Understanding wind power in forested landscapes: CFD modelling

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SWC Webinar
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SNIC NAISS National Academic Infrastructure for Supercomputing in Sweden

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Outline

1) State-of-the-art model development

- The influence of the surface.
- Forest footprint

2) Diurnal cycles

3) Wake modelling

State-of-the-art
Modelling wind flow over forested landscapes

- How does the forest influence the wind dynamics in wind parks wind parks ?
- How can these features be appropriately modelled using CFD?
- What are the suitable boundary conditions, *spatial and transient*

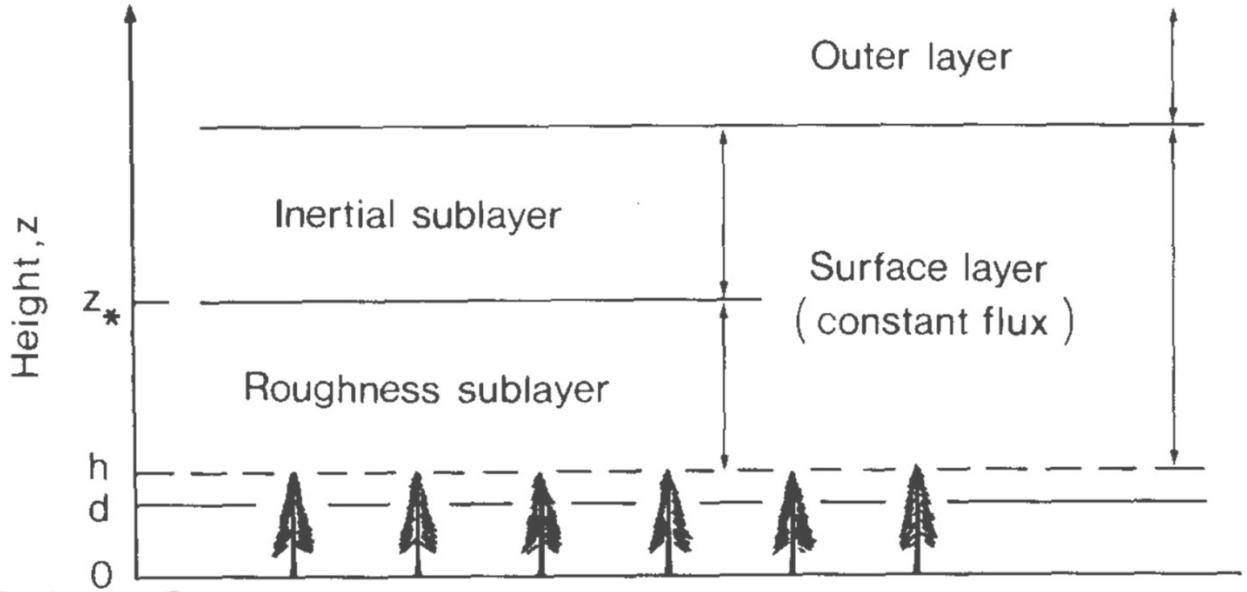
State-of-the-art
Modelling wind flow over forested landscapes

When representing the deceleration of wind due to forest, what is more commonly used in wind calculations ?

- A large roughness
- For typical Swedish forests, this could be $z_0 \approx 1 \sim 2$ m

Challenges of large roughnesses

- First and foremost, the usage of very large roughness imposes limitations in resolution
- This is due to the wall model:
  - In order to Monin-Obukhov to apply, $z_1 >> z_0$
  - More specifically, the first node should be above the roughness sublayer



$z_* = \alpha\, h$

$\alpha \approx 2\sim5$ the height of roughness elements

If a forest has trees of about 40 m, at what high do we need to set our first grid node?

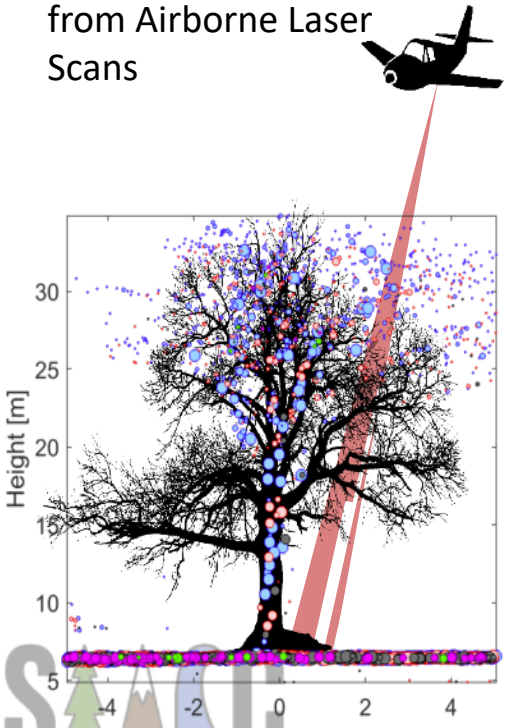
Basu and Lacser (2017) A cautionary note on the use o M-O similarity theory in very high-res. LES

Creating topographic and forest maps

Airborne Laser Scans (ALS) is the alternative. These are suitable for:

- Represent accurately the effect of the forest heterogeneities on the wind flow above
- Manipulation of forest characteristics to perform a variety of studies

Surface characteristics from Airborne Laser Scans



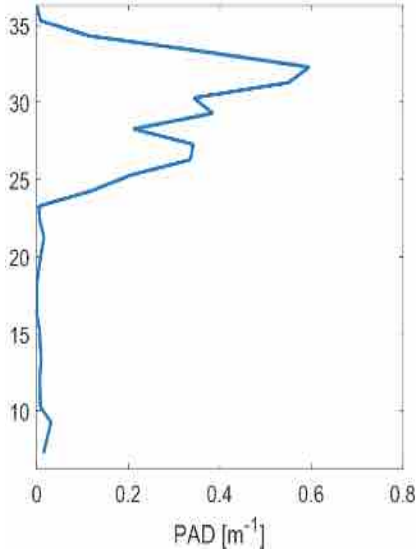
$$I_k = 1 - \sum_{i=1}^{k} r_{s_k}/r_{s_0}$$

$$\mathrm{PAD} = -2\cos\theta_l \ln\frac{I_2}{I_1}$$

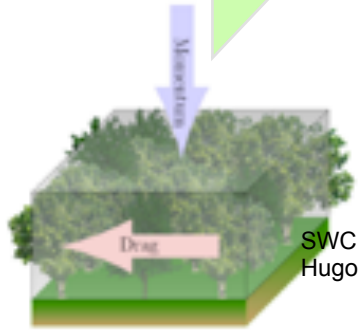
Plant Area Density

PAD

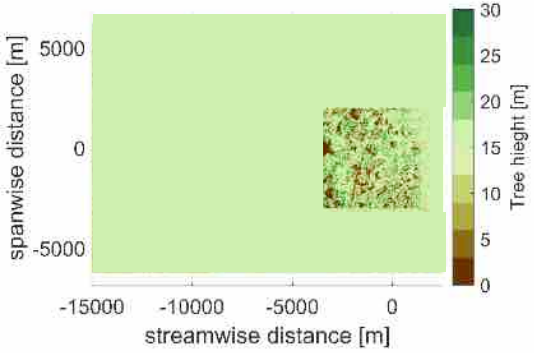
local profile



$$F_{D,i} = -C_D \mathrm{PAD}\,|\overline{u}_i|\,\overline{u}_i$$



Explicit forest modelling based on drag



Arnqvist et al. (2020) Robust processing of airborne laser scans to plant area density profiles

Modelling goal

Accurately represent the wind field over forests and complex terrains and its changes along the diurnal cycle

Evaluate effects on power production and dynamic loads

Main requirements:

1) Onshore, real terrain
   - Maps of *Elevation, Tree height, Plant Area Density* (PAD)
2) Representation of the continuous stratification changes along the day
   - Implement temperature changes in the forest and on the ground
3) Transient effects on the wake turbulence field
   - Rotor modelling: actuator disks/sector/line

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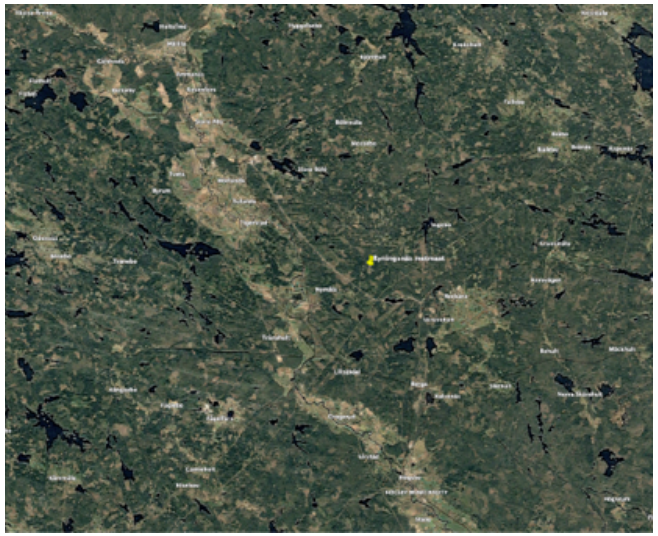
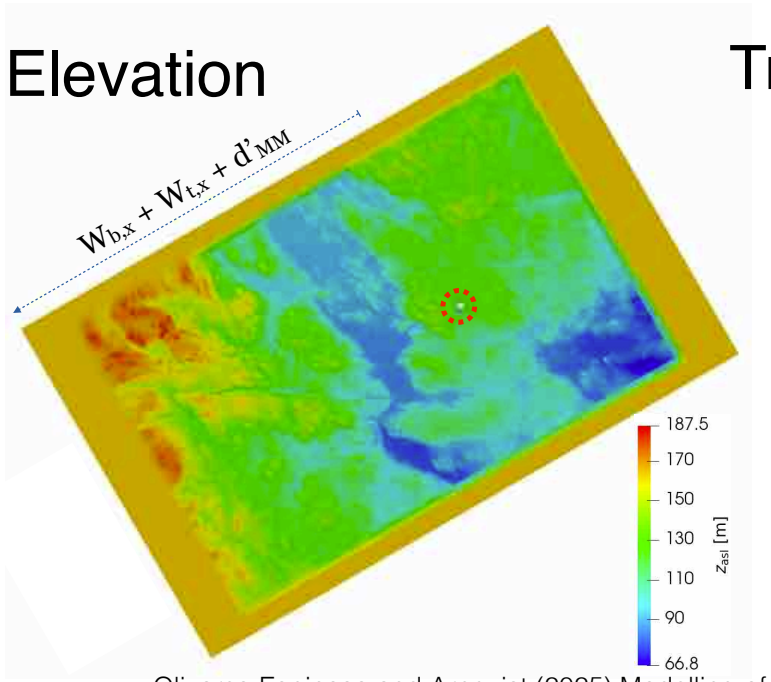
Terrain and forest fields in the computation

Forest site

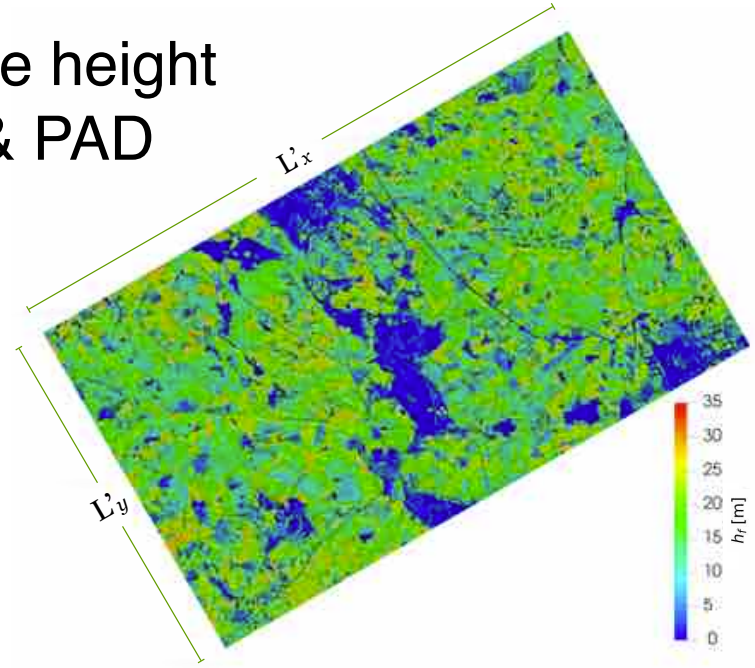


Google earth

Elevation



Tree height & PAD

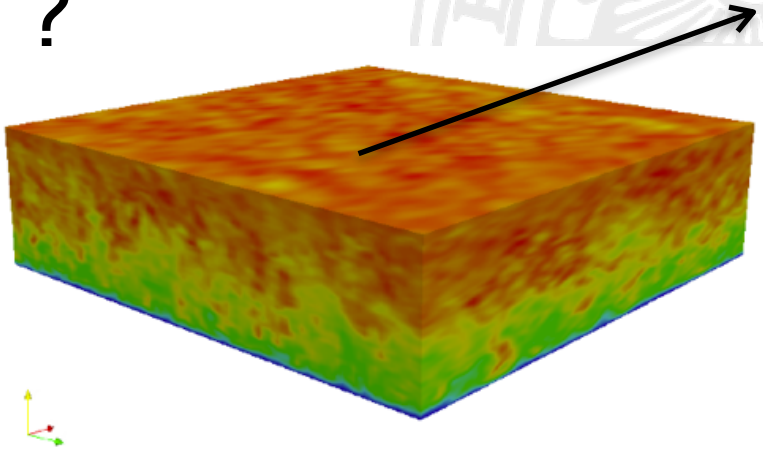


Olivares-Espinosa and Arnqvist (2025) Modelling of wind flows over realistic forests with LES (preprint)

Ground boundary conditions in the computation domain are realistic representations of

- Topography
- Forest distribution and density

What CFD technique ?



Up to here, implementation can be done on RANS or LES

A priori, LES is more accurate but runs slower: COST

What to consider:

- How important are transient phenomena
  - Turbulence and stratification along diurnal cycles, low-level jets, canopy waves, wake dynamics
- Representation of the TKE and dissipation effects
  - RANS requires tweaking. For instance, overestimation of TKE around rotors can appear
  - No fluctuations smaller than 30 min
- Loads estimation

Our model is implemented on LES because:

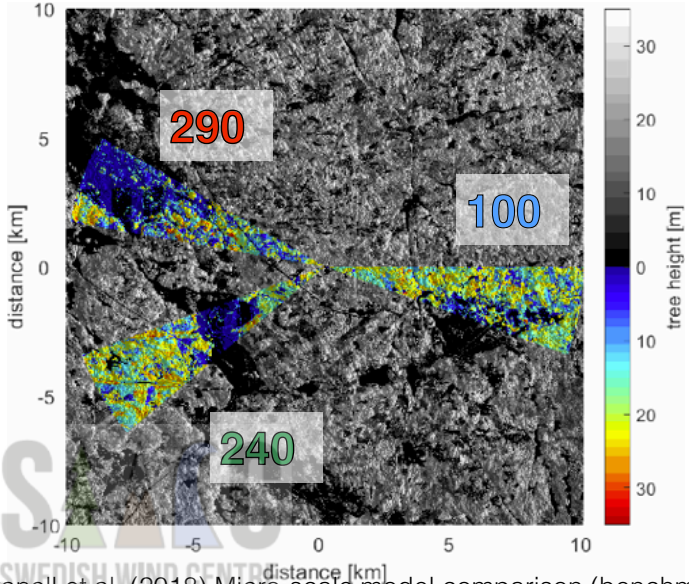
- The assessment of resolution, footprint and wake effects requires the study of turbulence, which could not be done based on mean fields from RANS
- But RANS is a good alternative & PAD maps can be used
- Current work includes the study of wake recovery over forests with RANS

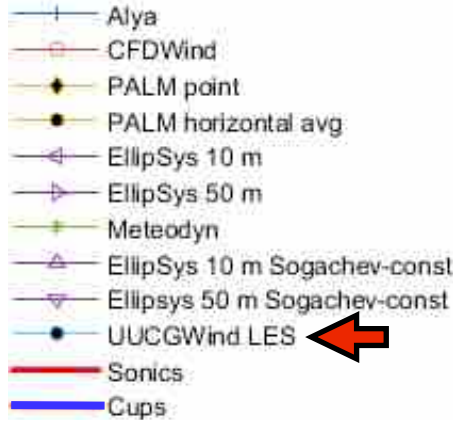
Results: velocity

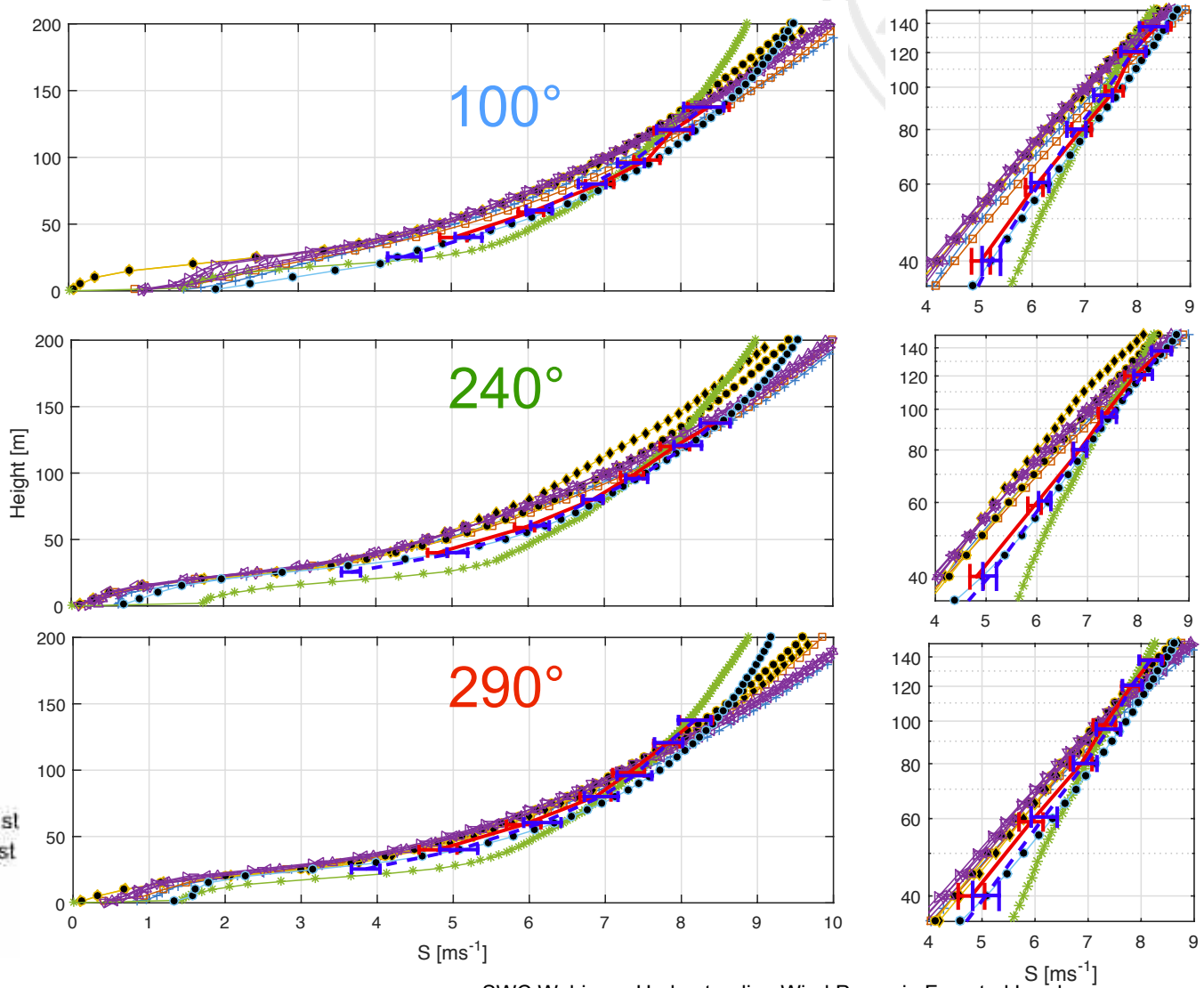
benchmark our LES model

Ryningsnäs

- Forest and topography shape the incoming wind profile distinctively at different heights
- Therefore, a large upstream fetch should be included in computations







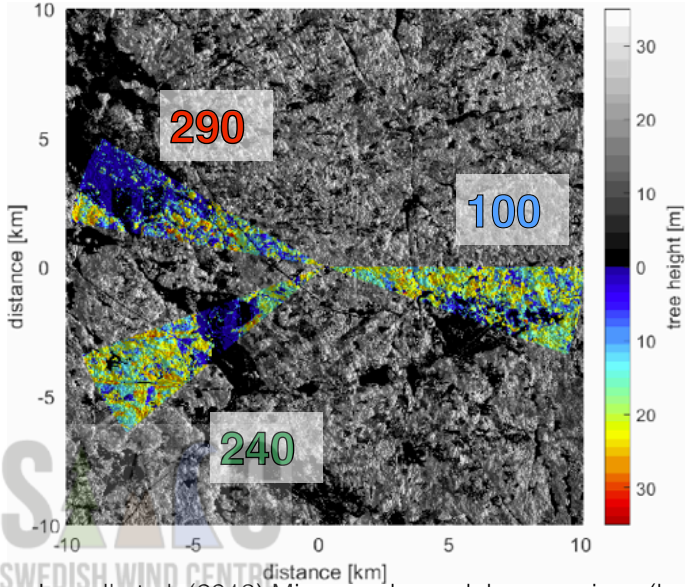
Ivanell et al. (2018) Micro-scale model comparison (benchmark) at the moderately complex forested site Ryningsnäs

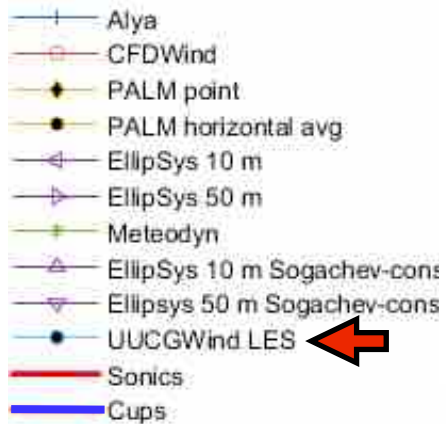
Results: wind shear

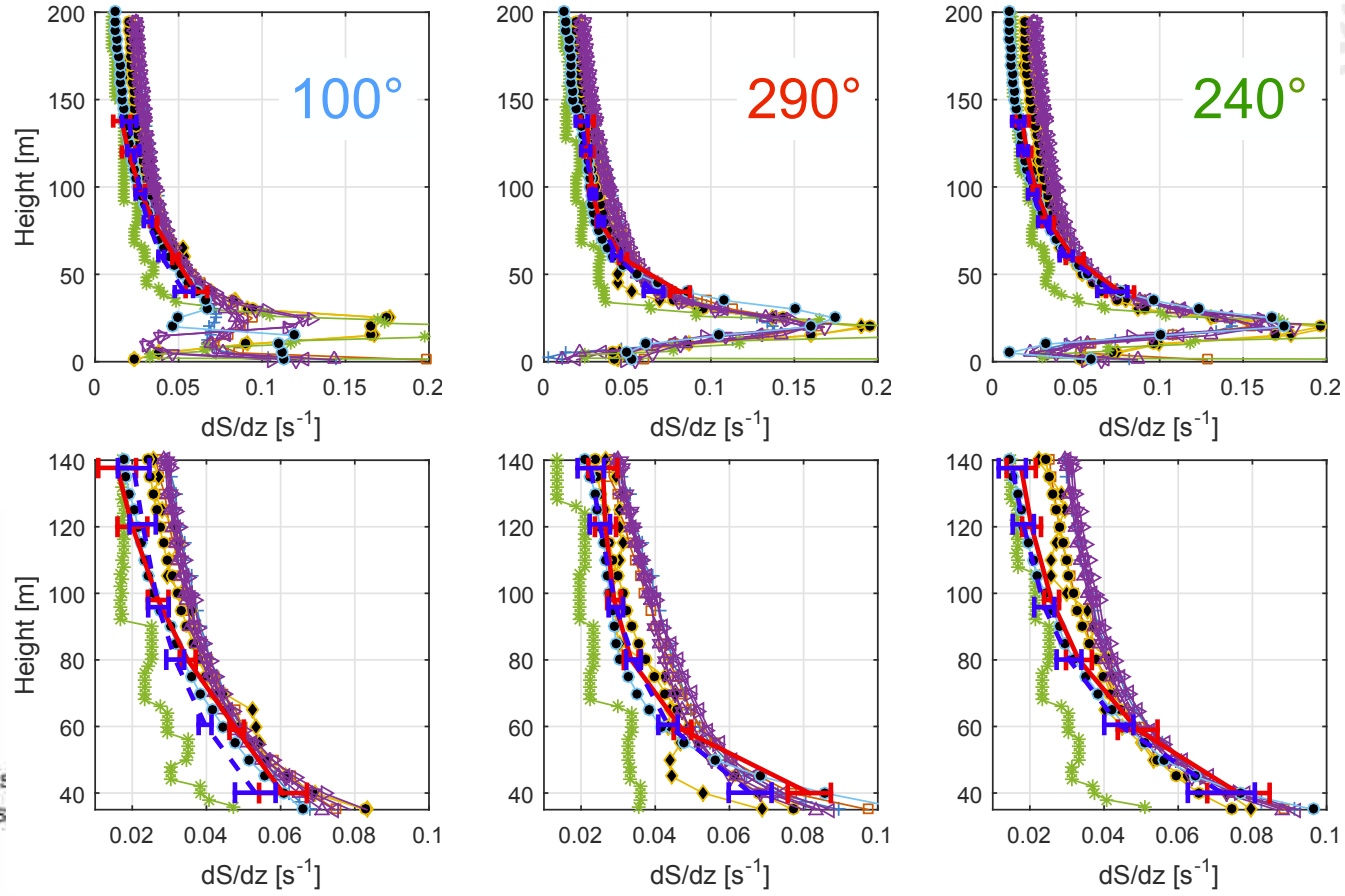
benchmarking our LES model

Ryningsnäs

- Forest and topography shape the incoming wind profile distinctively at different heights
- Therefore, a large upstream fetch should be included in computations







Ivanell et al. (2018) Micro-scale model comparison (benchmark) at the moderately complex forested site Ryningsnäs

Realistic forest model

Heterogeneity

- The forest (tree height, branch & leaf density) and topography are naturally heterogeneous
- The use of laser scans data to represent forest and topography in CFD permits to represent the effects of the their heterogeneity
- The heterogeneity shapes the wind differently for different heights, within the rotor area
- Using uniform quantities fails to represent this

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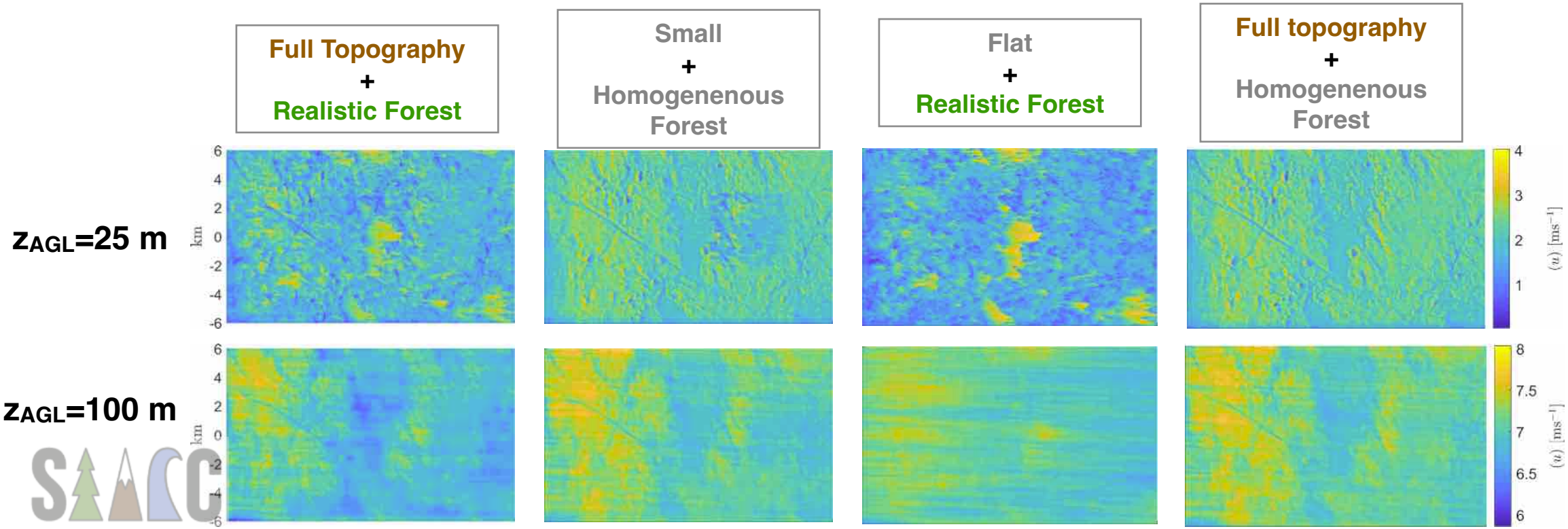
Realistic forest model

Keyword: Footprint

- Using uniform quantities fails to represent this **missing footprint** from upstream fetch

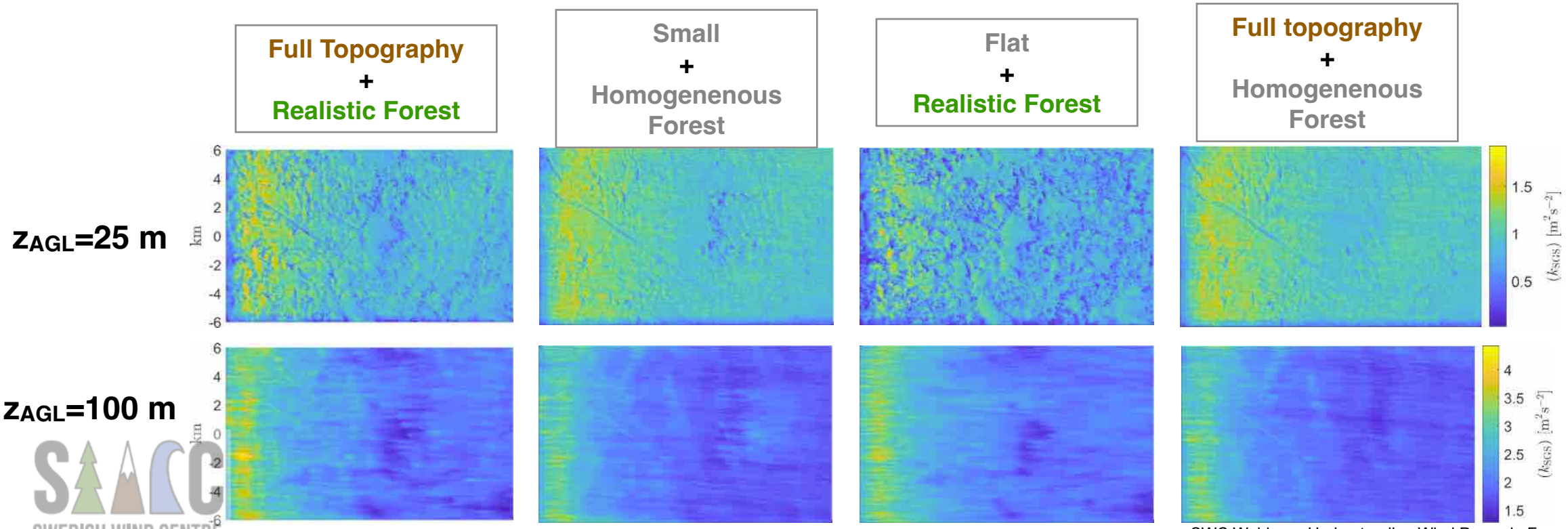


Olivares-Espinosa and Arnqvist (2025) *Modelling of wind flows over realistic forests with LES* (preprint)

Realistic forest model

Keyword: Footprint

- Using uniform quantities fails to represent this **missing footprint** from upstream fetch
- But representing forest with an equivalent roughness is also problematic !!
- z_0 is simply too large



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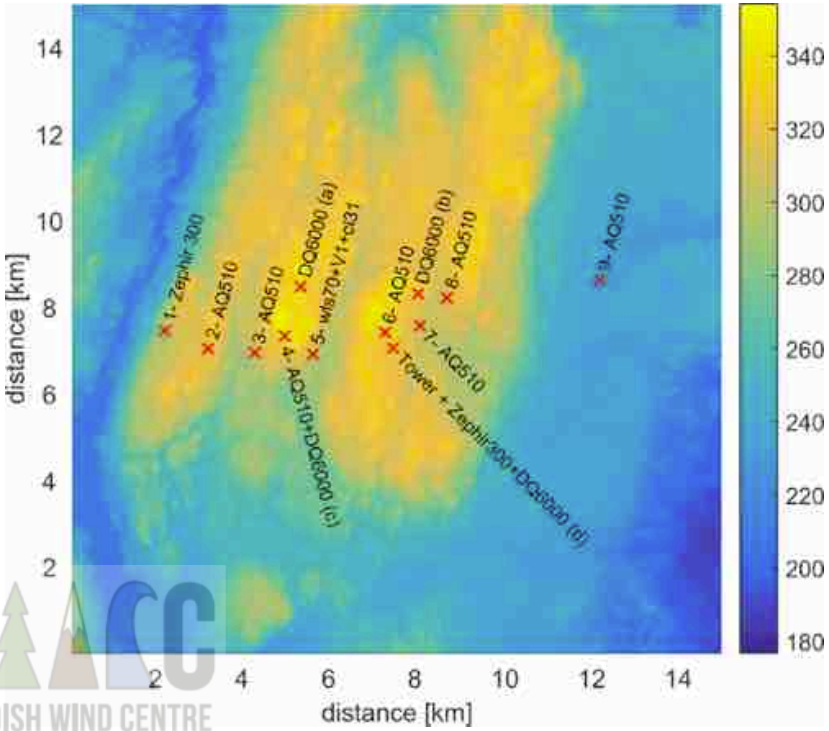
Diurnal cycle

Implementation of diurnal stratification

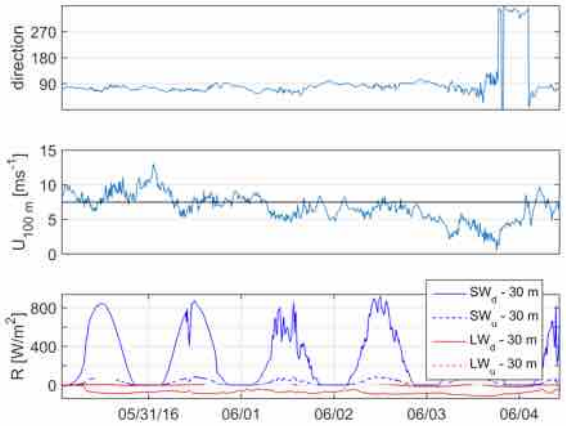
Hornamossen Benchmark

- What are the local changes in the wind flow along the diurnal cycle?
- Stratification changes driven by temperature and net radiation

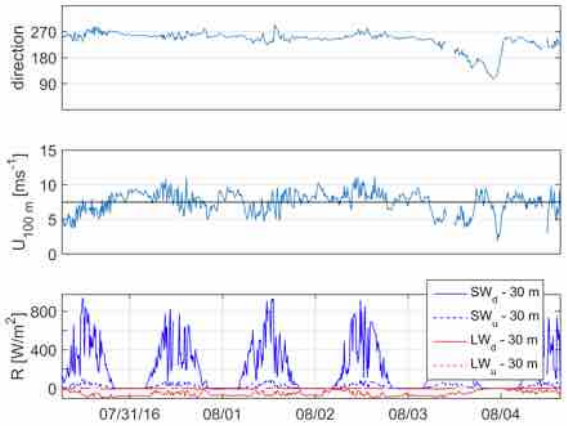


Inputs

East



West



Temperature changes

- *For the clearings*

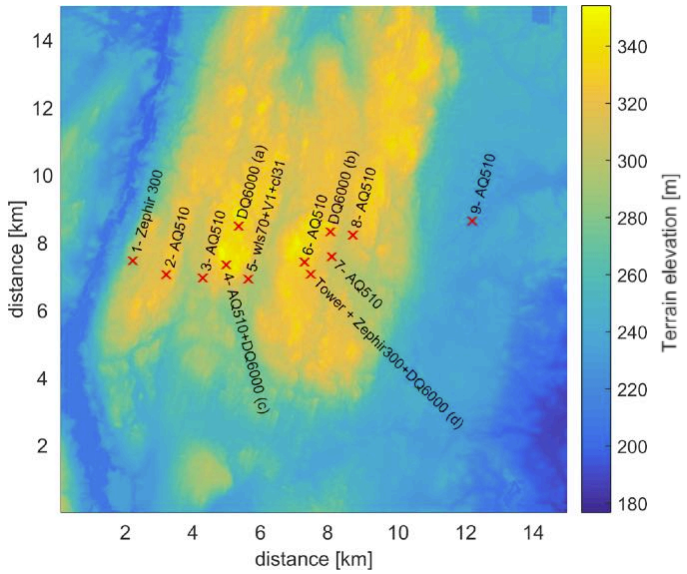
Heat-flux for warming/cooling

- *For the forests (PAD)*

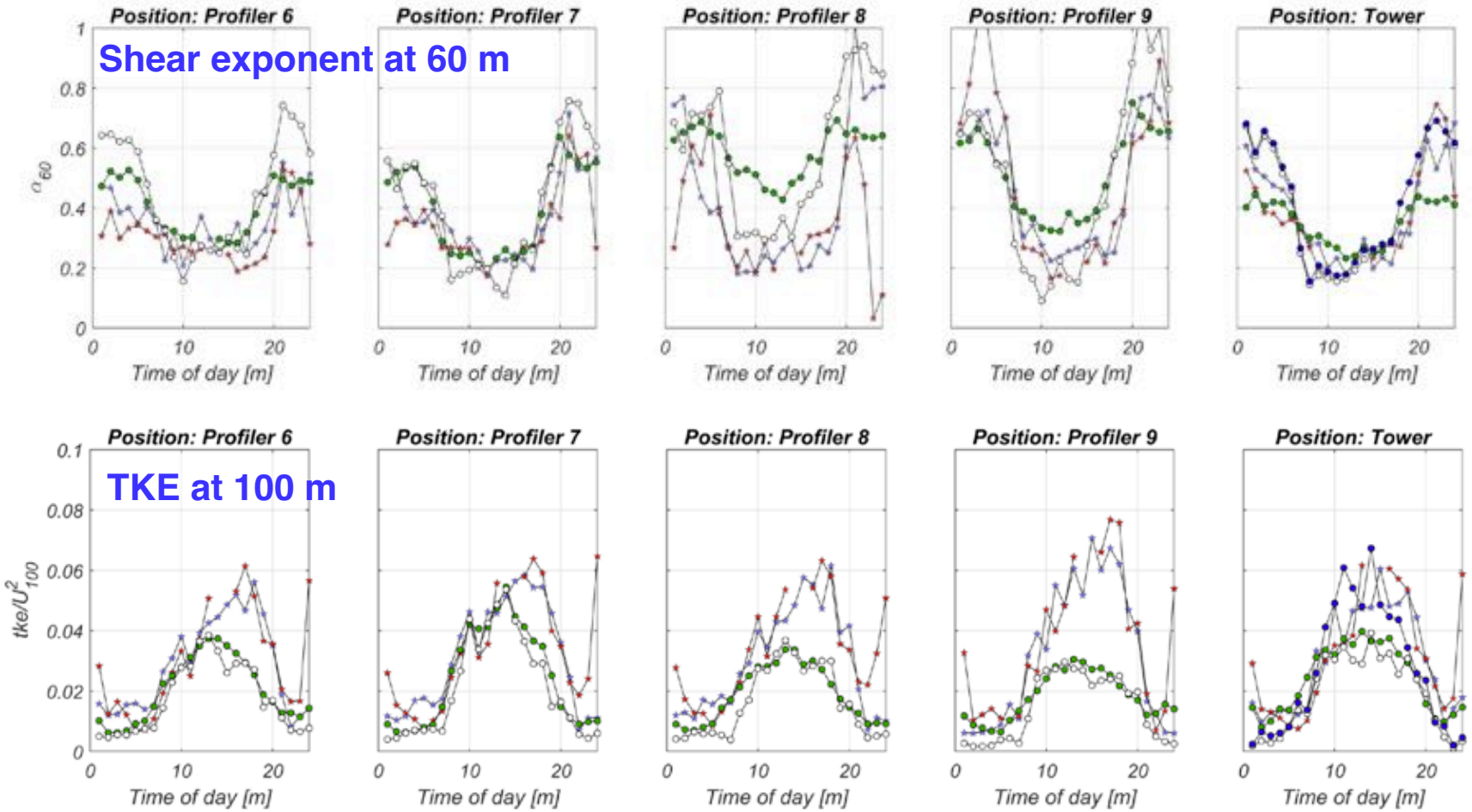
Olivares-Espinosa and Arnqvist (2023) *Modelling of wind turbine wakes over forests along the diurnal cycle*

Diurnal stability: changes along the diurnal cycle

Hornamossen



Tower, block average
Measurements profilers
Long term measurements
OpenFOAM LES $U_{g_{fixed}}$
OpenFOAM LES $U_{g_{tend}}$



Results from 2 simulations
with constant and varying geostrophic forcing

Wake modelling: Actuator Disk

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Wind turbine wakes over forests

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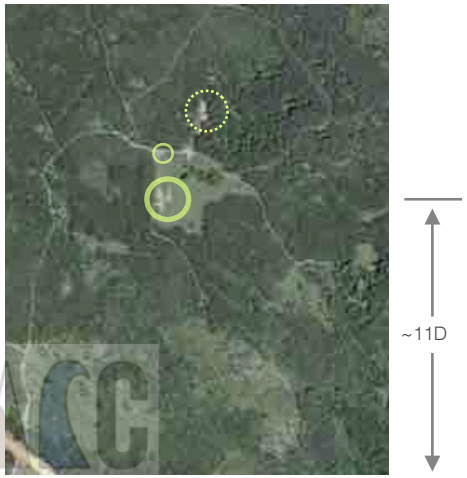
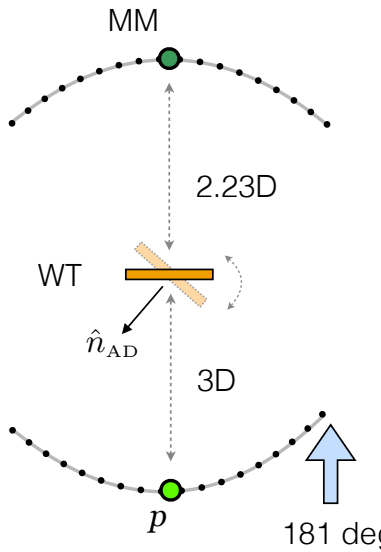
- <h_{forest}> ~ 20 m upstream of WT
- Metmast measurements between 40 and 140 m a.g.l.
- D=90 m
- Hub height at 80 m
- Rotor modelled with an Actuator Disk
- What are the changes in the turbulence field of the wake along the diurnal cycle



- Rotor steers to face incoming wind



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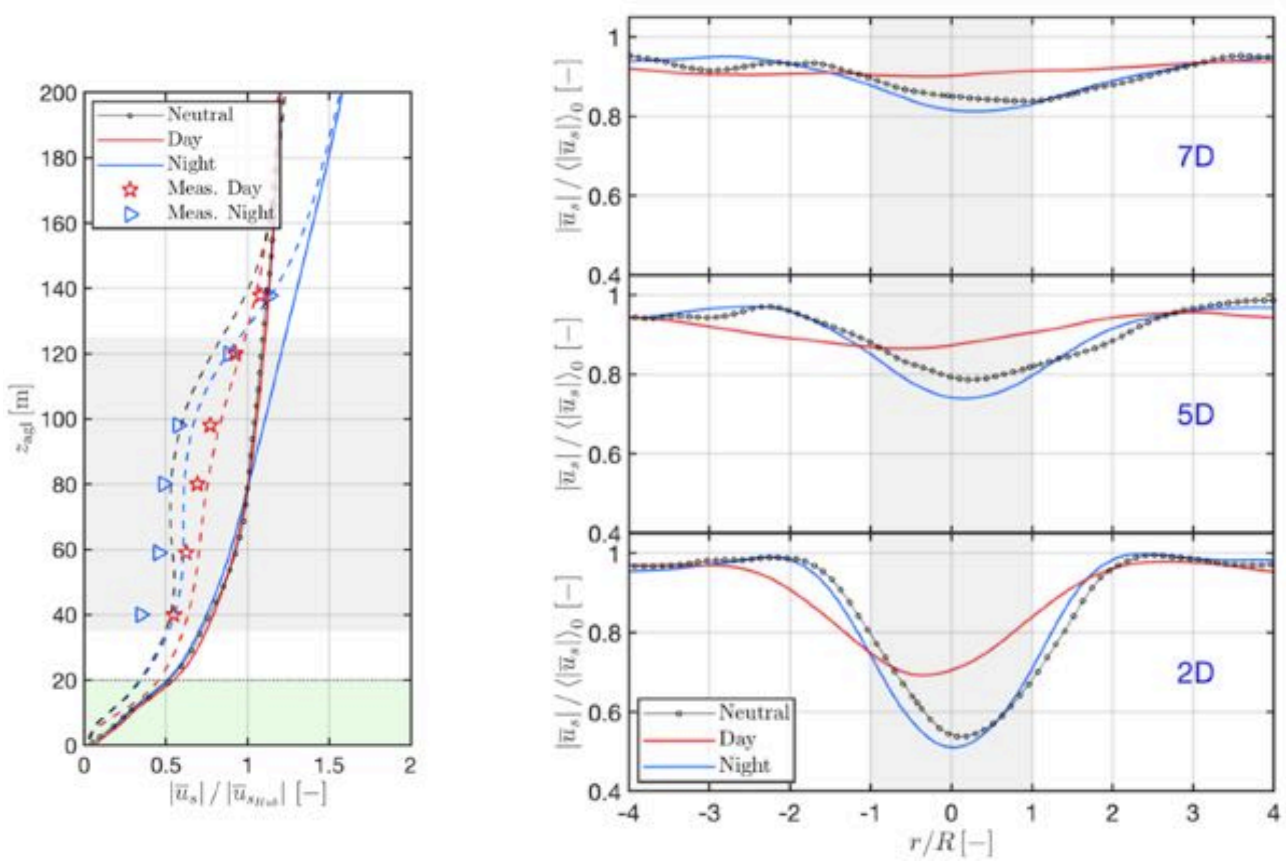
Wakes over forests



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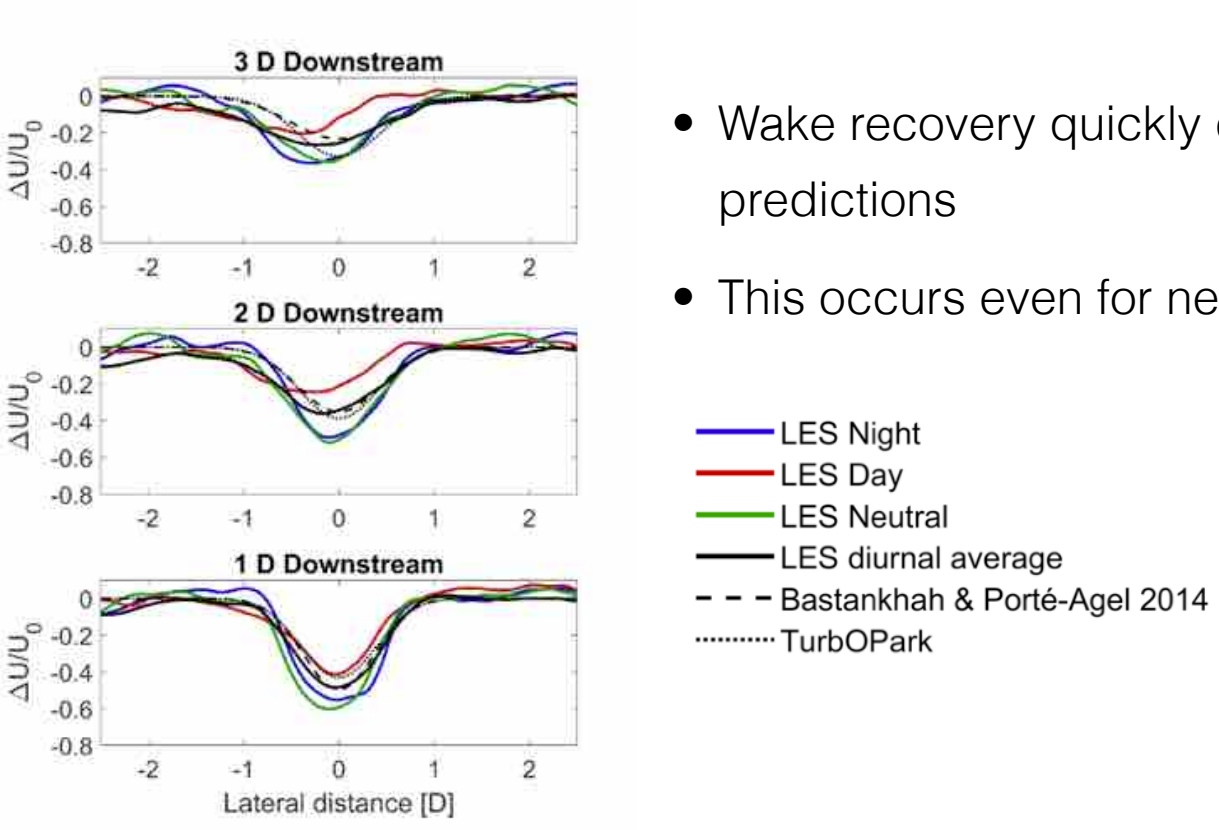
Wakes over forests

Comparing wake deficit with analytical models



- Wake recovery quickly differs from LES predictions
- This occurs even for neutral & diurnal average

Olivares-Espinosa, H. Arnqvist, J., Avila, M. and Chávez-Arroyo, R. *Expansion and recovery of wind turbine wakes over forests*. In preparation for Making Torque from Wind Conference in Bruges, Belgium, June 2026

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Arnqvist, J., Olivares-Espinosa, H. and Carlén, I., 2024. Wind energy relevant characteristics of turbulence over boreal forests. In Journal of Physics: Conference Series, Vol. 2767, No. 9, p. 092096. IOP Publishing

Olivares-Espinosa, H. and Arnqvist, J., 2023. Modelling of wind turbine wakes over forests along the diurnal cycle. In Journal of Physics: Conference Series, Vol. 2505, No. 1, p. 012043. IOP Publishing

Arnqvist, J., Freier, J., & Dellwik, E., 2020. Robust processing of airborne laser scans to plant area density profiles. Biogeosciences, *17*(23), 5939-5952.

Ivanell, S., Arnqvist, J., Avila, M., Cavar, D., Aurelio Chavez-Arroyo, R., Olivares-Espinosa, H., Peralta, C., Adib, J. and Witha, B., 2018. Micro-scale model comparison (benchmark) at the moderately complex forested site Ryningsnäs. Wind Energy Science, 3(2), pp.929-946

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