Forest simulation in industrial CFD codes

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Problem formulation

- Onshore wind power is growing rapidly
- Most suitable locations have already been built upon
- Installation planned in the northern parts of Sweden
  - Lower population density – easier to acquire permit
  - 58% tree coverage [1] & complex terrain
- Expensive and time demanding with physical measurements
  - Complement with CFD simulations
- No industry consensus on how to estimate wind conditions in forested areas
- **Objective is to decrease the uncertainty in the results of the CFD simulations**

Agenda

- Background - Forest simulation and modelling
- Sensitivity analysis
- Validation with LES data
- Simulations for clearings
- Case study Rynningsnäs
- Conclusions

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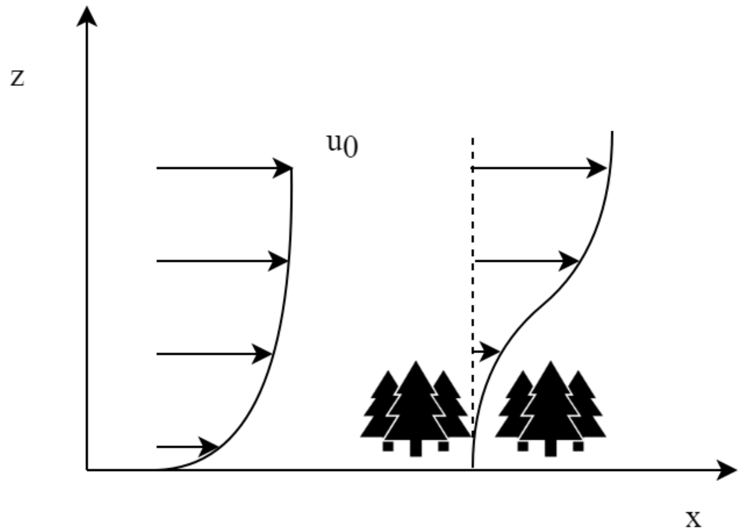
Forest simulation

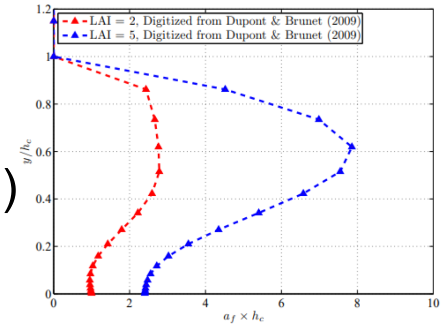
- Inlet profile logarithmic
- Expecting to see momentum being absorbed by the forest
- Higher turbulence regime above forest
- How is forest modelled in CFD tools?

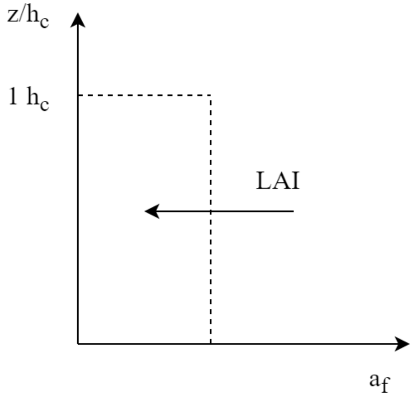


Forest simulation

Accuracy

1. Ideally: No slip BC for all forest with complete cell coverage
   - Computational heavy and not applicable large scale
2. Momentum sink $S_{u,i} = -\rho a_f c_d U^2$
   - a_f, leaf area density [m^2/m^3] → $LAI = \int_0^{h_c} a_f dz$
   - Provided from means of aerial scans (skogsstyrelsen)
   - c_d, quantify the drag or resistance of an object
3. Constant a_f over tree height, model used in WindSim
4. No information about the LAI, C_2 = const.





$$C_2 = \frac{LAI}{H} c_d$$

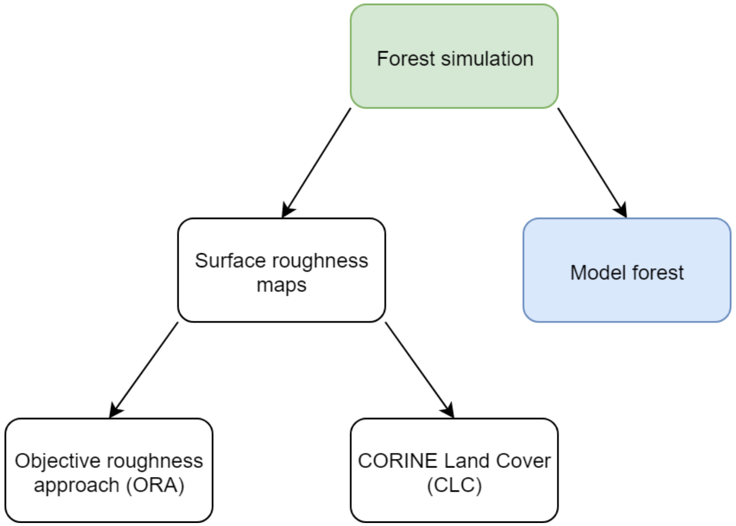
Forest characteristics	LAI	c_d	H [m]	C_2
Very sparse	0,25	0,2	30	0,0017
Slightly sparse	1	0,2	30	0,0067
Slightly dense	4	0,2	30	0,0267
Very dense	16	0,2	30	0,1067

Forest simulation

5. Instead of modelling forest: Imposing roughness maps from data bases

- For instance: CORINE 2006, Wind Atlas etc.
- Objective roughness approach (ORA) - Create roughness maps from tree height

- Modelling the forest is the main focus of the master thesis



Forest modelling

- WindSim, (commercial) software used for this study
- Uses the 3D Reynolds-Average Navier-Stokes (RANS) equation to simulate the flow characteristics

1. $$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial U_i}{\partial x_j} - \overline{u_i' u_j'}\right) + \overline{S_{u,i}}.$$

$$\overline{S_{u,i}} = -\overline{\rho C_2 U|U|}$$

- Last term is a momentum sink used to represent impact of e.g. a forest
- C_2 is the forest force resistive constant

Forest modelling

- Solve Reynolds stress by applying Eddy viscosity model
- Introduce k-ε turbulence model + transport equation k and ε
- Introduce turbulence sources

2. $$\tau_{ij} = -\rho\overline{u_i'u_j'} = \mu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3}\rho k\delta_{ij}$$

3. $$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

4. Rate of change = production - destruction + transportation + turbulent sources

4. $$\begin{cases} \dfrac{Dk}{Dt} = P - \varepsilon + \dfrac{\partial}{\partial x_j}\left(\left(\nu + \dfrac{\nu_t}{\sigma_k}\right)\dfrac{\partial k}{\partial x_j}\right) + S_k \\ \dfrac{D\varepsilon}{Dt} = (C_{\varepsilon1}P - C_{\varepsilon2}\varepsilon)\dfrac{\varepsilon}{k} + \dfrac{\partial}{\partial}x_j\left(\left(\nu + \dfrac{\nu_t}{\sigma_\varepsilon}\right)\dfrac{\partial \varepsilon}{\partial x_j}\right) + S_\varepsilon \end{cases}$$

Empirically derived parameters
- C_μ = 0,09
- $C_{\varepsilon1}$ = 1,44
- $C_{\varepsilon2}$ = 1,92
- σ_k = 1,0
- σ_ε = 1,0

5. $$\begin{cases} S_k = C_2(\beta_P|U|^3 - \beta_D|U|k) \\ S_\varepsilon = C_2(C_{\varepsilon4}\beta_P\dfrac{\varepsilon}{k}|U|^3 - C_{\varepsilon5}\beta_D|U|\varepsilon) \end{cases}$$

Empirically derived parameters from Sanz 2003 [2]
- β_P = 1,0
- β_D = 6,51
- $C_{\varepsilon4}$ = 1,24
- $C_{\varepsilon5}$ = 1,24

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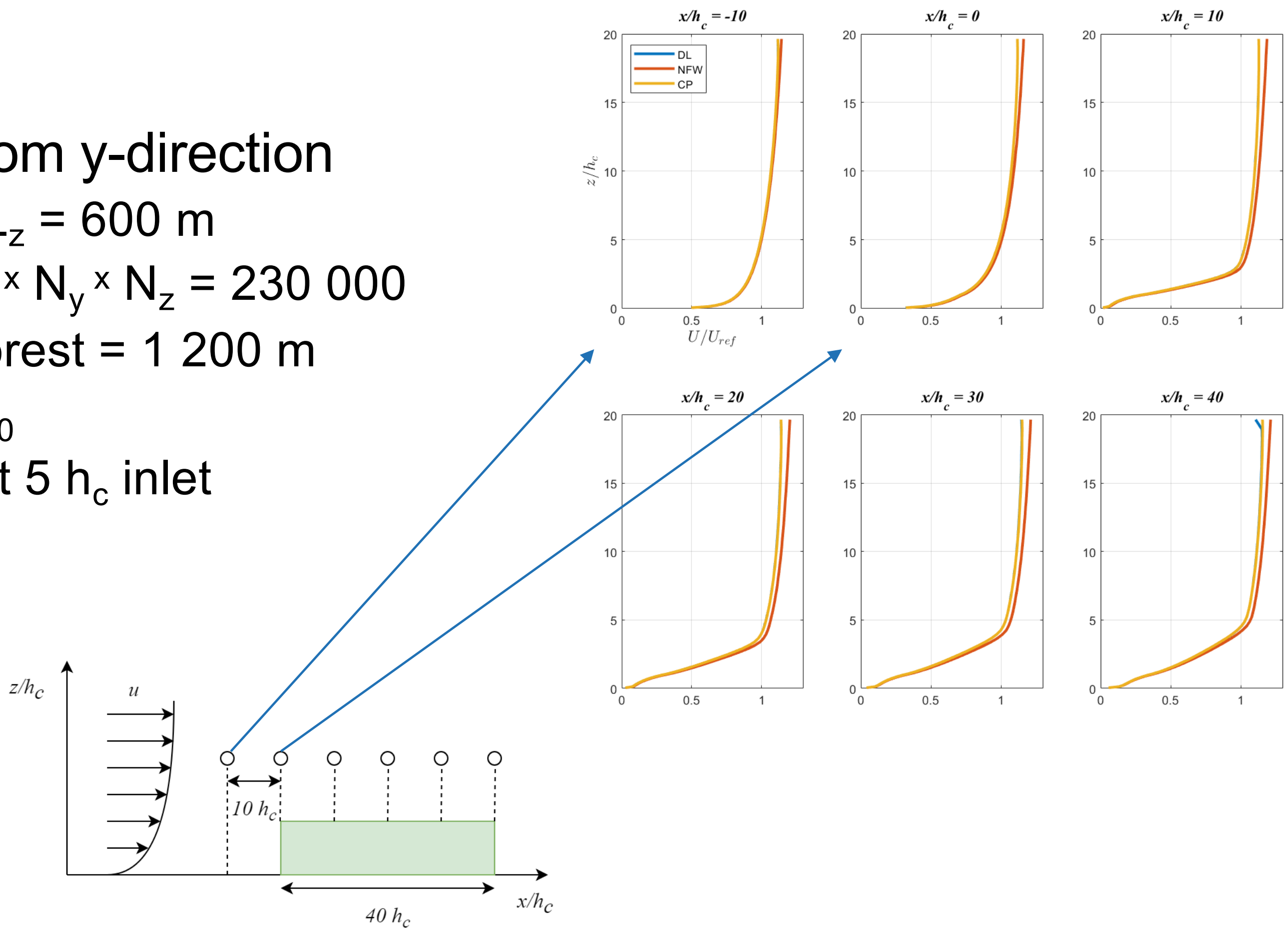
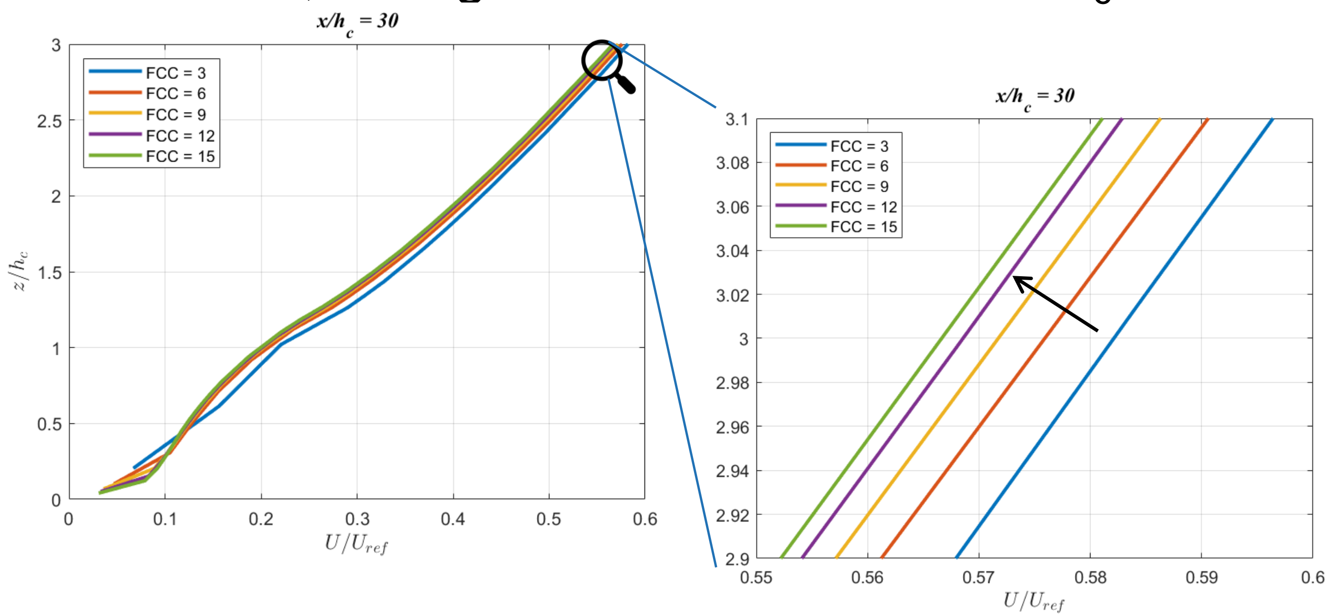
Top boundary condition

- 3D domain, no impact from y-direction
  - L_x = 2 400 m, L_y = 40 m, L_z = 600 m
  - Cell size x-y = 5 x 5 m, N_x x N_y x N_z = 230 000
  - h_c = 30 m, length of the forest = 1 200 m
  - Full forest with constant z_0
  - Wind speed normalized at 5 h_c inlet
- Top boundary conditions
  - Constant pressure (p = c)
  - ~~No friction wall (τ = 0)~~
  - ~~Diffusive link (p & τ = c)~~
- Avoid physical speed-up



Forest cell count

- Same domain as for top boundary condition
- Varying amount of cells in vertical direction of forest, between 3 – 15
- Limited amount of cells to employ in WindSim (60) – trade off
- Middle of the forest: FCC = 3 is 1,8% higher than FCC = 12 at 3 h_c



- Fewer amount of cells overestimates the wind speed

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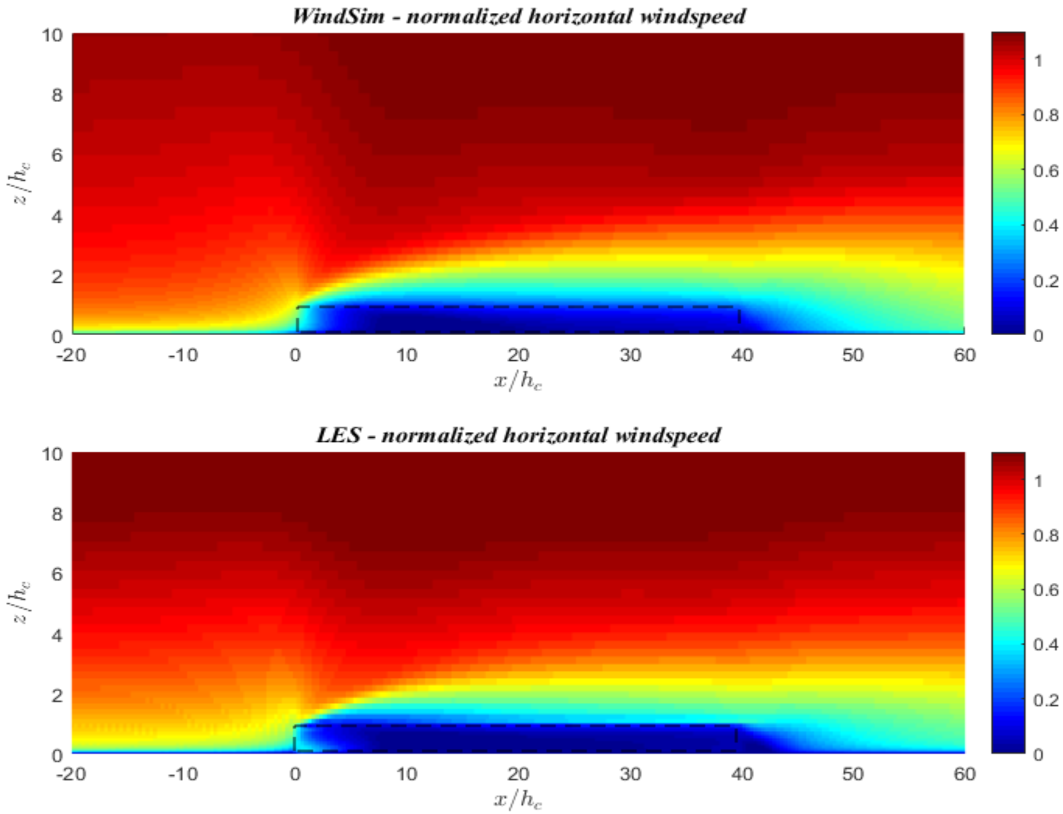
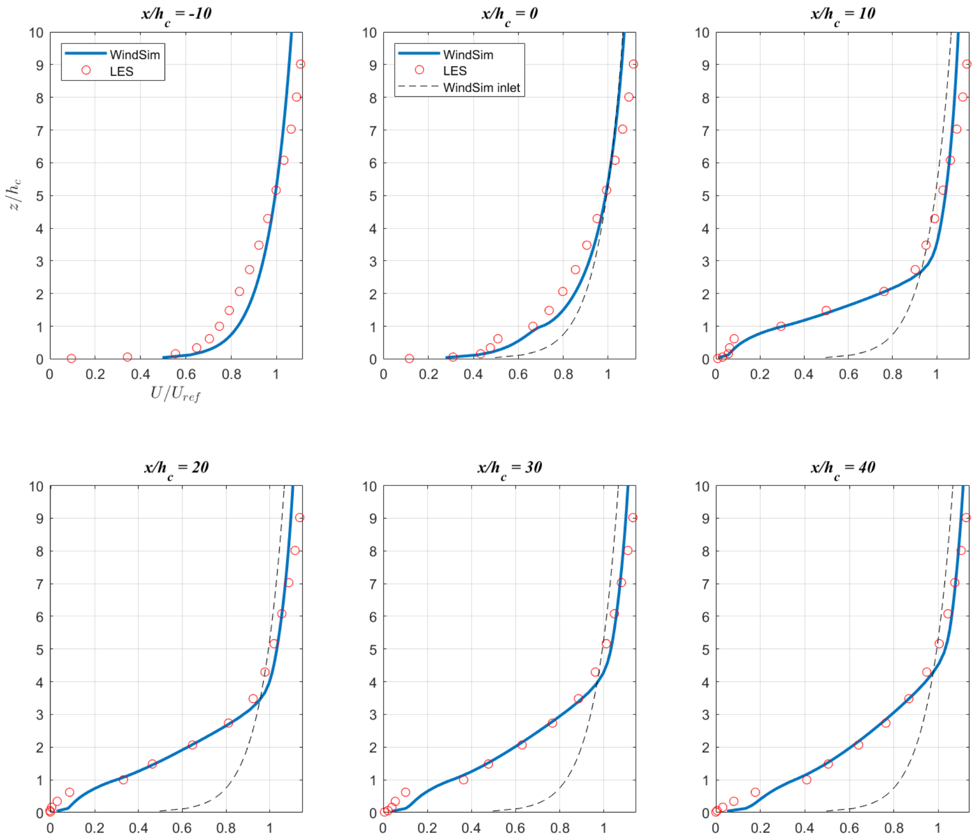
Validation with LES data

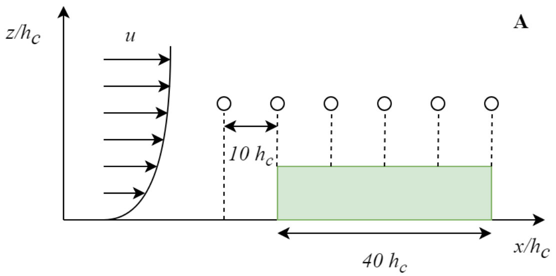
- LES data provided from Antonio [3]
- Same domain as in sensitivity analysis
- Full forest, LAI = 2 (slightly sparse)
  - Reduction of wind speed in front of the forest
  - Speed reduction in forest region
  - Similar share profile after leading edge of the forest
  - Similar recovery after forest



Validation with LES data

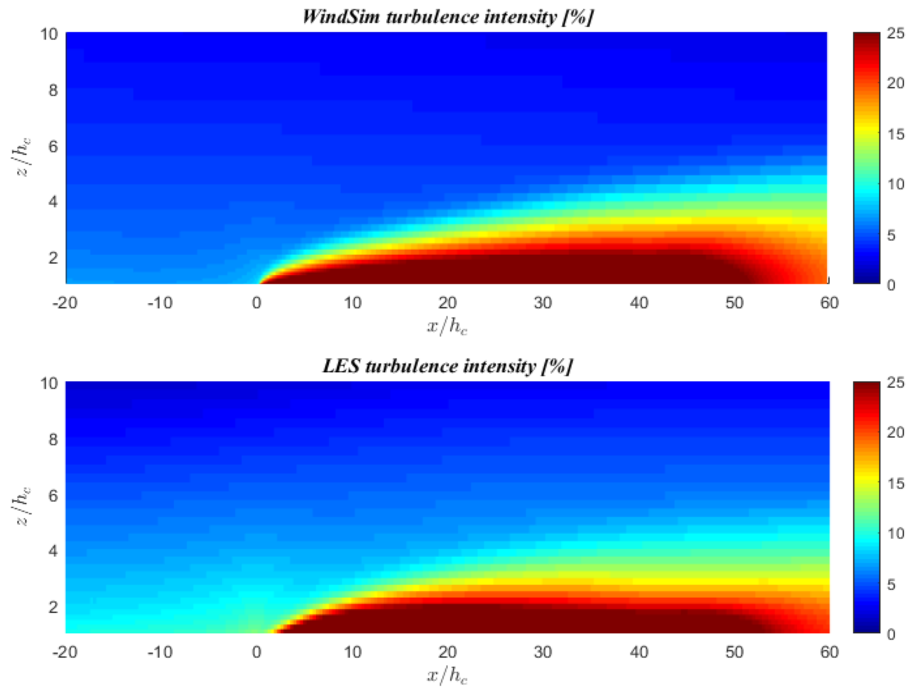
- Extracting vertical wind profiles
- Inlet is different due to laminar/ turbulent flow
  - WindSim continuously develops the wind profile
- Different LAD profile – reduction of wind speed inside forest
- Very good agreement above canopy





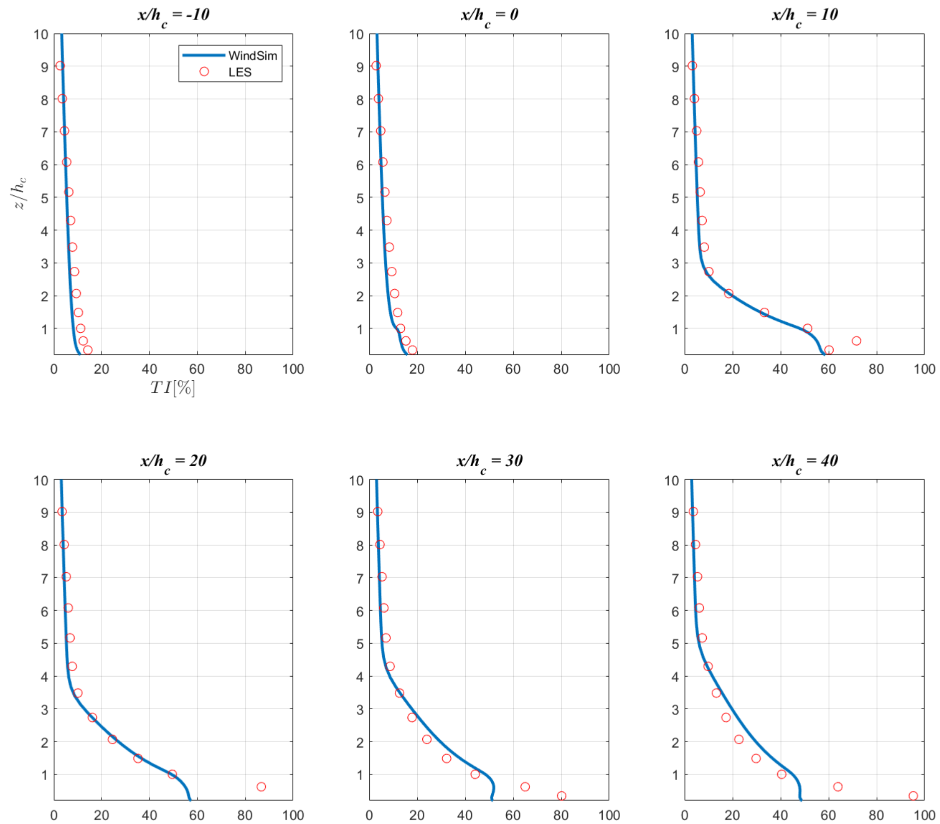
Validation with LES data

- $TI = \frac{\sqrt{k}}{U} \cdot 100$, dimensionless
- Figure starts at $z/h_c = 1$
- High turbulence region to 3 h_c
- Forest affects up to 5 h_c
- Good agreement
  - Except at the leading edge of the canopy
  - Accurately identify regions with low TI



Validation with LES data

- Good agreement above forest and at inlet
  - Similar gradient at all x/h_c
- Inside of the forest LES displays a higher TI



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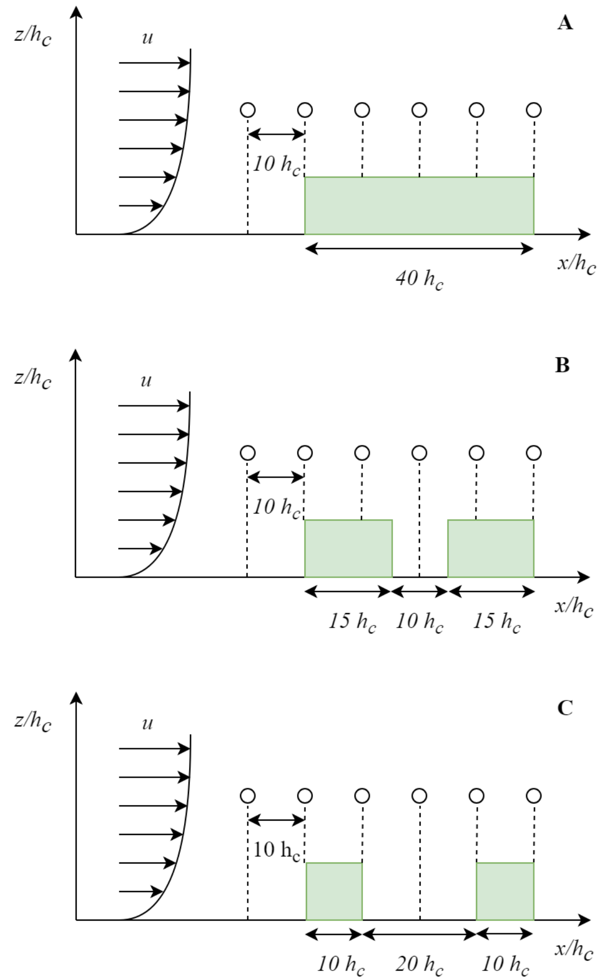
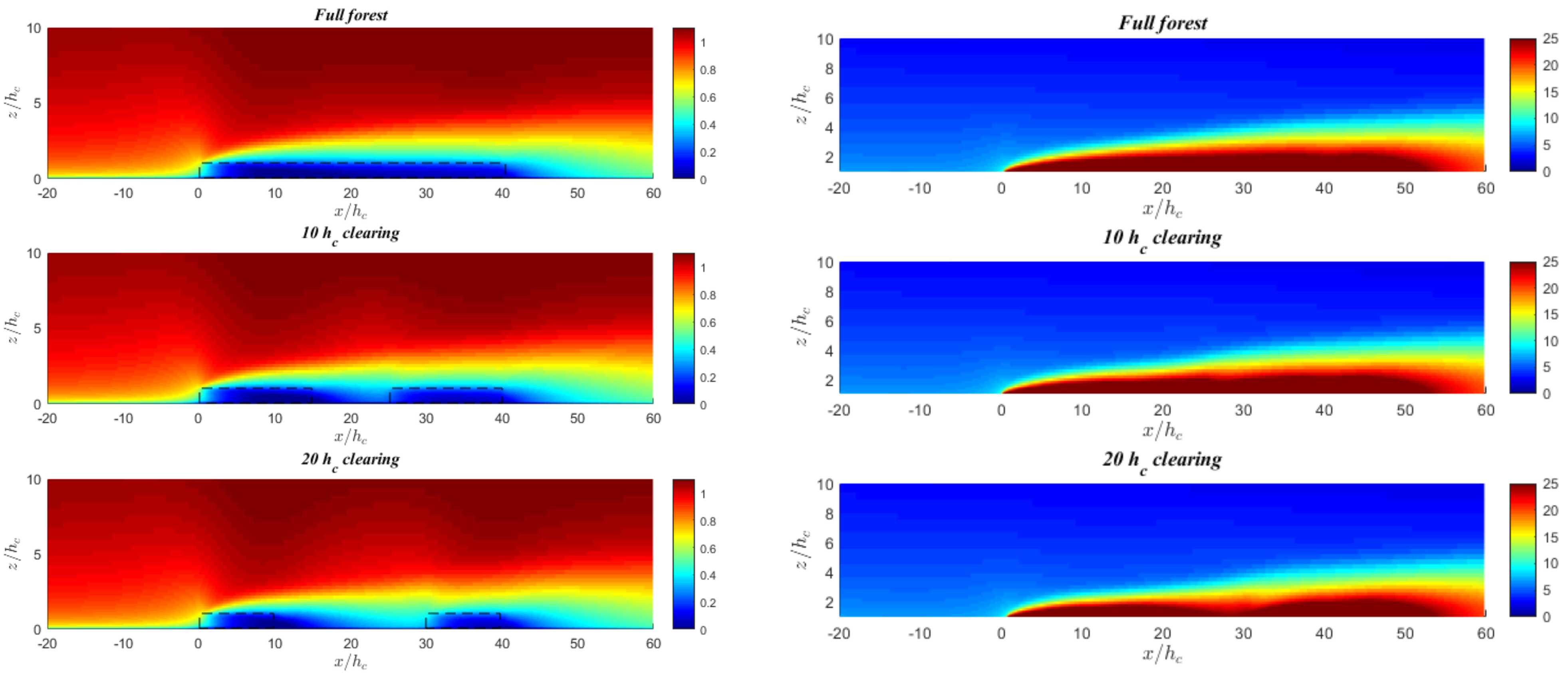
WindSim clearing results

- Forest is not always present but usually followed by clearings, which is why it is important to understand their influence on the wind profile and TI
- Varying clearing sizes between **full forest**, **10 h_c** and **20 h_c**
- With both LAI = 2 (slightly sparse) and LAI = 5 (slightly dense) forest

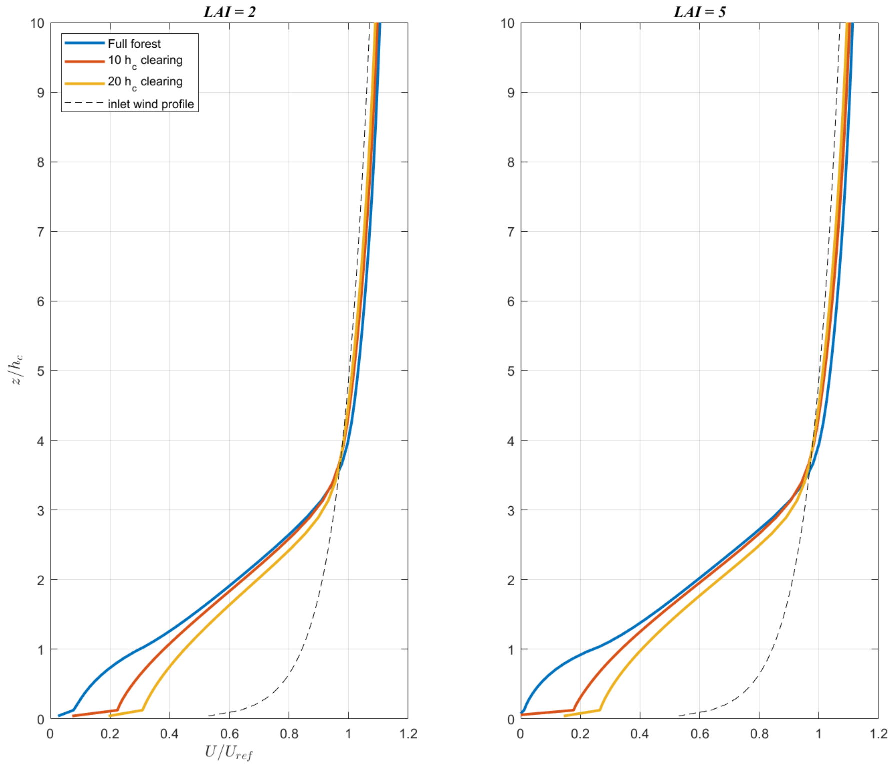


WindSim clearing results



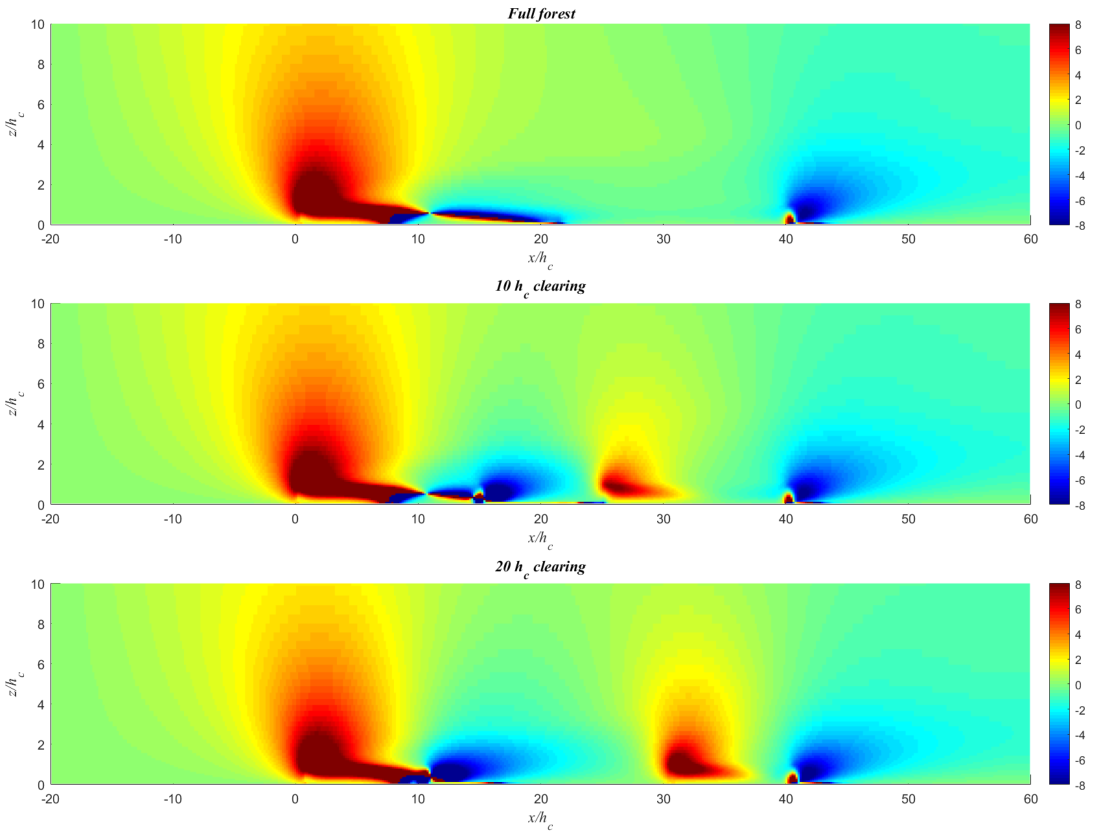
WindSim clearing results

- Profiles in the middle of the clearing
- Similar results for LAI = 2 and 5
  - Slightly higher horizontal wind speed for higher LAI above 4 h_c
  - Full forest yields the highest horizontal wind speed above 4 h_c
  - Higher wind speed below 3,5 h_c the larger the clearing



WindSim clearing results

- Displaying wind direction ± 8° with regards horizontal plane
  - IEC recommends angle < |8| [5]
  - 8° at approximately 3 h_c for LAI = 5, lower for LAI = 2
- Similar angle at the leading and trailing edge of the canopy for all clearings
- Larger clearing yields higher wind angle inside the clearing



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Case study

- Swedish forest Rynningsnäs
- Atmospheric measurements:
  - PAI, tree height and elevation
- Consist mainly of Scot Pines
- Simulating five different cases
  1. Bin discretization (RDV60)
  2. Industrial standard (RDV6)
  3. Constant C_2
  4. ORA20d
  5. Corine

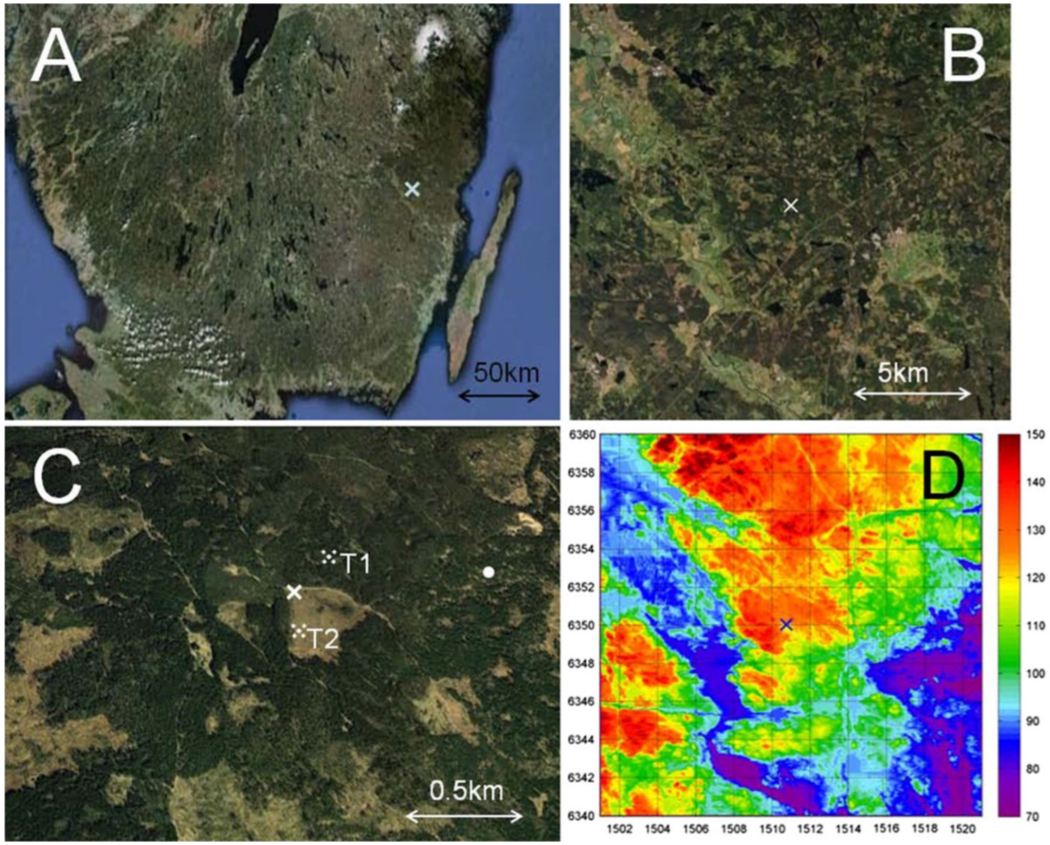
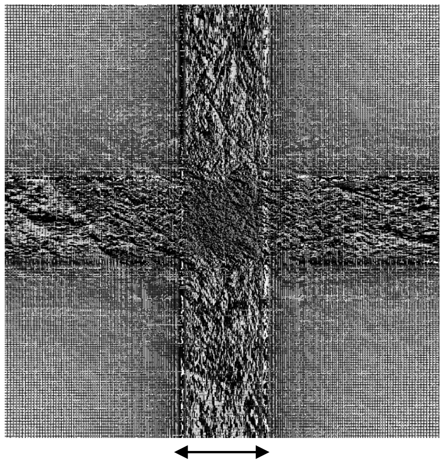


Figure from Elforsk report [7]

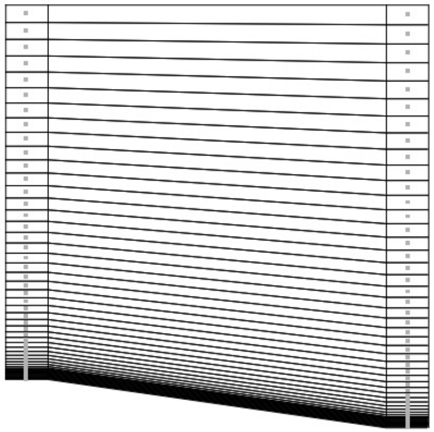
Case study – 3D Domain setup

- Domain size 30 x 30 km, recommendation to use 15 km upstream direction
- Refinement 2 x 2 km around mast, data from 100, 240 and 290°
- Refinement in the vertical direction, equispaced in forest
- Roughly 11 M cells

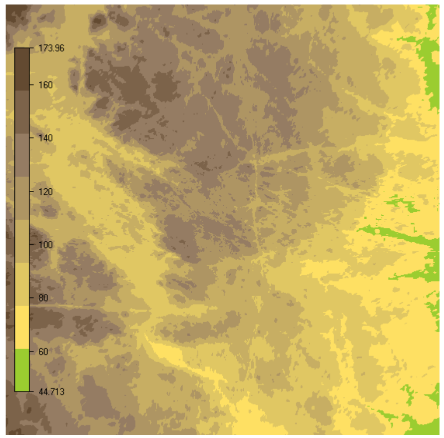
Grid (xy)



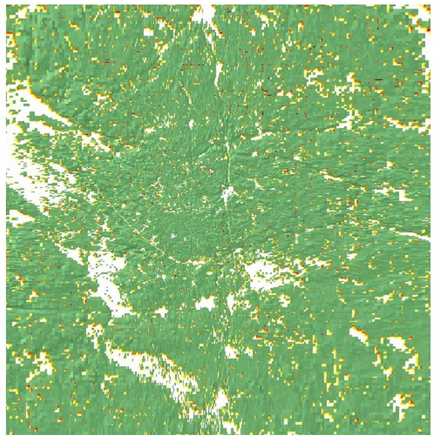
Grid (z)



Elevation height

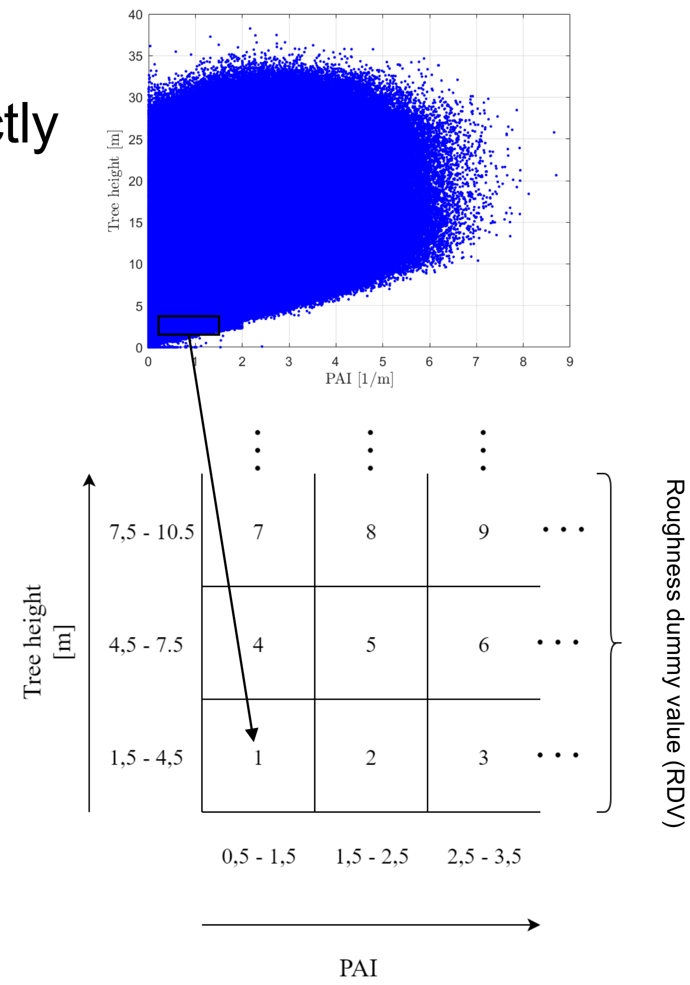


Forest



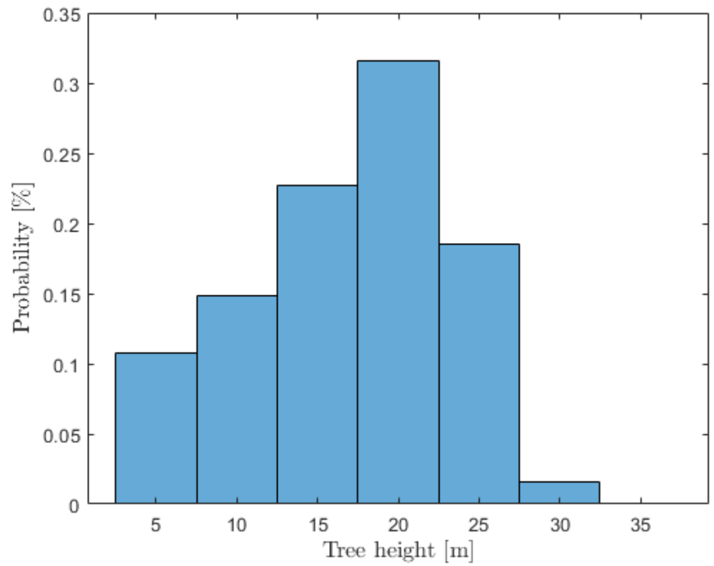
Case study – Bin discretization RDV60

- Problem: C_2 matrix can't be implemented directly in WindSim. Simplifications are required
- Poor correlation between tree height and PAI (used in same manner as LAI)
- Instead of 1 PAI per tree height bin → several PAI per tree height bin
- 10 tree height bins, each bin has 6 PAI amounting to 60 RDVs (roughness dummy values)
- Forest cell count 12



Case study – Industrial method RDV6

- Easier with PAI α h_c
- Resulting in six tree height bins with six unique C_2 values
  - Forest height below 2,5 m and PAI below 0,1 was neglected and considered as roughness length = 0,05

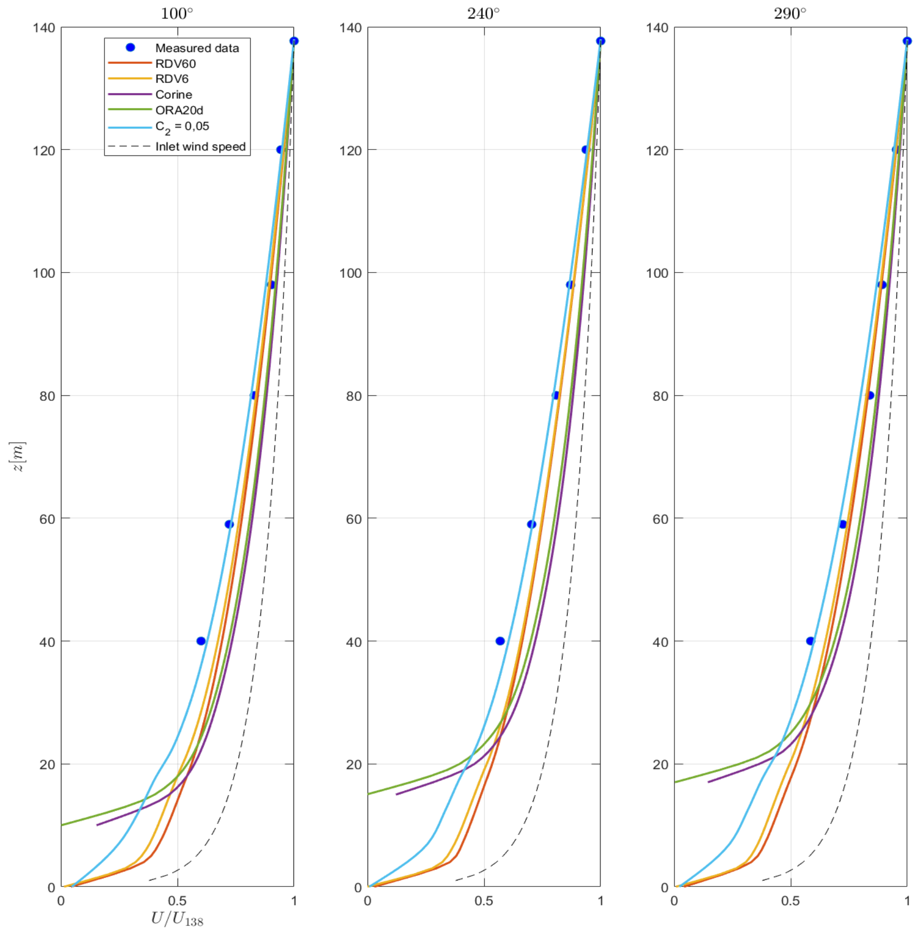


Case study – Auxiliary simulations

1. C_2 = 0,05: Some industries apply a constant C_2 for the whole forest
2. ORA20d: Objective roughness approach (ORA), roughness map from dividing tree height with a factor of 10 and adding the displacement height [6]
   - Resolution 20 $\times$ 20 m in the refinement
3. Imposing only roughness map from Corine 2006 database,
   - Resolution of the roughness map was 100 $\times$ 100 m

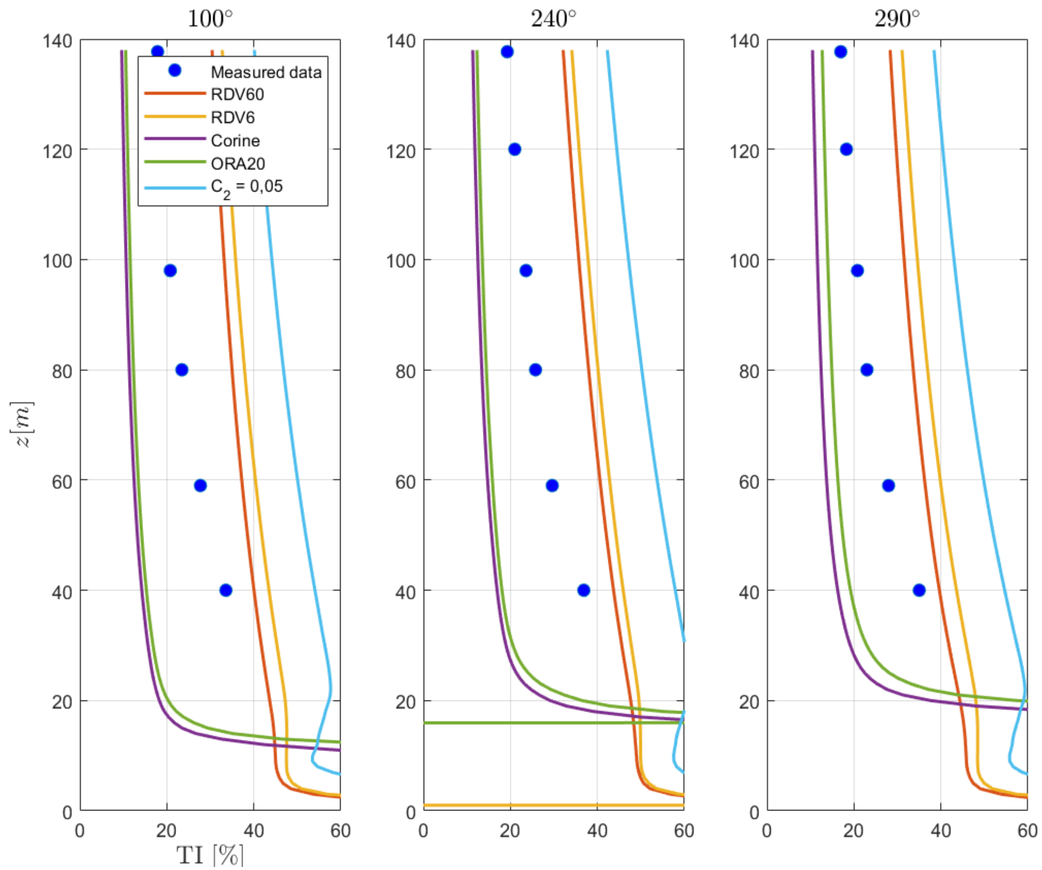
Case study – horizontal wind speed

- Data normalized with U_{138} of measured data
- Similar share for RDV60 and RDV6
  - Good agreement above 80 m
  - Overestimates below 80 m
- Best agreement reached with C_2 = 0,05
- ORA20d and Corine overestimates wind speed



Case study - TI

- Poor agreement with measured data for RDV6 and RDV60
- Constant C_2 severely overestimates the TI
- Roughness map approach underestimates the TI
    - ORA20d slightly better estimation than Corine



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Conclusions for the case study

- RDV60 had better agreement with TI than RDV6
  - RDV6 slightly better estimation of the horizontal wind speed
- Best estimation for wind speed was achieved with constant C_2 = 0,05
  - Indicates that the impact of the forest is underestimated, most likely due to a too low drag coefficient (0,2)
- Roughness map approach
  - ORA20d yielded better horizontal wind speed and TI than Corine
- Overall: modelling the forest resulted in better agreement with the measured data
- Overestimated TI yields an underestimated horizontal wind speed and vice verse

References

[1]: Fridman, J. (2018). “Forest statistics 2018”. In: Official Statistics of Sweden, Swedish University of Agricultural Sciences, ISSN 0280-0543, p. 81.

[2]: Sanz, C. (2003).A note on k – ε modelling of vegetation canopy air-flows, page191-197. Tech. rep. No.108. Kluwer Academic Publishers.

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[5]: IEC (2018). “International standard”. In: International Electrotechnical Commission Third edition. IEC 61400-1:2005(E), p. 23.

[6]: Floors, R., P. Enevoldsen, N. Davis, J. Arnqvist, and E. Dellwik (2018). “From lidar scans to roughness maps for wind resource modelling in forested areas”. In: Wind Energy Science 3.1, pp. 353–370.doi:10.5194/wes-3-353-2018.url:https://www.wind-energ-sci.net/3/353/2018/.