Data-driven models for wind, gusts, and loads

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Outline

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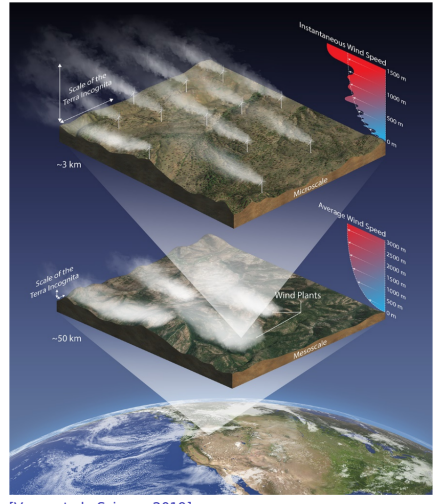
Motivation: Wind is complex

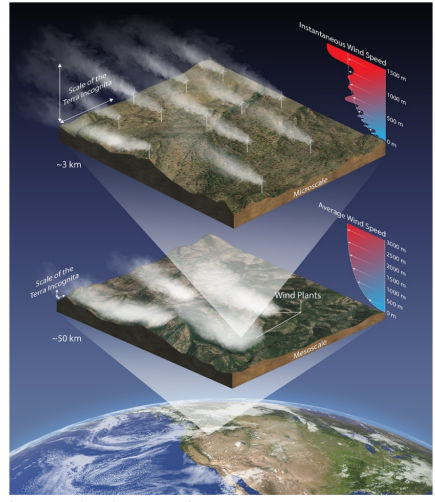
- Complexity of small scale turbulence, e.g., intermittency
- Influences of temperature, ground surface & topology, etc.
- Non-stationarity by daily & seasonal cycles, large weather systems, climate change, etc.



[Veers et al., Science 2019]

Motivation: Wind is complex

- Complexity of small scale turbulence, e.g., intermittency
- Influences of temperature, ground surface & topology, etc.
- Non-stationarity by daily & seasonal cycles, large weather systems, climate change, etc.
- Wind field models can only reproduce certain aspects required for certain applications

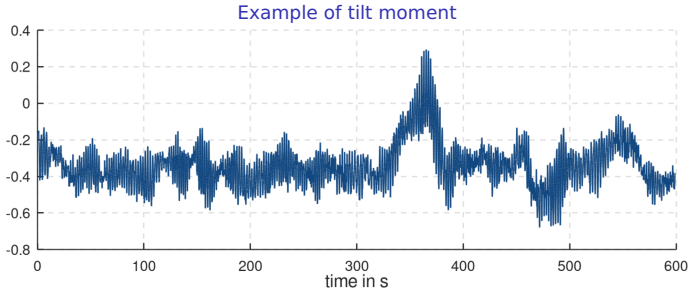


[Veers et al., Science 2019]

Outline

Load events in WEC caused by spatial wind structures – PASTA

- Load events from field measurements not reproduced in load simulations
- Hypothesis: Something missing in inflow wind fields
- Joint research project with Nordex SE and ICM Chemnitz



Load events in WEC caused by spatial wind structures – PASTA

- Idea: spatial inhomogeneity of wind generates tilt moment
- Use “Center of Wind Pressure” CWP

$$\mathbf{r}_{CWP} \propto \sum_i \mathbf{r}_i \, u^2(\mathbf{r}_i)$$

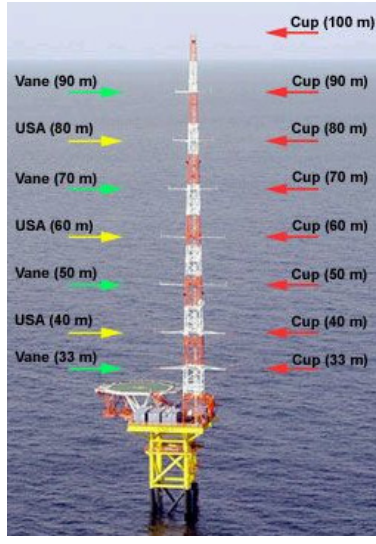
- Challenge: wind measurements at many points necessary to reproduce dynamics

⇒ FINO 1 and GROWIAN measurements used for further investigations

Load events in WEC caused by spatial wind structures – PASTA

⇐ GROWIAN

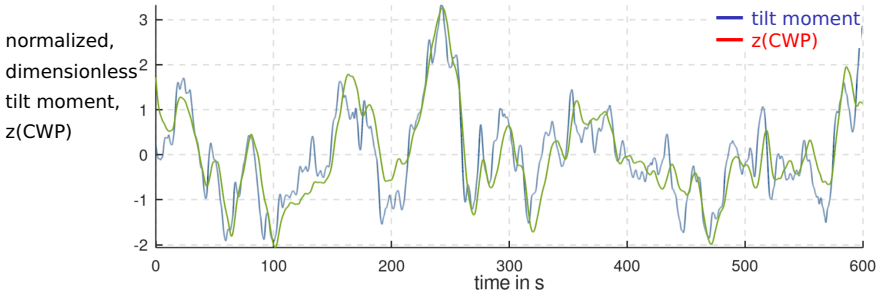
FINO 1 ⇒



- Spatially resolved measurements
  on grid (GROWIAN) and vertical profile (FINO 1)
- High frequency data available, 2.5 Hz and 1 Hz
- CWP dynamics reflected

Load events in WEC caused by spatial wind structures – PASTA

- CWP dynamics reproduces tilt moment dynamics quite well



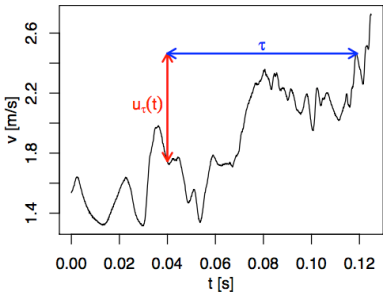
- Basis of strongly simplified load model
- Publication in preparation

Outline

Multi-point statistics of wind gusts – EMUwind

Simplest gust idea:
wind speed increment

$$\delta u_\tau(t) = u(t+\tau) - u(t)$$



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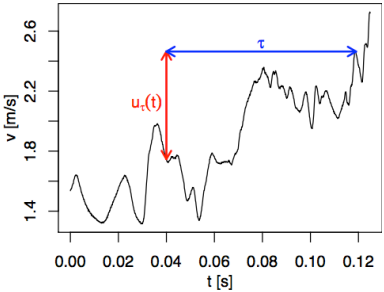

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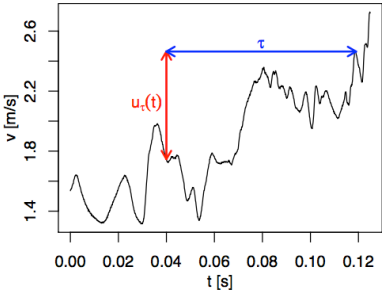

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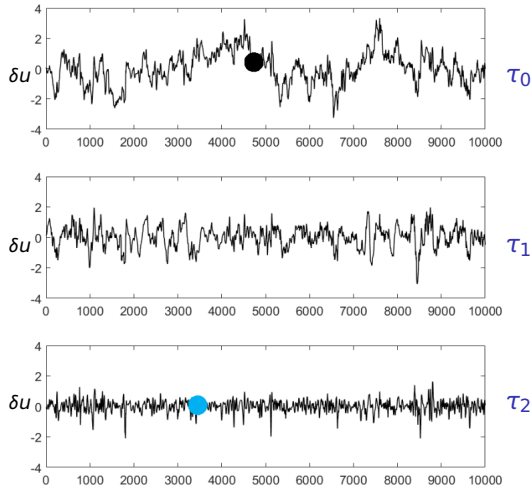
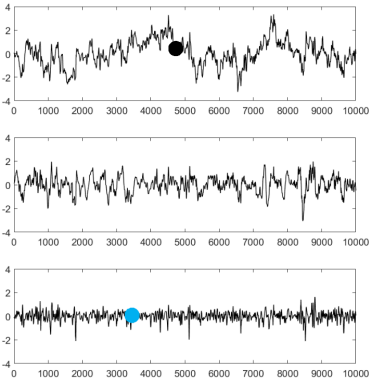
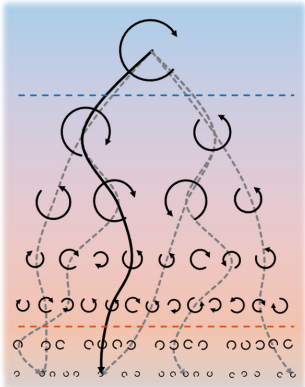


Multi-point statistics of wind gusts – EMUwind

Cascade process in turbulence [Richardson, ca. 1920]





Modeled by
Fokker-Planck equation

$$-\partial_\tau p(\delta u) = \left[-\partial_{\delta u} D^{(1)}(\delta u) + \partial^2_{\delta u} D^{(2)}(\delta u)\right] p(\delta u)$$

for evolution of
δu_τ with scale τ

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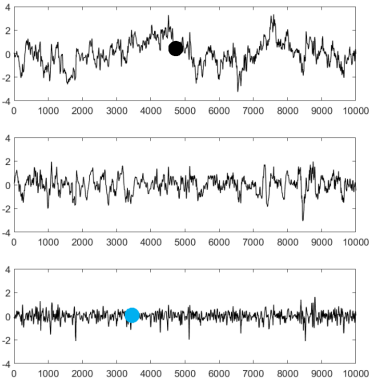

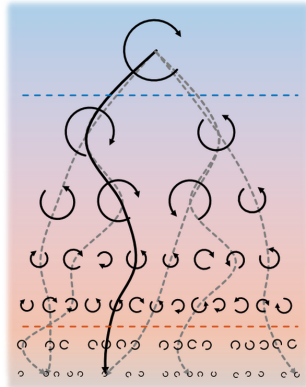

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Stochastic model for turbulent cascade:

Estimation directly from data

Multi-point statistics of wind gusts – EMUwind

Generation of surrogate wind time series

1. Get PDF for next point from current window
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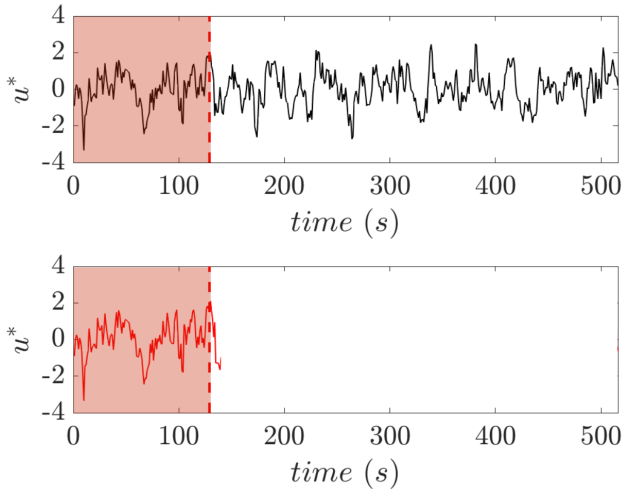

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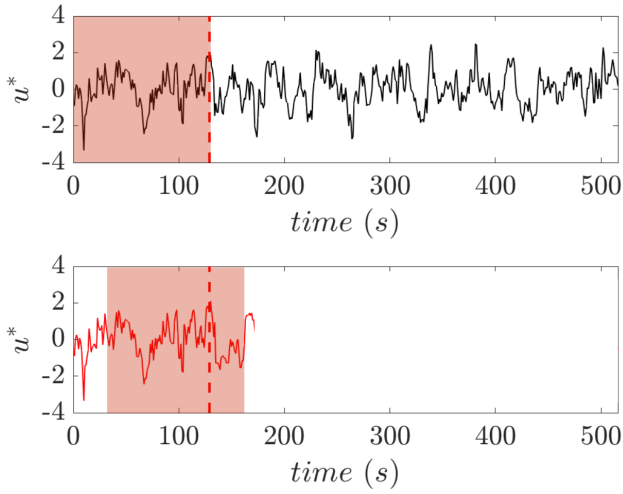

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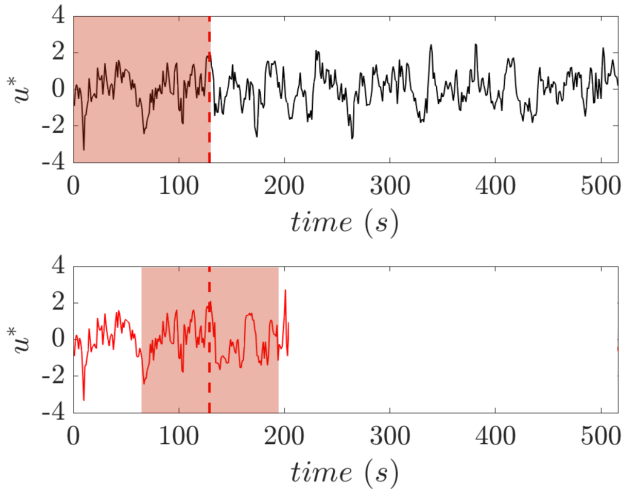

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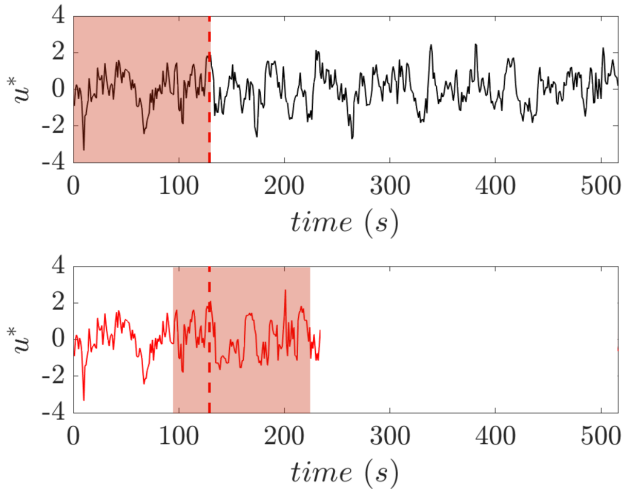

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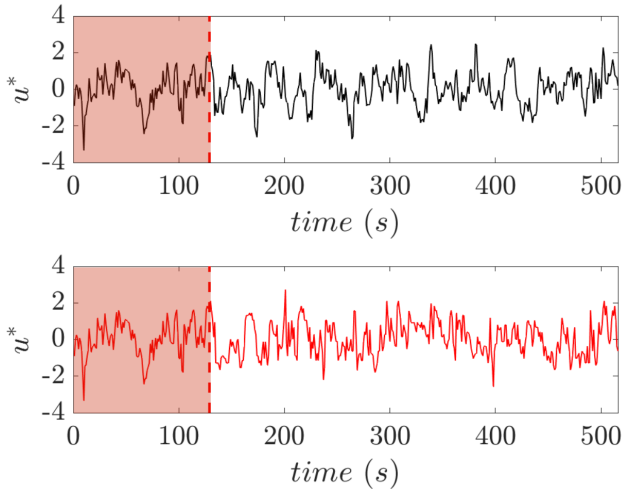
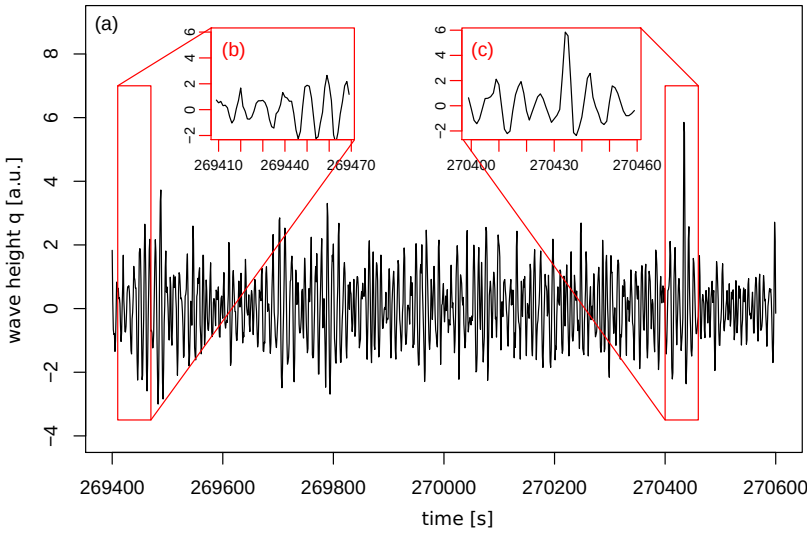
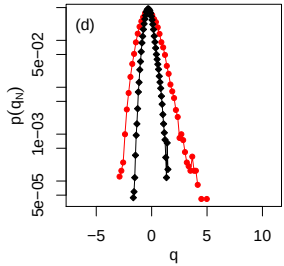
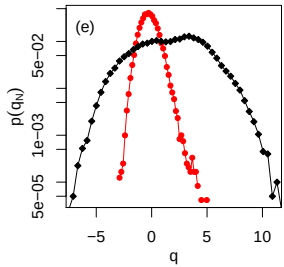


Gust prediction: short-term forecast







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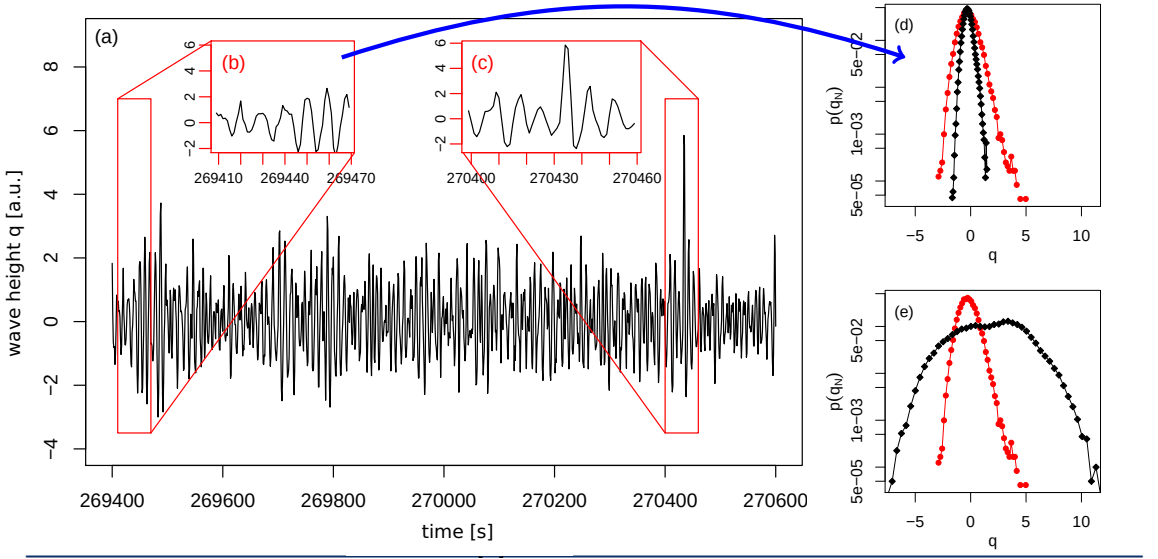

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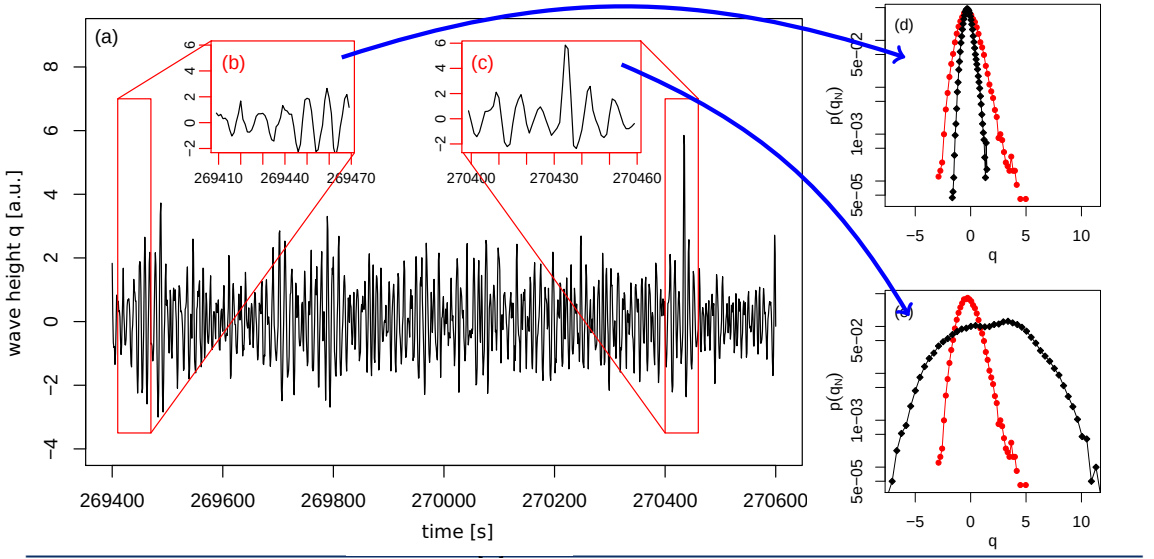
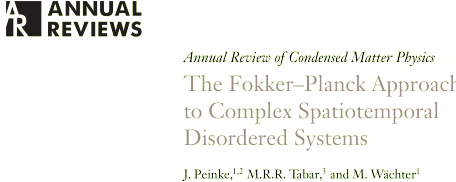


Multi-point statistics of wind gusts – EMUwind

Summary

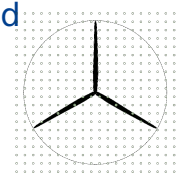
- Joint multi-point statistics of wind speeds reproduced by model of turbulent cascade
- Estimated directly from measurement data
- Enables generation of surrogate data with correct joint multi-point statistics
- Enables probabilistic short-term forecast of gust events



[Peinke, Tabar, Wächter, ARCMP 2019]

Outline

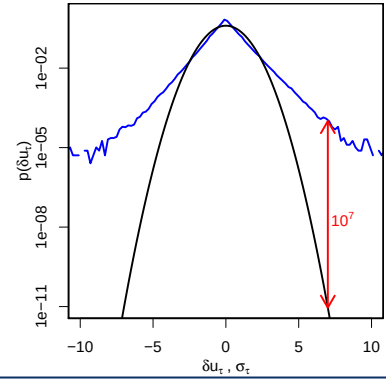
Superstatistical model for wind fields – EMUwind



Motivation

- Synthetic wind fields necessary for wind turbine design process
- IEC 61400 standard models use purely Gaussian random fields
- Occurrence of extreme wind fluctuations greatly underestimated

Increment $\delta u_\tau = u(t+\tau) - u(t)$



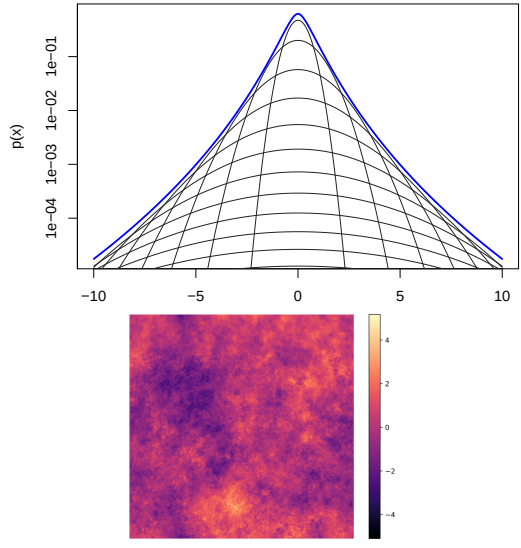
Superstatistical model for wind fields – EMUwind

Intermittency by super-statistics

- Superpose many Gaussians with different variances
- Apply log-normal weights
  ⇒ K62 model of turbulence

Application to wind fields

- Generate ensemble of Mann-type wind fields,
  - log-normal variances,
  - correlated
- Can exactly reproduce statistics of extreme fluctuations, both empirical or theoretical (K62)



[Castaing et al., Phys. D 46, 1990]

Superstatistical model for wind fields – EM

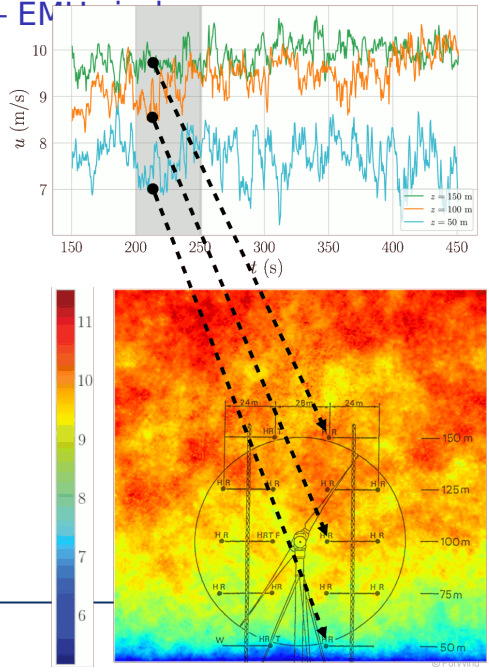
Constrained wind fields

- Method can include given measurement points
- More generally, arbitrary functional of given values

Example: GROWIAN

- Measurements on a 4 × 5 grid over rotor plane
- Included in high-resolution wind field

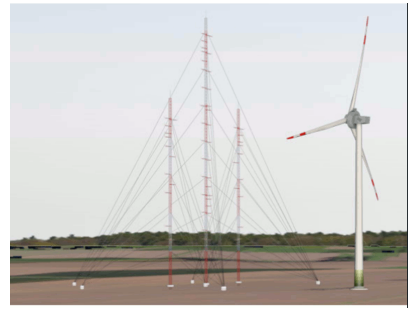
[Friedrich et al., PRX Energy 1, 2022]
[Friedrich et al., Phys. Rev. Lett. 125, 2020]



Superstatistical model for wind fields – EMUwind

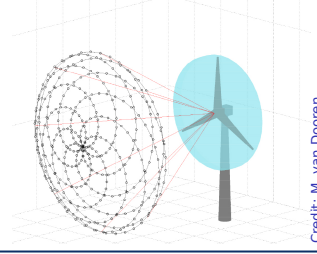
Conclusions, applications, outlook

- Superposition approach leads to Mann-type wind fields with realistic turbulence statistics
- Reproduces extreme fluctuations
- Further validation needed


Credit: DLR, CC-BY-SA 3.0

Applications

- Refinement of coarse-grid measurements
- Reconstruction of Spinner Lidar wind fields
- Investigate and apply site-dependent intermittency

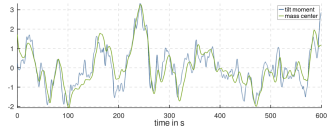

Credit: M. van Dooren

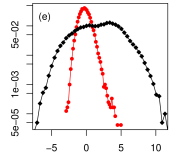
Outline

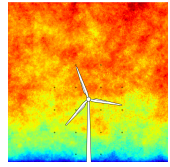
Summary

Field measurements are indispensable for fundamental and applied research

- Simplified model of wind-induced loads by “Center of Wind Pressure”
- Gust modeling and prediction by joint multi-point statistics
- Realistic wind fields by super-statistical approach







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