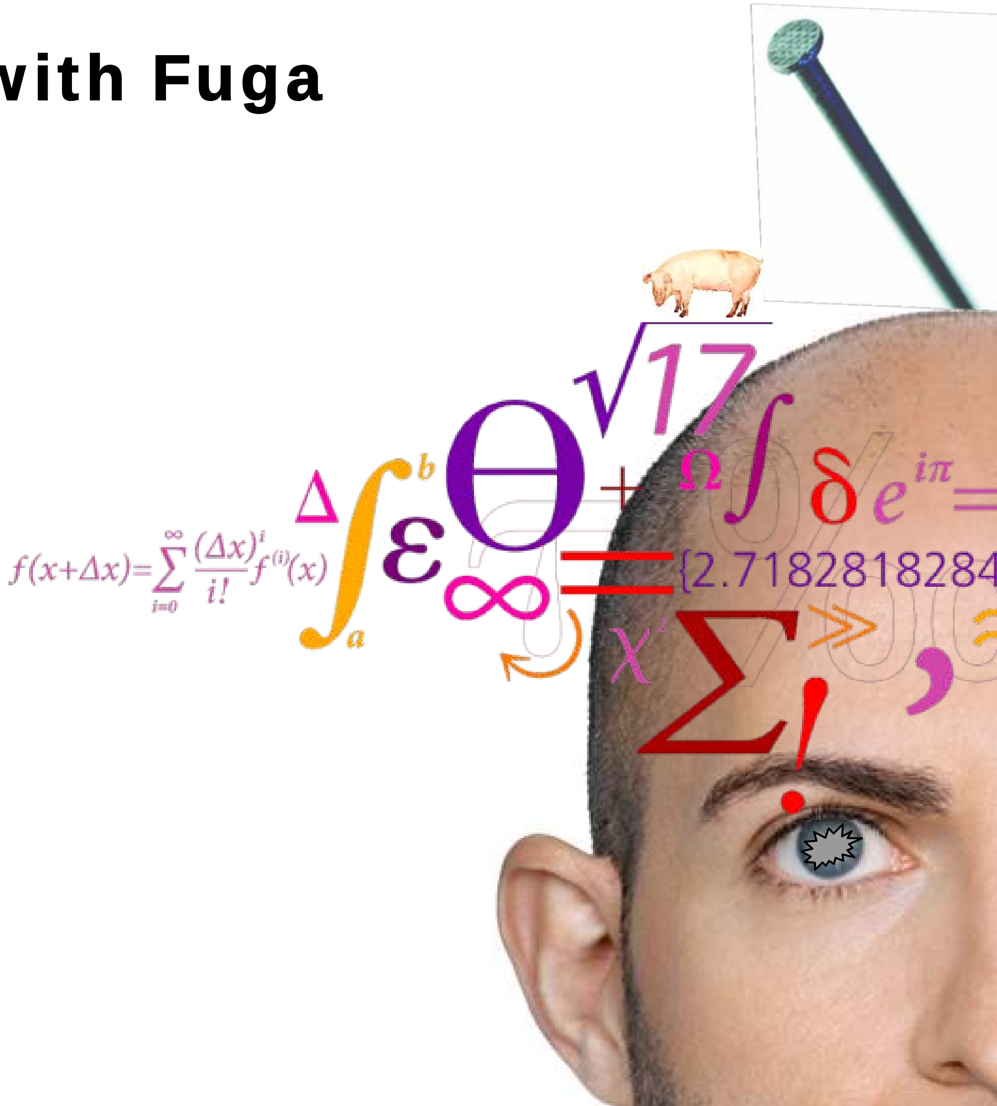
Fast wake modelling with Fuga

Søren Ott & Morten Nielsen



Fuga – main features*

- Solves linearized RANS equations
- Closure: mixing length, k-ε or 'simple' ($\nu_t = \kappa u_* z$)
- Fast, mixed-spectral solver using pre-calculated look-up tables (LUTs)
- No computational grid, no numerical diffusion, no spurious mean pressure gradients
- Integration with WAsP: import of wind climate and turbine data.
- 10^6 times faster than conventional CFD!

* Søren Ott, Jacob Berg and Morten Nielsen: 'Linearised CFD Models for Wakes', Risoe-R-1772(EN), 2011

Stage 1

- Objective:

  - Implement and validate a linearized CFD model

- Results:

  - Preludium: A fast solver that produces Look-Up Tables (LUTs)

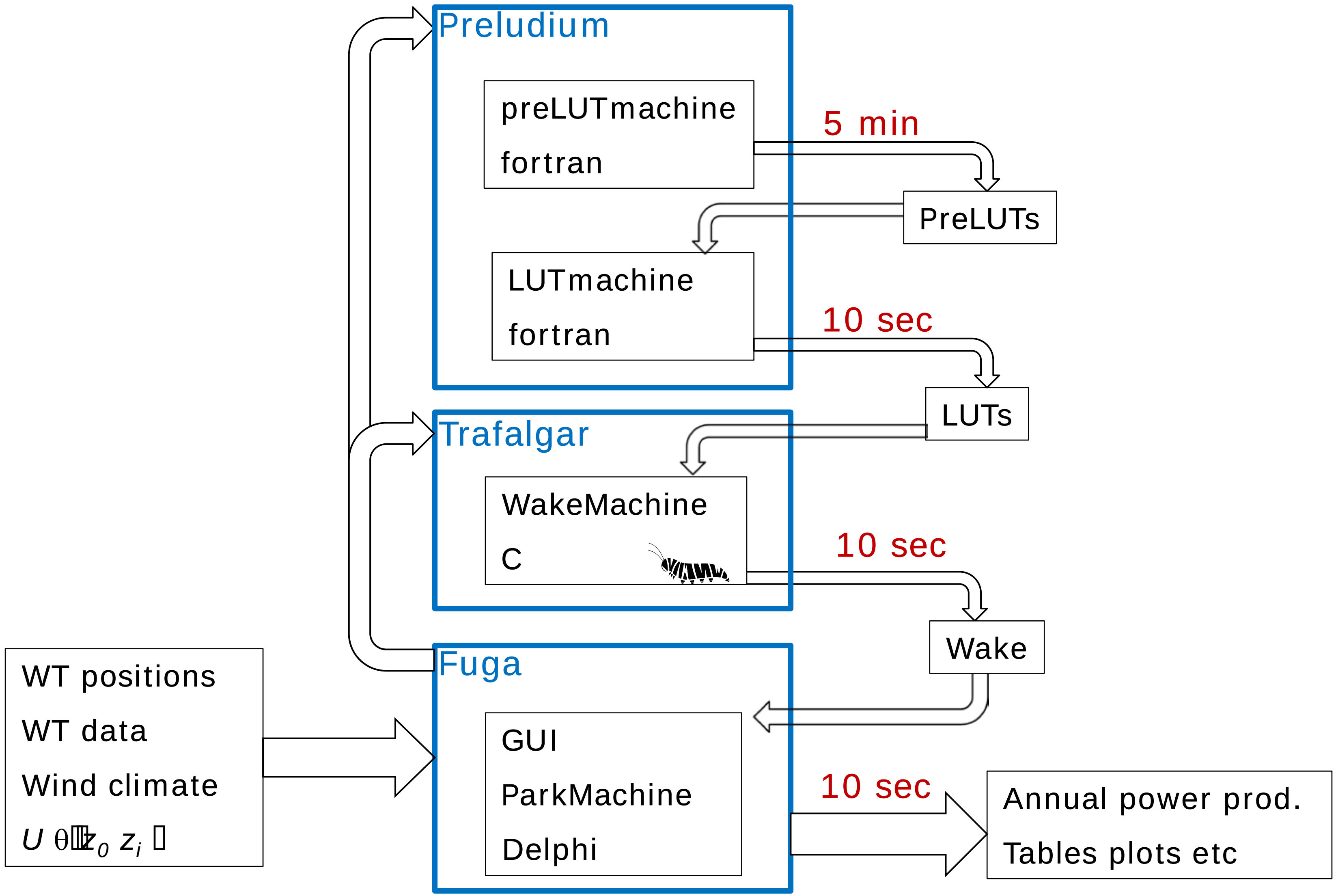
  - Trafalgar: Constructs solitary wake LUTs using FFIT

  - Fuga: Graphical user interface. Superposition of wakes with non-linear adjustment of the C_ts.

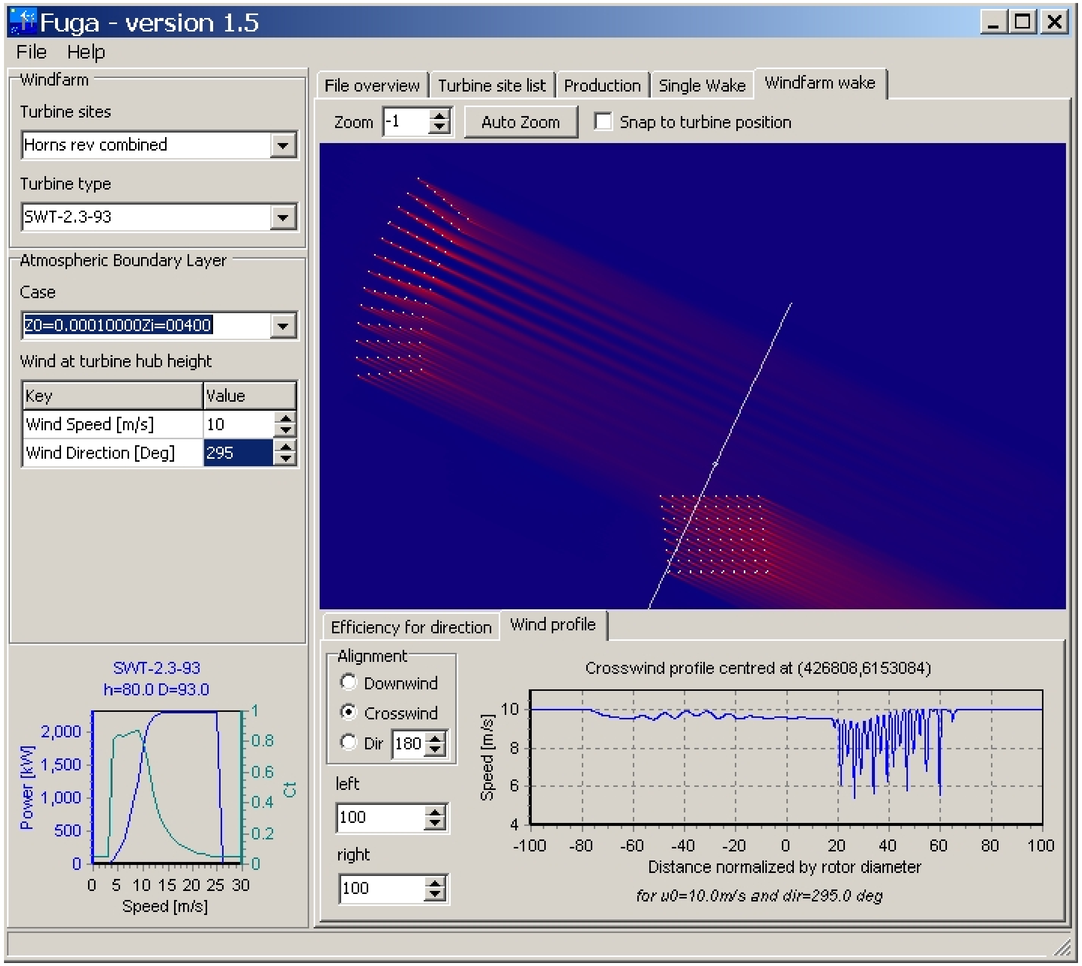
  - Choice of closure

  - Validation against Horns Rev1, Nysted 1 and Nibe.

Block diagram



User friendly GUI



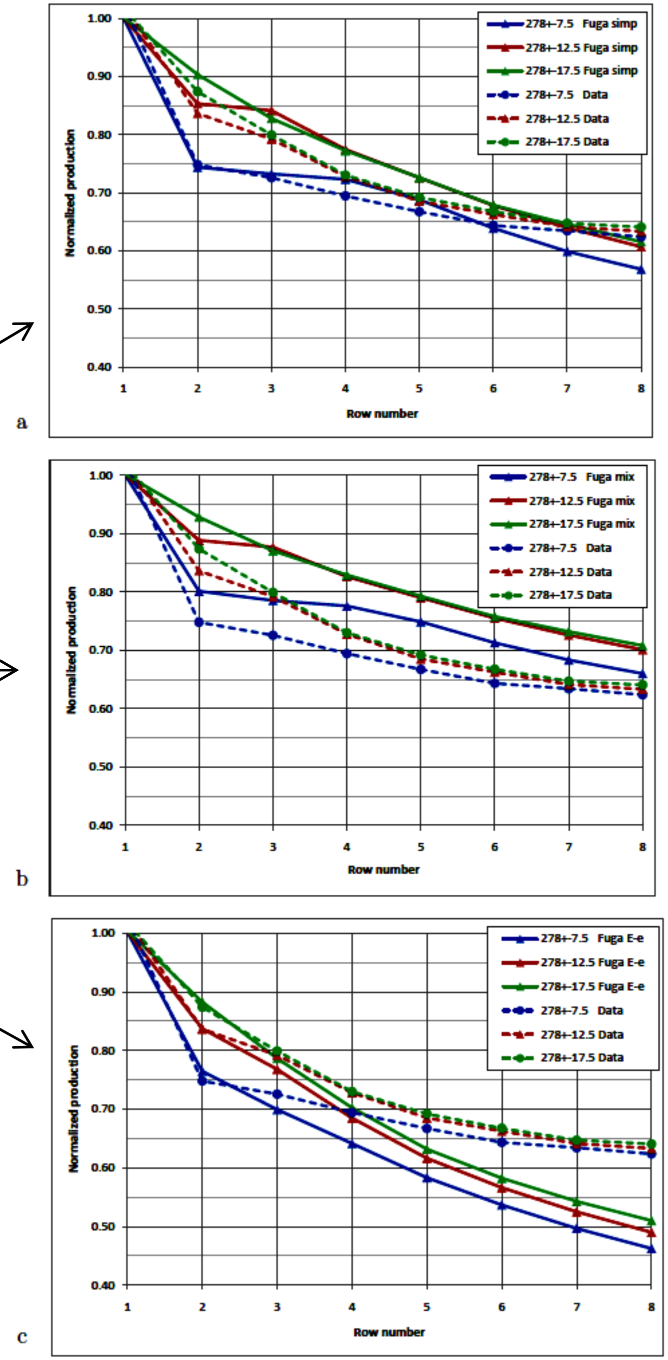
Choice of closure

Simple : $\nu_t = \kappa\, u_*\, z$

Mixing Length

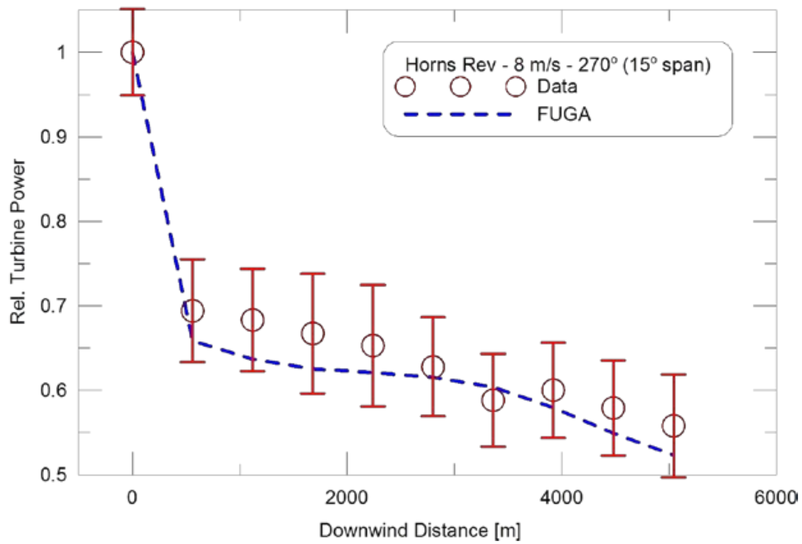
k - ε

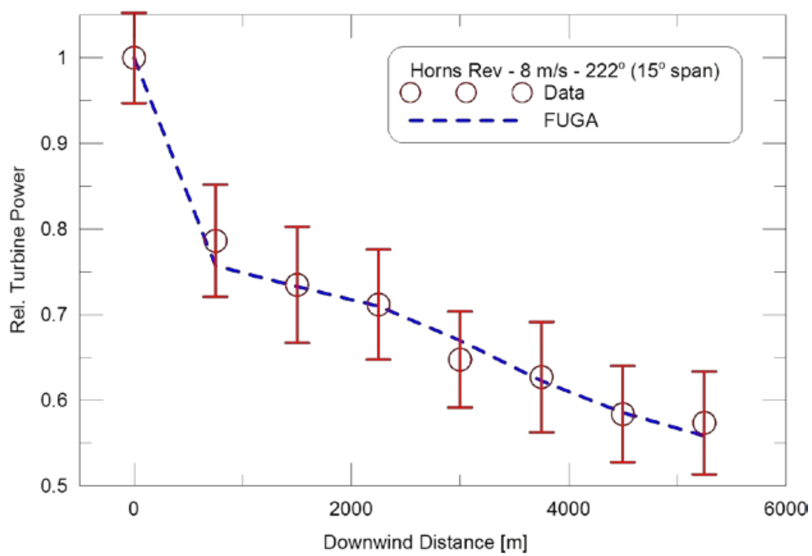
Nysted data

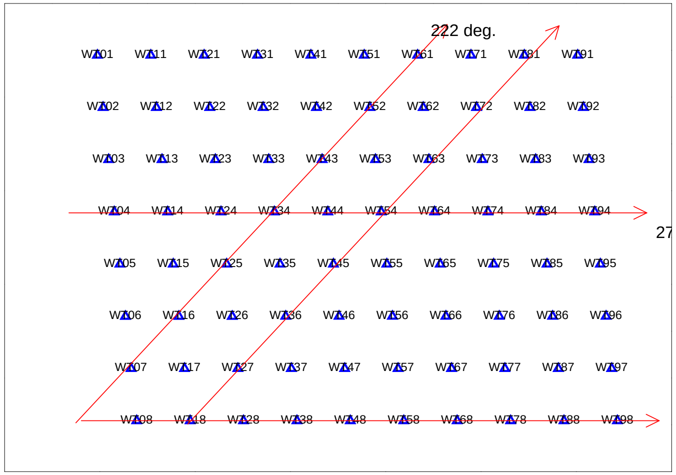


This one!

Validation: Horns Rev data. 8 m/s



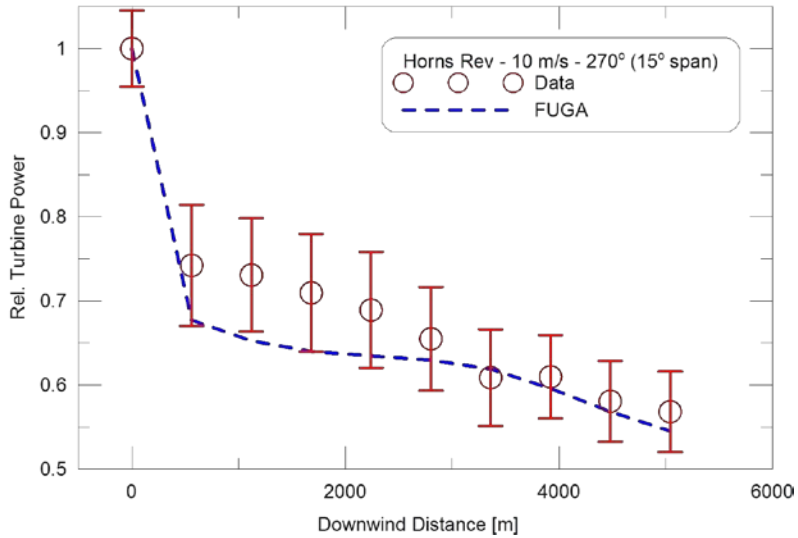


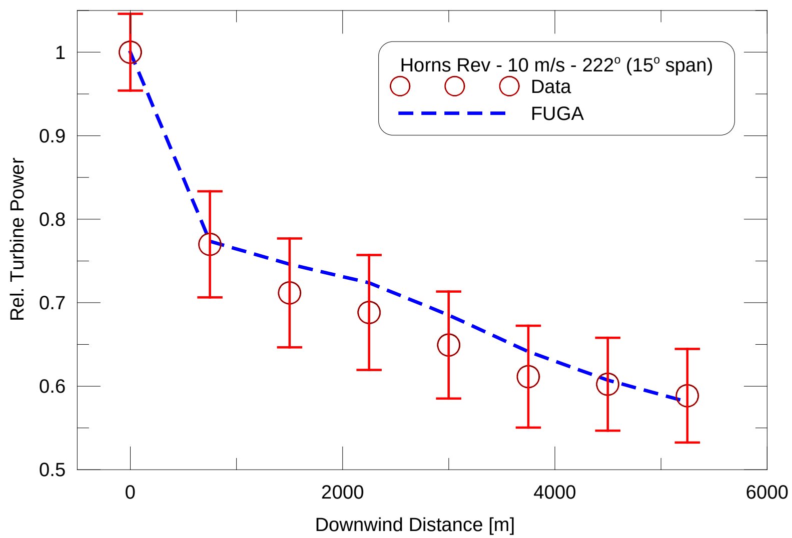


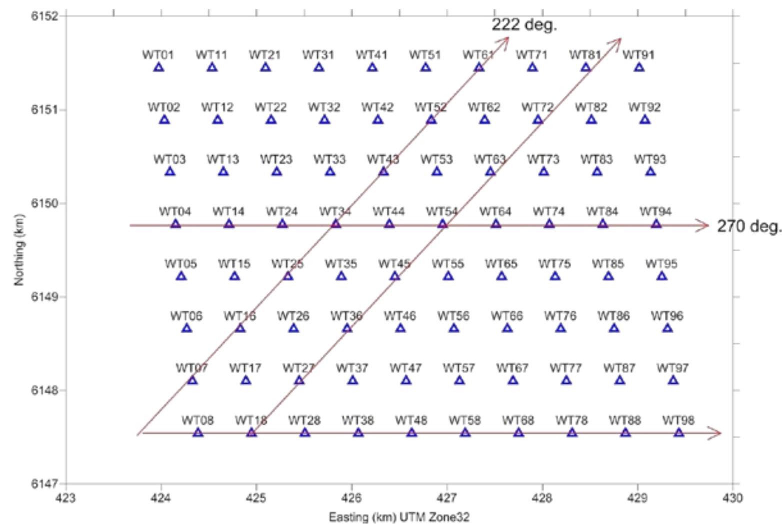
Simple closure: $\nu_t = \kappa u_* z$

No adjustable parameters!

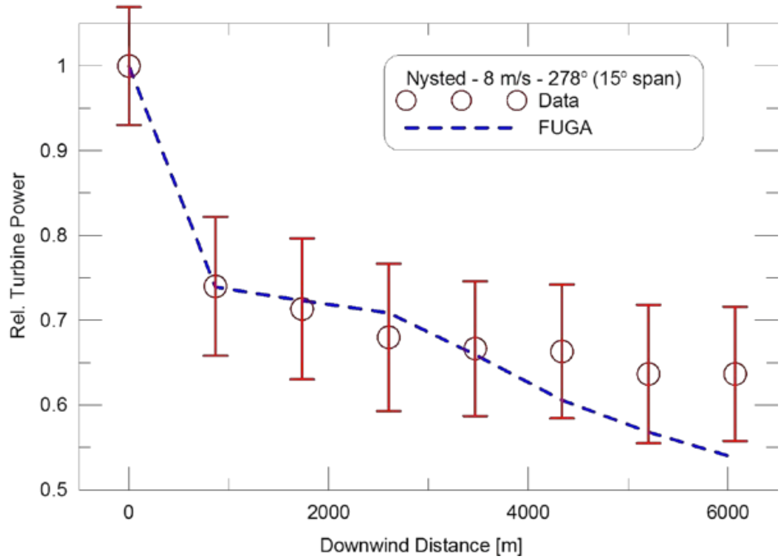
Validation Horns Rev data. 10 m/s

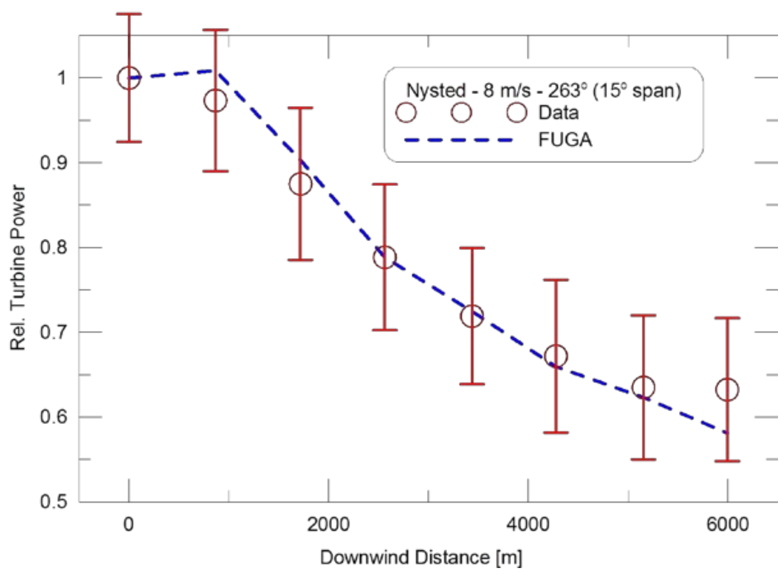


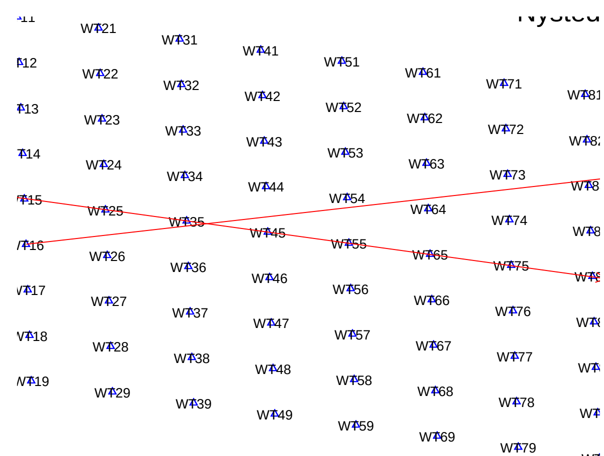




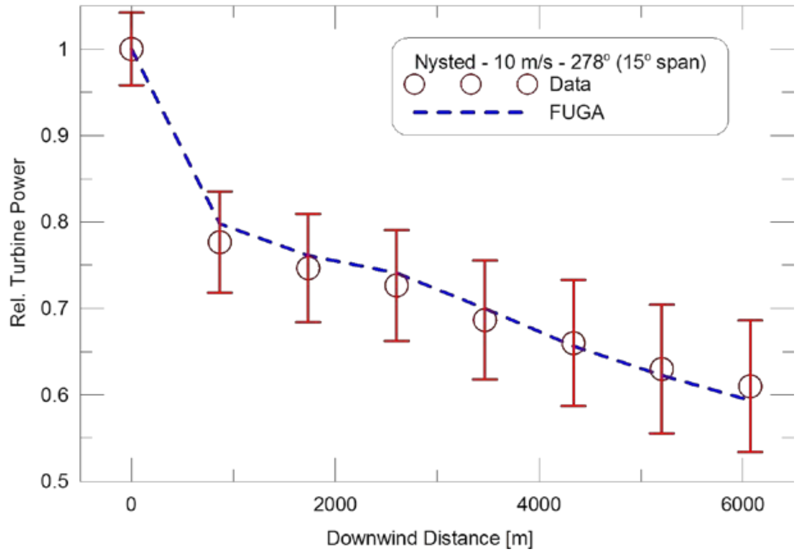
Fuga predictions vs. Nysted data. 8 m/s

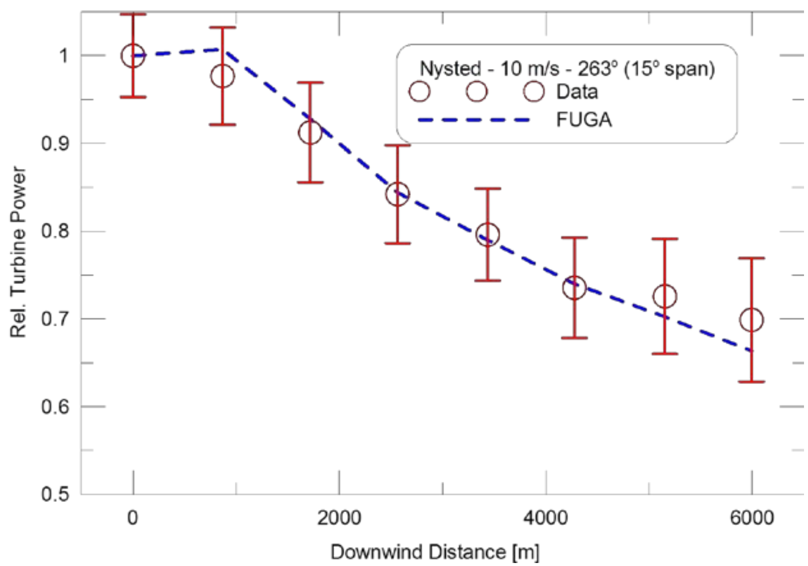


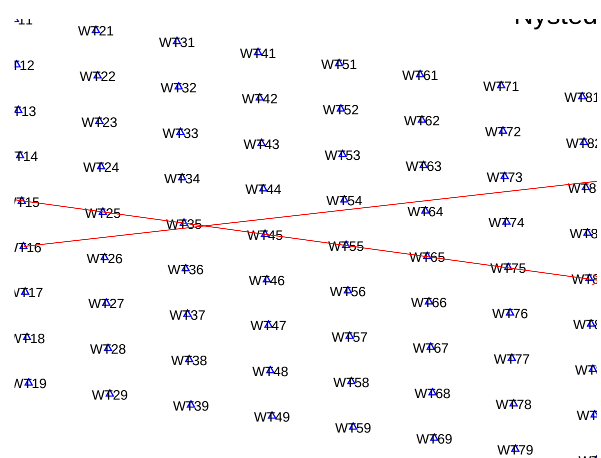




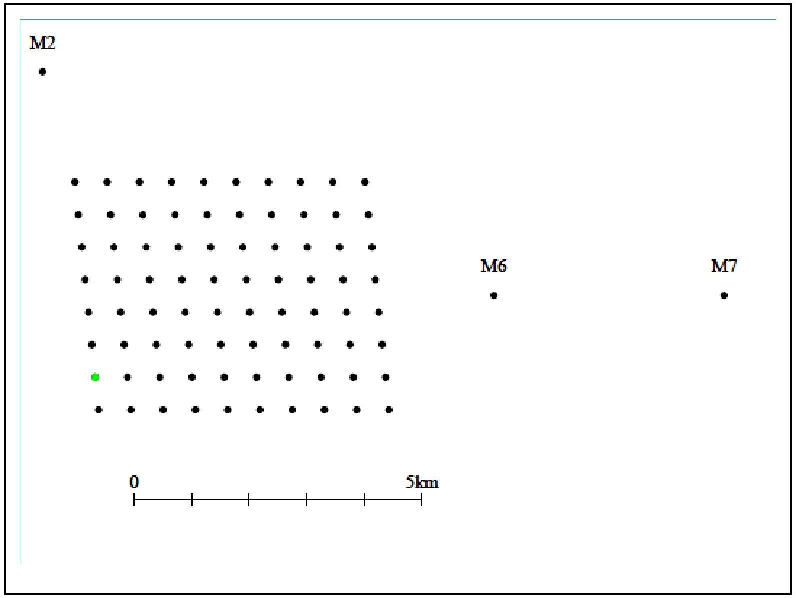
Fuga predictions vs. Nysted data. 10 m/s

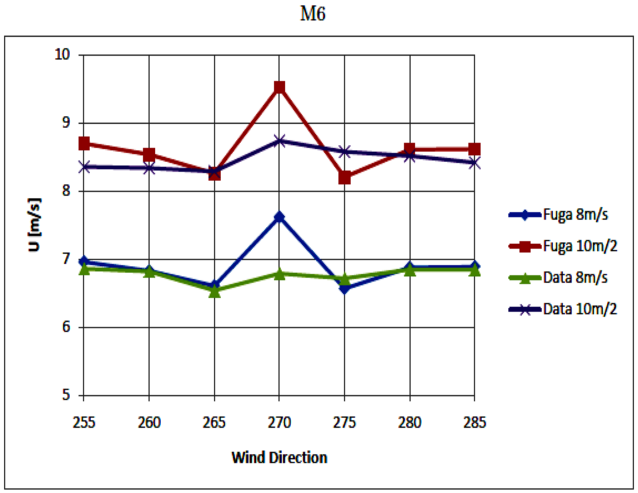


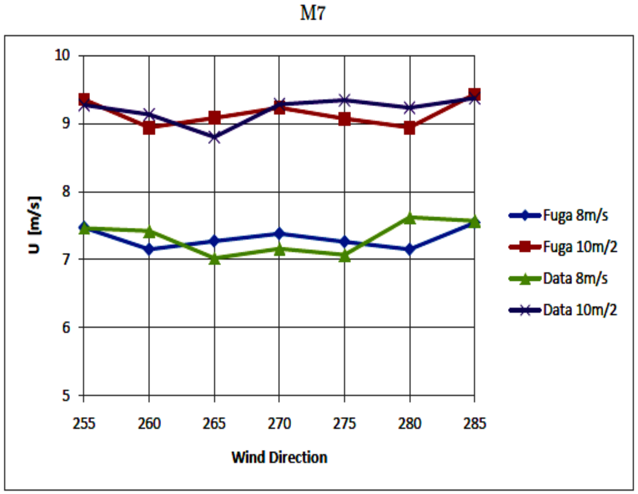




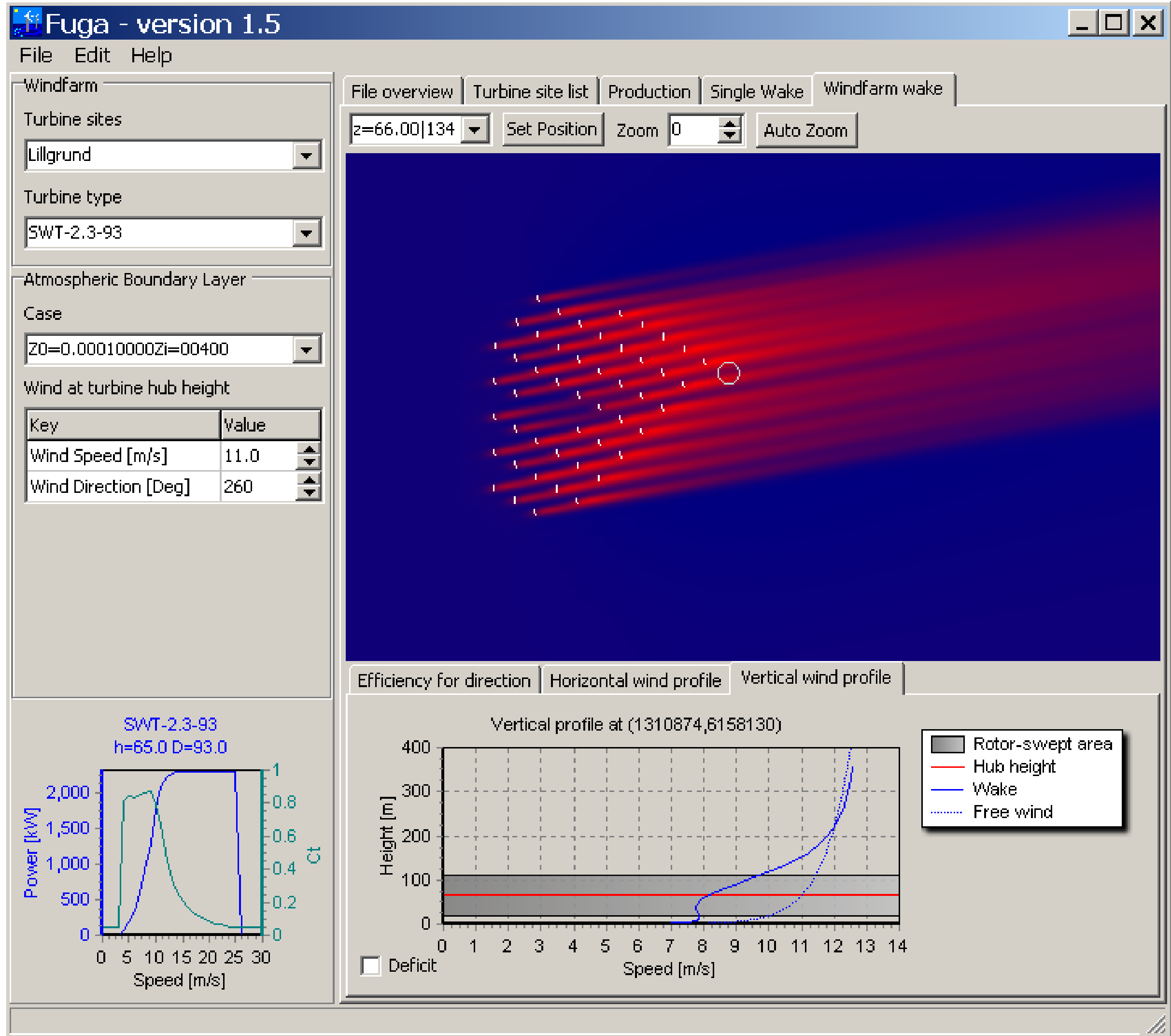
Validation: Farm wake effect (Horns Rev 1)





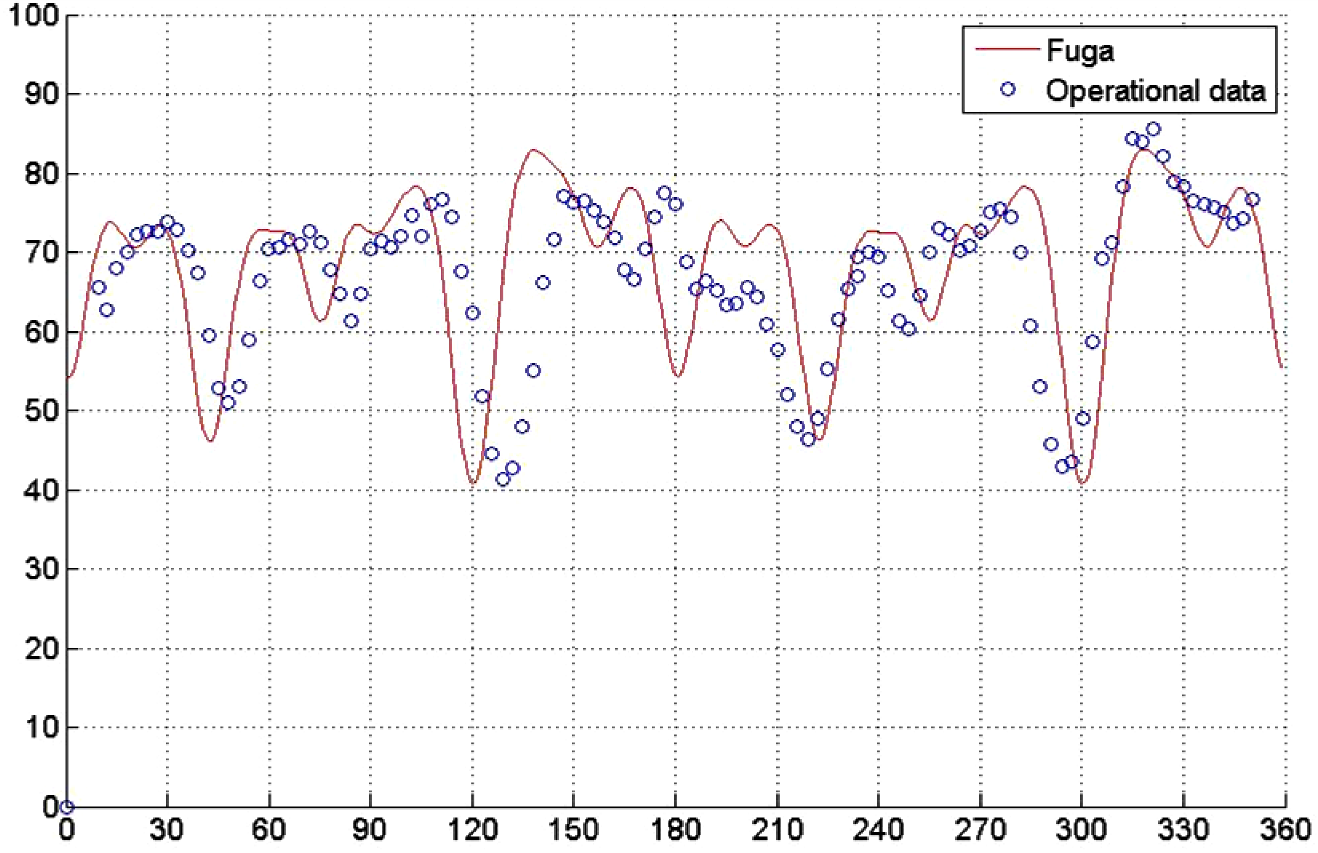


Lillgrund



Farm Efficiency

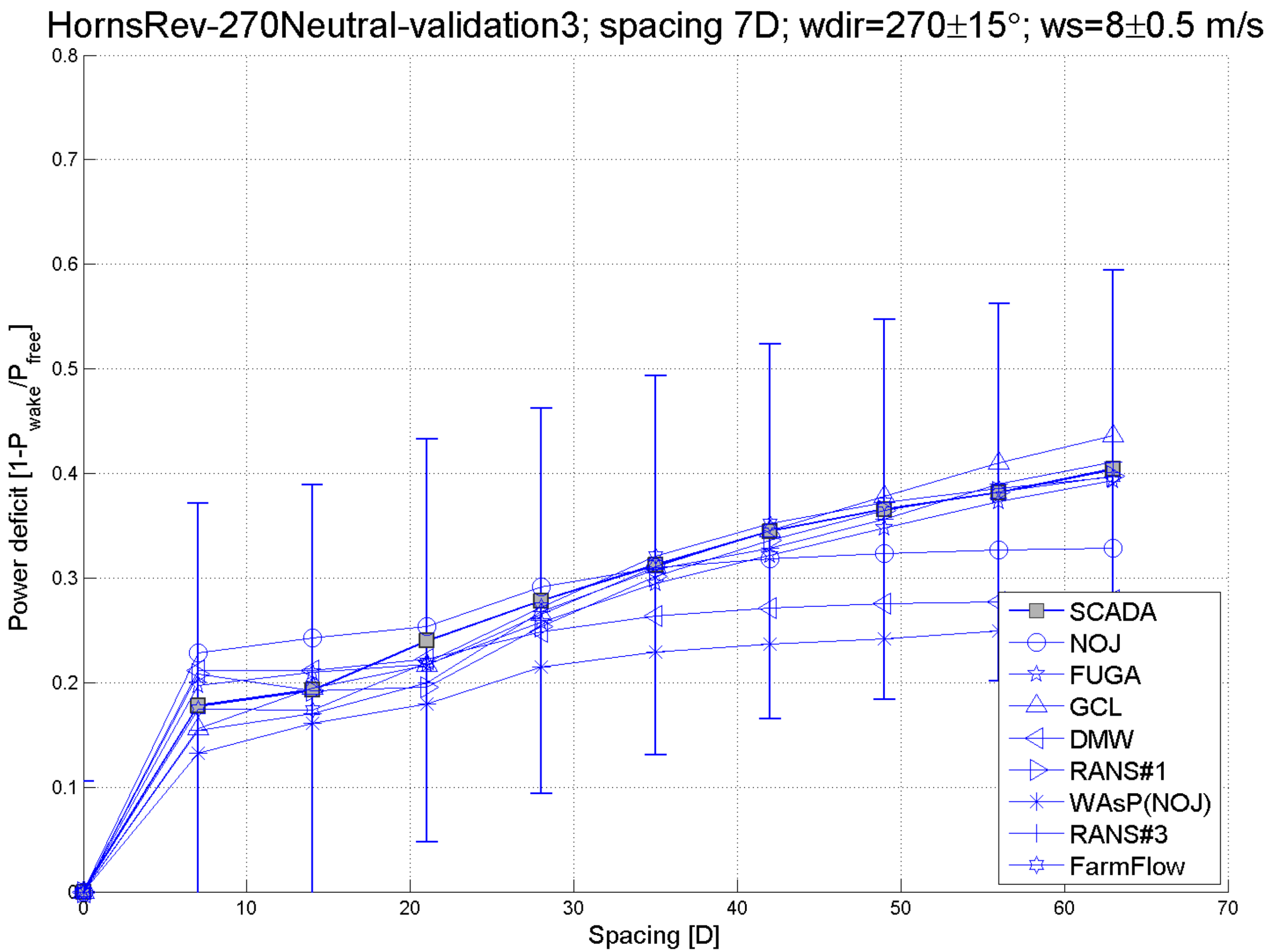
Validation: Lillgrund.



Simple closure: $\nu_t = \kappa u_* z$ and +/- 3 degree filter

Flow cases, part 1- engineering inflow sector

Thanks to Kurt S. Hansen for this slide



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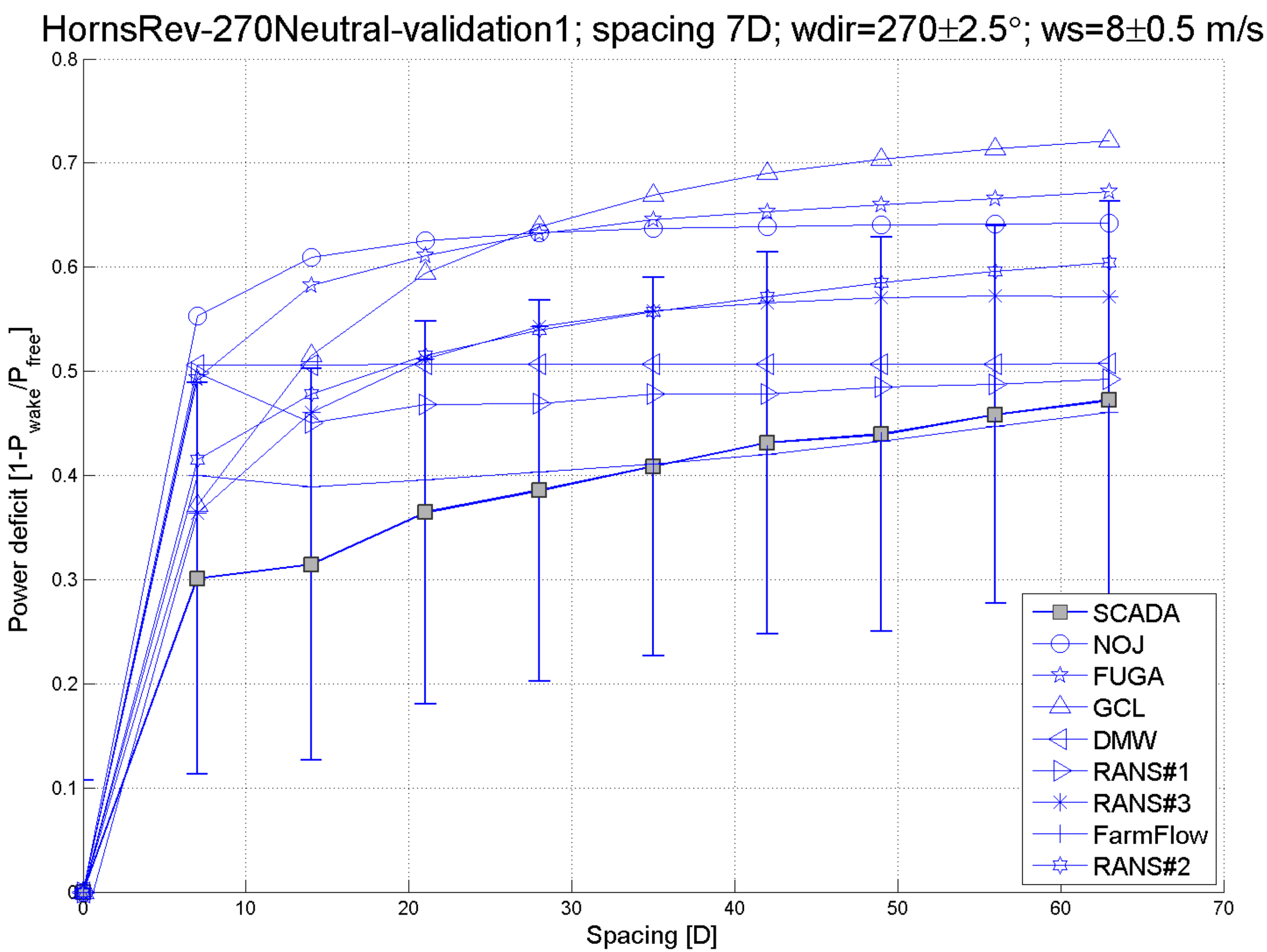
Flow cases, part 1 – narrow inflow sector

Thanks to Kurt S. Hansen for this slide



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Added features. Carbon Trust contract 2

- Flexibility: multiple turbine types, differentiated wind climate
- Rotor plane integration (7 point method)
- Stability : ‘simple’ approach using Monin-Obukhov theory
- Meandering: Use ideas taken from the Dynamic Wake Meandering (DWM) model
- Incorporation of HAWC2 library
- Validation: blind test against Rødsand data

Stability

Stability is taken into account through

- the mean profile:

$$U(z) = u_*/\kappa\ \{\log(z/z_0) + \psi(z/L) - \psi(z_0/L)\}$$

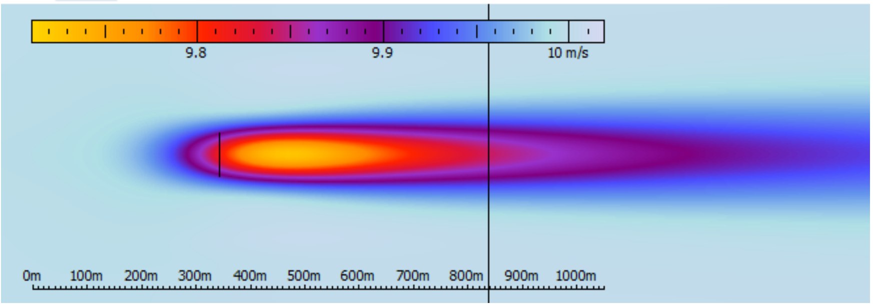
- the eddy viscosity :

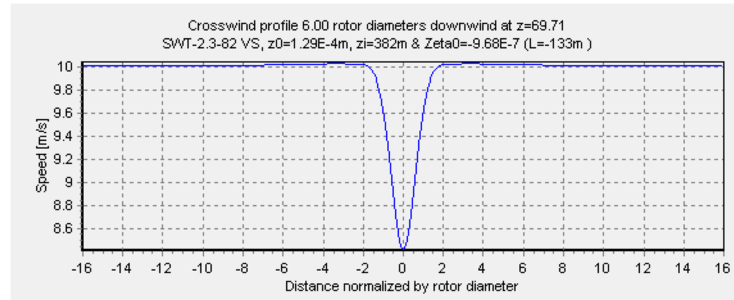
$$\nu_t = \kappa u_* z / \{1 + \varphi(z/L)\}$$

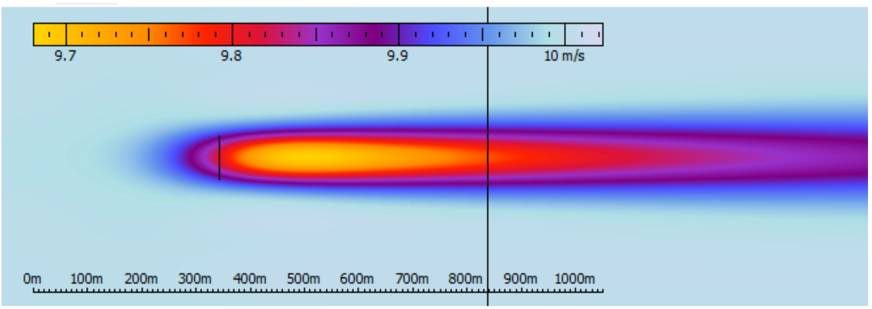
Notes:

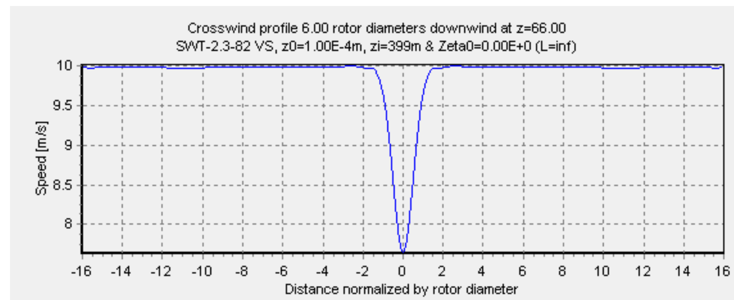
- No buoyancy, no temperature equation
- No influence of the wake on the eddy viscosity
- Monin-Obukhov theory only strictly valid in the surface layer
- With winds from shore the boundary layer is in a transient state
- Numerical problems for stable conditions

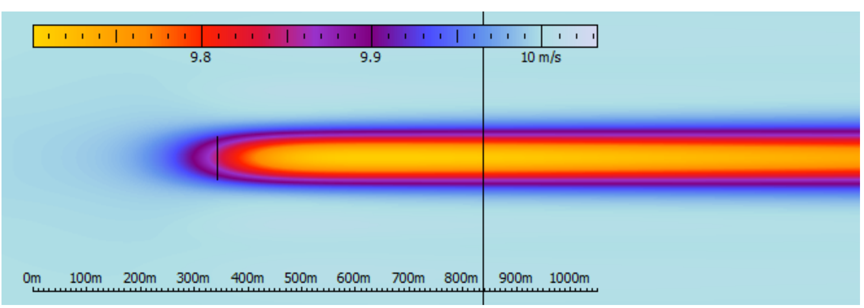
Variable atmospheric stability – horizontal profiles

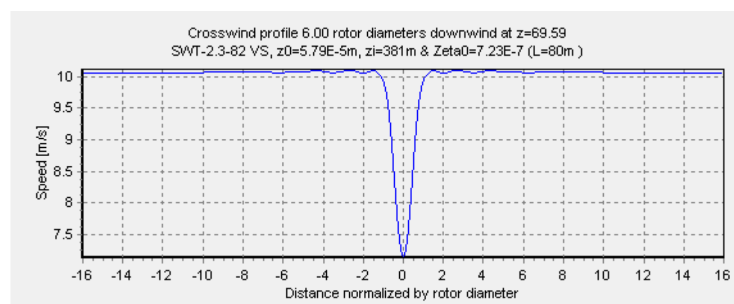




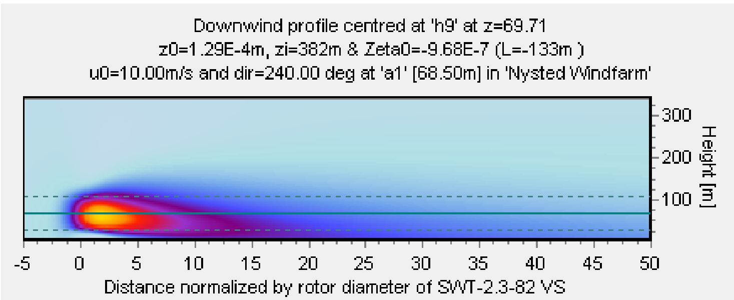


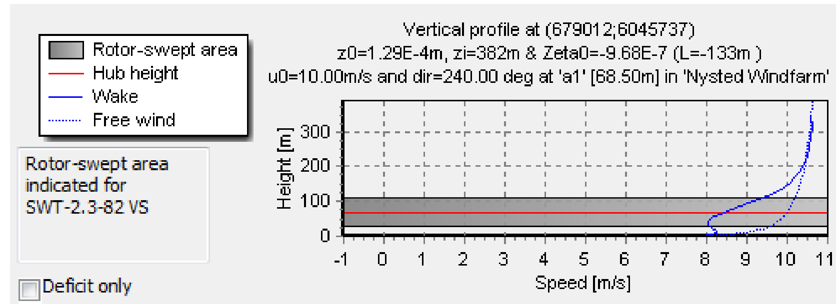


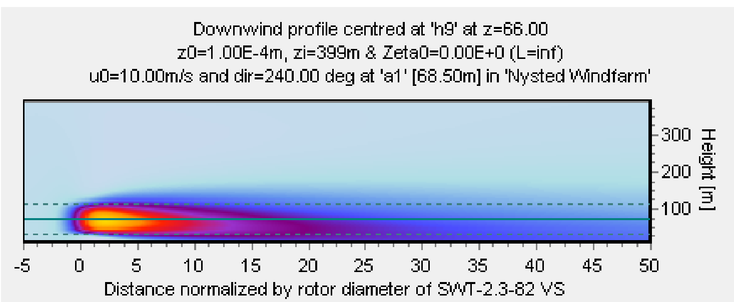


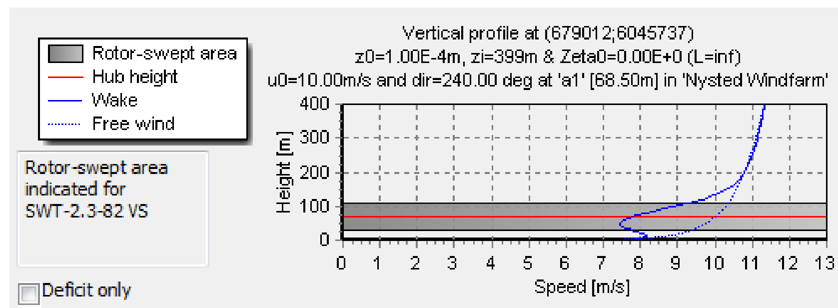


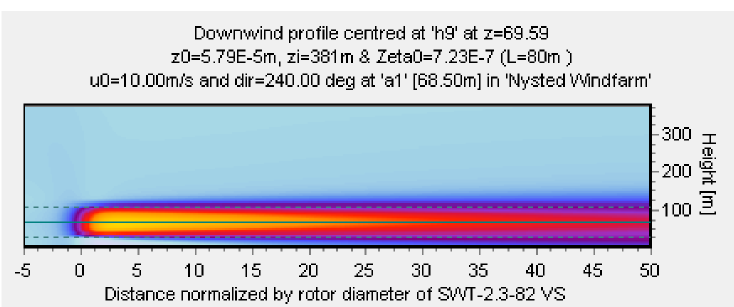
Variable atmospheric stability – vertical profiles

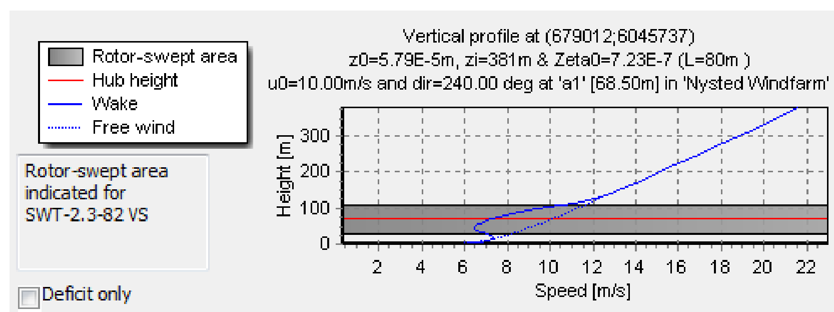






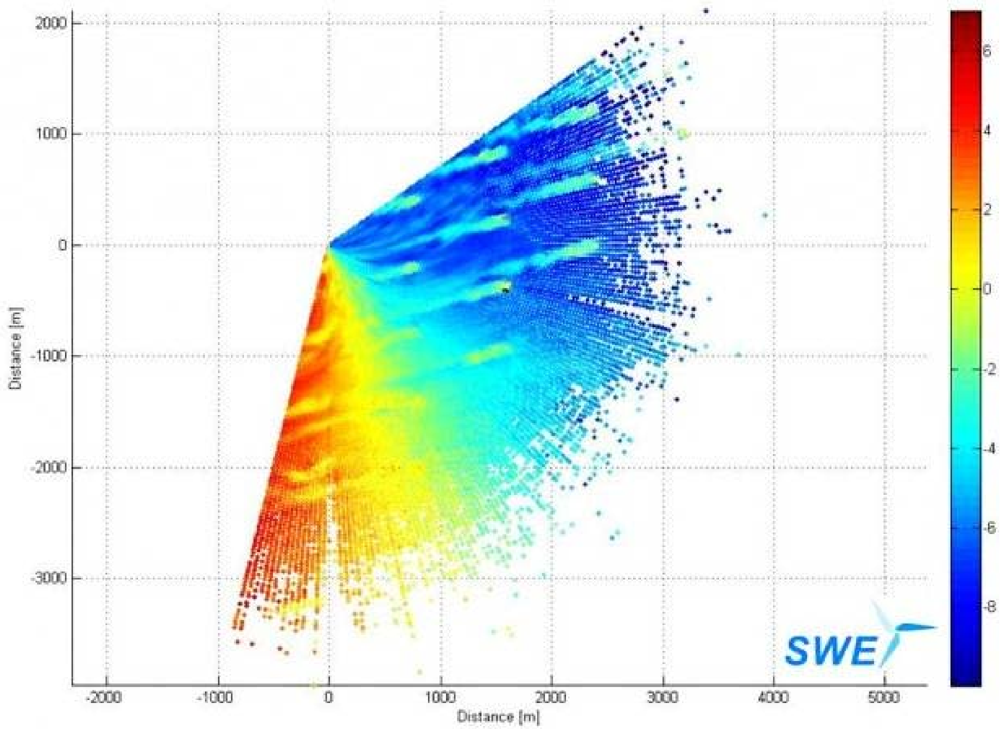


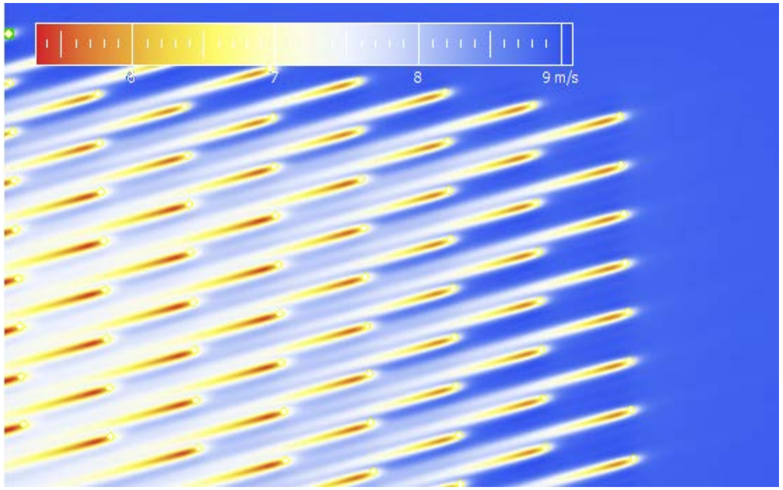


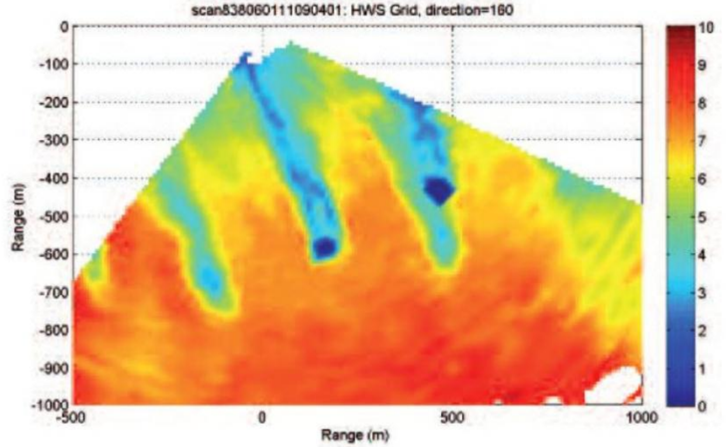


Meandering

Measurements with SgurrEnergy's Galion Lidar.

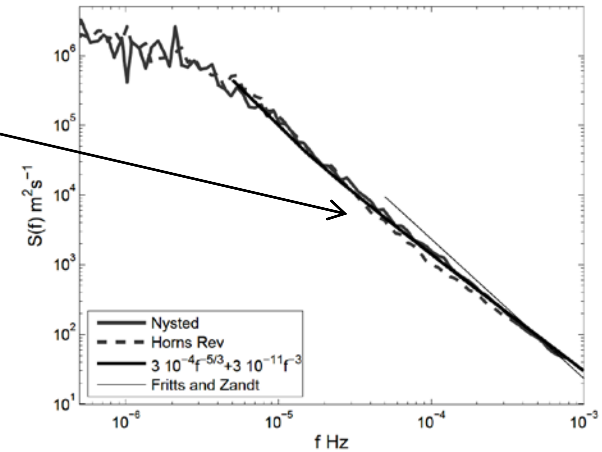






Spectral regimes

Larsén, Vincent & Larsen 2011



Universal range

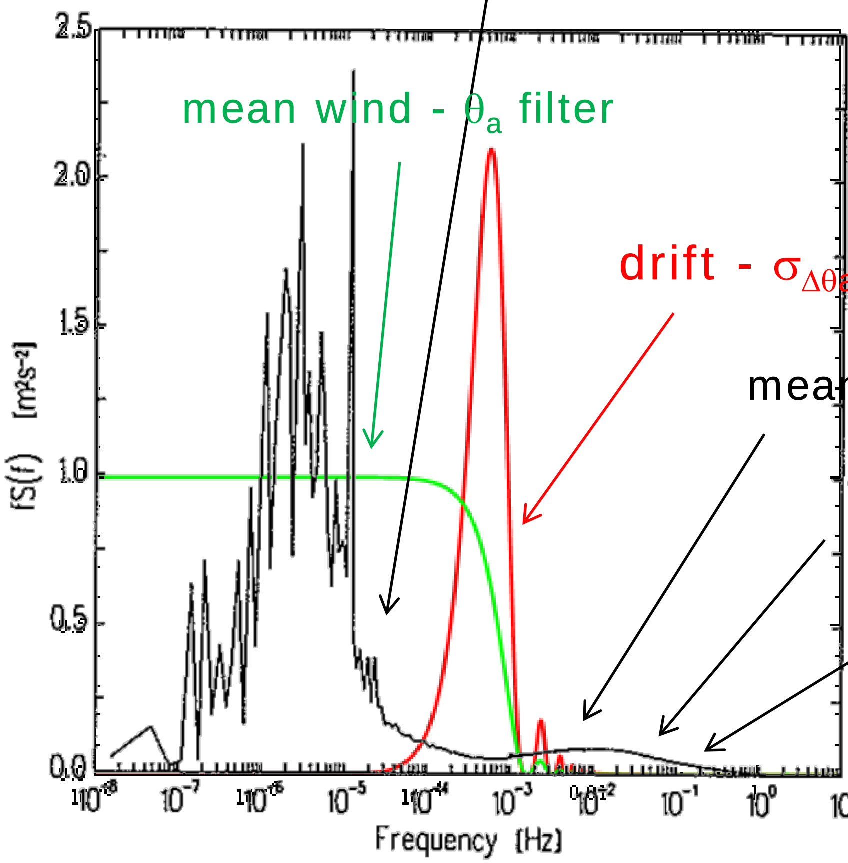
mean wind - θ_a filter

drift - $\sigma_{\Delta\theta a}$ filter

meandering

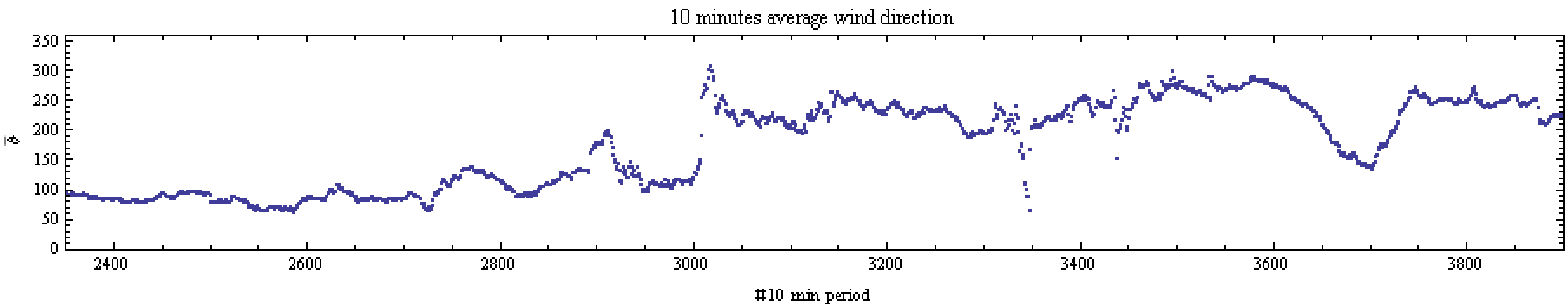
'scrambling'

eddy viscosity and RANS



Courtney & Troen 1990

Non-stationarity and drifting wind direction



- No RANS without stationarity.
- Conventional wisdom says: 10 minutes of data represents a piece of a stationary time series. Each 10 min defines a single RANS flow case.
- But the 'mean' wind direction varies. Each 10 min should be represented by a range of flow cases.
- How much does the 'mean' wind direction vary in 10 minutes?

Horns Rev 1 met mast data

Drifting wind direction

- Definitions:

  Wind direction : θ

  10 minutes average of θ : θ_a

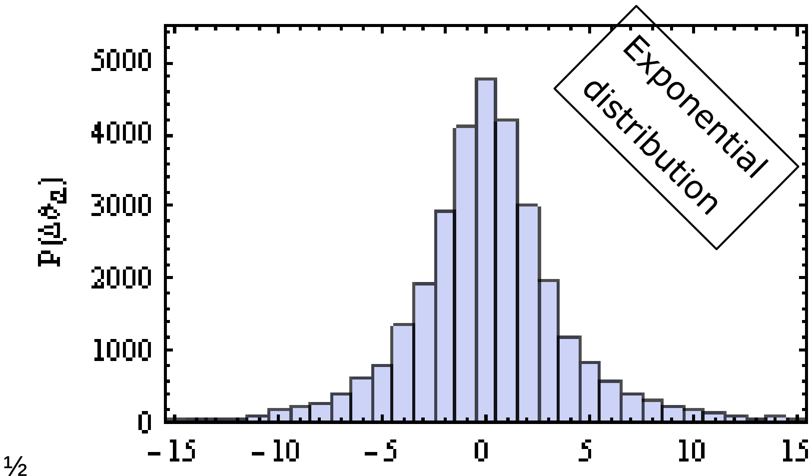
  Drift of θ_a during 10 minutes:

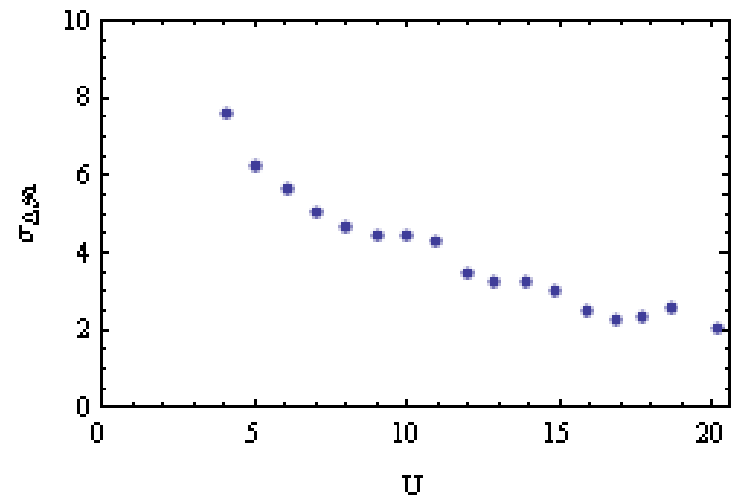
  $\Delta\theta_a = \theta_a(t+10\text{min}) - \theta_a(t)$

  Rms value of $\Delta\theta_a$: $\sigma_{\Delta\theta a} = <(\Delta\theta_a)^2>^{1/2}$

- $\sigma_{\Delta\theta a}$ is a measure of the shift of the average wind direction during 10 minutes.

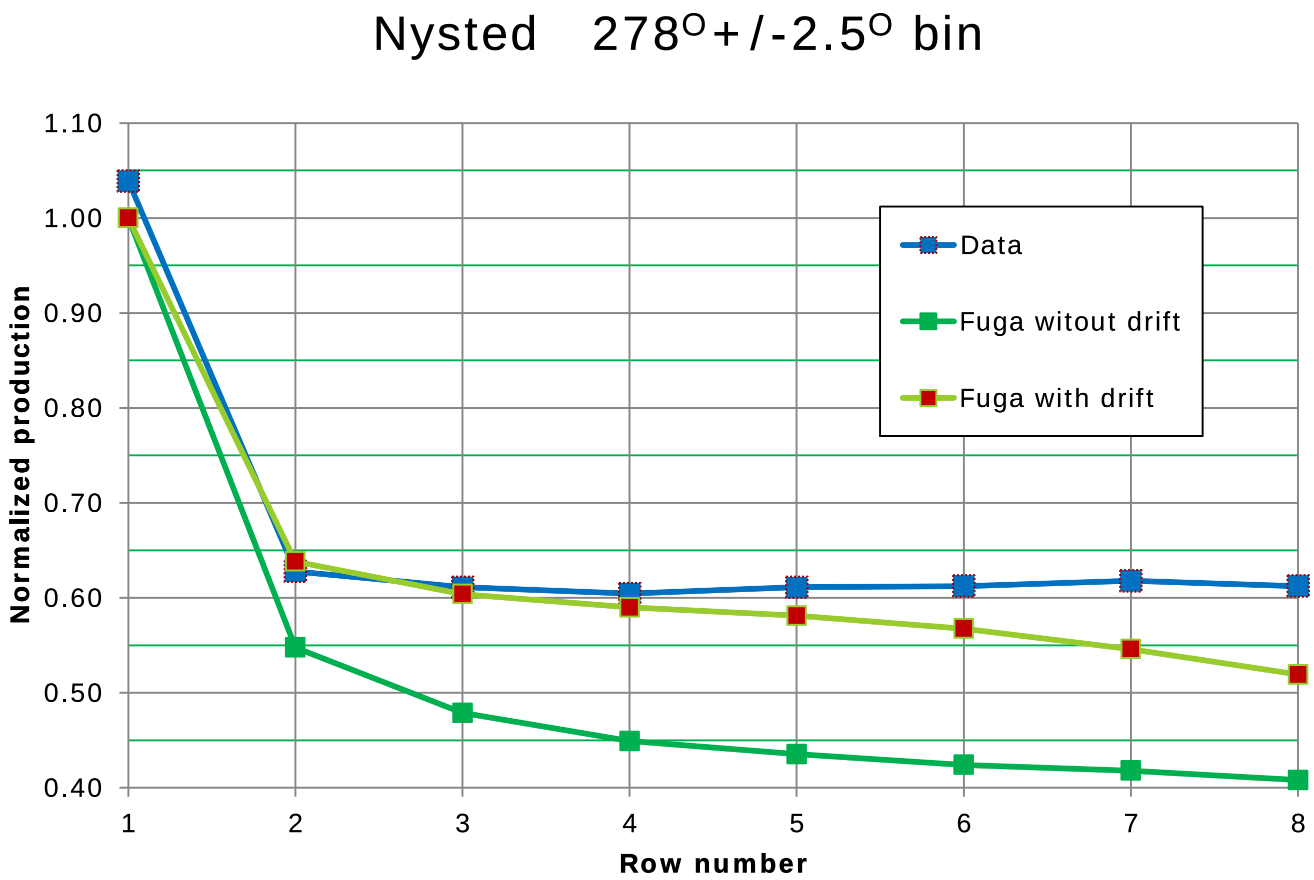
- $\sigma_{\Delta\theta a}$ can be obtained from 10 minutes average wind vane data.





$\sigma_{\Delta\theta a}$ = 4.7 degrees

Effect of mean value drift



Meander model

- Meandering is modeled using Mann turbulence.
- The wake centreline is assumed to follow a passive fluid particle.
- Low pass filtering to average over a transverse slab.
- Spectra for different stabilities and heights fitted by Alfredo* to 10 minutes time series.
- Linear de-trending was applied to the time series. This removes the wind direction drift.
- Meandering and wind direction drift are modelled as separate and independent processes.

* Peña, Gryning & Mann (2010): On the length-scale of the wind profile,

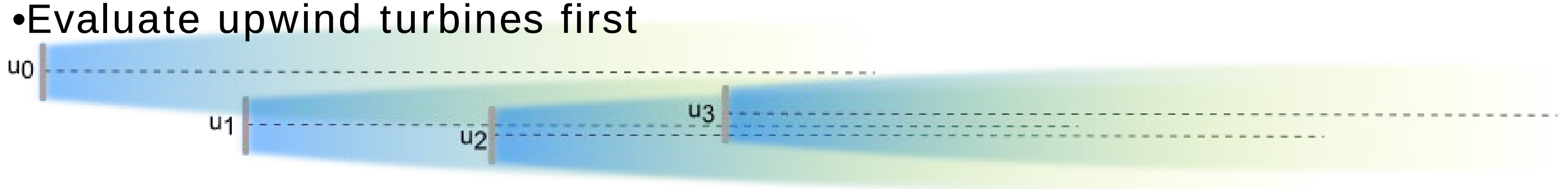
Q. J. R. Meteorol. Soc. 136: 2119–2131

Windfarm wake

•Superposition

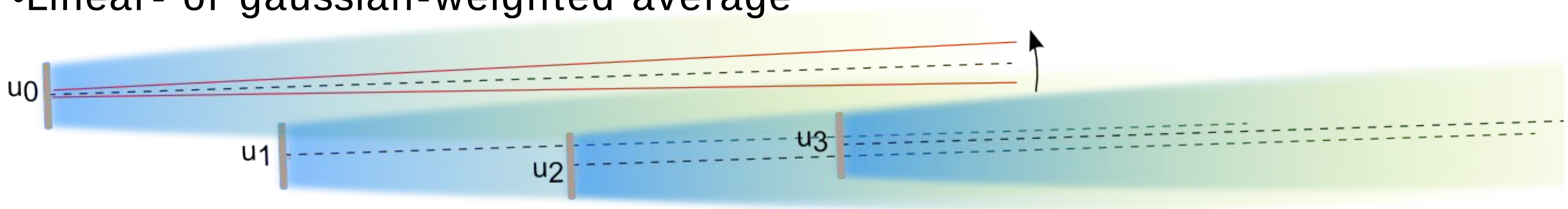
•Local thrust for sheltered wind speed

•Evaluate upwind turbines first



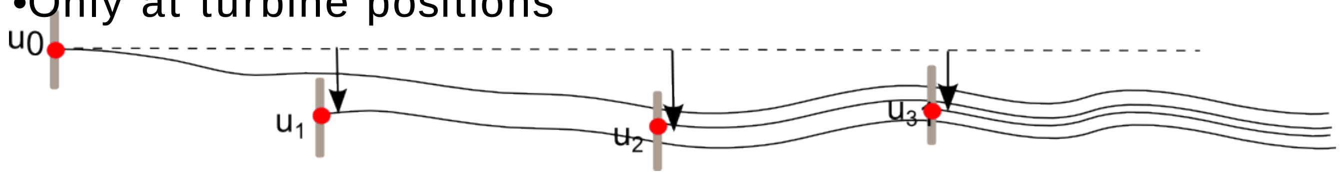
•Simple solutions for a set of wind direction

•Linear- or gaussian-weighted average



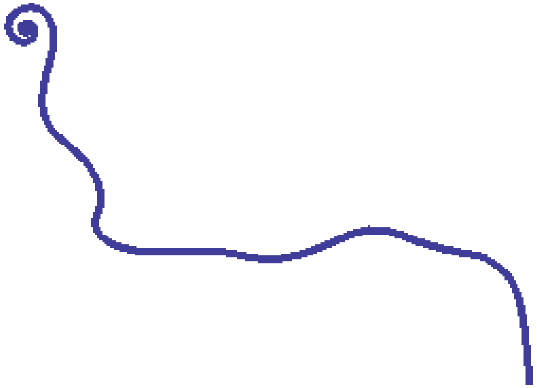
•Wake meander by stochastic simulation of wake deflection

•Only at turbine positions



DWM problem

- DWM uses Mann turbulence only for *v* and *w*, while a fived value is assigned to *U*.
- Thus the centre ‘particle’ stays in a 2D slab.
- Problem: attractors because this flow field is compressible.



- Better to use the full, incompressible 3D field.

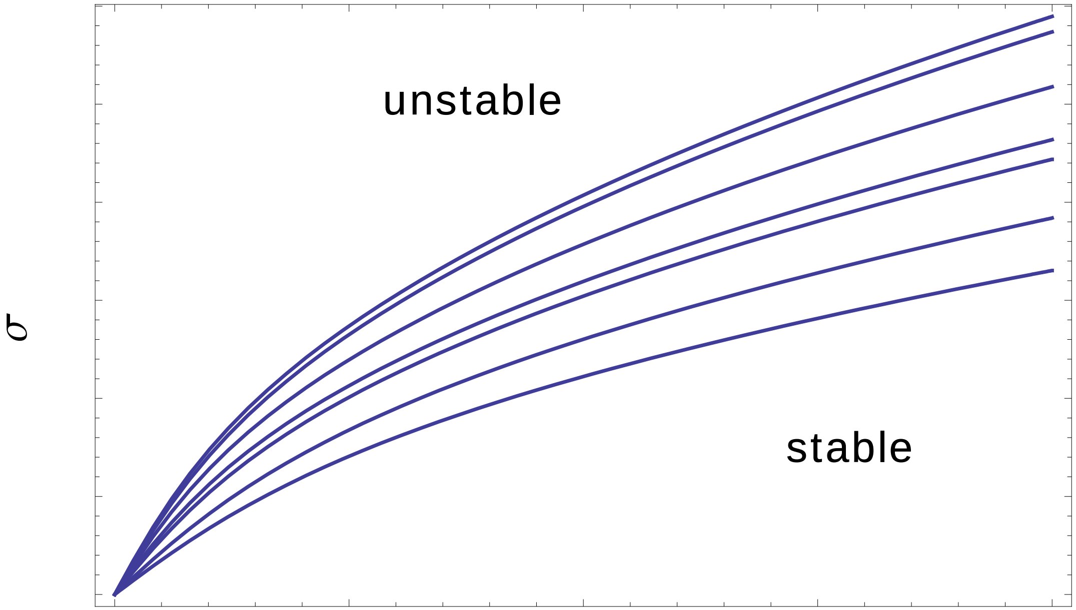
A model for turbulent diffusion in Mann turbulence

A good fit to the Lagrangian velocity auto-correlation function:

$$\langle v(t+\tau)\ v(t)\rangle = \sigma^2(1 +$$

Meandering by Mann turbulence

σ/u_* is rather small – not much meandering.
Did de-trending kill the important scales?



Conclusions

- Fuga is fast and yields good results. It is a useful tool.
- Full CFD is 1000000 times slower and not necessarily better.
- There is almost no meandering in Mann turbulence. What went wrong?
- Non-stationarity of the wind direction is important for the interpretation of measurements. Sampling in very small wind direction bins introduces a large uncertainty because a ‘true’ wind direction cannot be precisely defined.
- Distance effect: lack of correlation for large spatial separation between met mast and turbines. Again: don’t use small bins!
- Meandering means almost nothing for AEP estimates.
- Rotor plane integration lowers wake effect - unfortunately