WHEN TRUST MATTERS

WESC 2023

Blockage and cluster-to-cluster interactions from dual scanning lidar measurements

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23 May 2023

Foreword

- Object wind farms: Hohe See and Albatros
- Project sponsors (shareholders):
  - EnBW
  - Enbridge

A big thank you to them for allowing this material to be made public!

- All results presented within are for conditions on the plateau of the thrust curve

→ % changes in wind speed and power are NOT representative of the effects for the wind farm over the distribution of site conditions.

Overview

Context

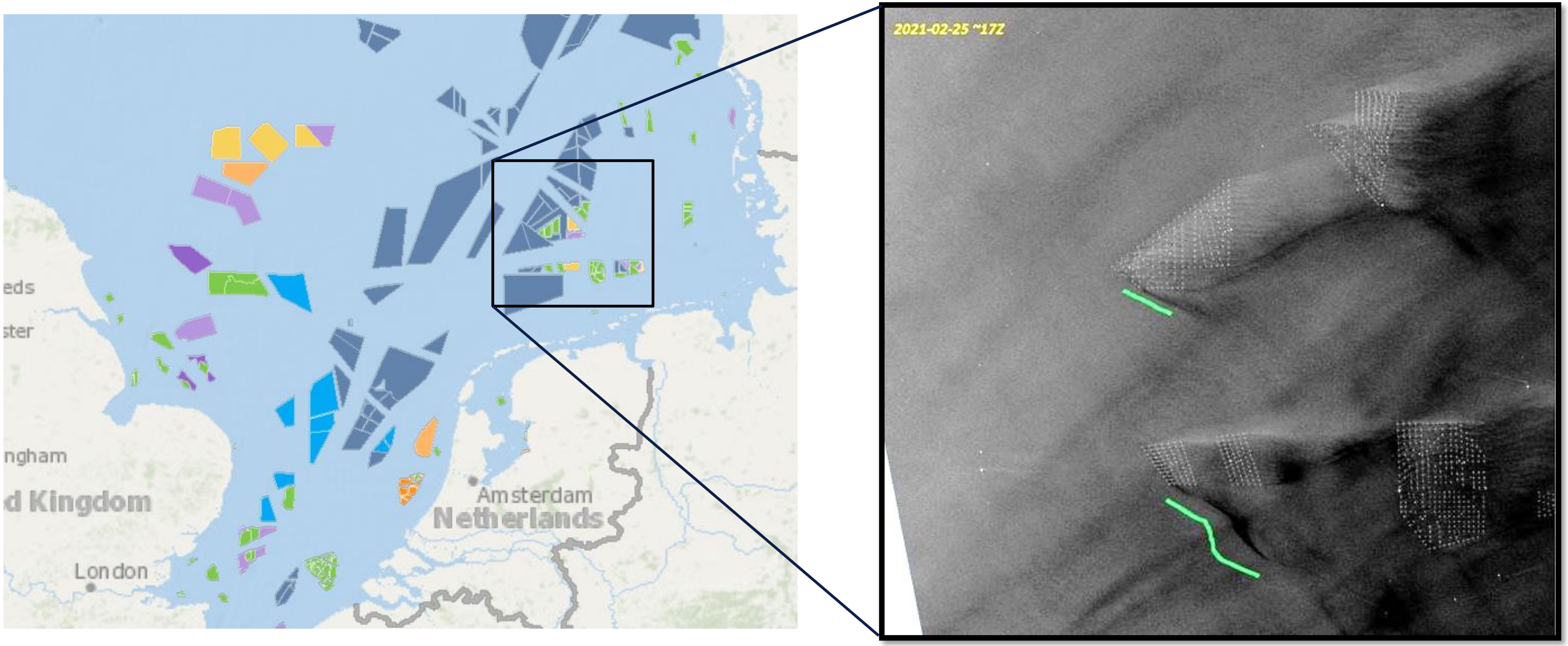
Measurement setup

Simulations (WRF – CFD)

Simulations vs measurements

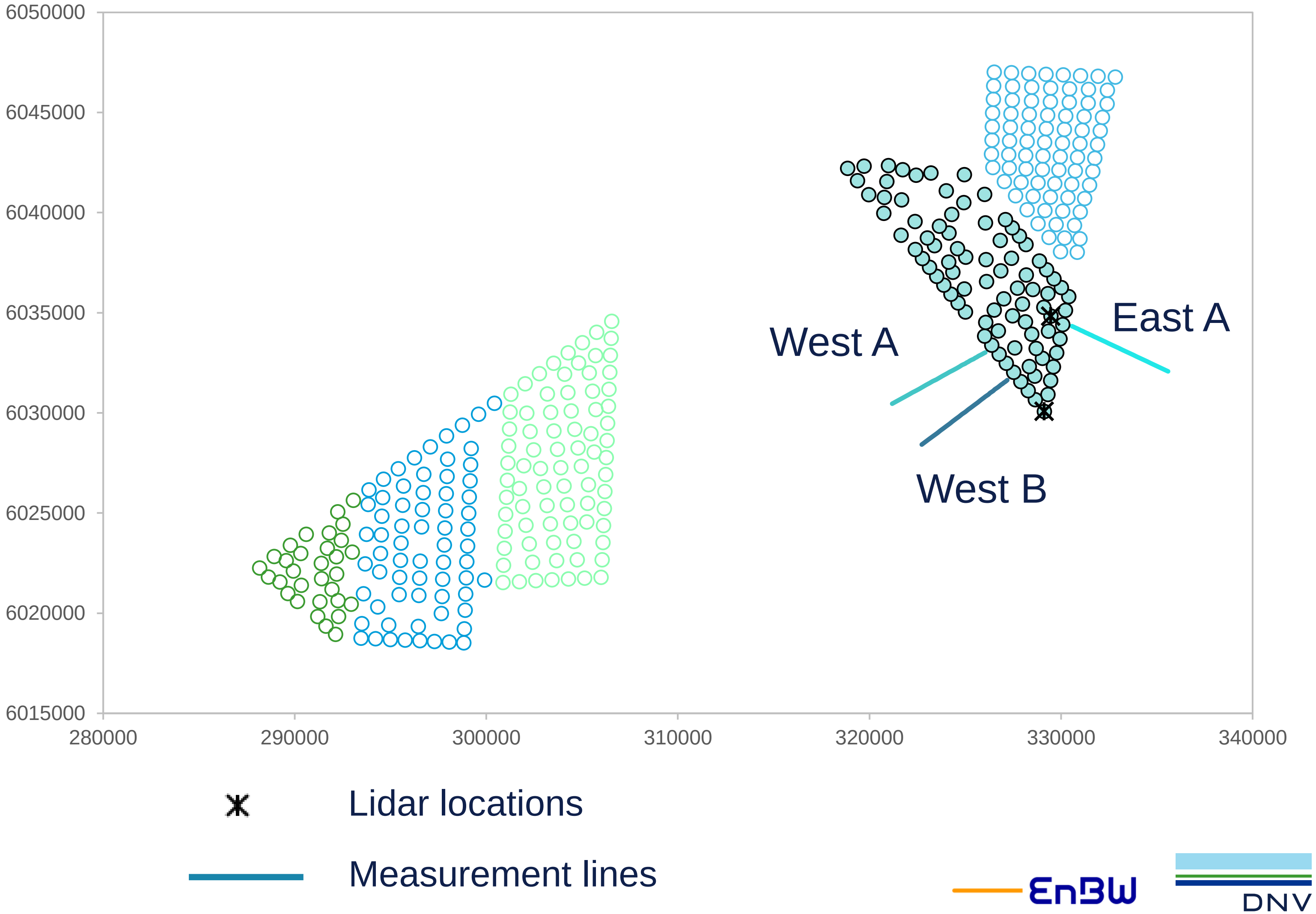
Summary & lessons learned

Context: North Sea, increasing installed power density



Measurement campaign

- Object wind farms with neighbouring clusters:
  - One adjacent
  - 3 located at a distance of
    - ~125 - 180 RD
    - Or 14 -23 km
- Measurement setup
  - Three measurement lines (2x in the west, 1x in the south-east)
  - Each line consists of eight measurement points
  - Measurement distances ranging from
    - 1.1 to 11.8 km from lidar location
    - 0.5 to 6 km from the edge of the wind farm



Simulations

- WRF
  - 4 nested domains, innermost with 62 km x 62 km, finest horizontal resolution: 1 km
  - vertical resolution: 10m first cell height, 10 more levels of to 250m, 41 levels overall (19.3 km).
  - MYJ PBL scheme
  - driven by ERA-5 reanalysis, ERA-5 SST
  - period concurrent with the measurement campaign (Nov 2021 – Feb 2023)

  →**processed to derive boundary conditions for CFD model** (particularly potential temperature profile)

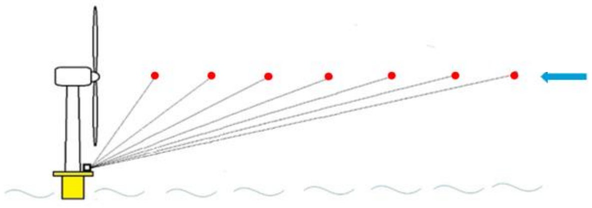
  →Per groups of directions, two sets of profiles for

  →Stable

  →Unstable conditions

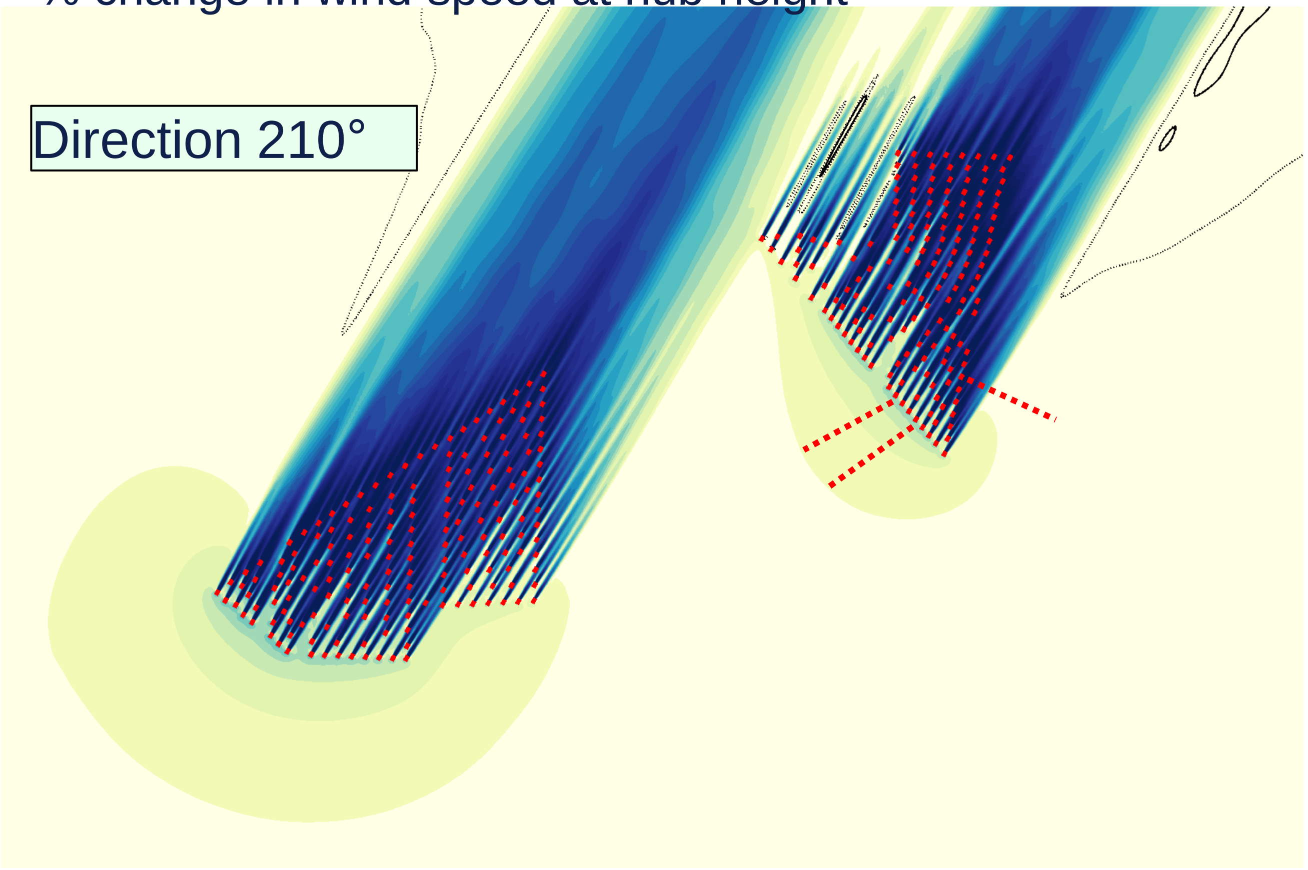
- CFD
  - Domain size: 30km buffer around wind farms, 17 km vertical extent.
  - Steady state RANS (k-ε, modified turbulence constants)
  - Transport equation for potential temperature
  - Buoyancy in momentum and turbulence equations
  - Coriolis
  - Turbines via actuator disk
  - WRF – informed boundary conditions
  - Discrete set of directions (steps of 10°)
  - Reference wind speed @ HH: ~ 8 m/s
  - CFD.ML
    - Machine learning model to interpolate pattern of production to a fine direction resolution, between directions solved by CFD

Example 1:
South-Westerly wind directions

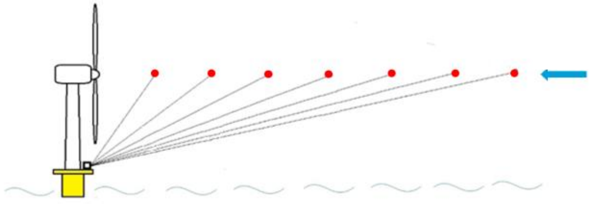


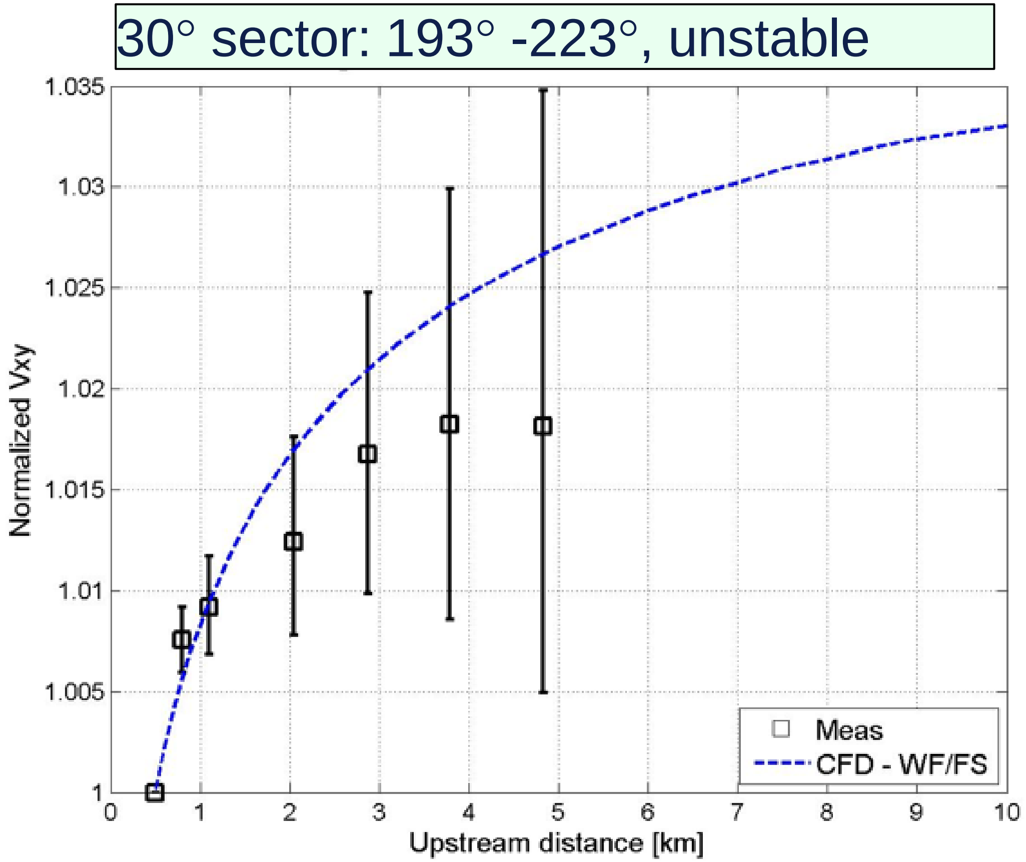
- Focus on directions where the measurements along the lidar lines are only blockage affected
  - Example from direction 210°
  - Unstable conditions
  - Wind speed on the plateau of the thrust curve

% change in wind speed at hub height

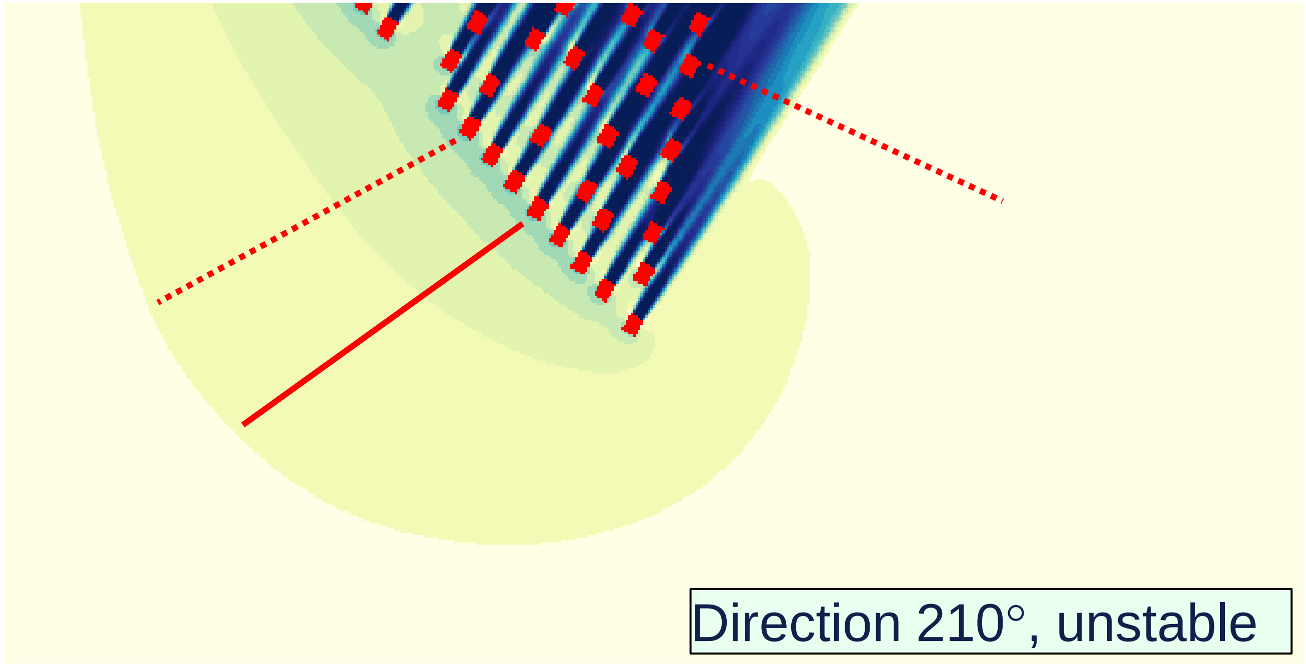


Measurements along line West B, unstable, plateau of thrust curve





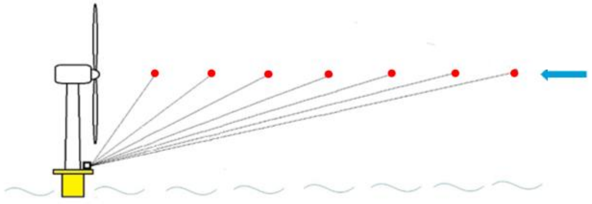
% change in wind speed at hub height



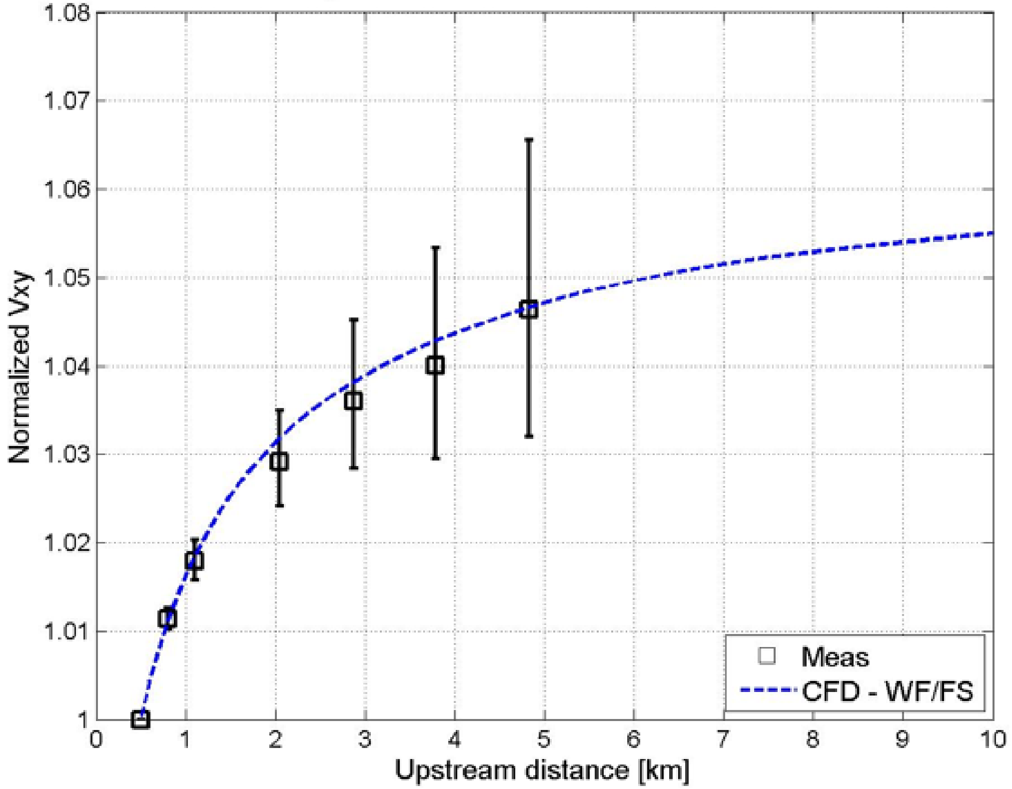
Measurements capture blockage (~1.8% wind speed reduction between 4.8 km and 0.5 km)
CFD captures 1st km, then overestimates magnitude for distances beyond 2 km

EnBW DNV

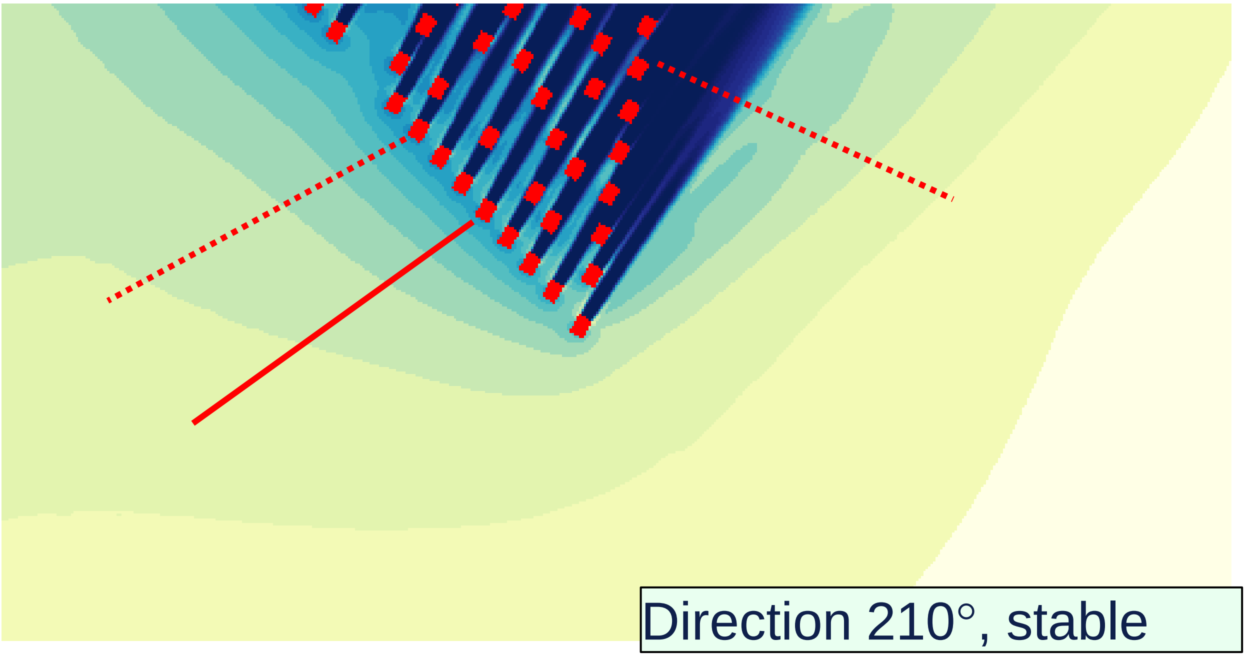
Measurements along line West B, stable, plateau of thrust curve



30° sector: 193° -223°, stable



% change in wind speed at hub height

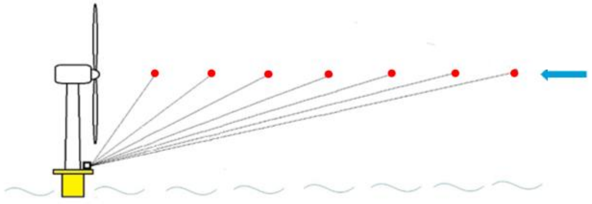


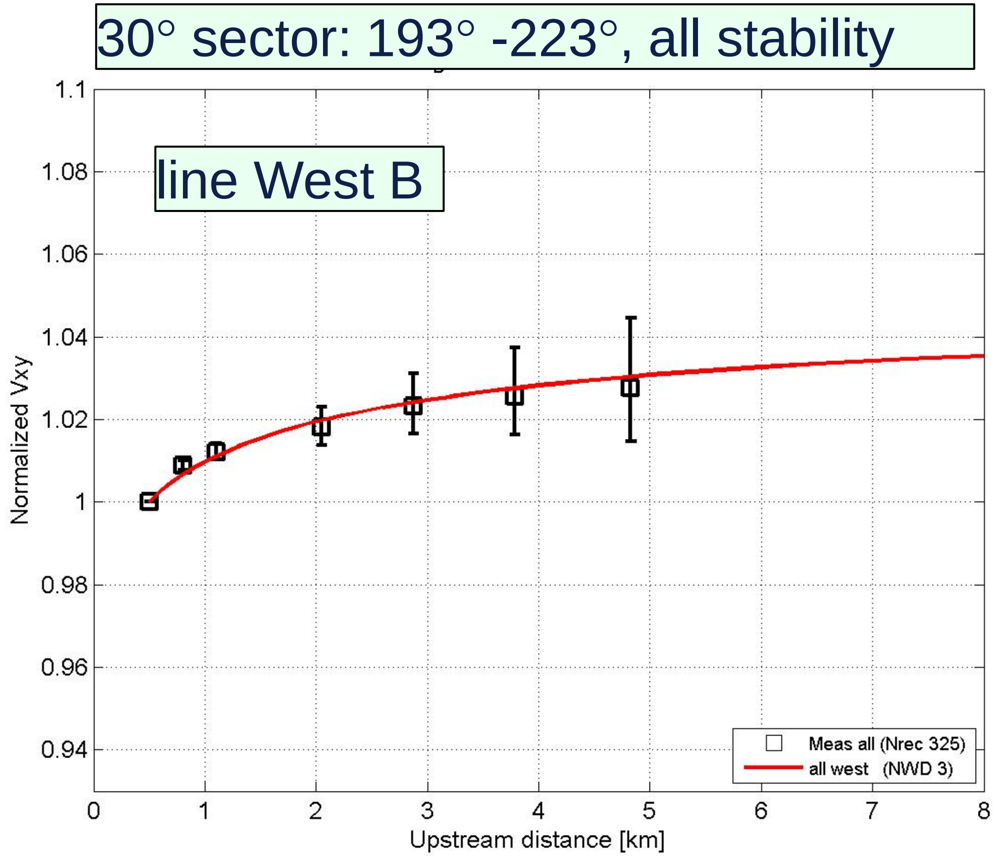
Direction 210°, stable

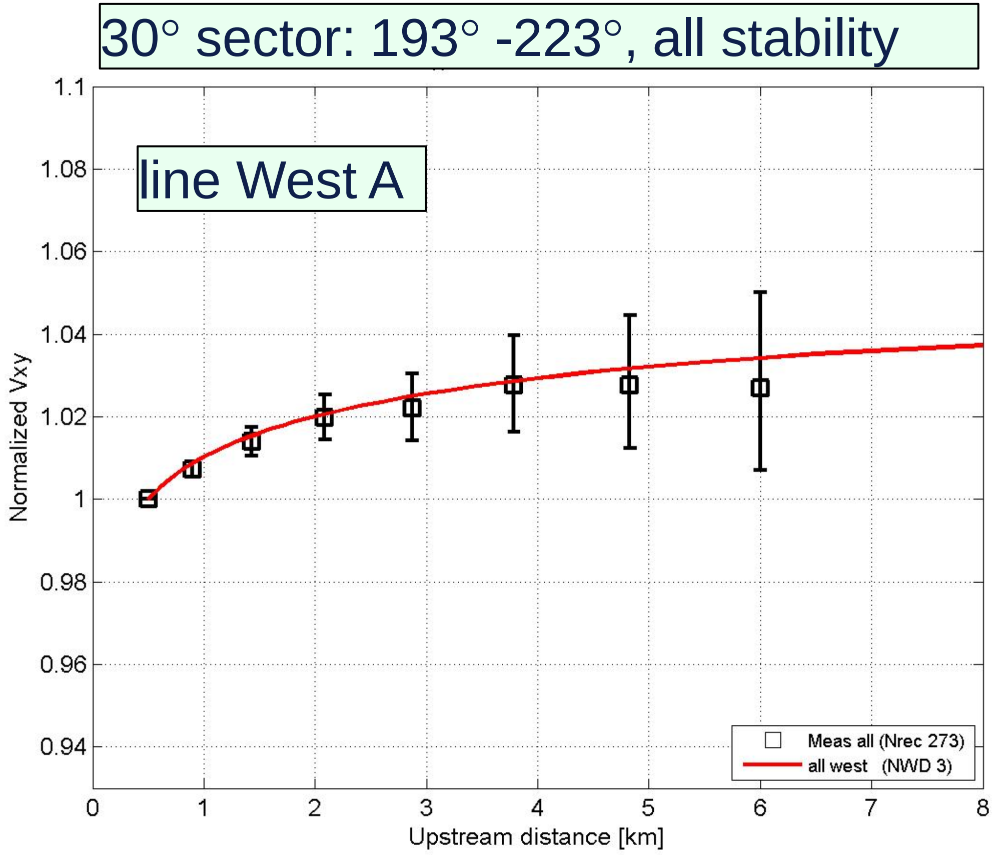
Measurements capture blockage (~4.8% wind speed reduction between 4.8 km and 0.5 km)
CFD gets the magnitude right

EnBW DNV

Line West B and West A,
All stability, plateau of thrust curve



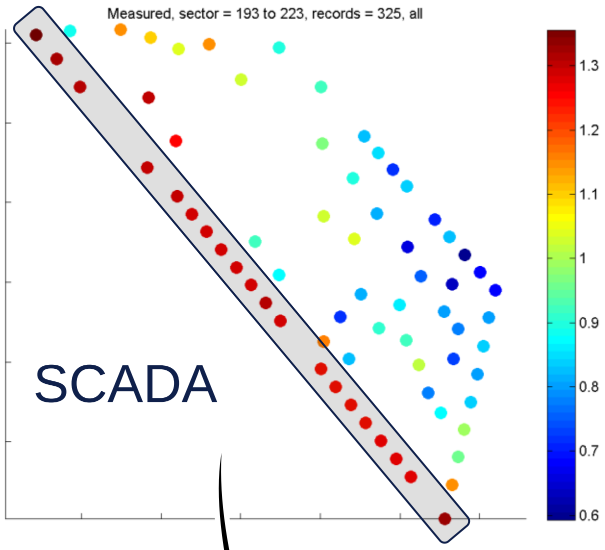


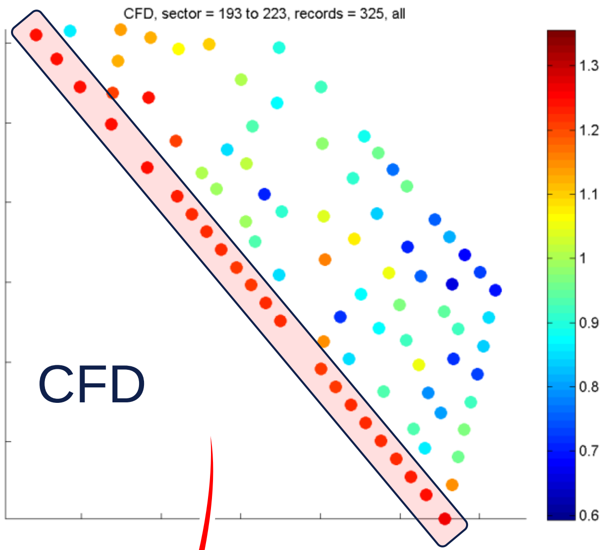


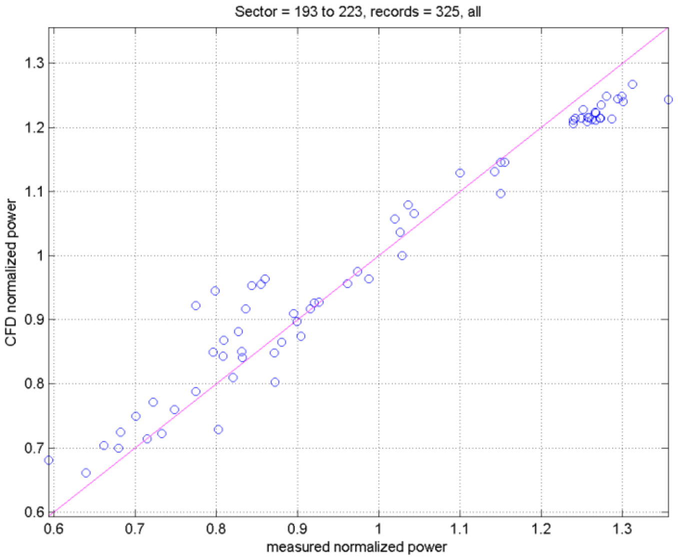
Over all stability, measurements capture ~3% wind speed reduction between 4.8 km and 0.5 km, CFD gets the magnitude right

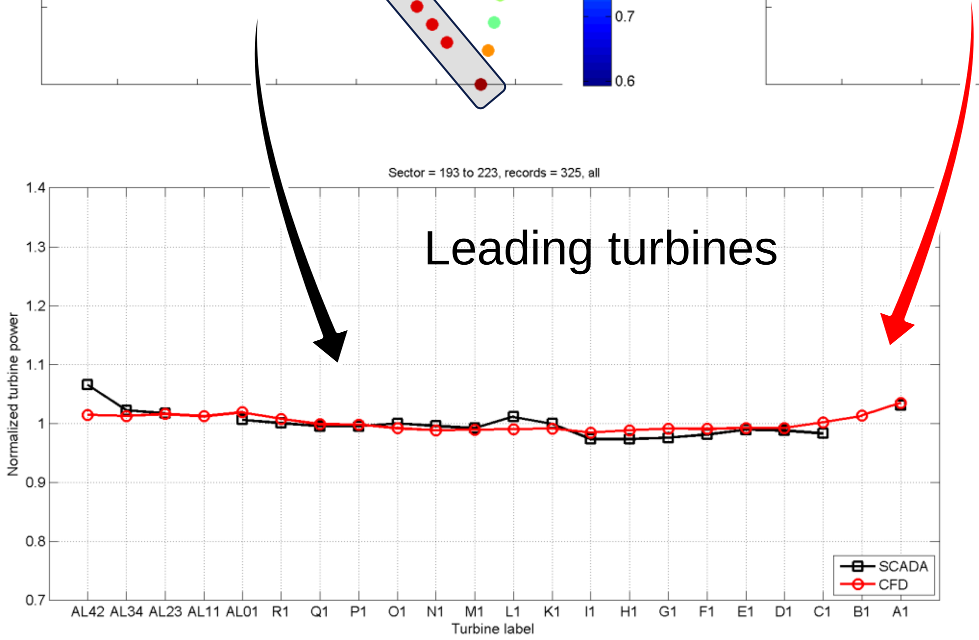
Pattern of production (193° -223°), all stability

CFD vs SCADA, array



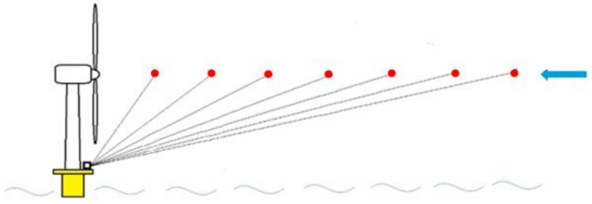




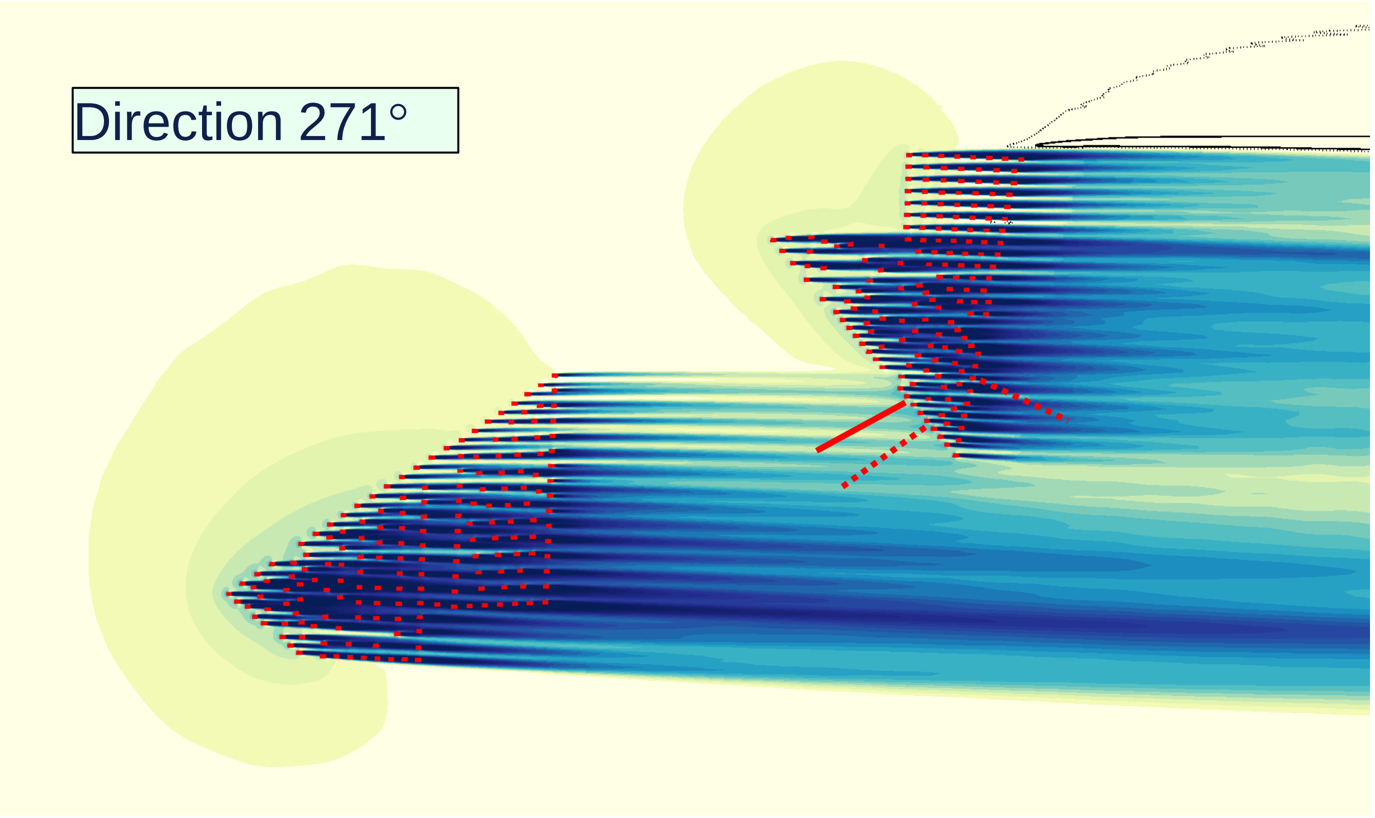


- Whole array normalised power well captured by CFD model. (Note: turbines with availability < 85% not plotted in SCADA PoP plot).
- Leading turbines PoP: not a large variation across the line of leading turbines

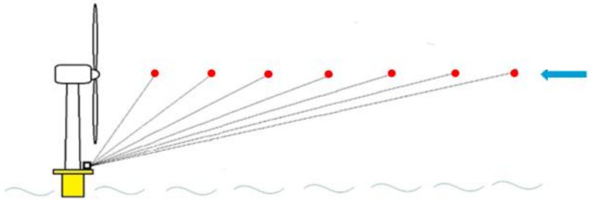
Example 2:
Westerly wind directions

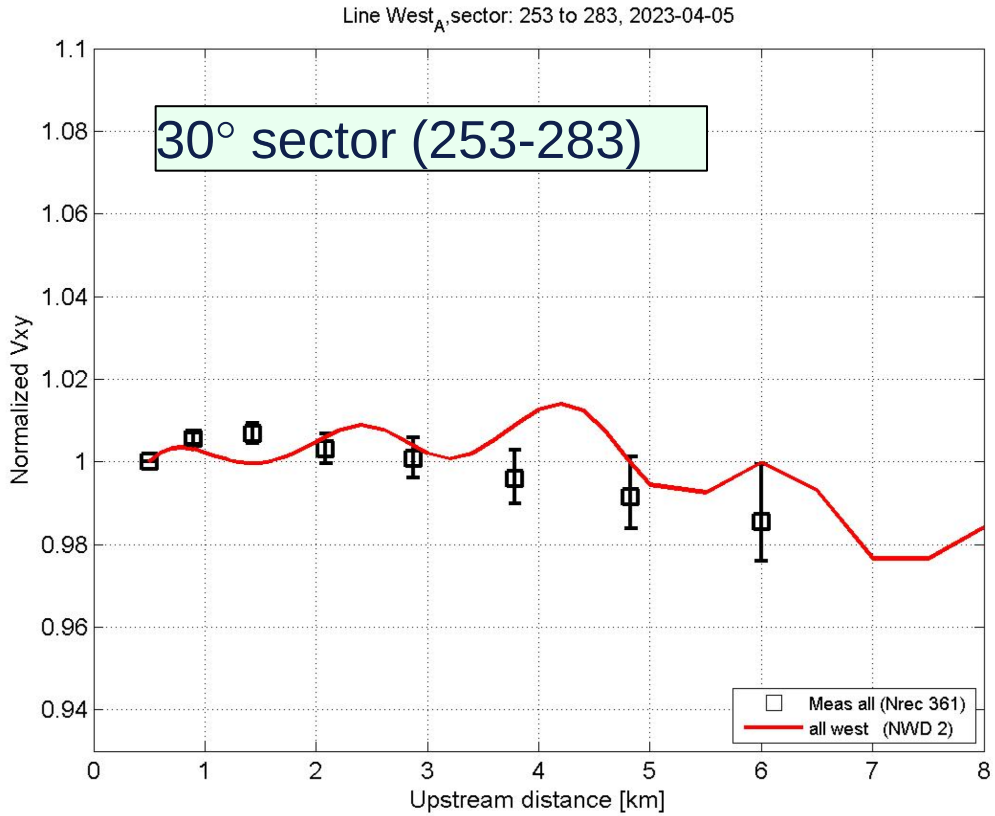


- Directions where the measurements along the lidar lines are affected by both blockage AND wakes from neighbouring clusters
  - Example from direction 271°
  - Unstable conditions
  - Wind speed on the plateau of the thrust curve

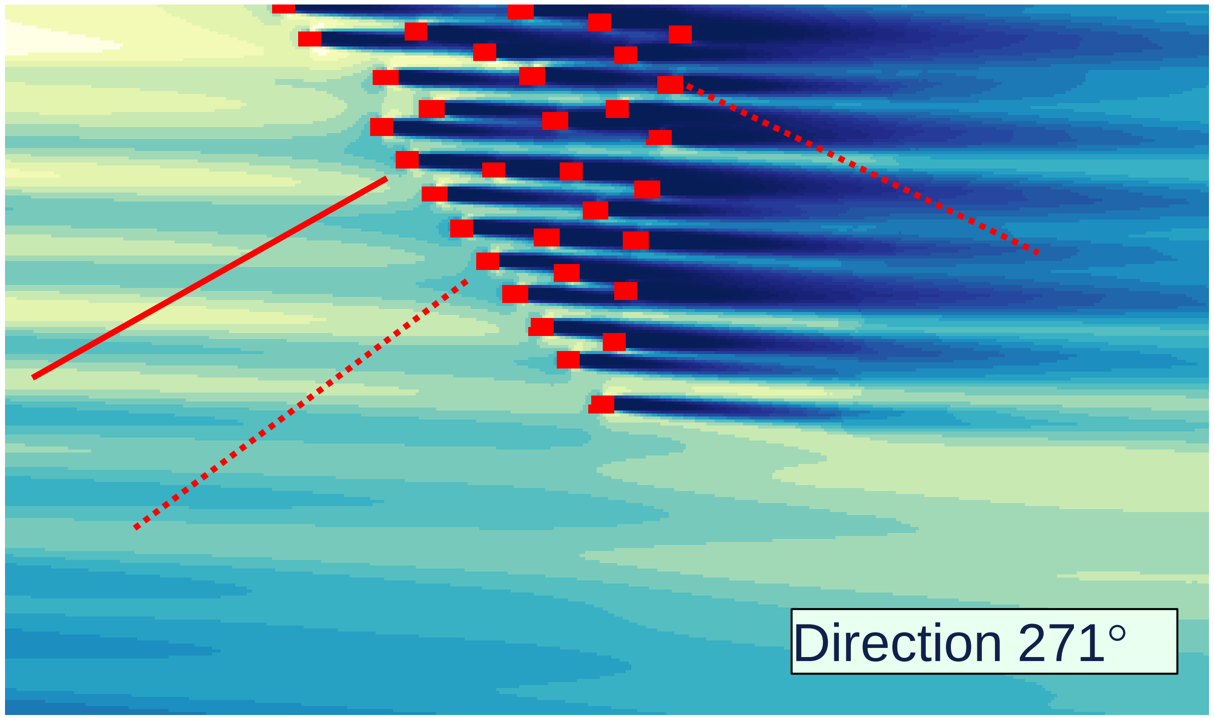


Measurements along line West A,
All stability, plateau of thrust curve





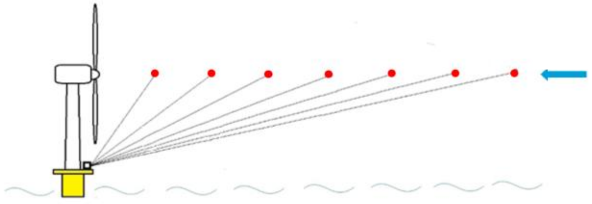
% change in wind speed at hub height

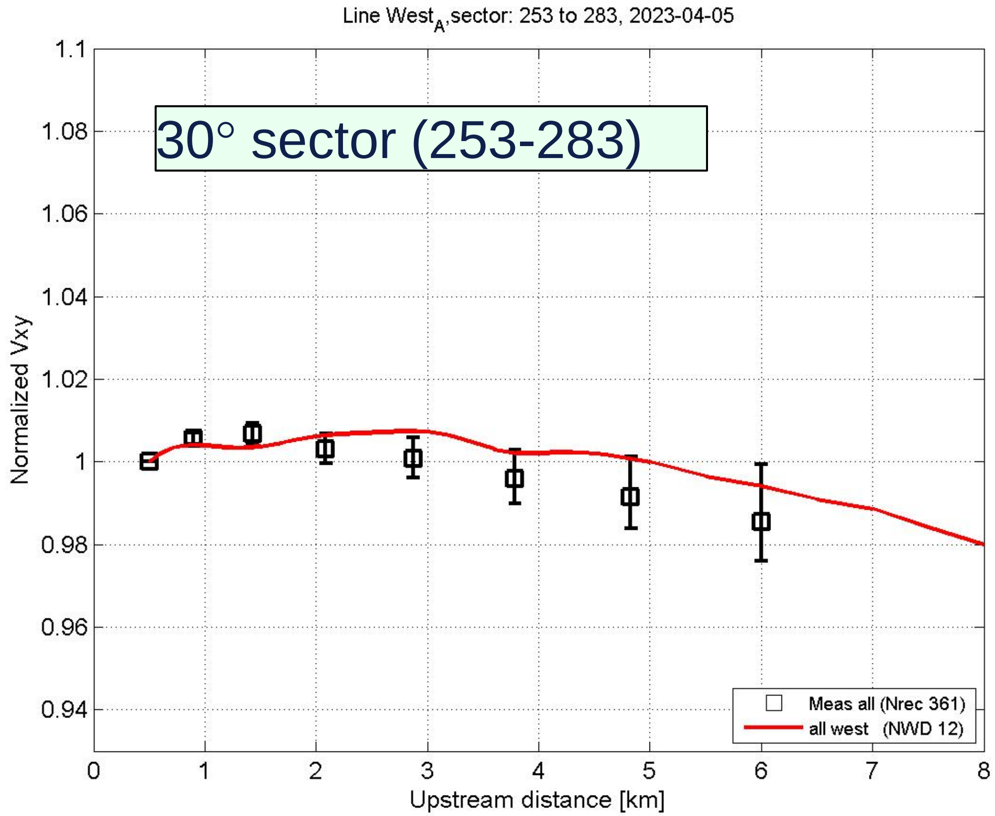


Blockage only visible in first 1.5 km in measurements. Recovering cluster wake drowns the blockage signal for larger distances. CFD, having solved only 2 directions within 30° sector, still shows spatial oscillations resolving individual wakes.

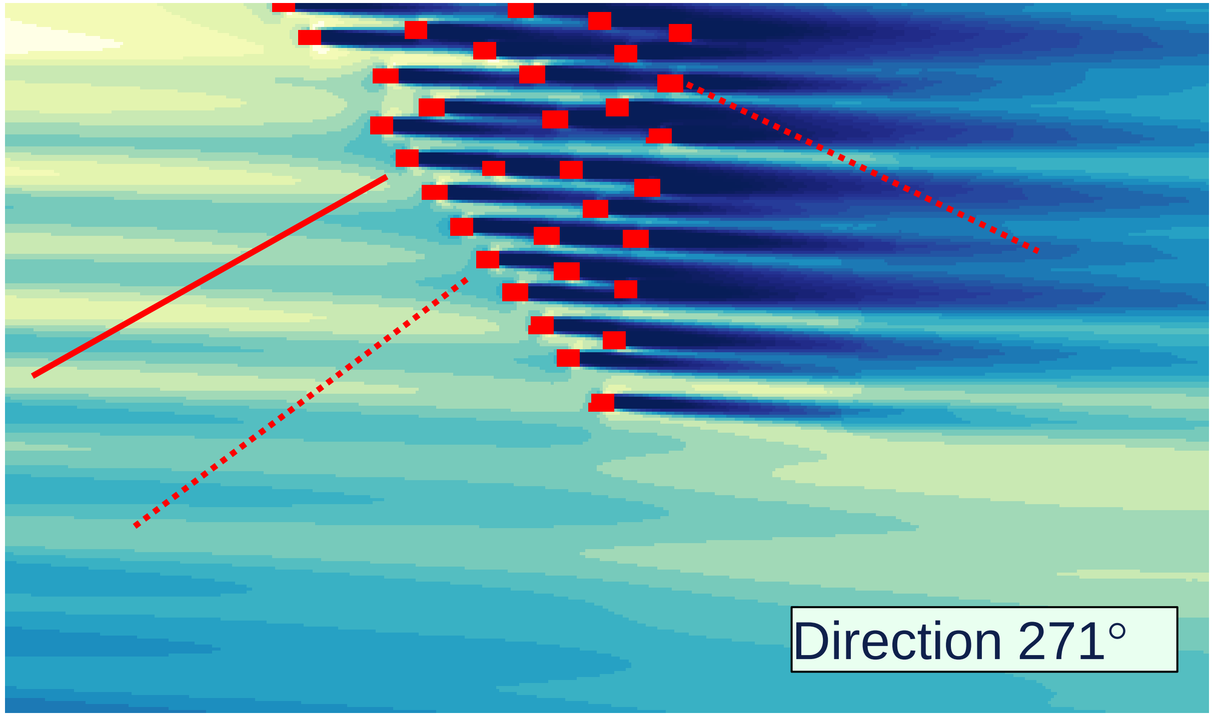
EnBW DNV

Measurements along line West A, All stability, plateau of thrust curve



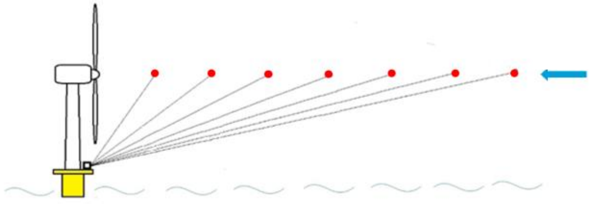


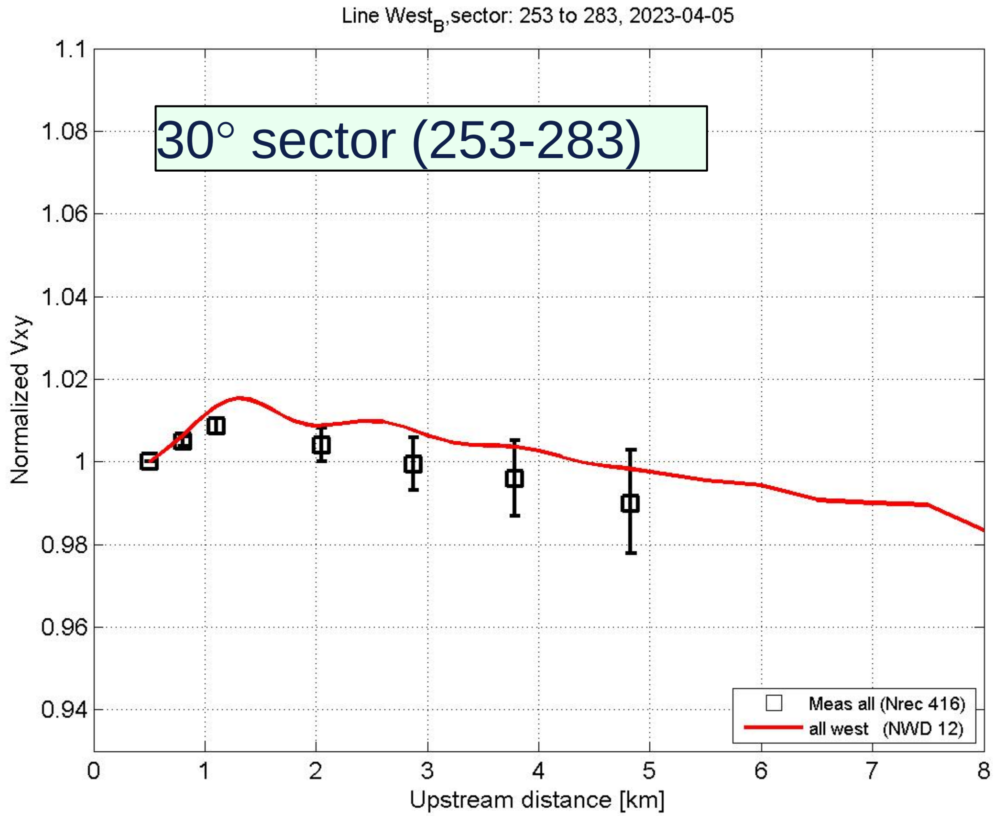
% change in wind speed at hub height



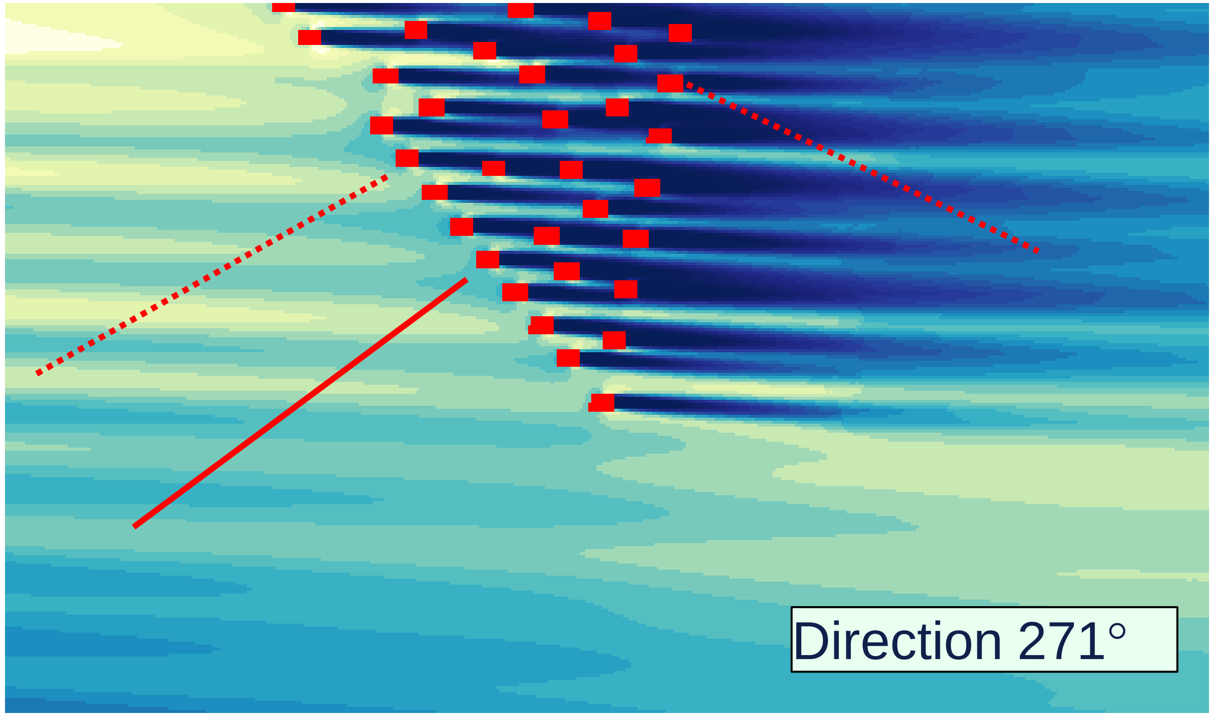
Solving for more directions smoothes out spatial oscillations that were associated with resolved wakes

Measurements along line West B, All stability, plateau of thrust curve



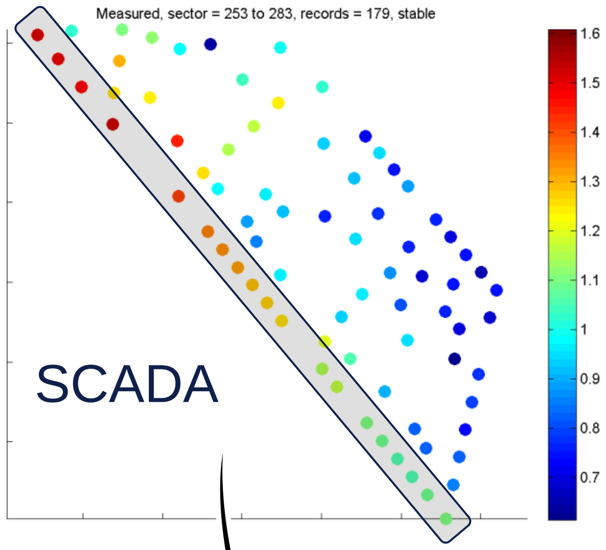


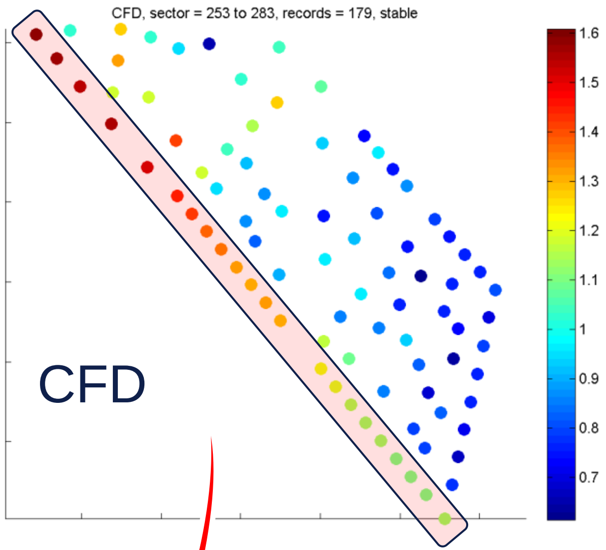
% change in wind speed at hub height



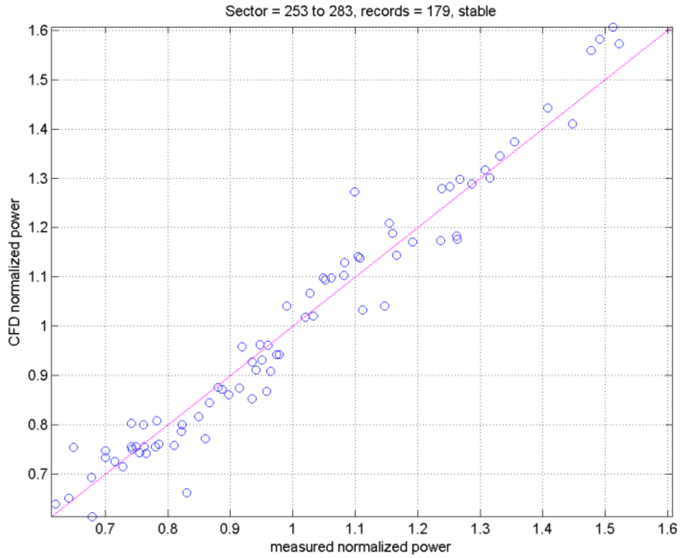
Measurements and CFD capture cluster wakes and blockage

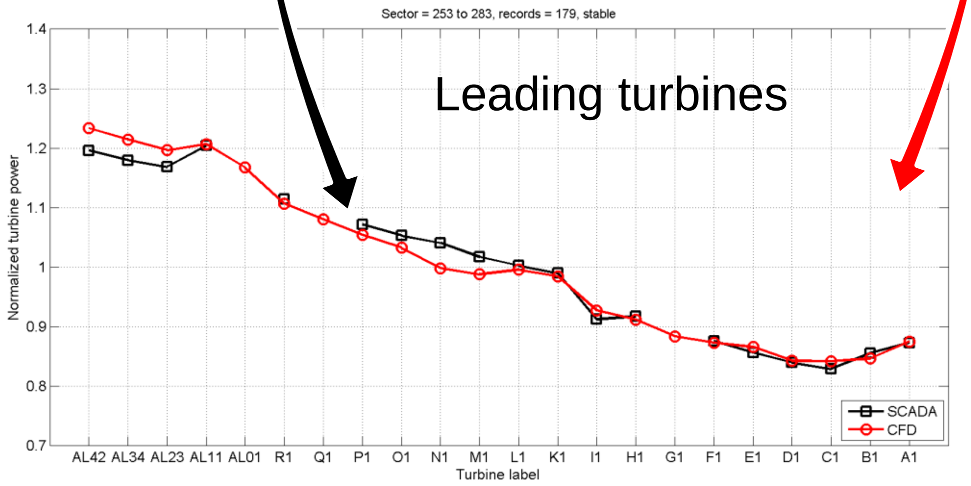
Pattern of production (253° -283°), stable





CFD vs SCADA, array



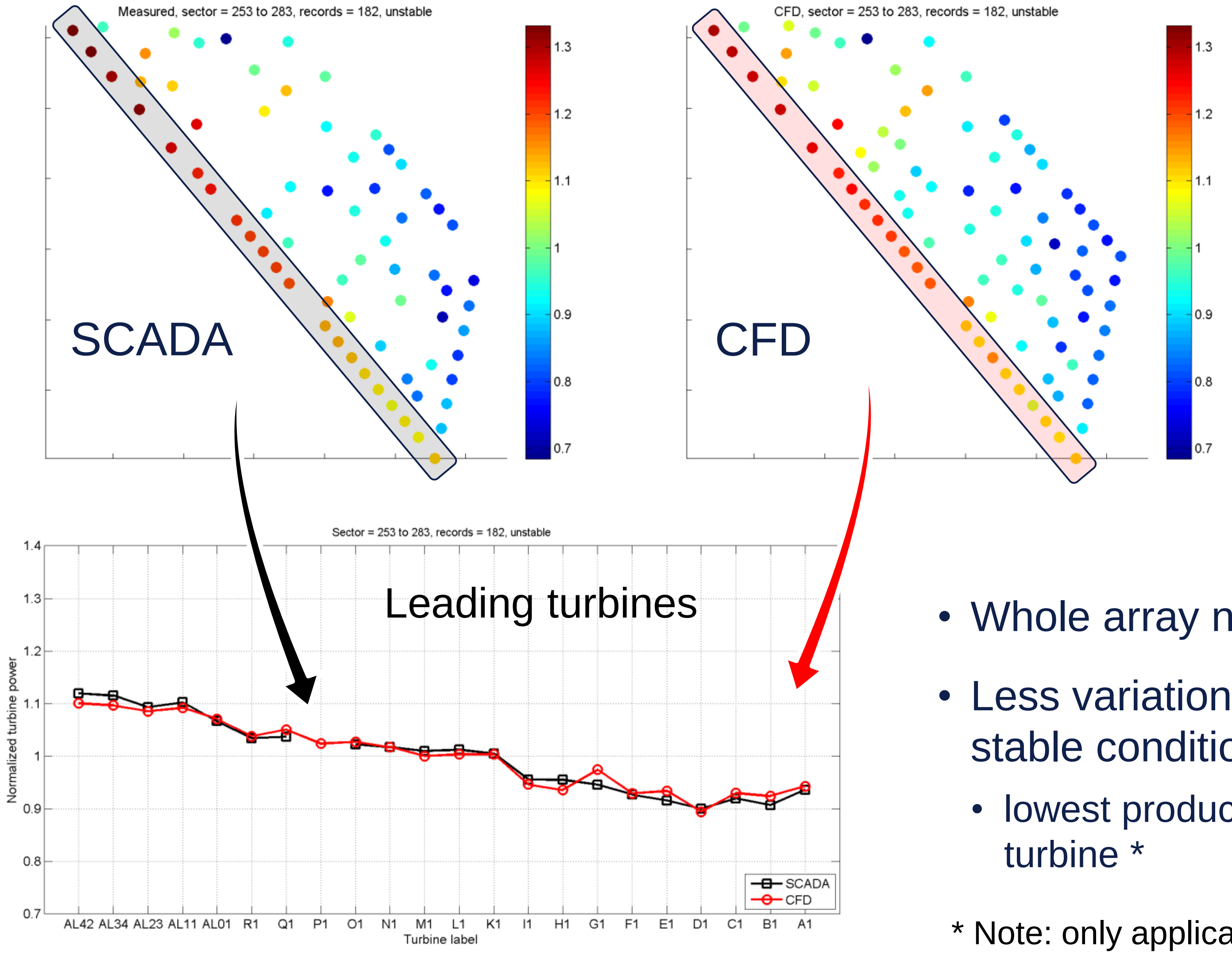


- Whole array normalised power well captured by CFD
- Large variation across the line of leading turbines
  - lowest producing produces 33% less than highest producing turbine *

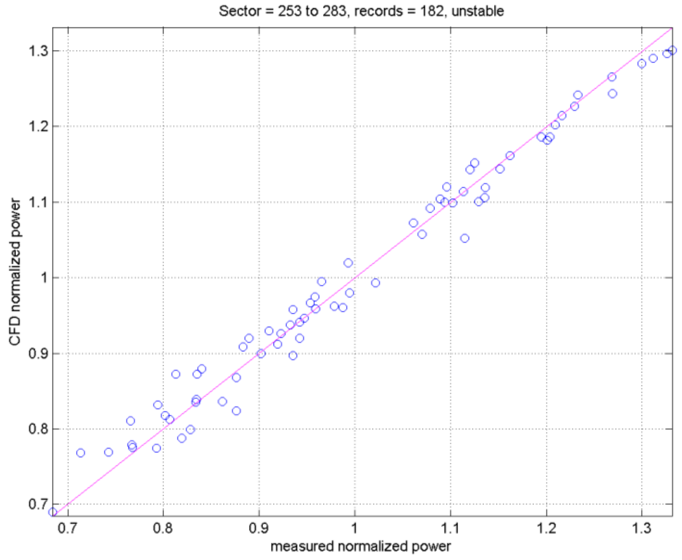
* Note: only applicable on plateau of thrust curve, will be less at higher wind speeds!

EnBW DNV

Pattern of production (253° -283°), unstable



CFD vs SCADA, array

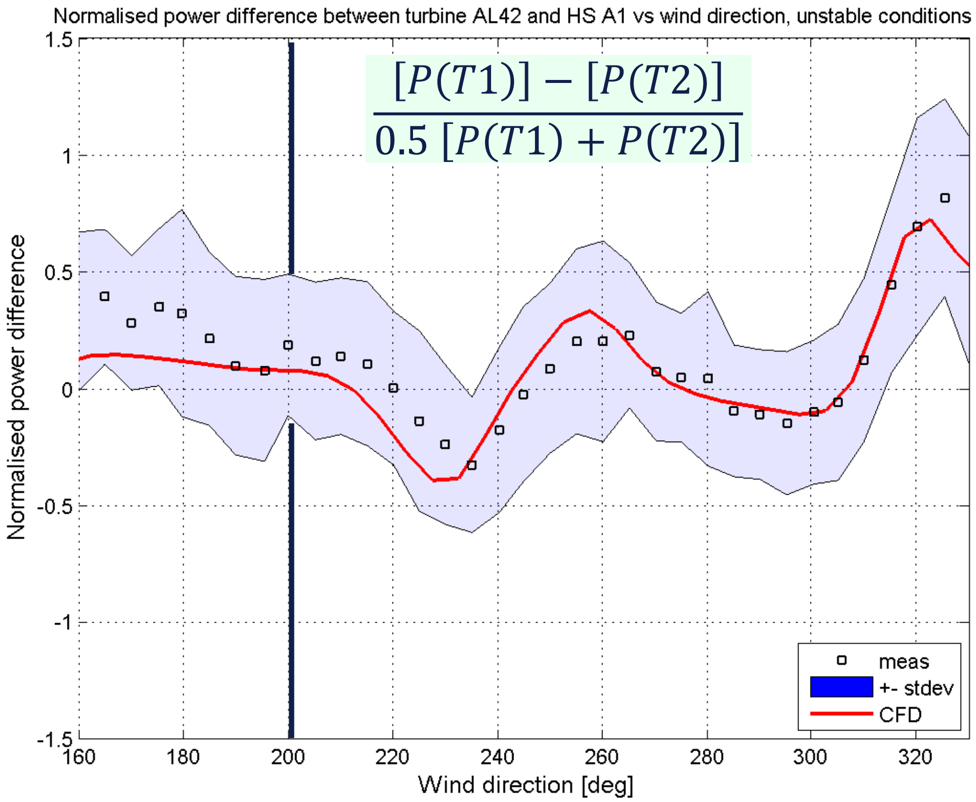


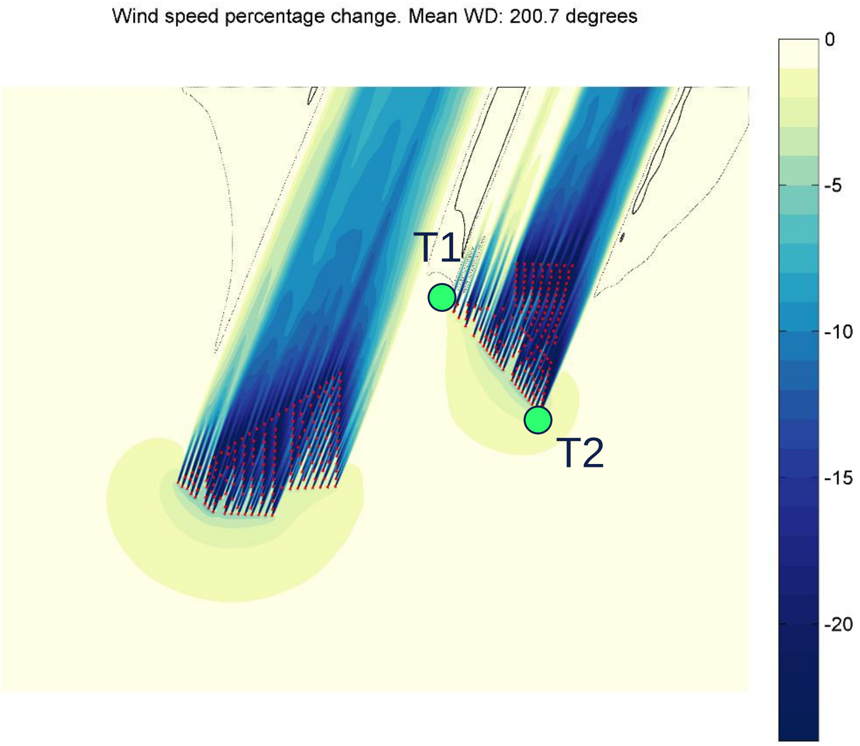
- Whole array normalised power well captured by CFD
- Less variation across the line of leading turbines than in stable conditions
  - lowest producing produces 20% less than highest producing turbine *

* Note: only applicable on plateau of thrust curve, will be less at higher wind speeds!

Power difference vs direction for corner turbines,

Unstable conditions, plateau of thrust curve



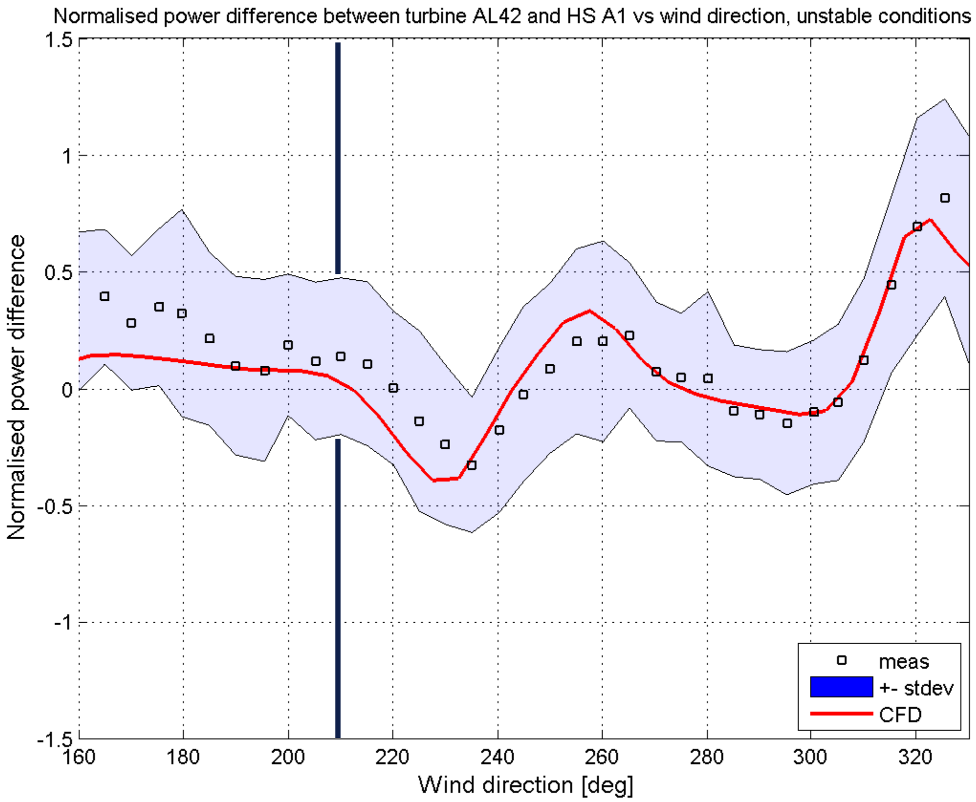


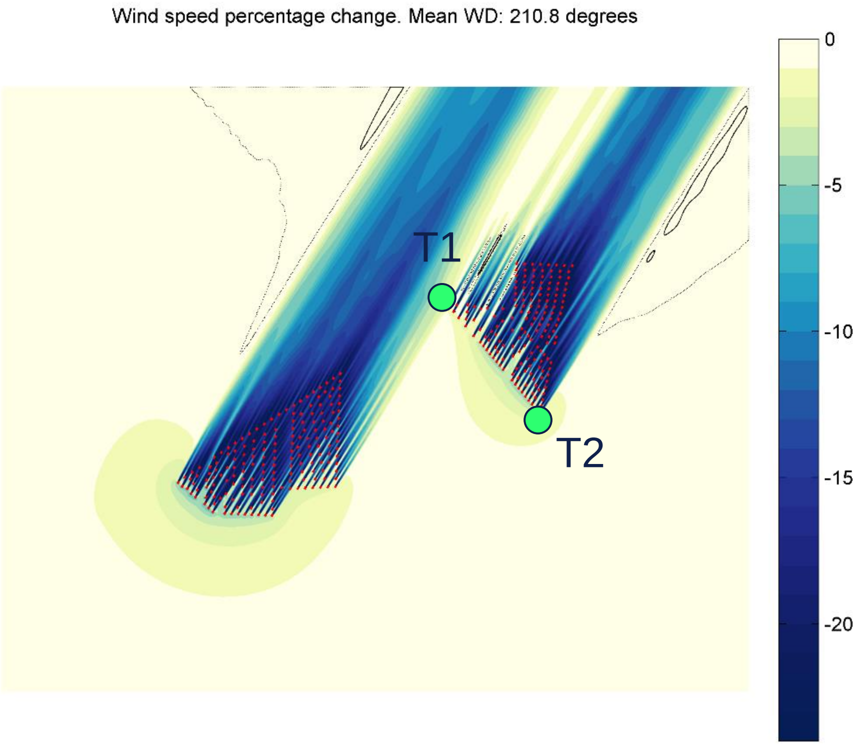
Filtering conditions: both T1 & T2 operating normally, 85% availability for HS and AL, max (P(T1), P(T2)) on plateau of thrust curve, potential T(sea)> potential T(air)

[ ] : ensemble averaged over filtered conditions

Power difference for corner turbines vs wind direction

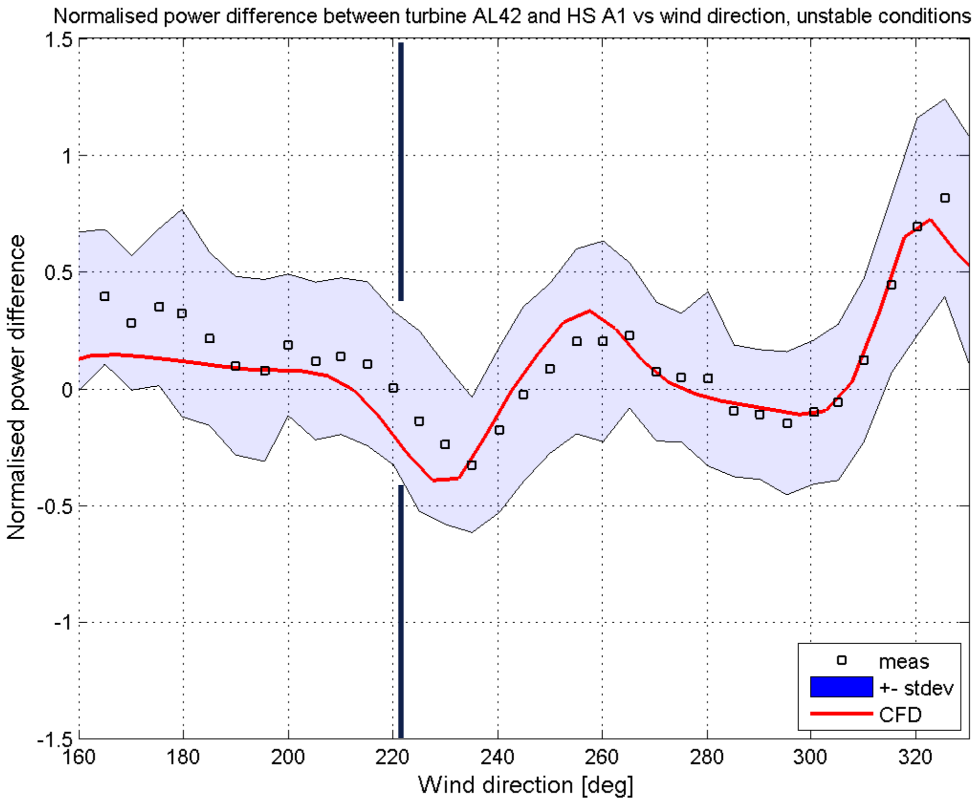
Unstable conditions, plateau of thrust curve

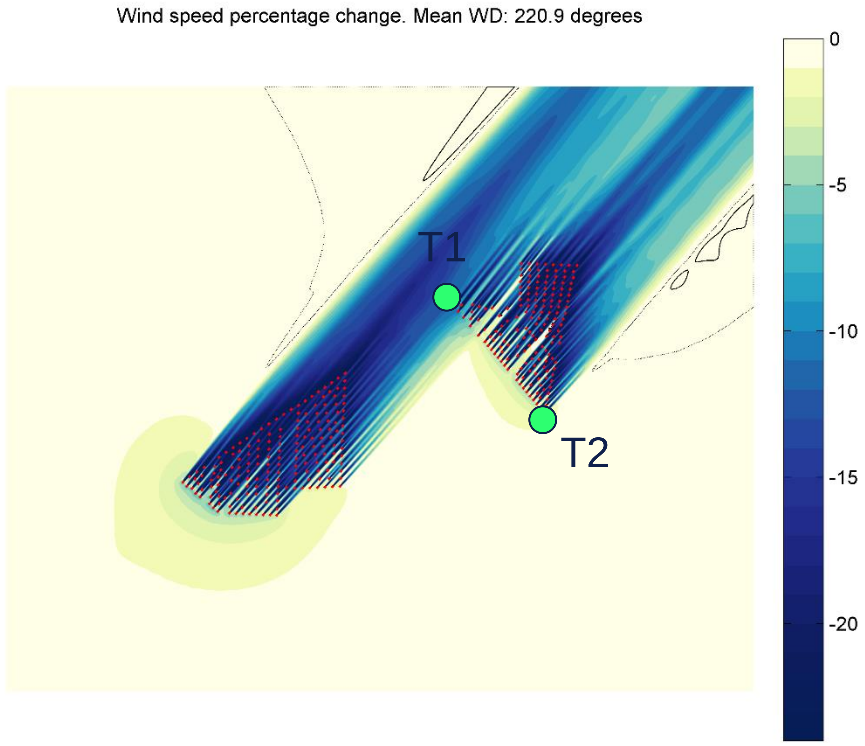




Power difference for corner turbines vs wind direction

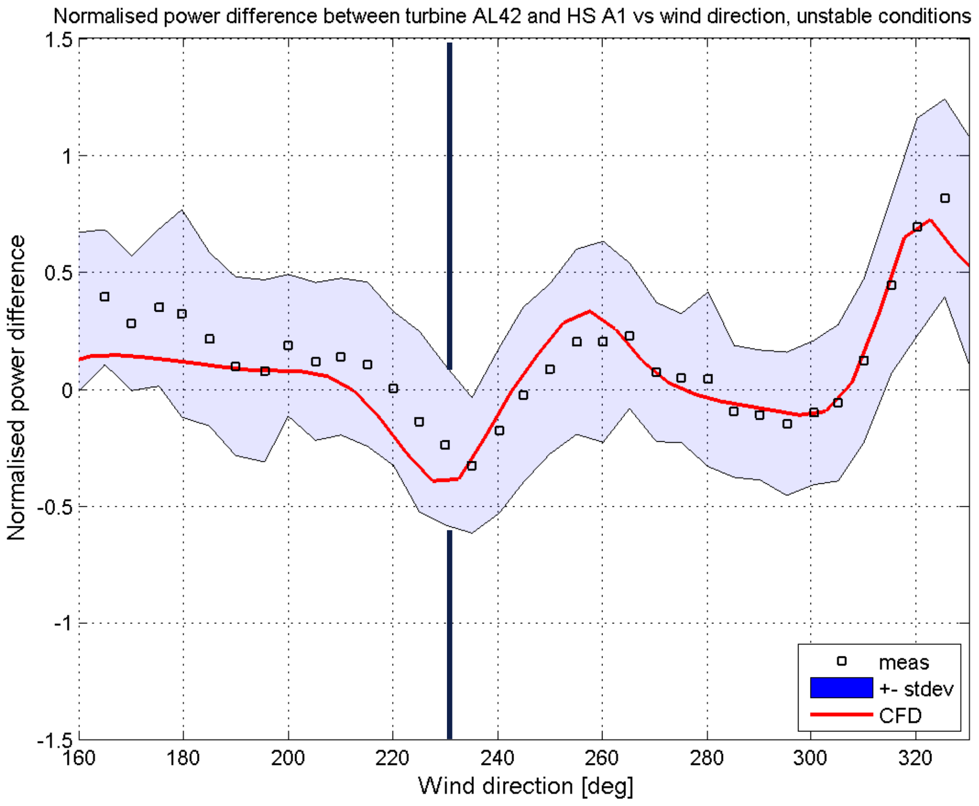
Unstable conditions, plateau of thrust curve

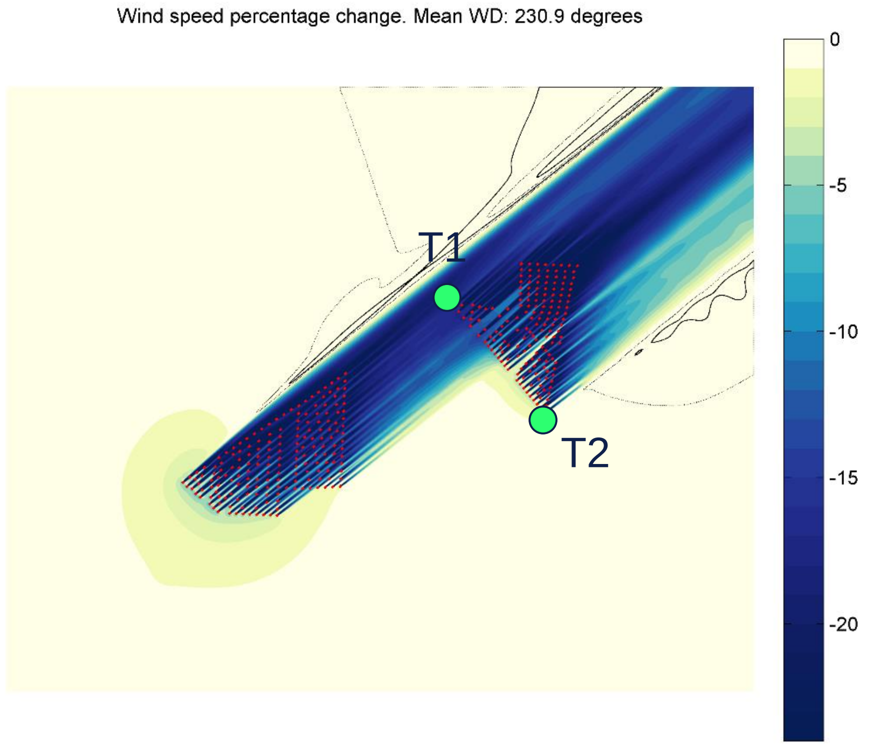




Power difference for corner turbines vs wind direction

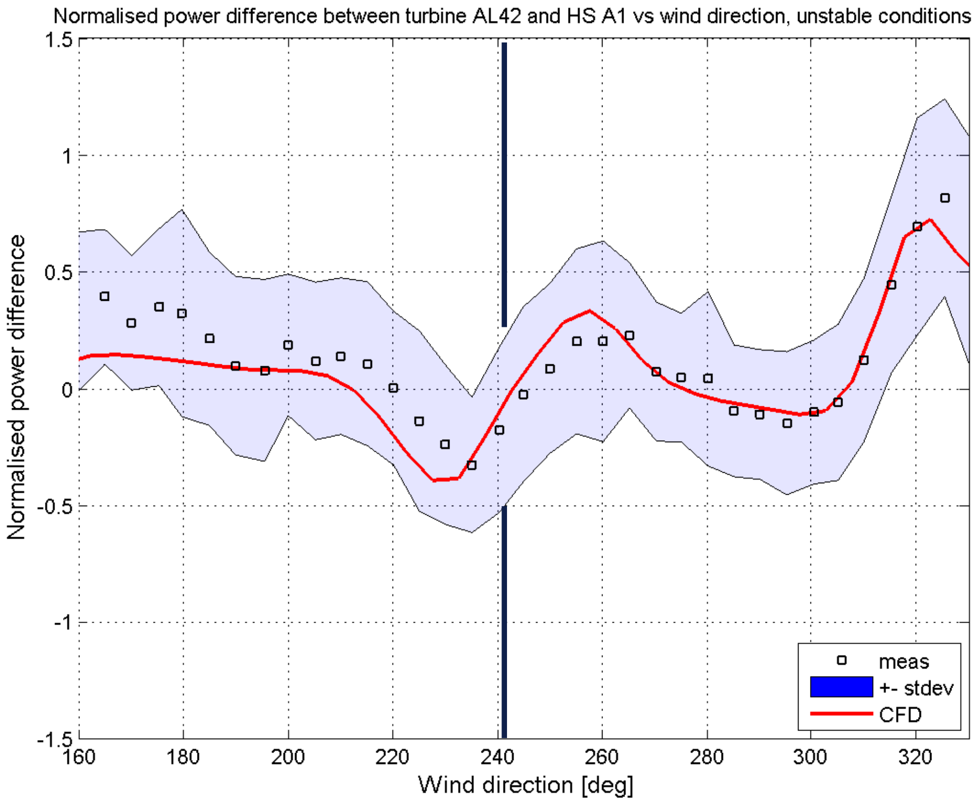
Unstable conditions, plateau of thrust curve

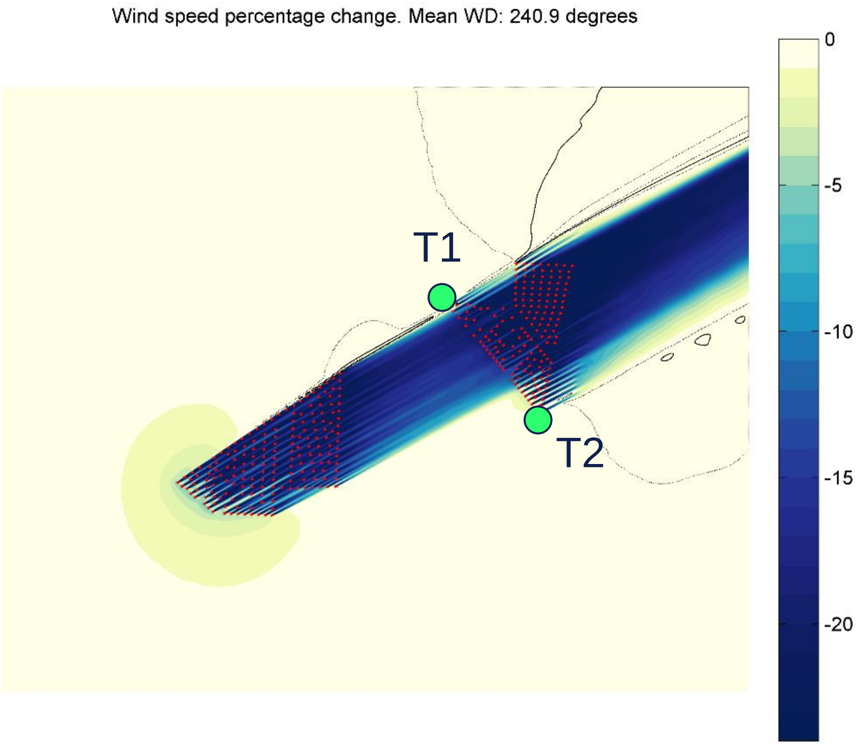




Power difference for corner turbines vs wind direction

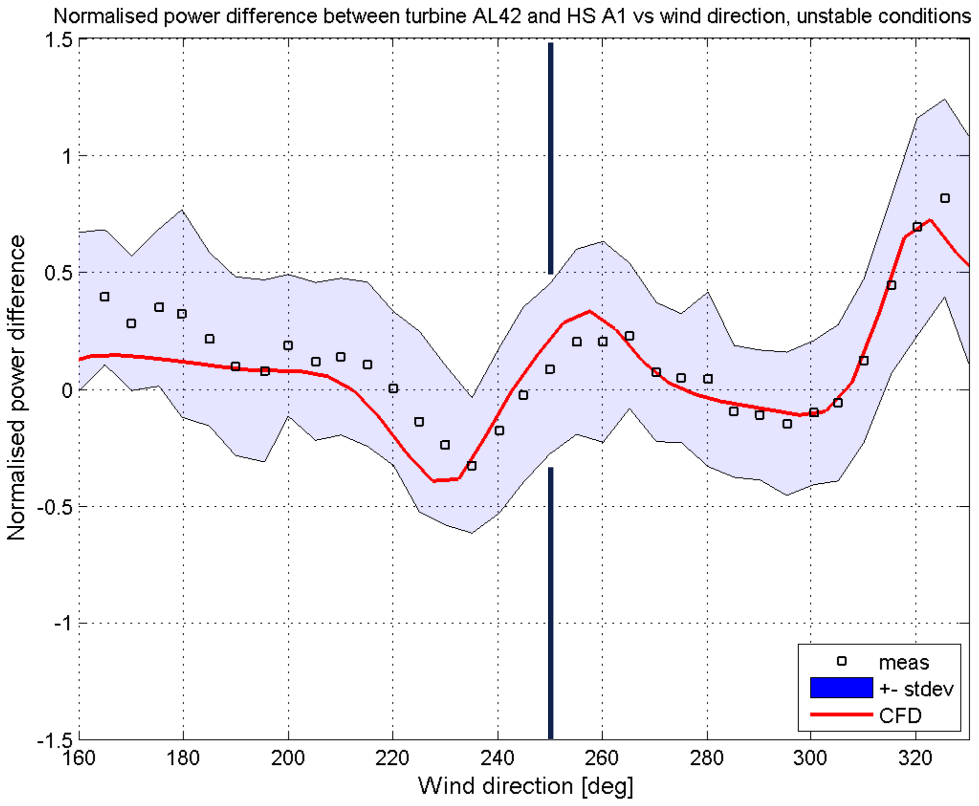
Unstable conditions, plateau of thrust curve

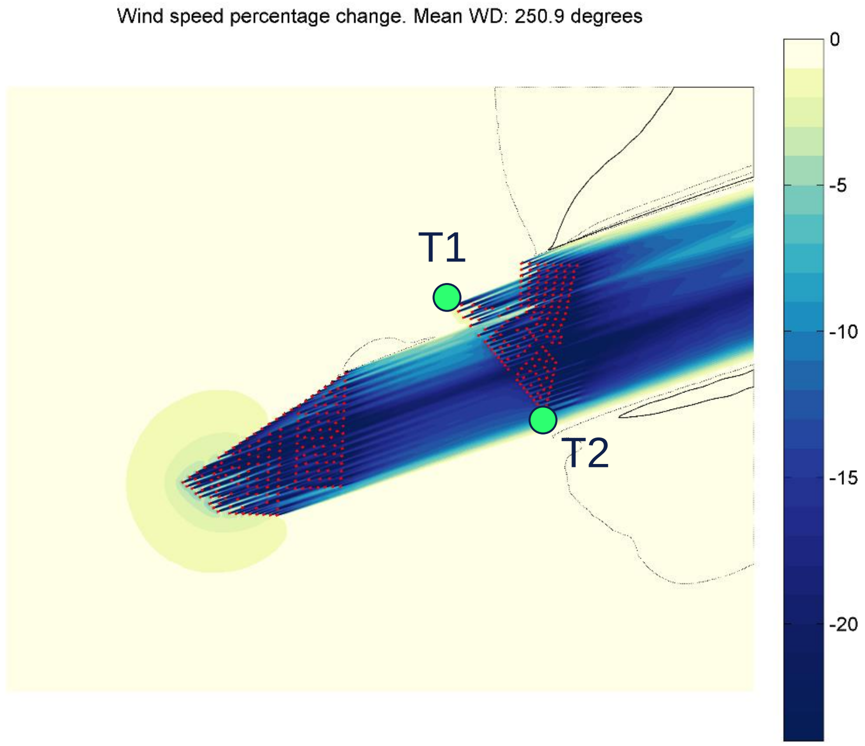




Power difference for corner turbines vs wind direction

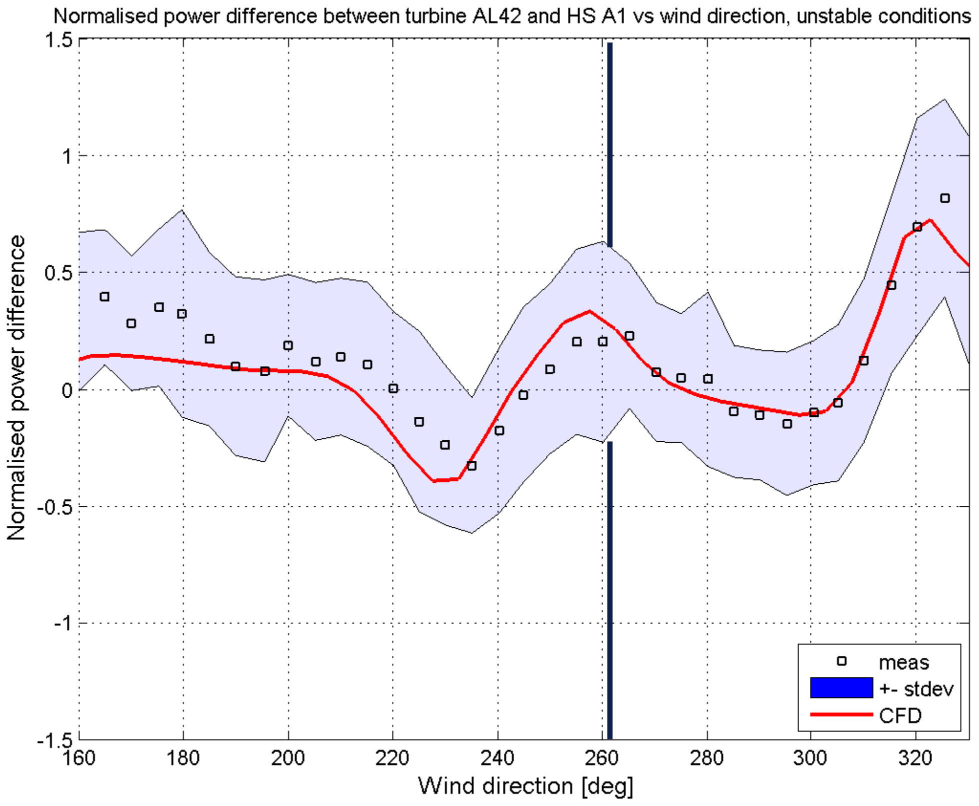
Unstable conditions, plateau of thrust curve

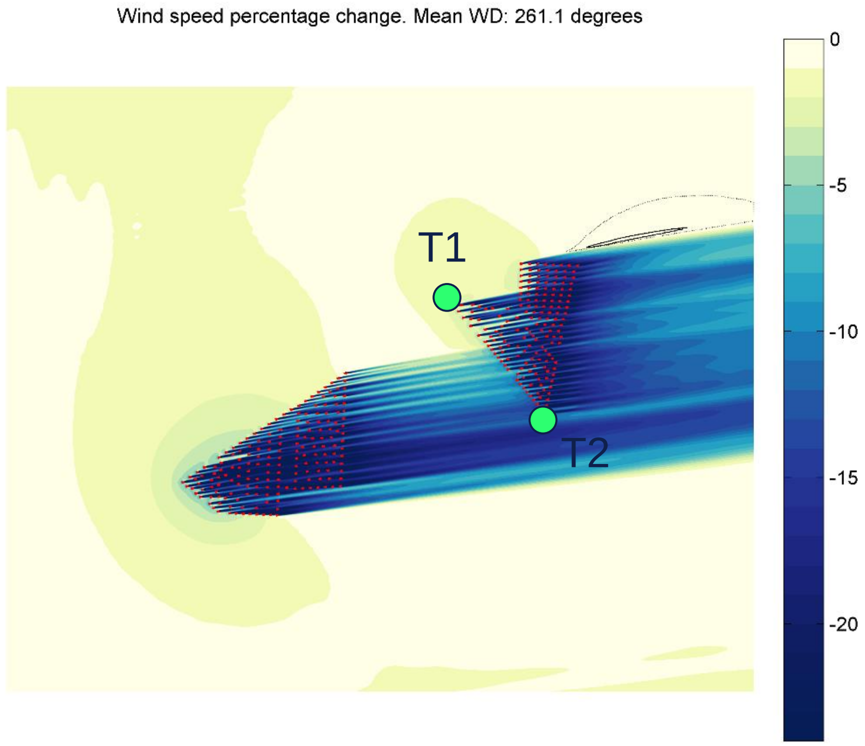




Power difference for corner turbines vs wind direction

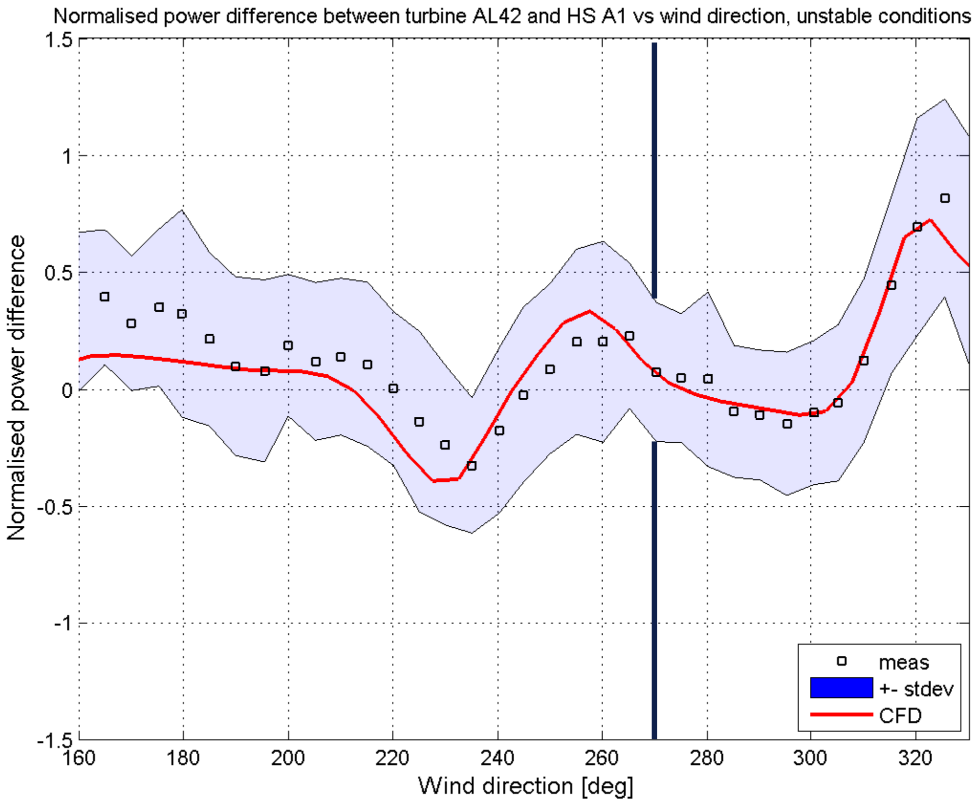
Unstable conditions, plateau of thrust curve

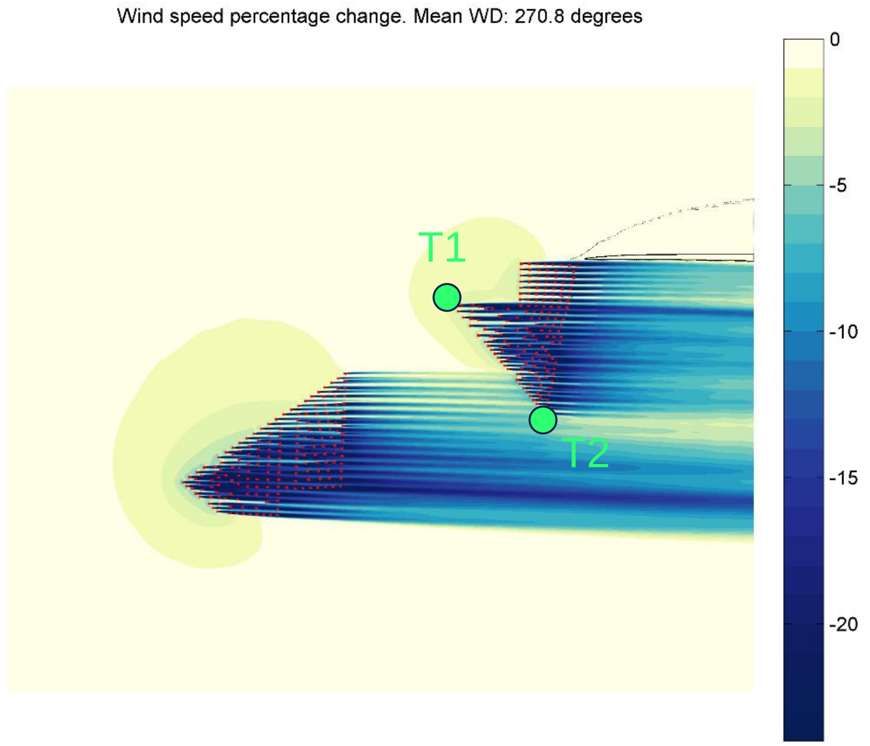




Power difference for corner turbines vs wind direction

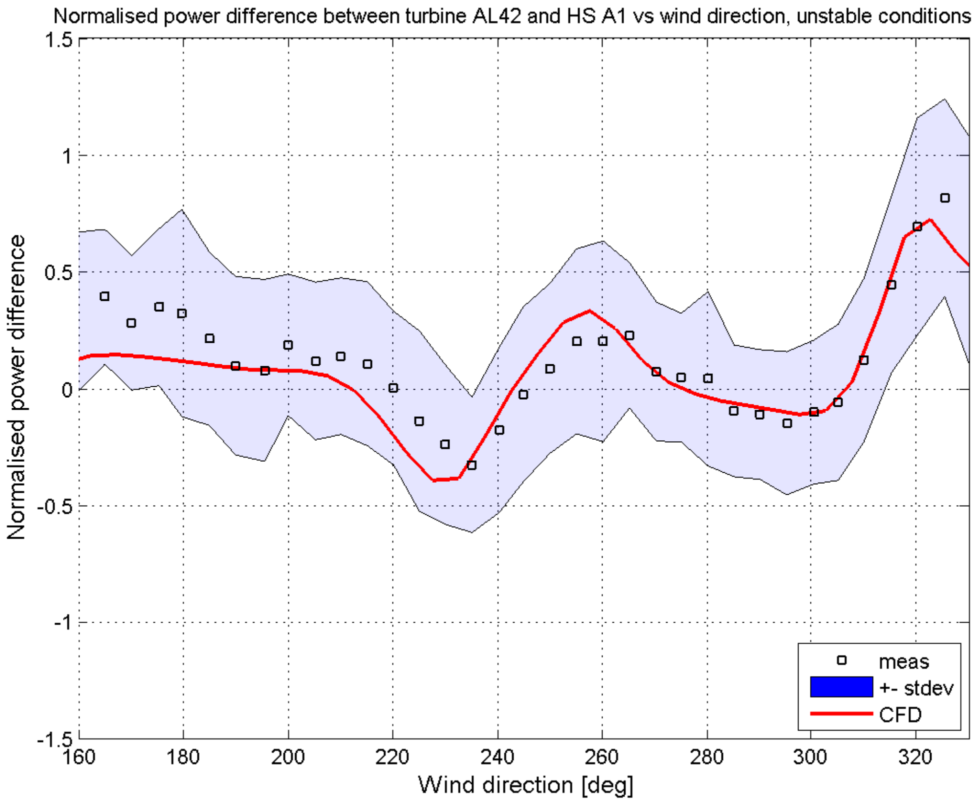
Unstable conditions, plateau of thrust curve



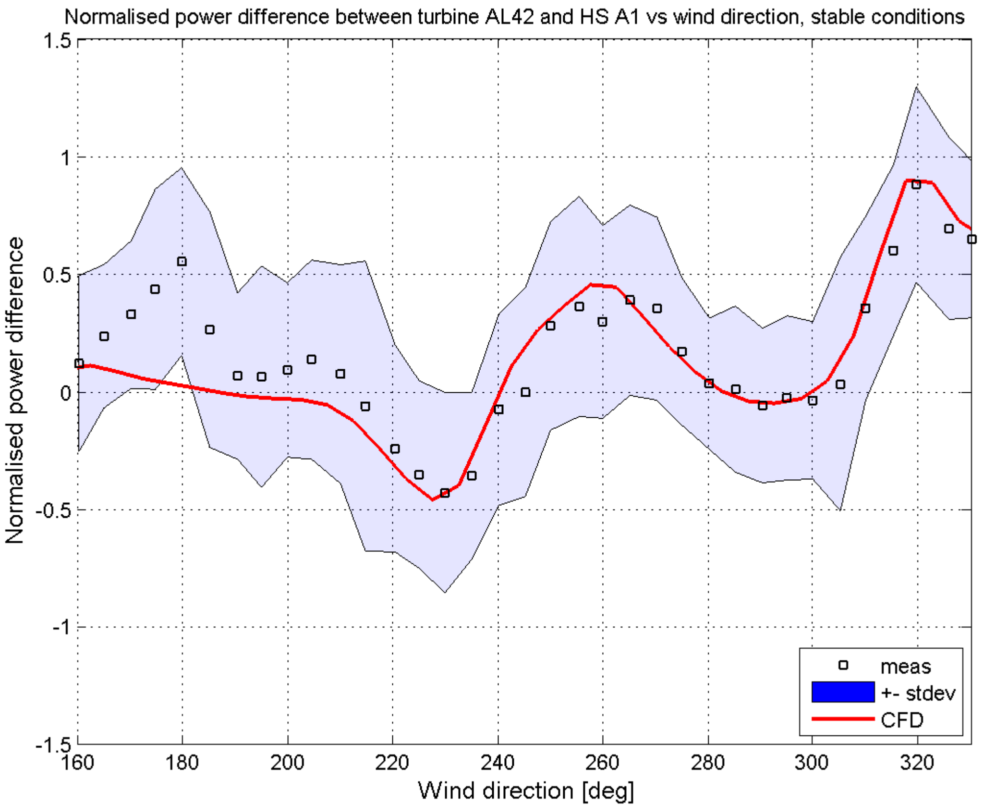


Power difference for corner turbines vs wind direction

Unstable conditions, plateau of thrust curve



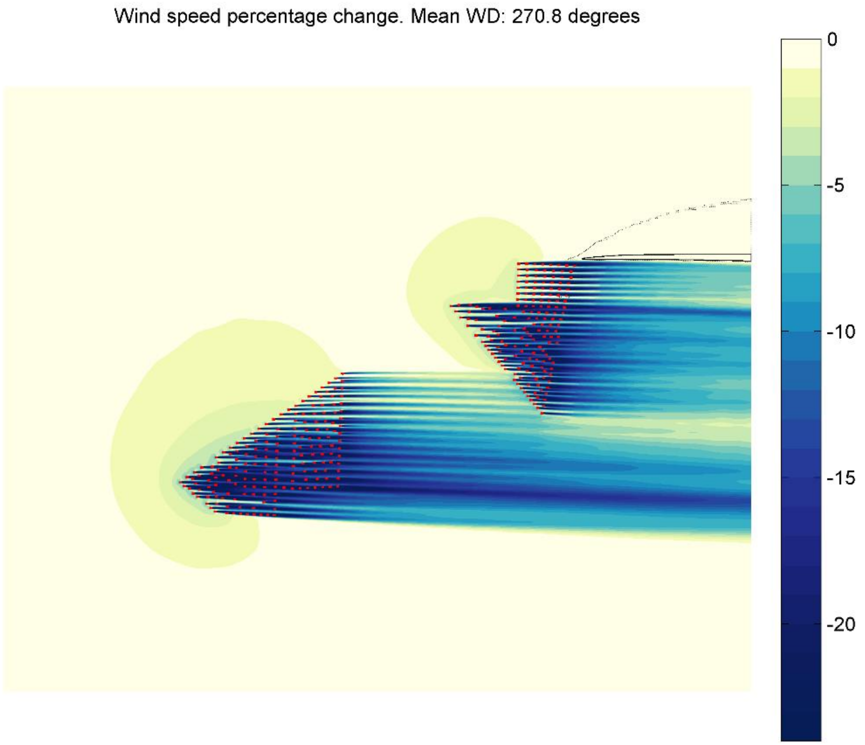
Stable conditions, plateau of thrust curve



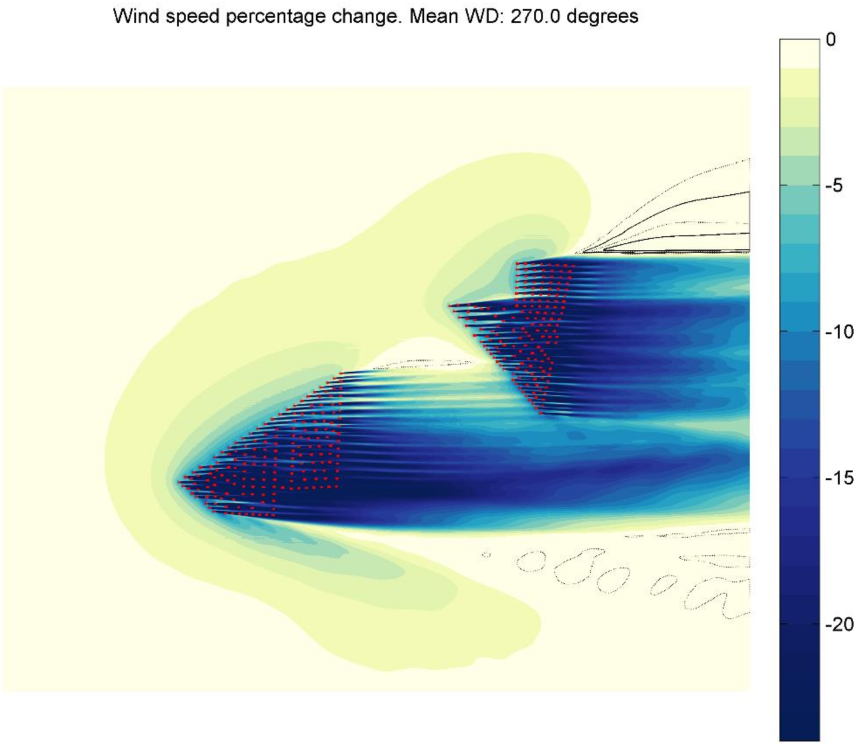
- Signal amplitude slightly increased when conditions are stable

Wakes and stability – SW directions

Unstable conditions

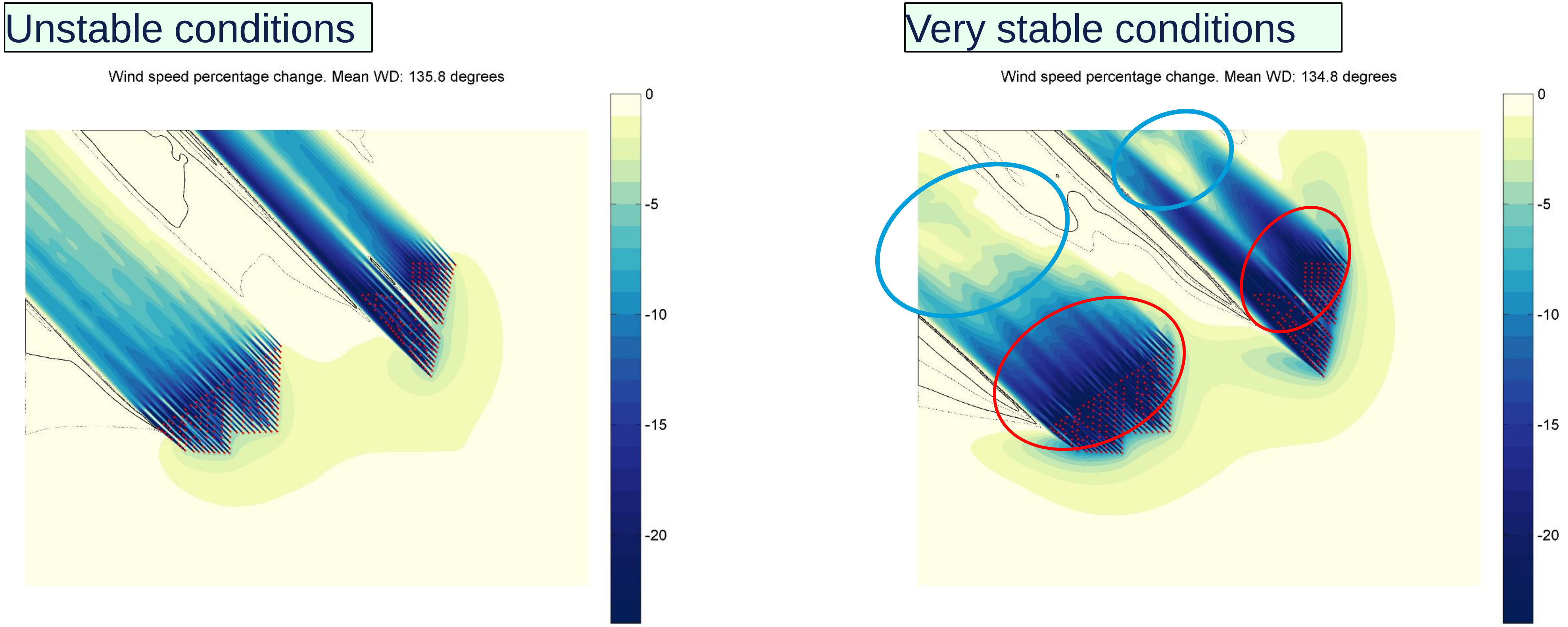


Stable conditions



- As expected, wakes are typically showing larger velocity deficits in stable than unstable conditions
- Cluster wakes persist a long distance, also in unstable conditions

Wakes and stability – SE directions – non trivial trend with recovery for far wake



- As expected, near-wakes are typically showing larger velocity deficits in stable than unstable conditions
- But: recovery of the cluster wake is faster in very stable conditions!

Gravity wave re-energising the back of the wind farm?

Summary & lessons learned

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Summary

Dual scanning lidar successfully measuring blockage and recovering cluster wakes upstream of the wind farm

WRF – informed CFD captures the magnitude of the blockage and of the cluster wakes

Cluster wakes for the W directions show larger power deficits in stable than in unstable conditions.

Magnitude well captured by CFD.

Non-trivial dependence of the recovery of the cluster wakes identified when the conditions become very stable. (SE directions)

Blockage and wakes difficult to separate when wind farm operates in the wake of another cluster. But both clearly play significant role in turbine interaction losses.

Thank you for your attention ☺

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