-pass filtering



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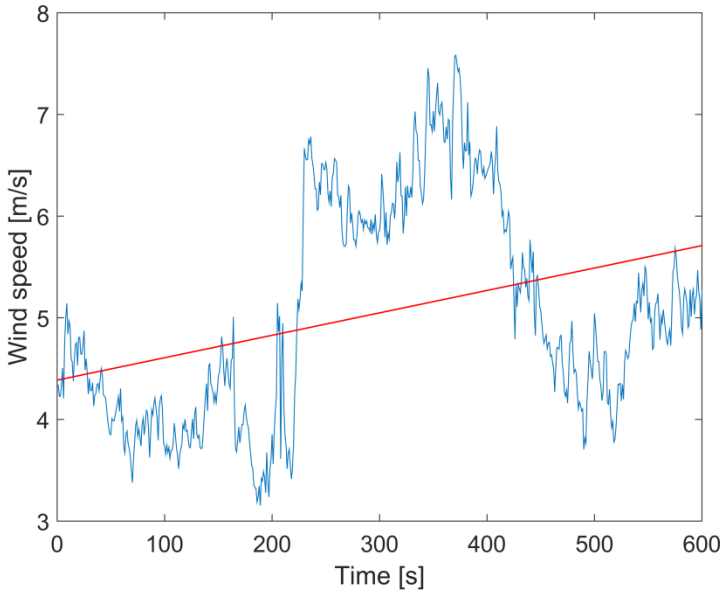

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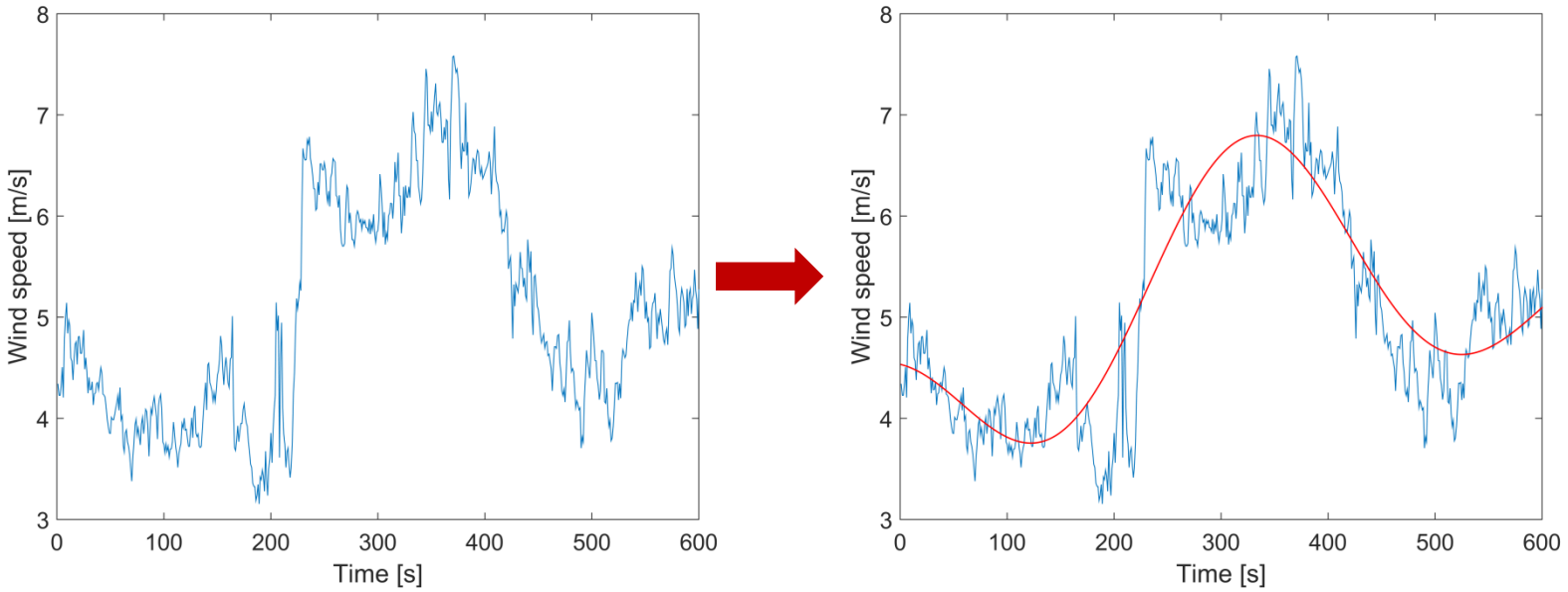
High-pass and low-pass filtering



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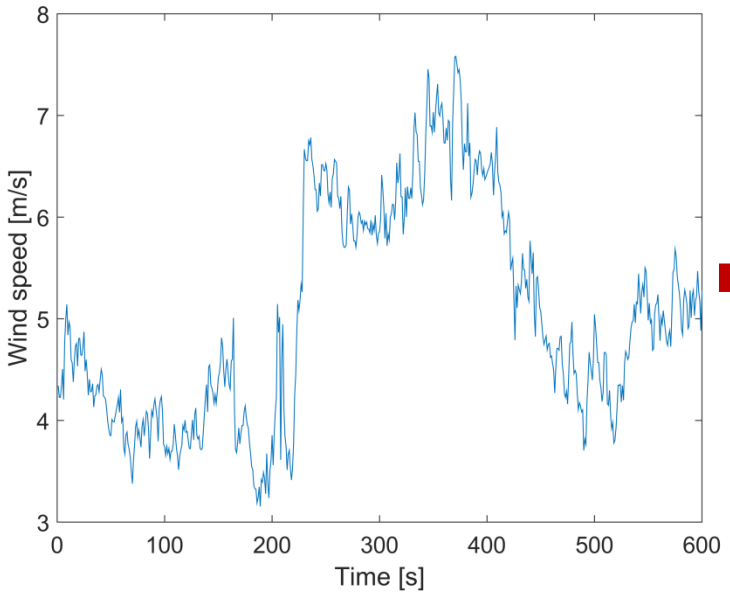
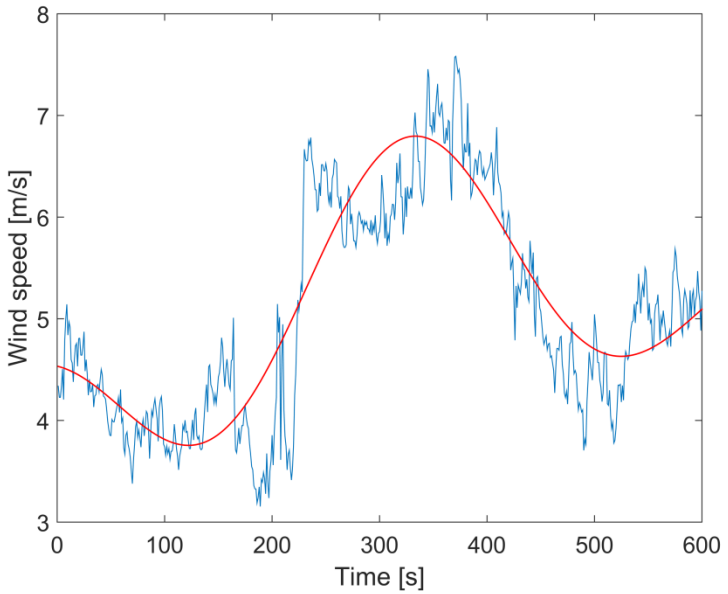
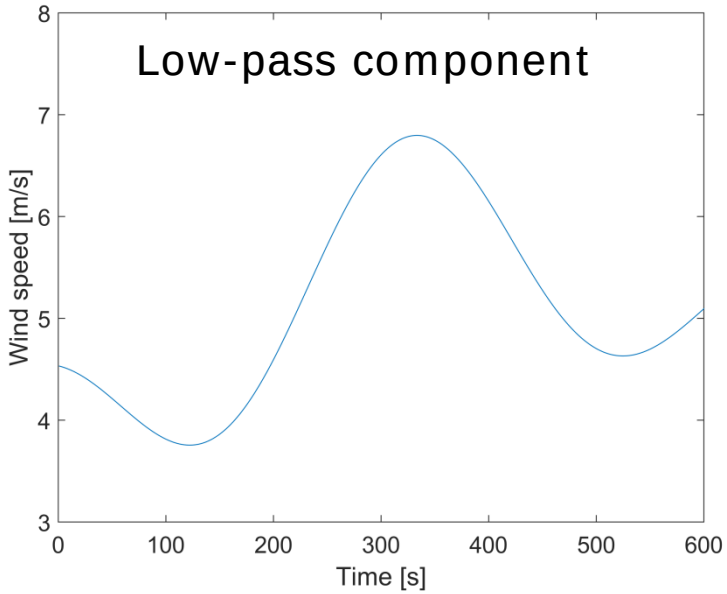
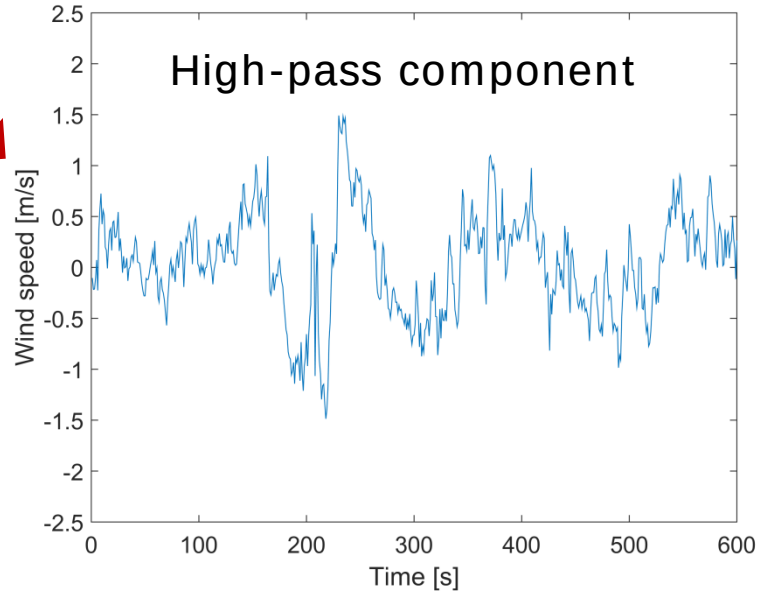
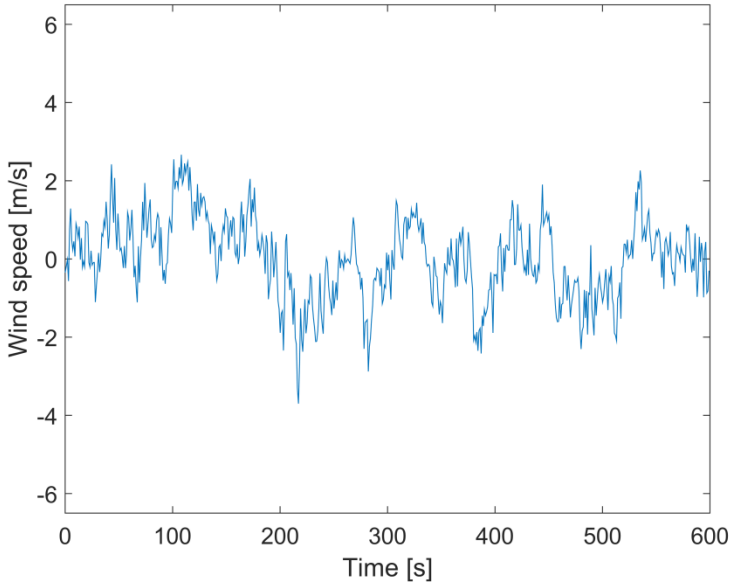








Constrained simulation



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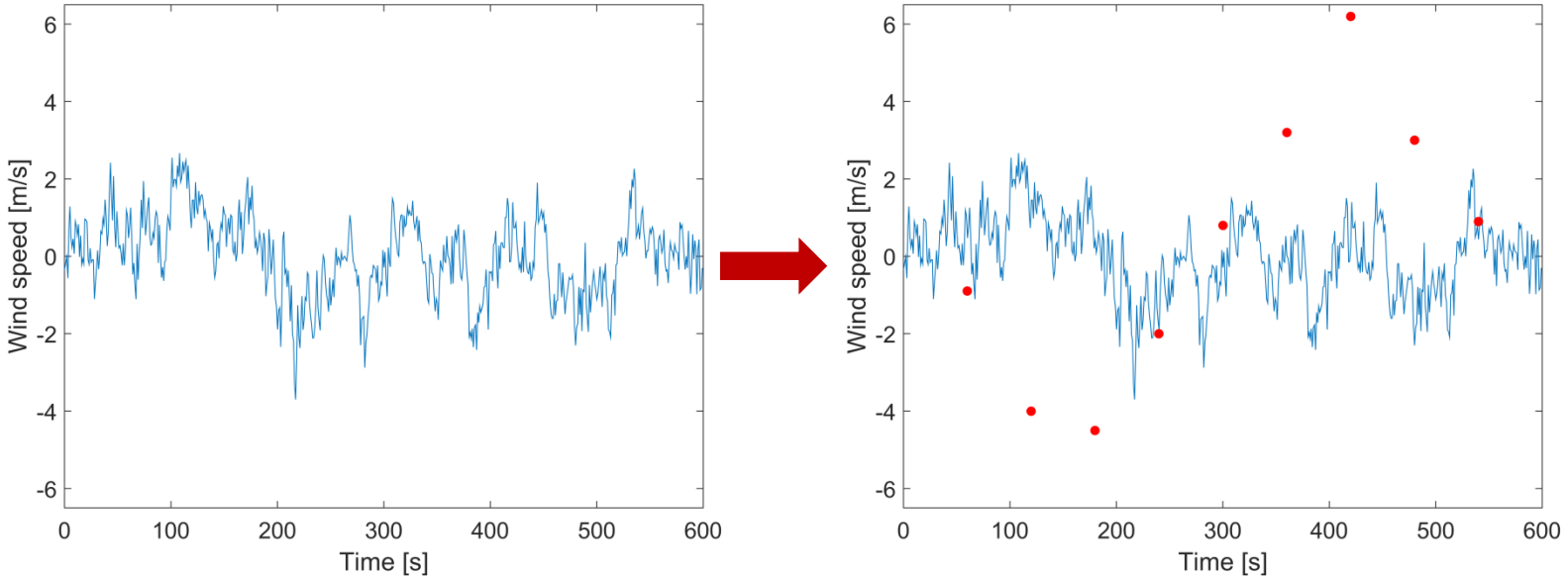

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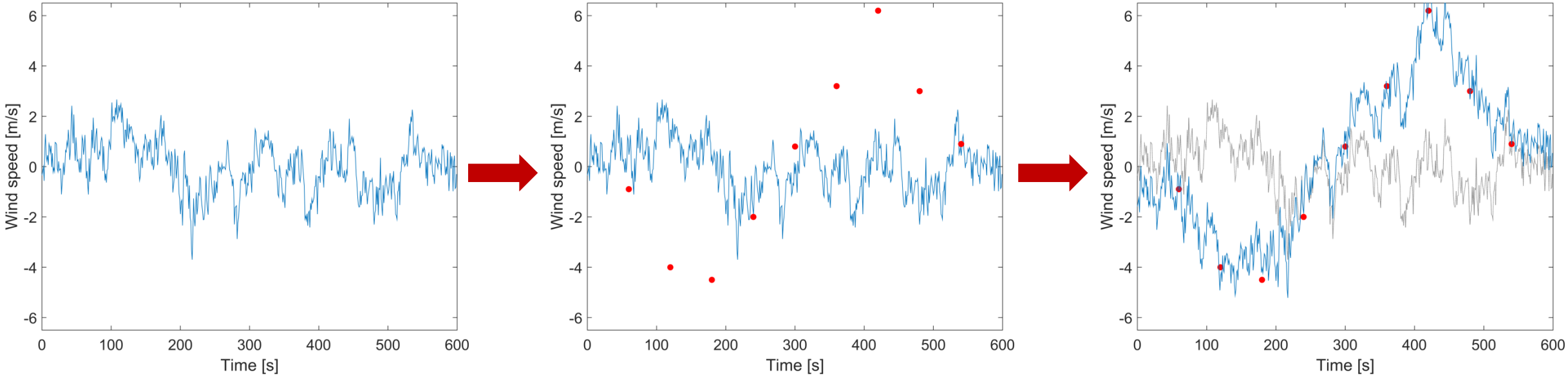
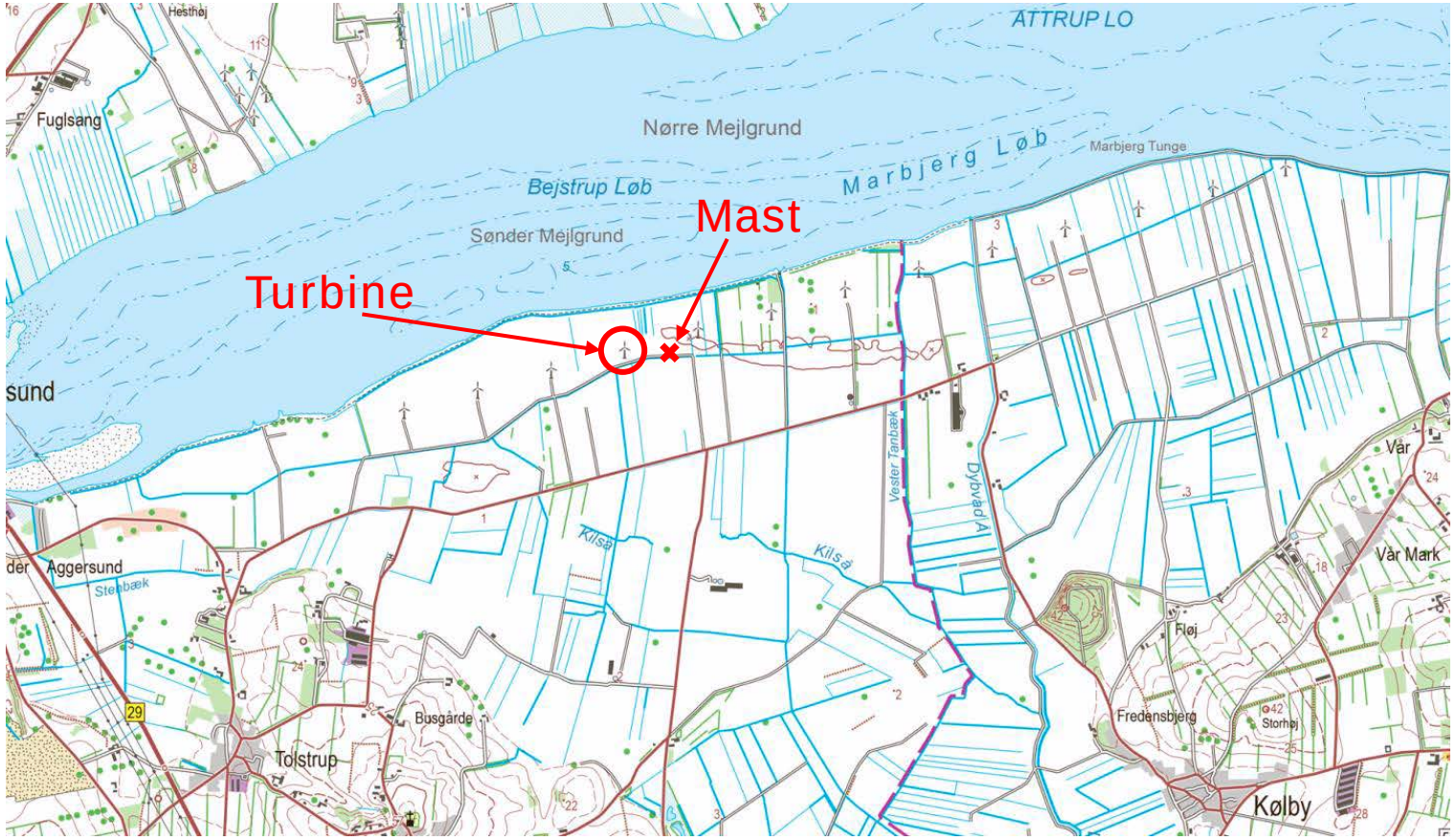


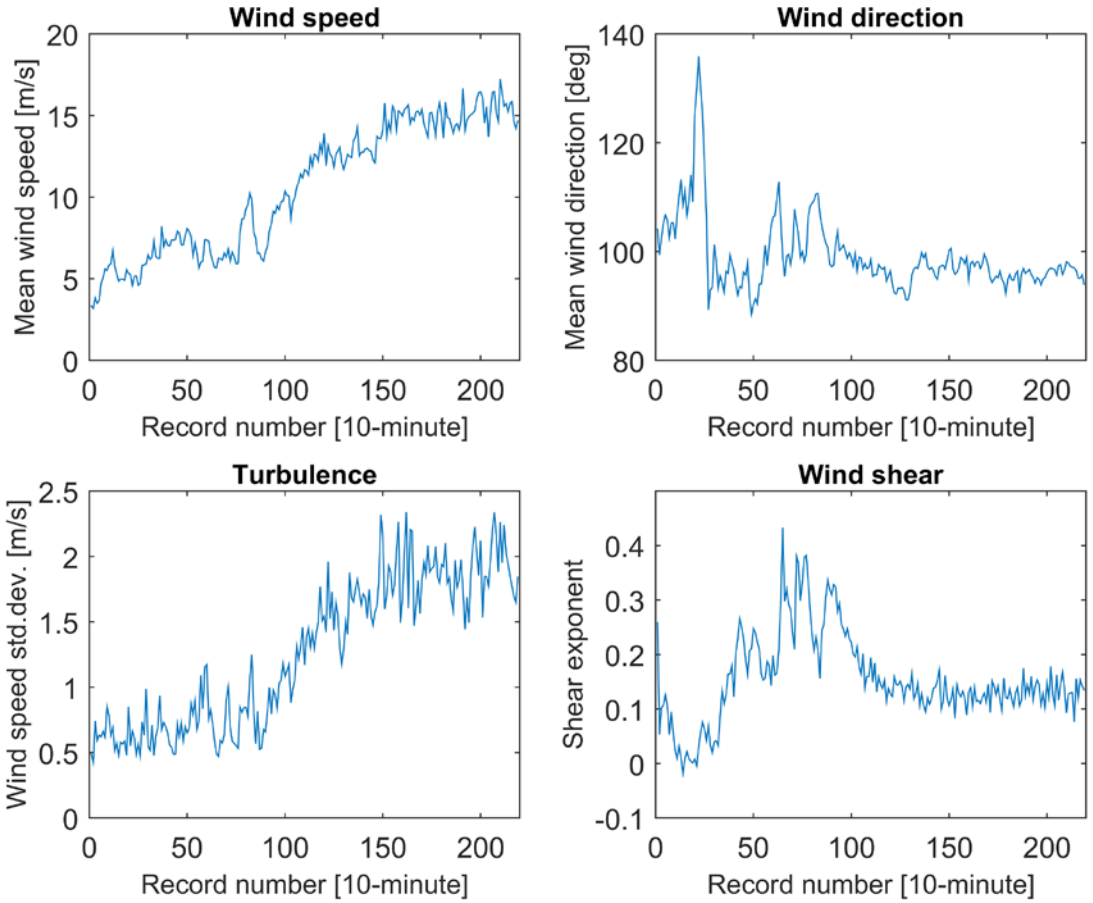
Measurement campaign at Nørrekær Enge

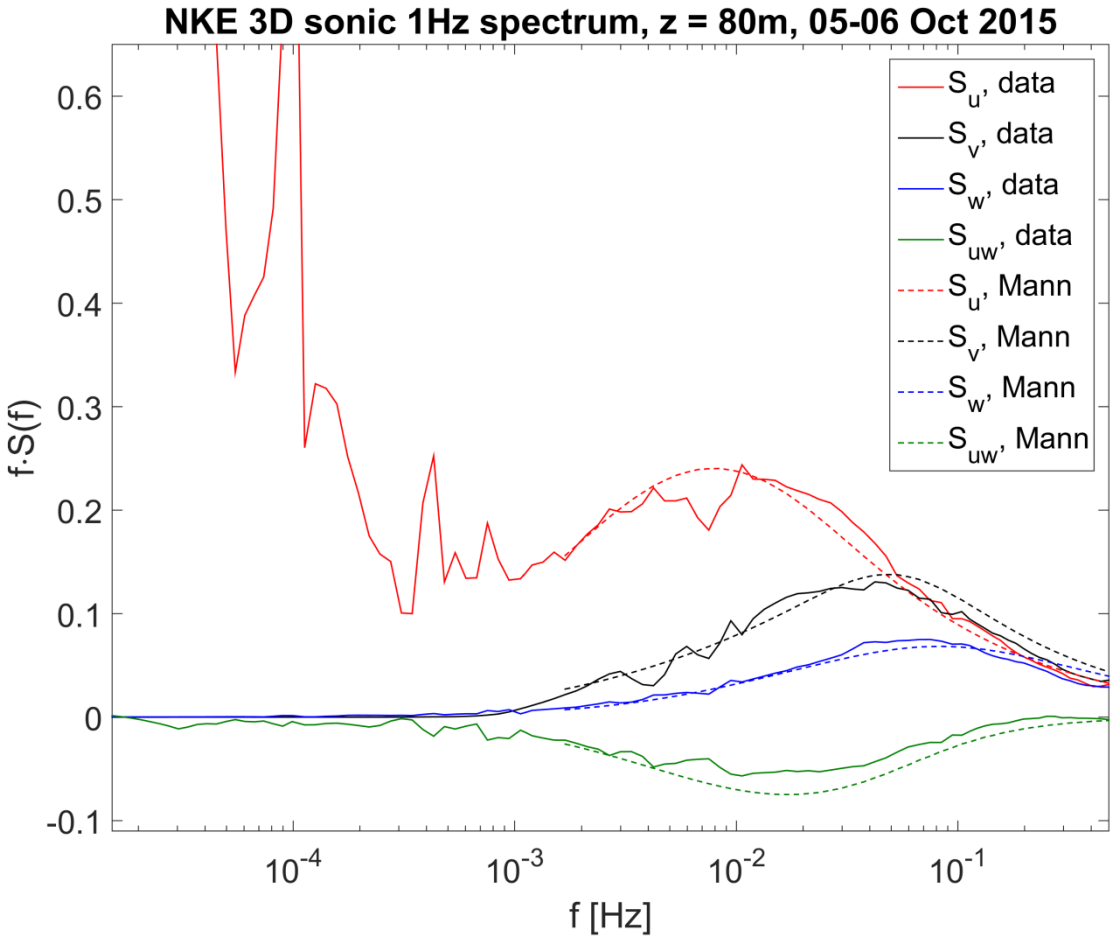
- Site in Northern Denmark
- 2.3MW turbine,
  mast at 2.5D southeast
- Sonic data from lower tip
  to hub height
- 6-month load measurement
  campaign



Wind conditions

A specific 2-day period with variations in wind conditions



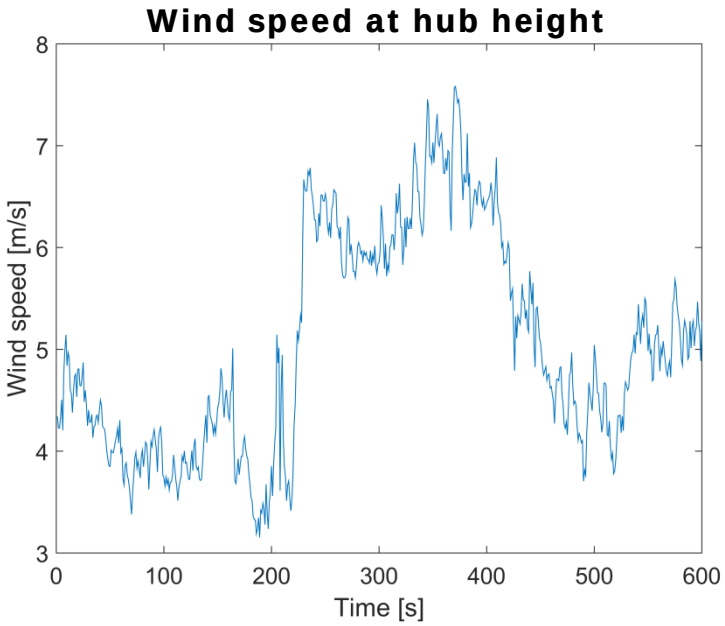


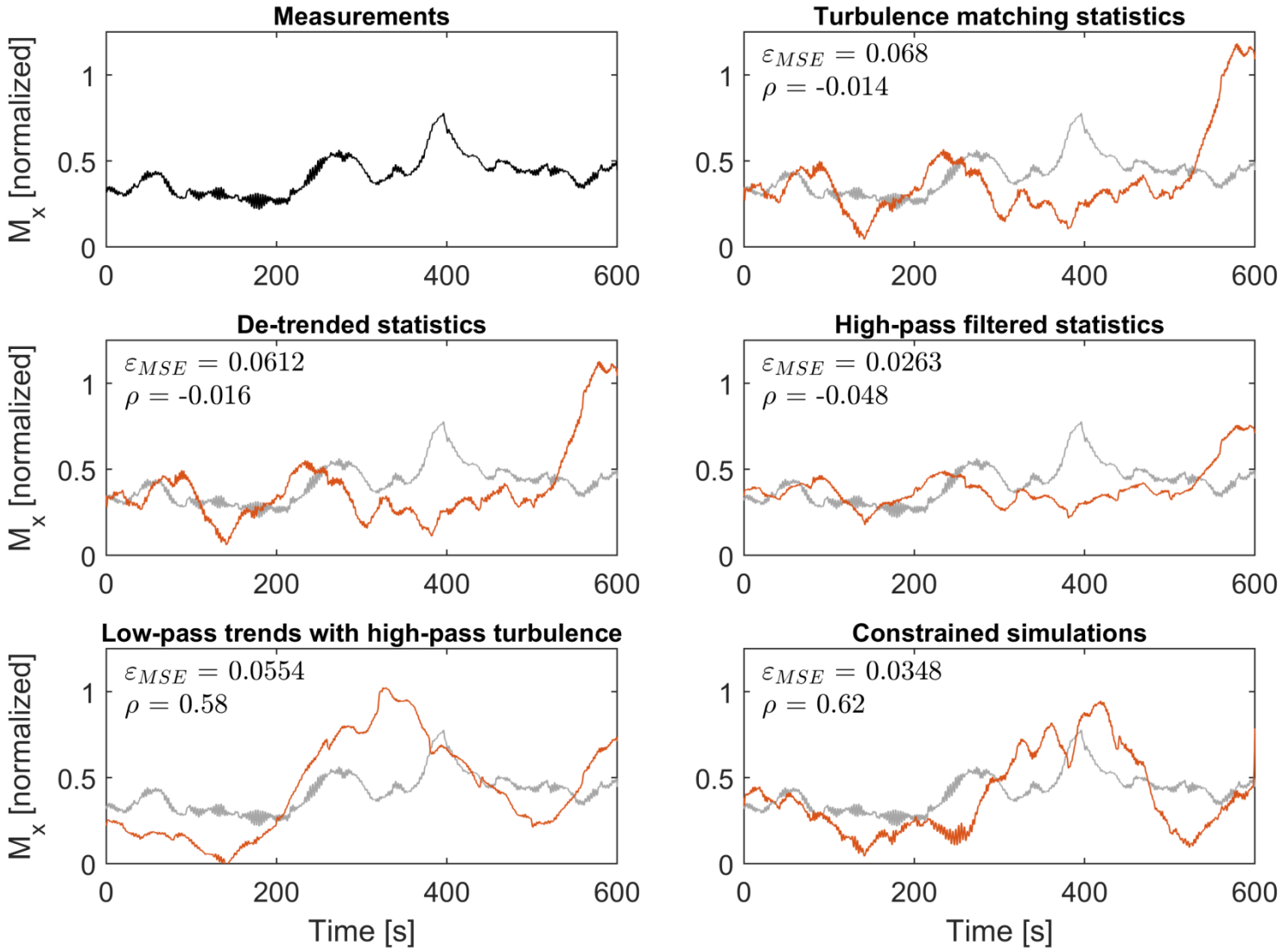
Load simulation setup

- An aeroelastic model of the turbine at Nørrekær Enge is implemented in Hawc2
- Wind statistics from the mast are used to generate random realizations of turbulent wind fields
- Mann turbulence model used (spectral parameters fitted from the 3D sonic data)
- Simulation cases using:
  - 10-minute statistics from non-processed data
  - Statistics from de-trended time series
  - Statistics from high-pass filtered data (low-frequency trends eliminated)
  - Low-pass series input as fully coherent trends, turbulence from high-pass filtered data
  - Constrained simulations with time series from sonic at hub height

How do the time series compare?

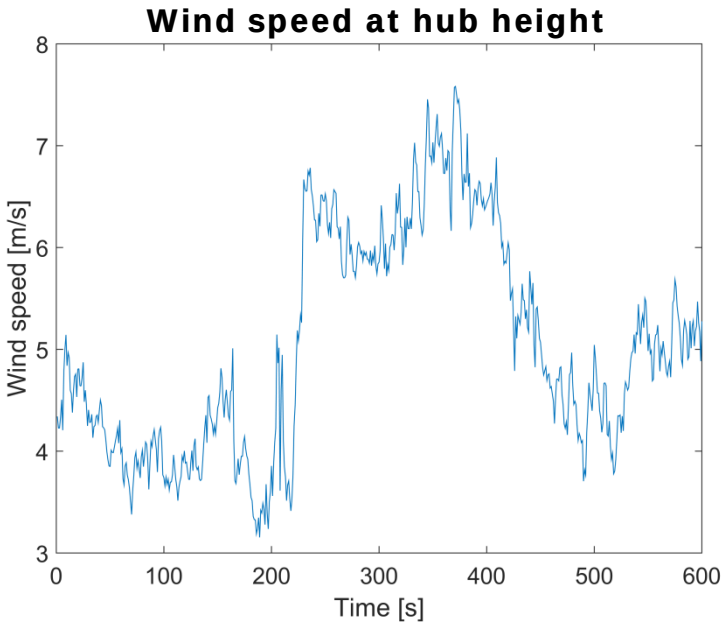
- Tower base bending moment M_x (moving average)

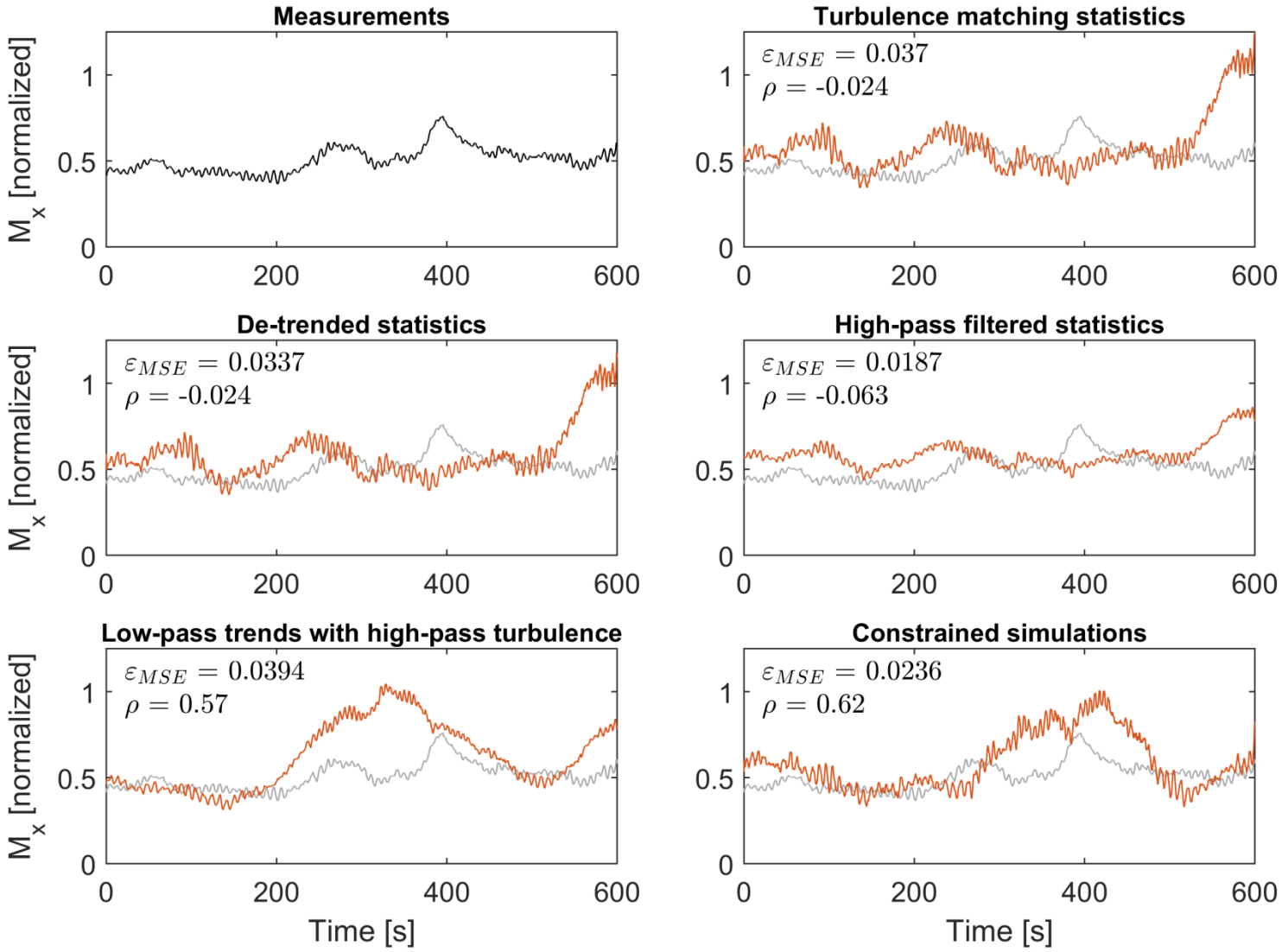




How do the time series compare?

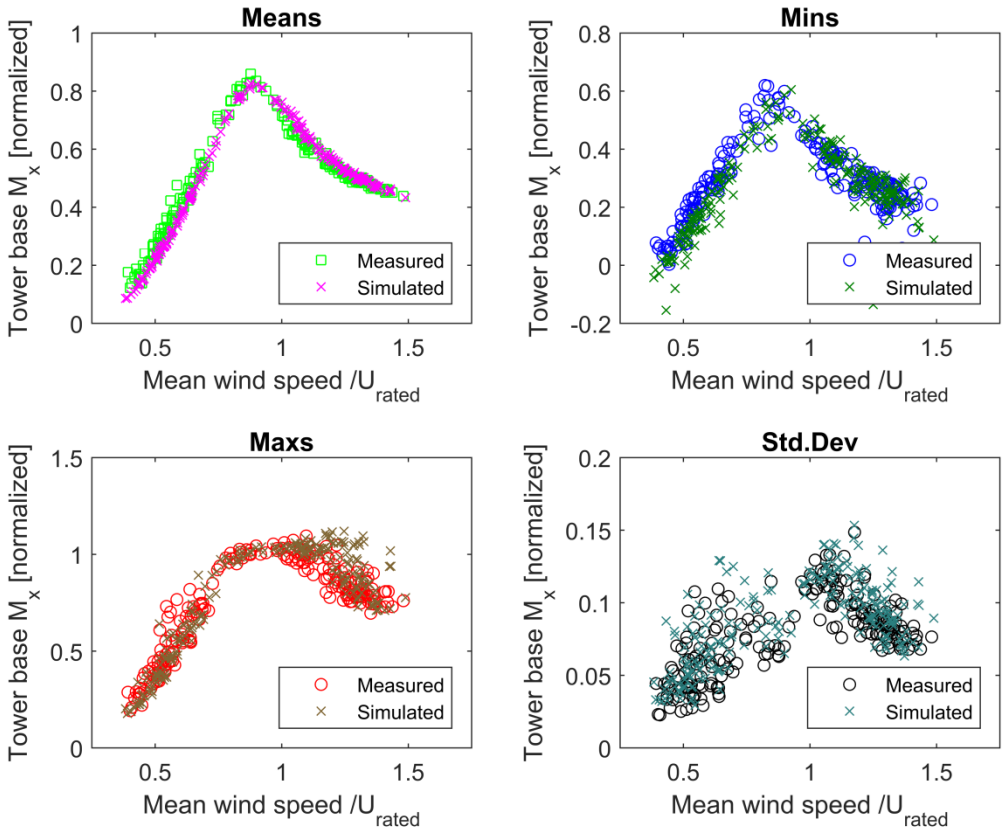
- Blade root flapwise bending moment M_x (moving average)



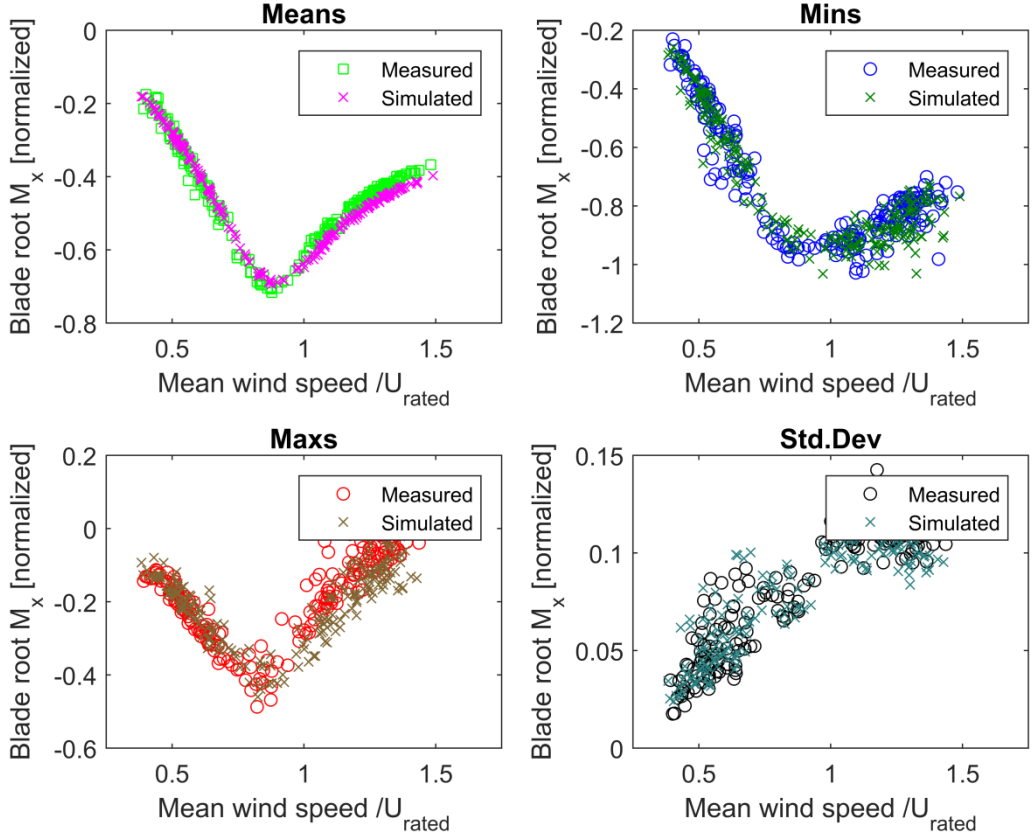


Load statistics – one-to-one comparison

Tower base fore-aft bending moment



Blade root flapwise bending moment

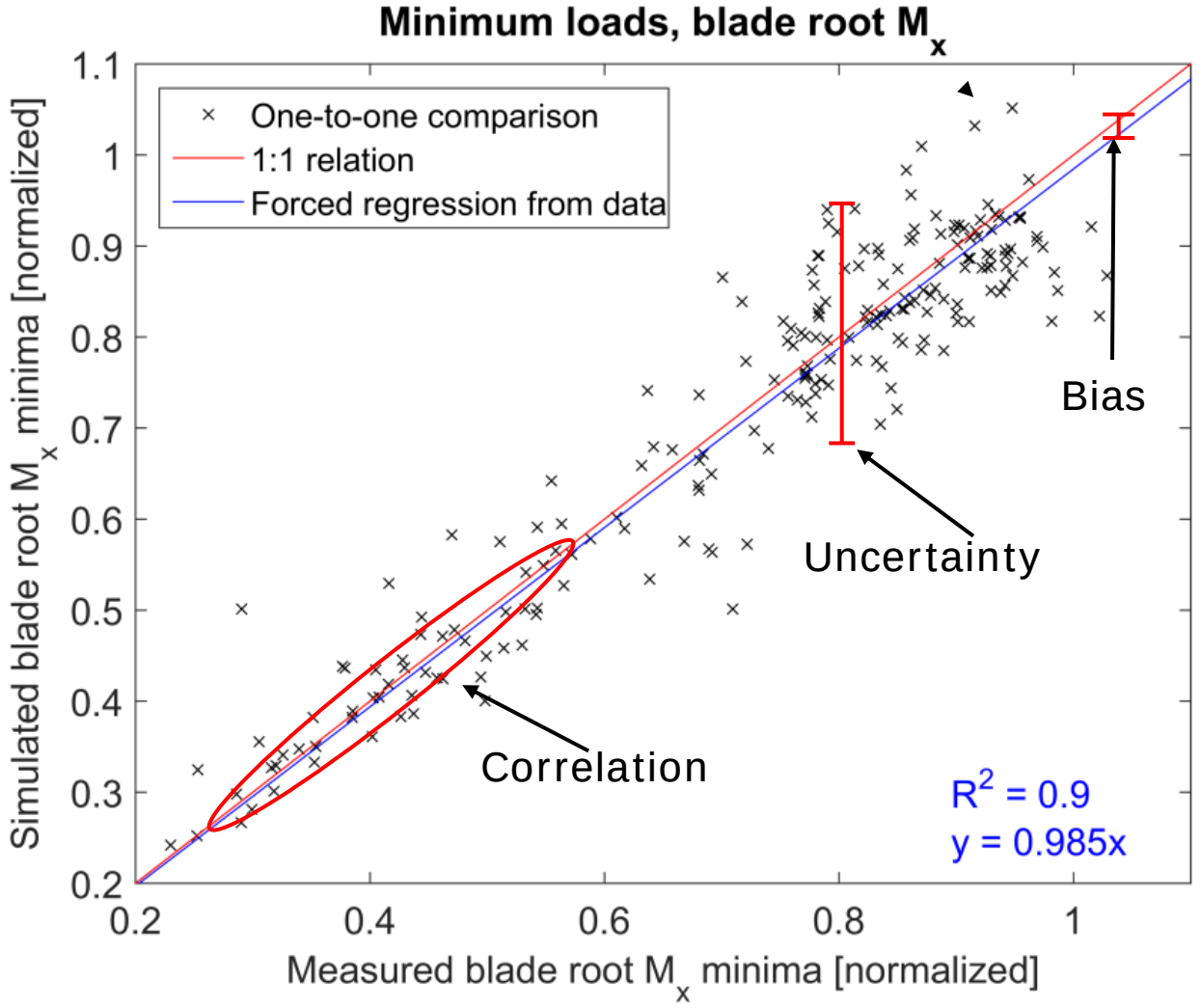


How do we assess the one-to-one results?

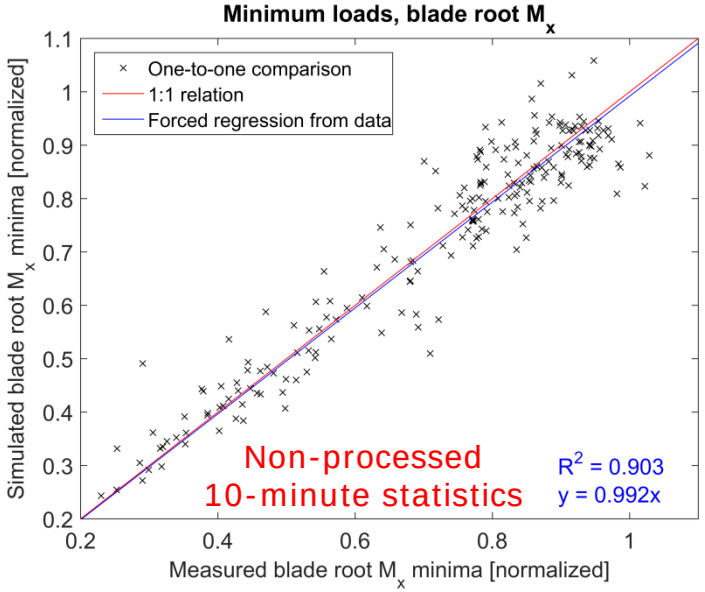
- R-square value
  (correlation between
  measured and simulated data)

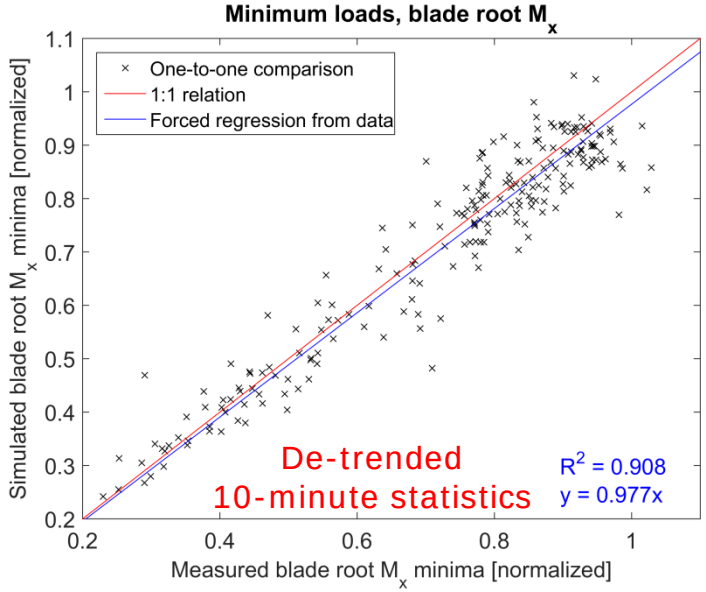
- Uncertainty
  (standard deviation of the ratio between
  measured and simulated data)

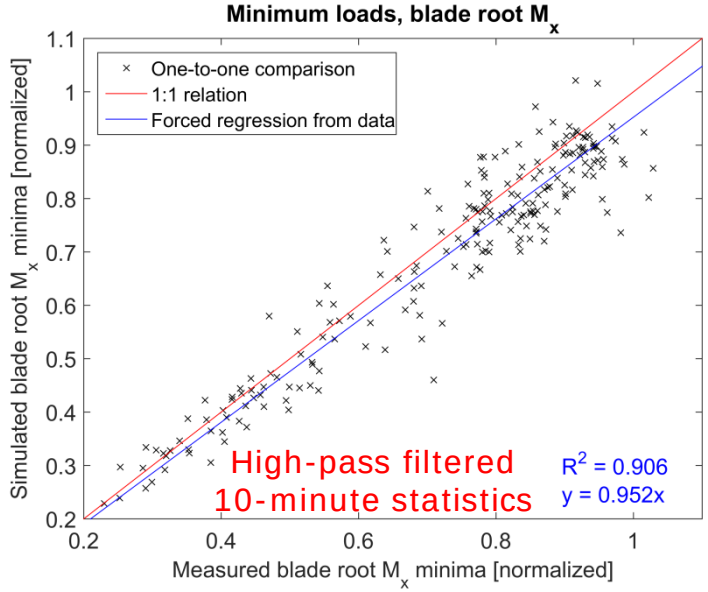
- Bias (mean ratio)

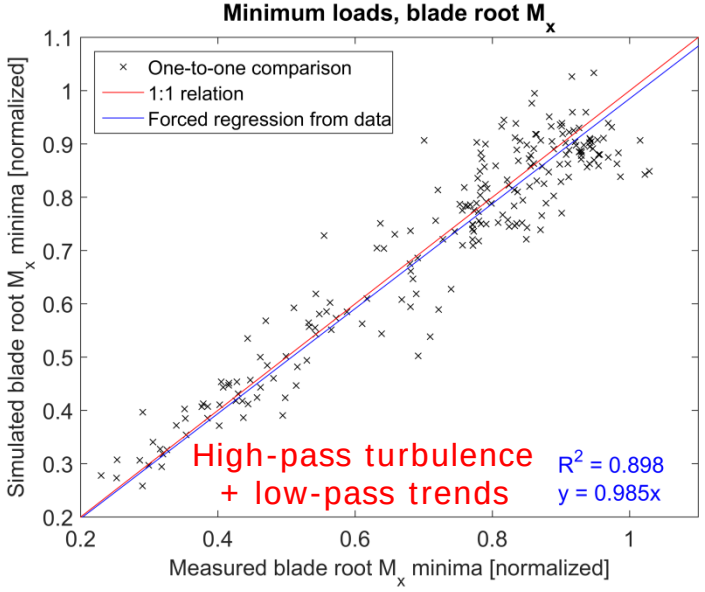


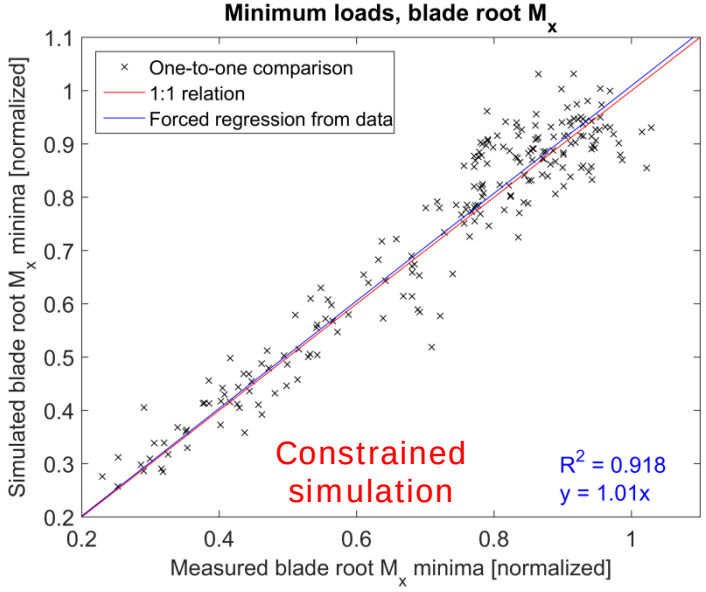
Example one-to-one load comparison: blade root flapwise bending moment extremes











Load type	Maximum difference	IEC safety factor
Blade root, fatigue	1.1	1.1
Blade root, extreme	1.05	1.25
Tower base, fatigue	1.1	1.1
Tower base, extreme	1.05	1.25

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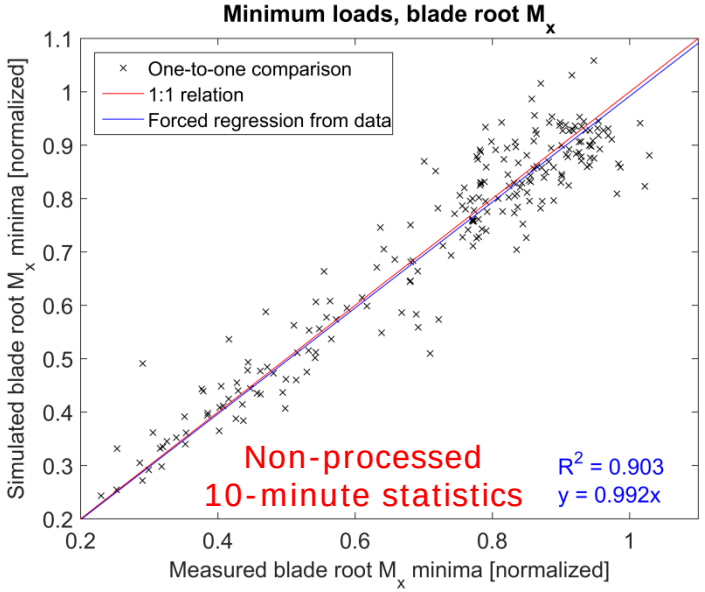

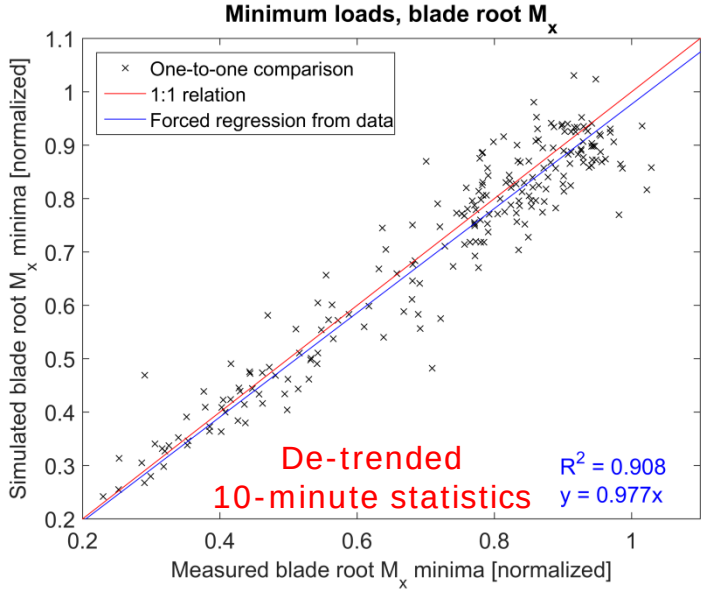

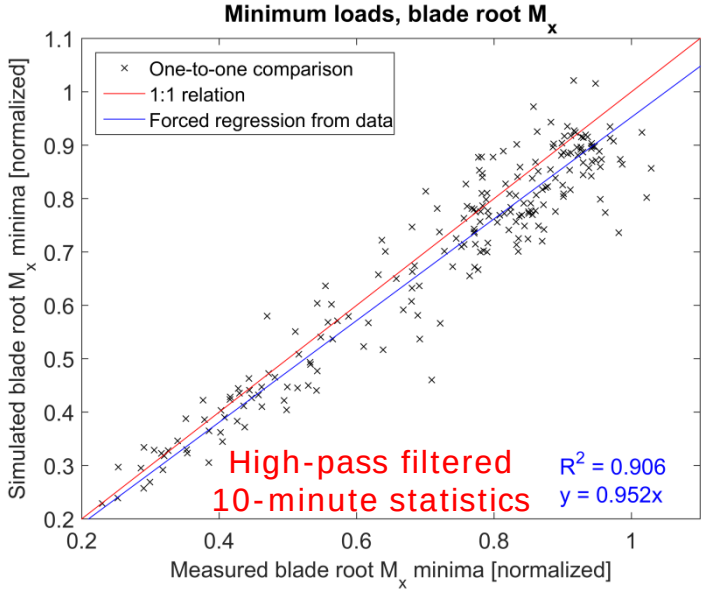

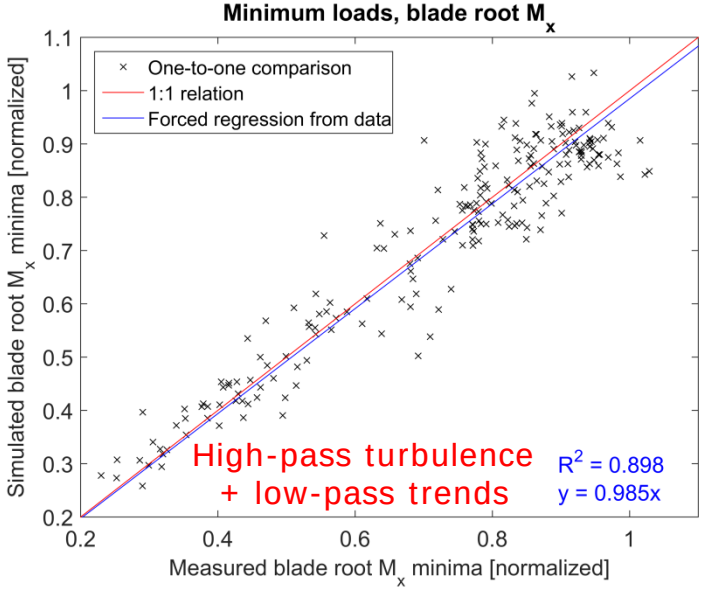

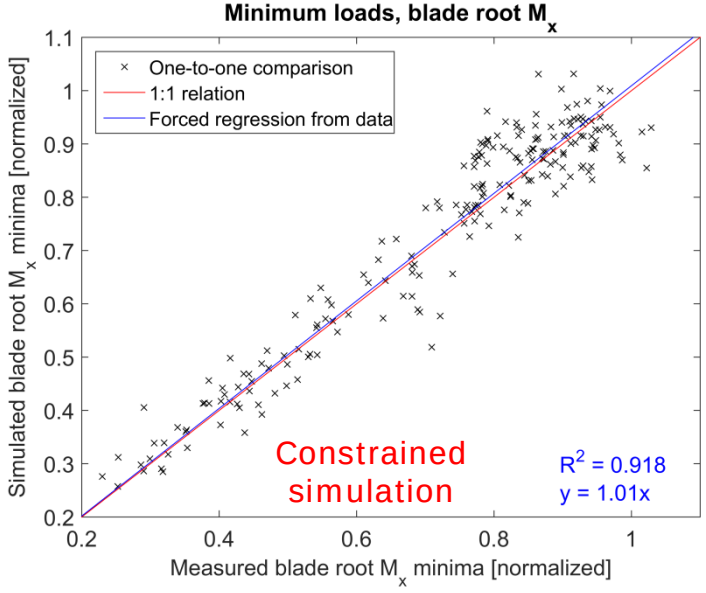

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Load simulation results - summary

- Blade root fatigue and extreme loads, as well as tower base extreme loads were estimated with almost zero bias
- Tower base fatigue loads were overestimated with up to 10% for most approaches (model uncertainty?)
- The constrained wind fields gave load time series with best visual match to measurements
- Statistically, there was noticeable but not drastic difference between load estimations
- Linear de-trending and using high-pass filtered data resulted in model bias for both fatigue and ultimate loads
- Constrained simulation results were close to the unprocessed statistics results, but some uncertainties were reduced

The paradox of “even number of errors”

- We want to find the best approach to validate our model

- However, the “best” approach is evaluated here using the same model

…… What if the error in wind conditions simply cancels
the model error (a.k.a. “even number of errors”?)

Conclusions

- We demonstrated several methods for taking trends in wind speed into account, and assessed their effect on the accuracy of load predictions

- Due to limitations in the free measurement sector direction, we used a case study with relatively benign conditions. More analysis at challenging wind conditions is on our wish list.

- Linear de-trending and high-pass filtering failed to show any benefit over using statistics from raw data

- Constrained simulation and using low-pass filtered data as trends showed good results, but little difference to using statistics from raw data.

- We consider the constrained simulation as the most beneficial method – can be used for more special events as gusts, storms, simulations with shorter time periods, etc.