Cumulative Interactions between the Global Blockage and Wake Effects as Observed by an Engineering Model and Large-Eddy Simulations

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Federal Ministry
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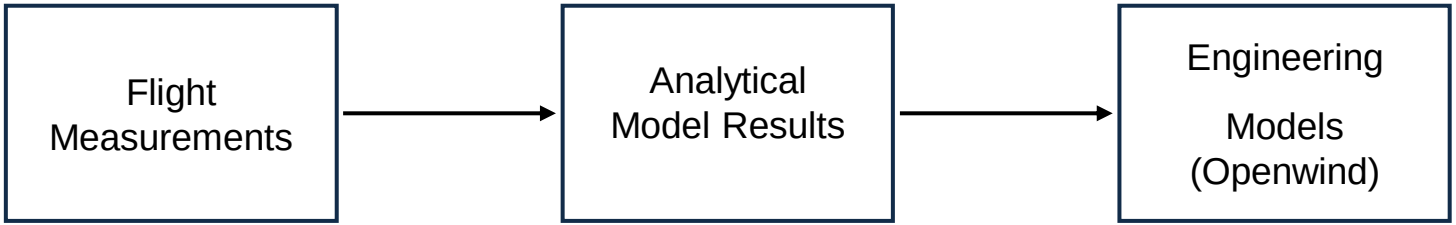
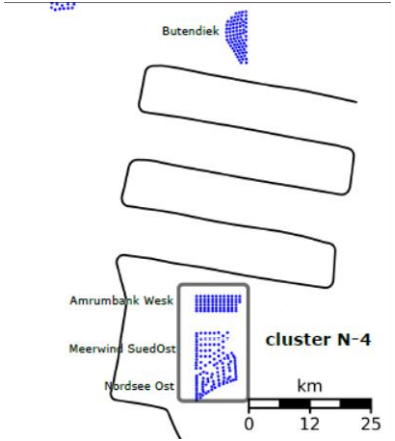
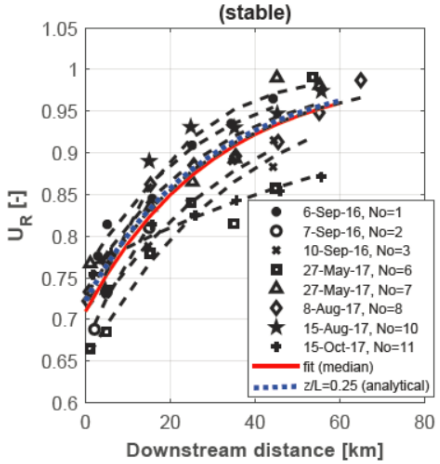
by the German Bundestag

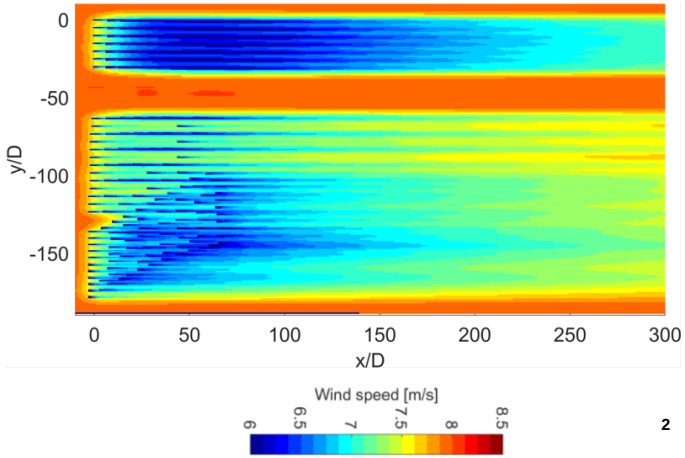
Overview

- Engineering (industry) model development from WIPAFF flight measurements to X-Wakes and beyond









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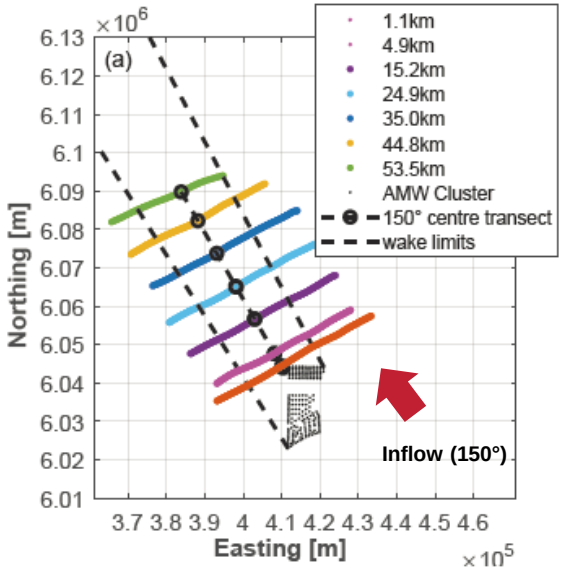
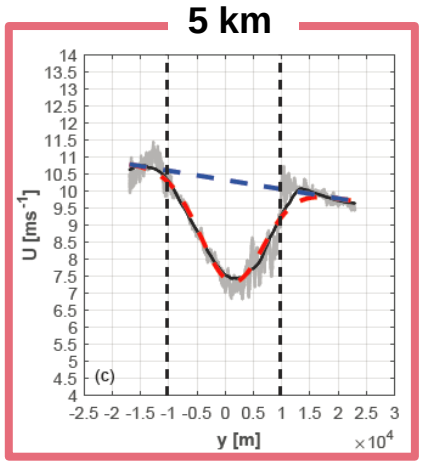
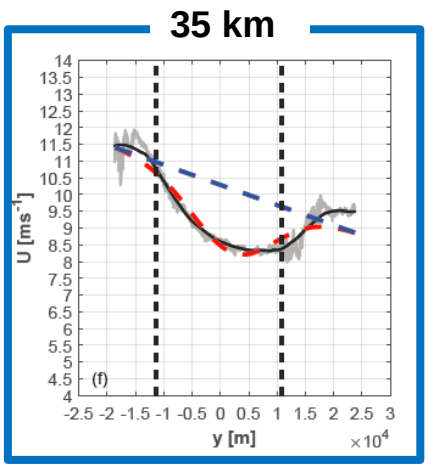
Analysis of WIPAFF Flight measurements

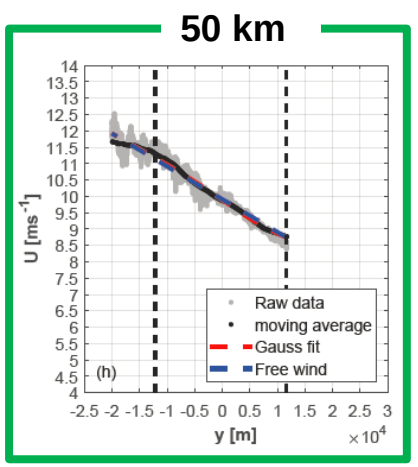
- Analysis of numerous flight measurements to extract horizontal wind speed profiles:

research aircraft Dornier DO 128-6 (TUB)







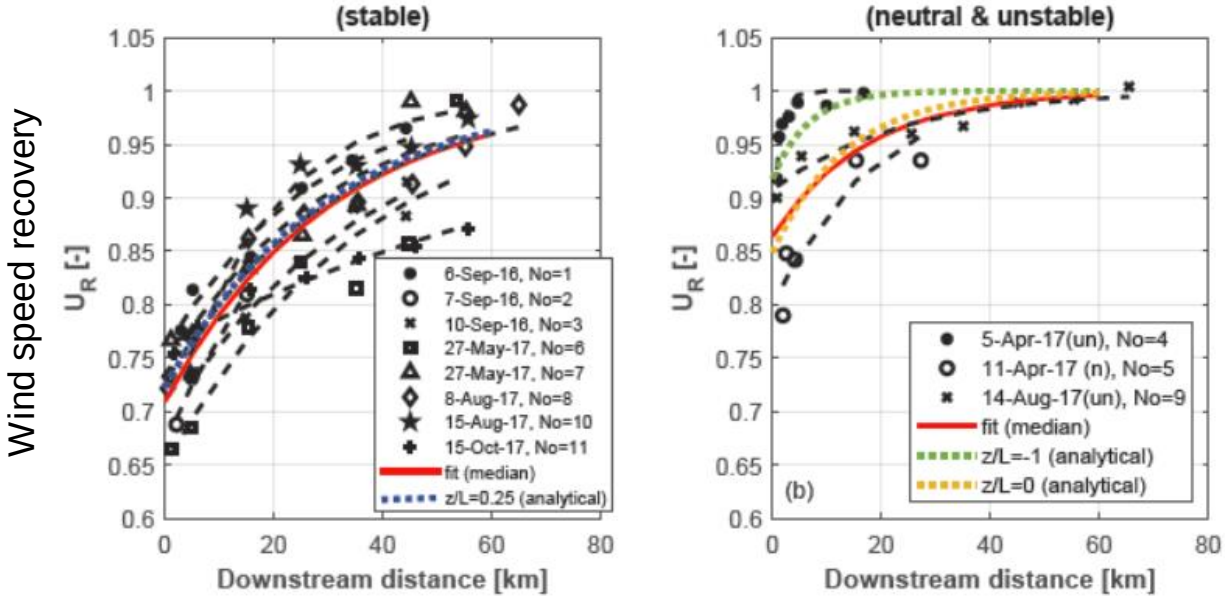


Increasing distance downstream

*Horizontal wind speed profiles looking downstream during **strong stable conditions** (z/L = 1.1)*

Aggregation of measurements agreed with analytical model

- Accumulation of all analyzed campaigns into either stable (left) or neutral/unstable conditions (right)
- Note the line of the analytical model (left: blue, right: green, yellow) in both figures originally proposed by Stefan Emeis



Analytical Model

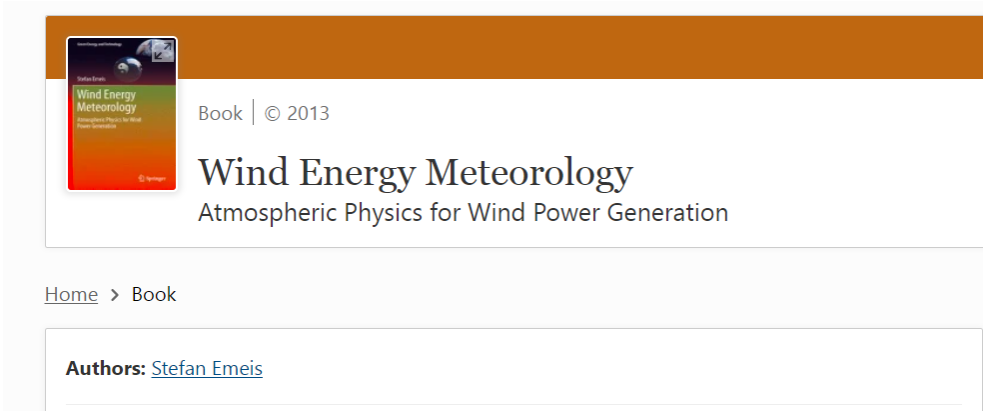
- Analyical infinite wind farm model of Emeis:
- Upstream internal wind farm part:

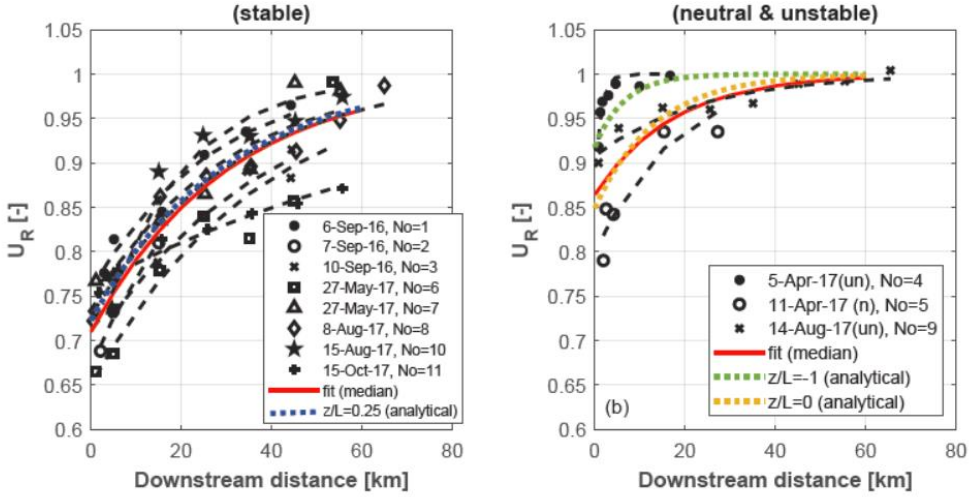
$$U_{R0} = \frac{U_0}{U_\infty} = \frac{\frac{h+\Delta z}{\Delta z} I_u + \frac{\Phi_m}{\kappa^2} C_d}{\frac{h+\Delta z}{\Delta z} I_u + \frac{\Phi_m}{\kappa^2} C_{t,eff}},$$

- Downstream wind farm part:

$$U_R = \frac{U}{U_\infty} = 1 + \left(\frac{U_0}{U_\infty} - 1\right) \exp\left(-\beta t\right),$$

- The blue and yellow/green curves are the downstream part





Engineering Model

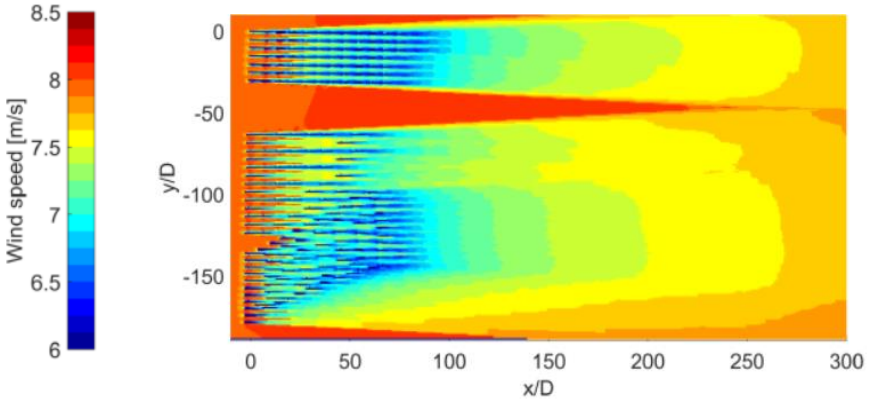
- Modify analytical Emeis model for two-dimensional, real wind farms for use in Openwind
- New **“**Atmospheric Stability Model (ASM)**”** Openwind based on an area distributed wind farm drag
- Principally to estimate long wakes behind wind farms in stable conditions but can be used in conventional energy assessments

https://www.ul.com/software/openwind-wind-farm-modeling-and-layout-design-software

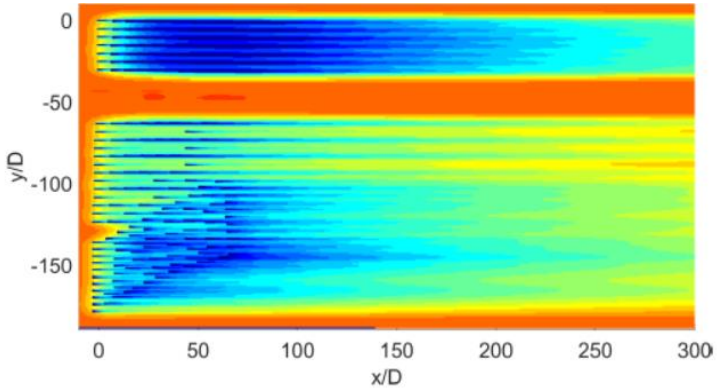
Atmospheric Stability Model (ASM)

- Calculate the wind farm drag together with the turbine wake effect (e.g. Eddy-Viscosity model)
- Extrapolate downstream to account for nearby wind farms (e.g. between ABW and NSO for northerly winds)

Openwind neutral:



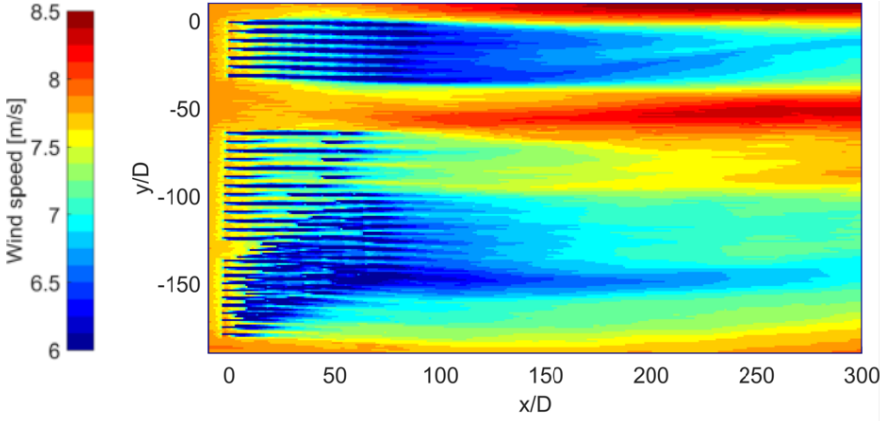
Openwind stable (ASM):



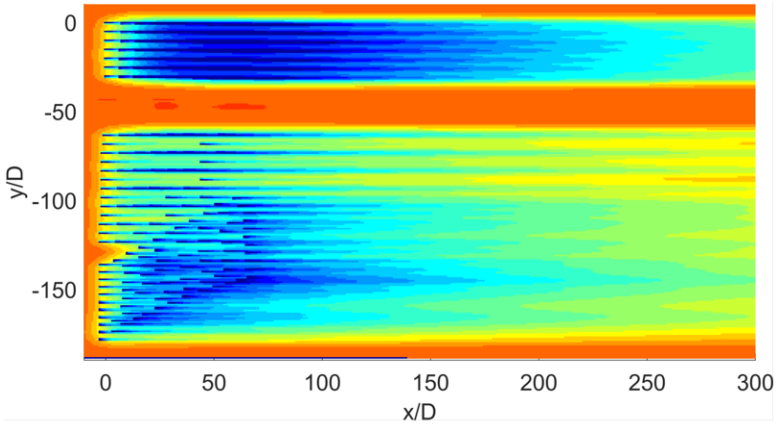
Large Eddy Simulation (LES) Model

- **Aim**: to see whether ASM gives detailed plausible two-dimensional results
- Compare with LES results from PALM simulations
- Cases: Neutral for different boundary-layer heights, one weakly stable case

Stable LES



ASM

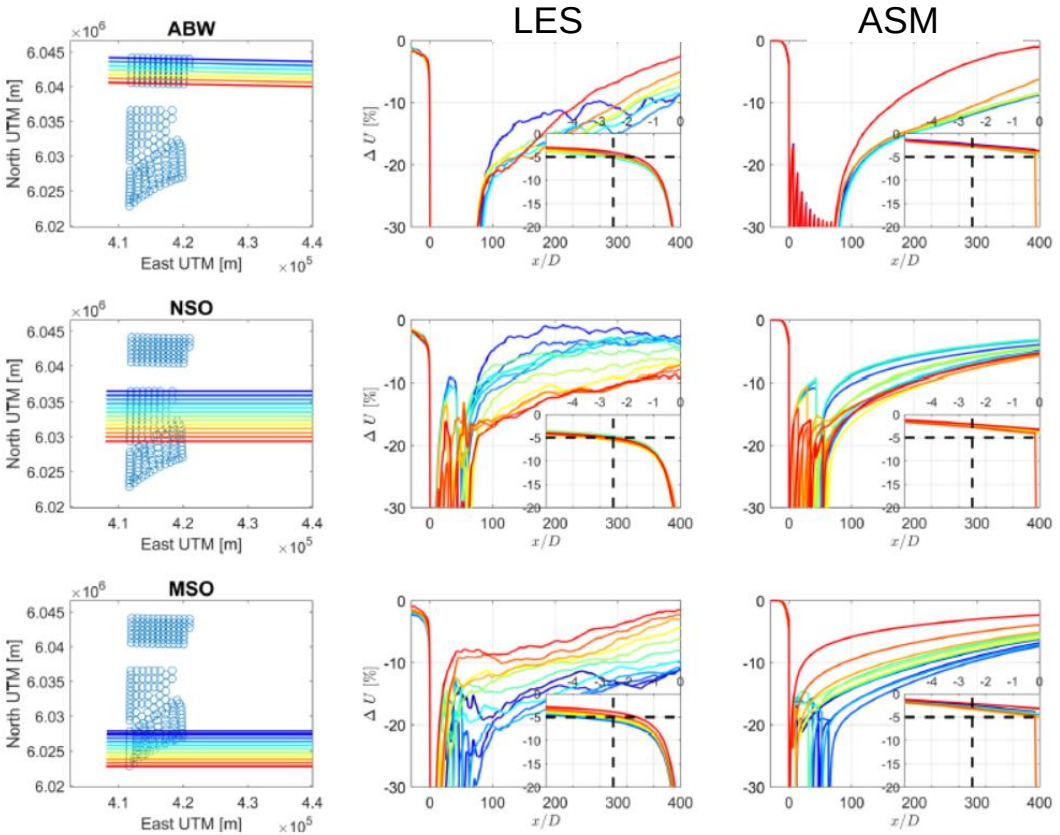


Detailed comparison with LES Results

- Lines here show the wind speed reduction

$$\Delta U(x/D) = 100(U - U_0)/U_0$$

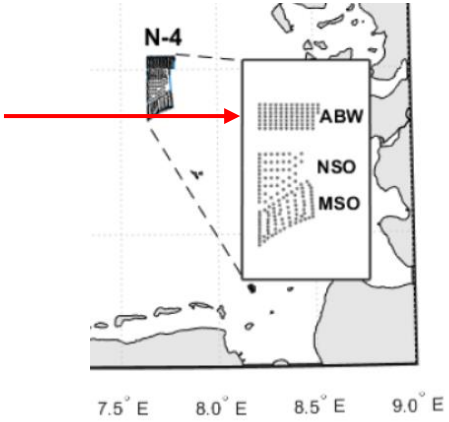
- Wakes plausible
- Induction underestimated
- Overall trend captured
- Results improve more toward the middle of the wind farms

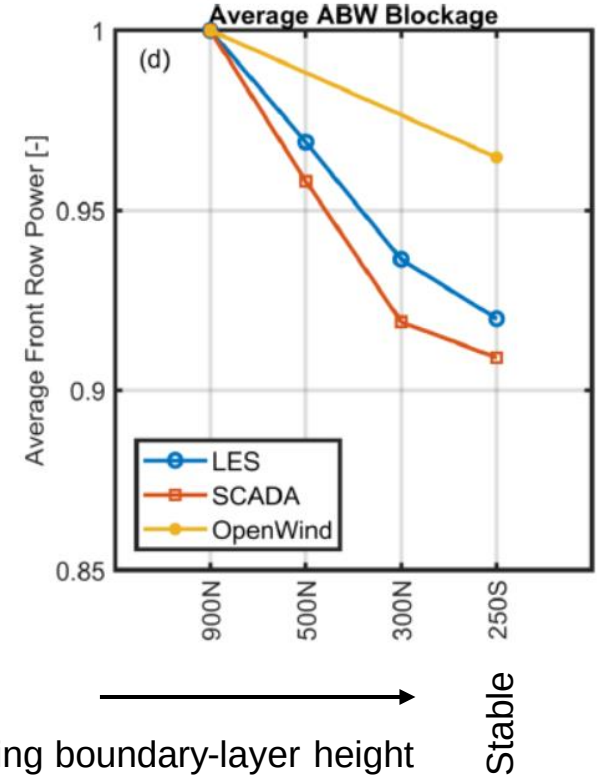


Comparison with SCADA - Induction

- Need to account for boundary-layer height
- And improve ASM induction …

(SCADA data courtesy of RWE)

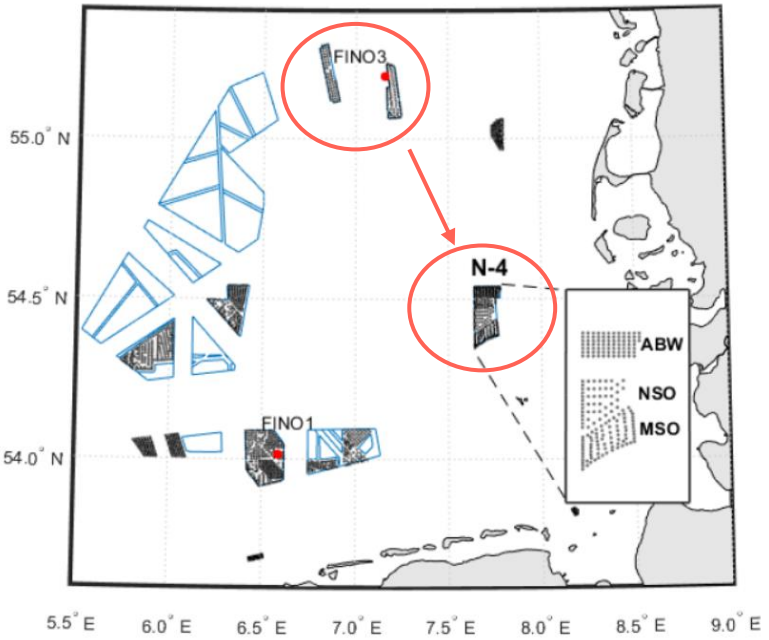




Decreasing boundary-layer height

Outlook

- Ongoing work to optimize the ASM set-up using SCADA from many available wind farms
- Implementation of three-layer model (3LM) of Allaerts and Meyers (2019)
  - Ongoing UL PhD of Sebastiano Stipa (see WESC 2023 Presentation https://zenodo.org/record/8000511)
- Investigation of boundary-layer heights at FINO1 as input to engineering models



Thank you

SCADA data courtesy of RWE

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