Large-eddy simulations of wind farm clusters for the further development of industry models

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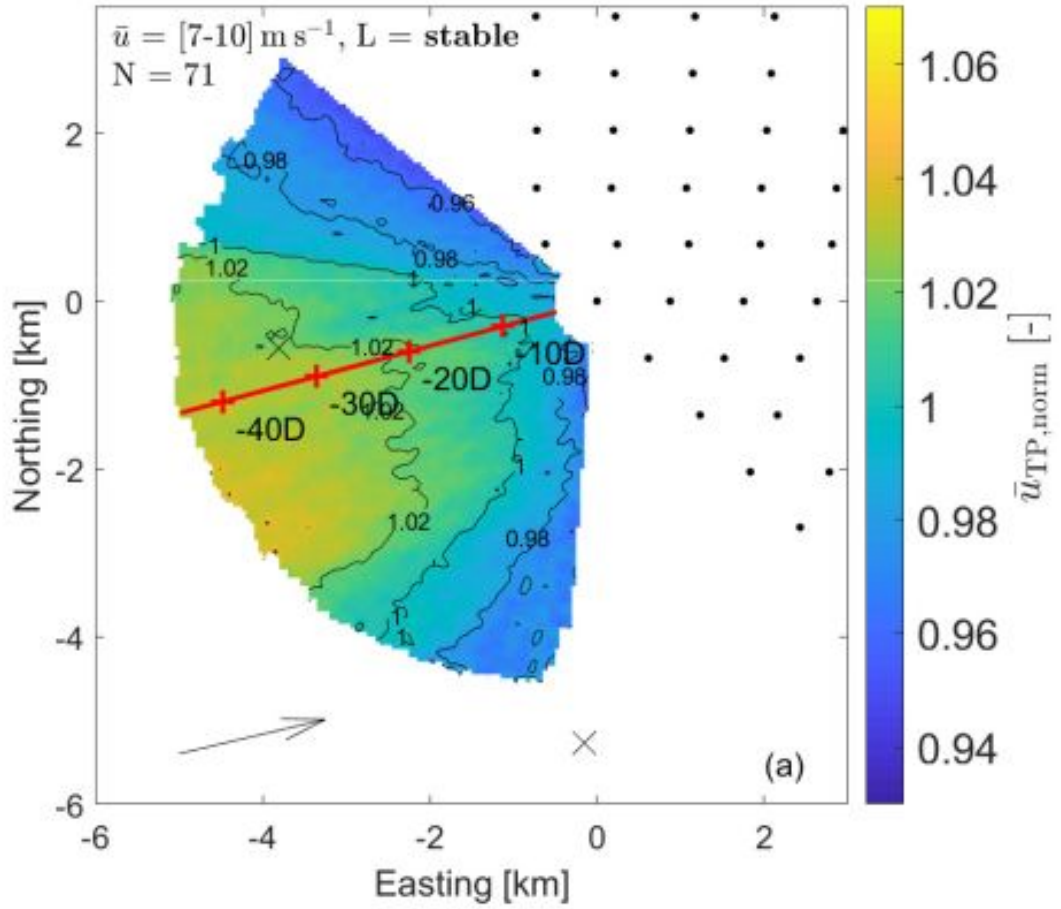
Introduction

What is missing in Industry Model?

- Industry models sacrifice physical description of many flow phenomena to gain computational performance
- Effects on the single wind farm/ wind farm cluster scale not well represented
  - Global Blockage Effect
  - Wake recovery dependency on atmospheric stability
- Effects on the inter-cluster scale
  - Long lasting cluster wakes
  - Dynamics of cluster wake recovery

X-Wakes contribution: Schneemann et .al 2021
https://doi.org/10.5194/wes-6-521-2021



Understanding the Global Blockage Effect

LES setup

Farm and domain

Turbines' Specification			
P_{rated} [MW]	C_t [-]	D [m]	H_{hub} [m]
8.	0.85	160.	110.

- **Palm** LES v6 (*Maronga et al. 2020*)
- Precursor + main run with inflow recirculation method

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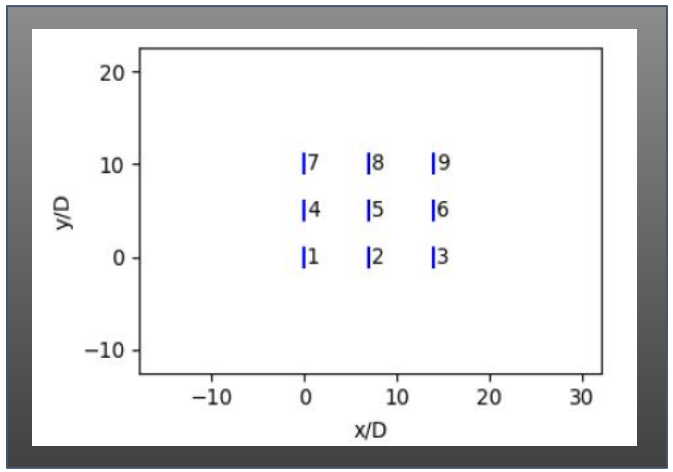

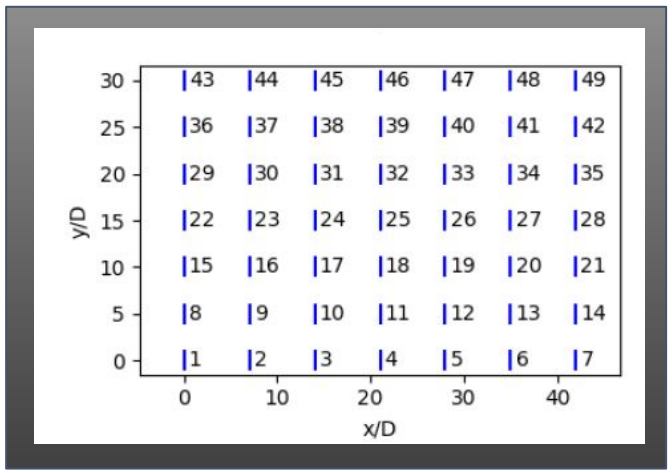

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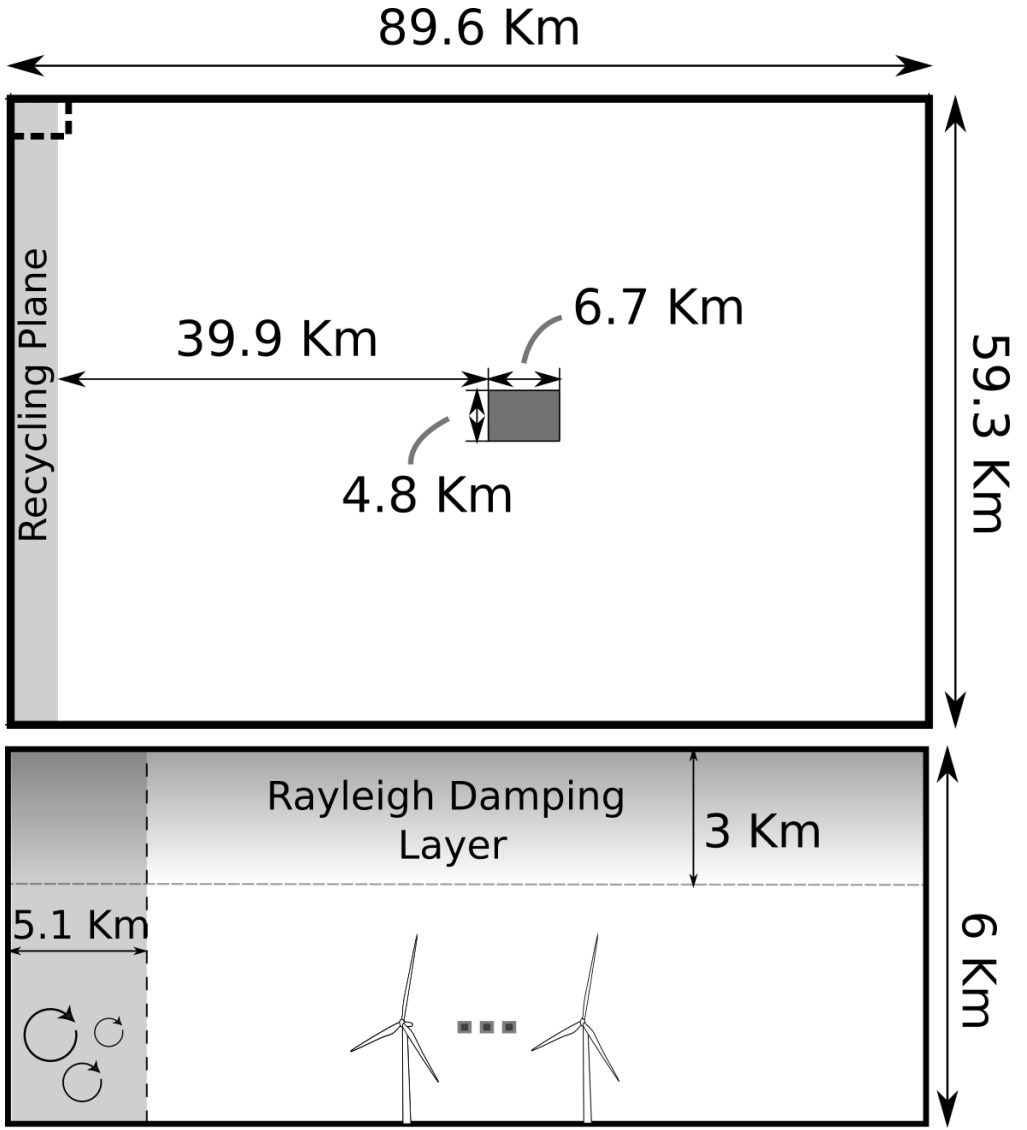
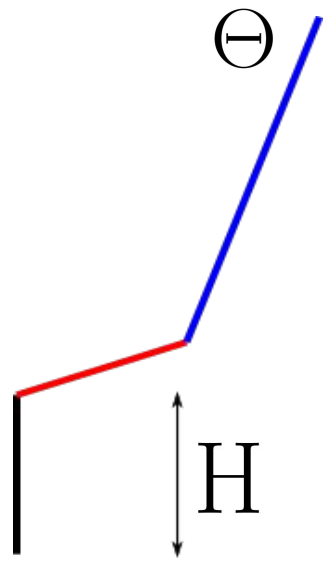
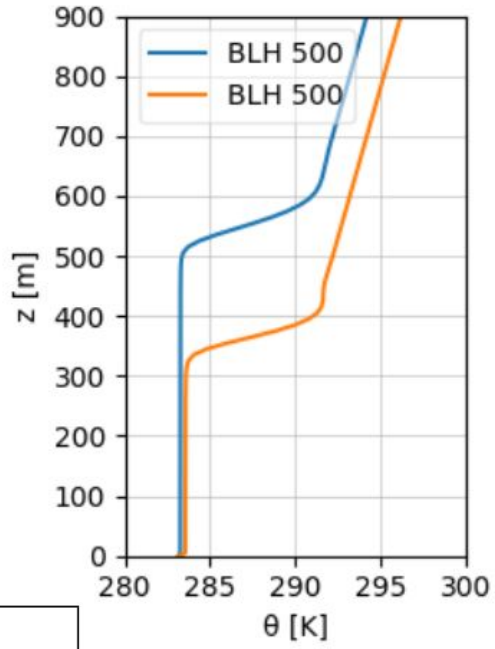


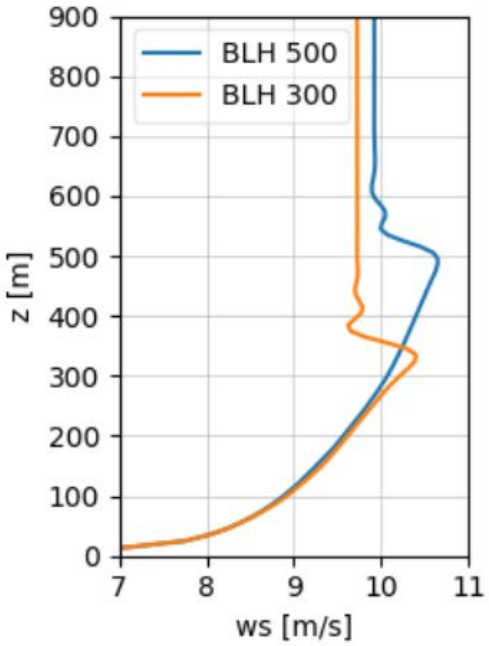
LES setup

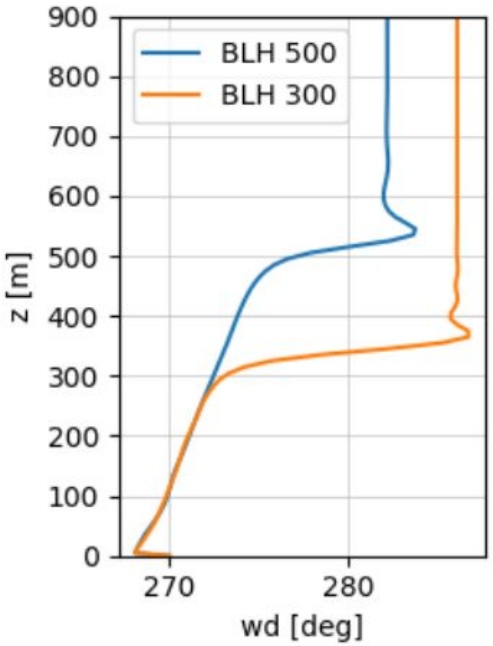
Precursors and inflow profiles



Farm 3x3 turbines	
Inversion height H $[m]$	Lapse rate Γ_a (Γ_b) $[K/100m]$
300	8 (1)
400	8 (1)
500	8 (1)





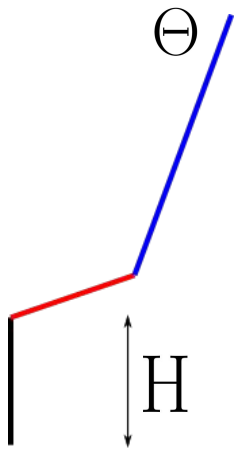


- 50h of simulated time to develop quasi-steady state ABL profiles

Simulation results:

Velocity deficit

- Sensitivity to height of inversion layer



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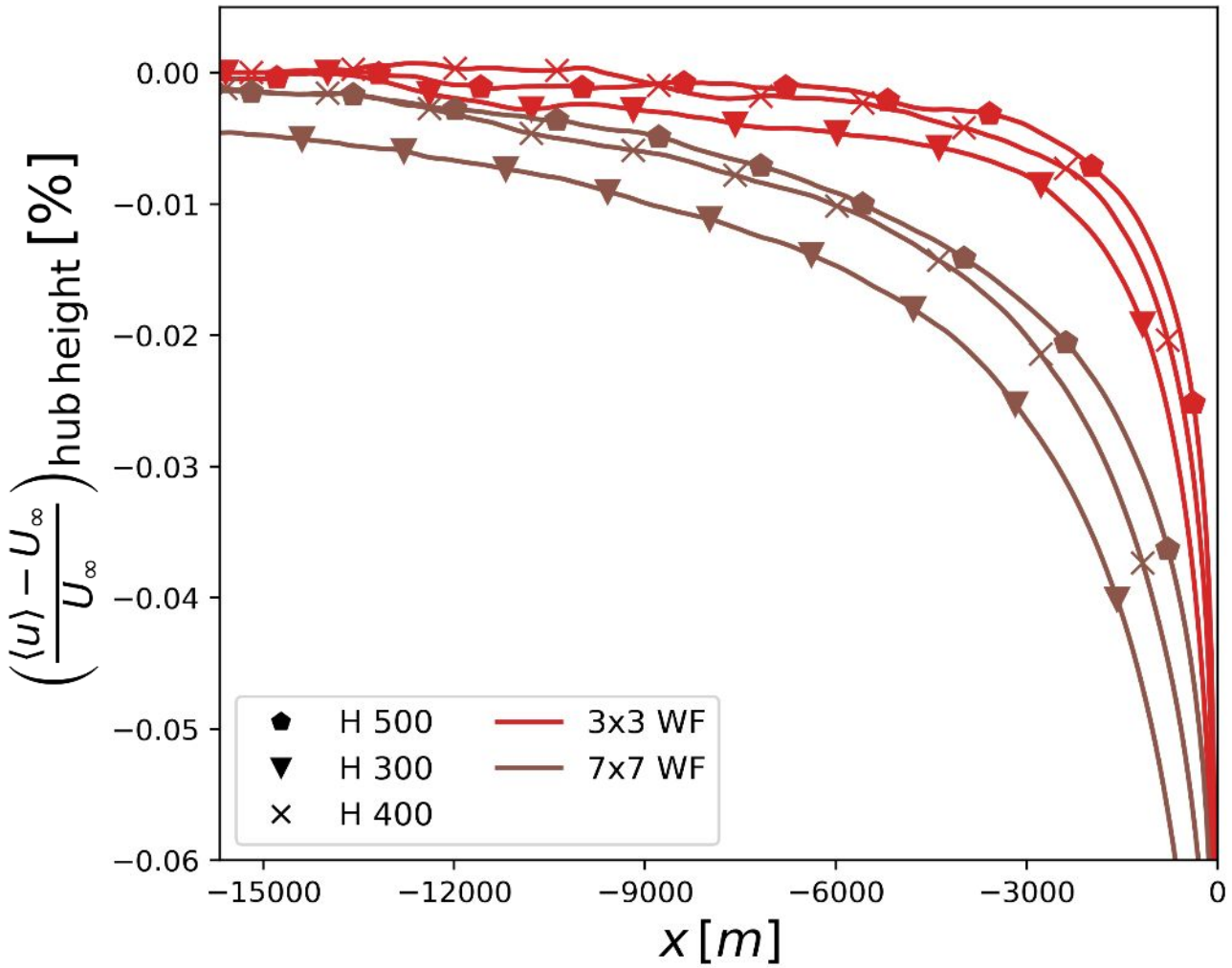
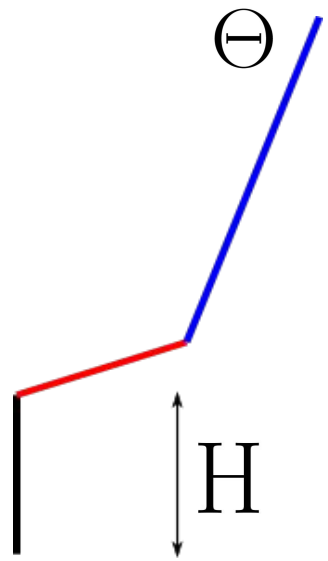
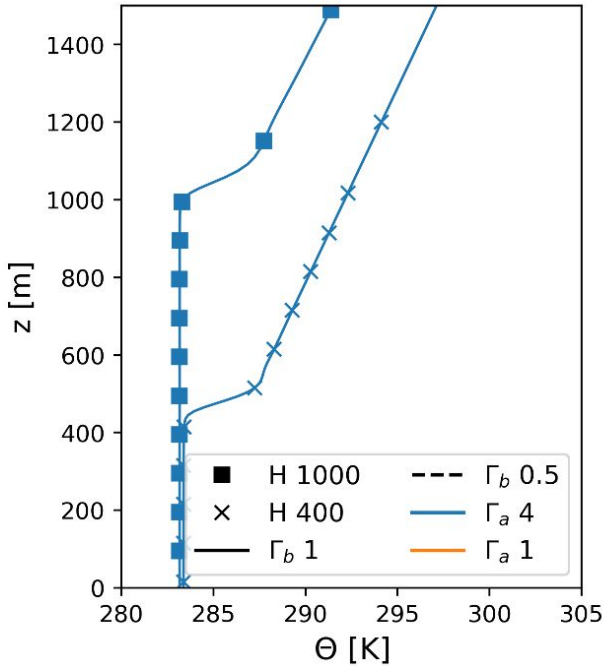
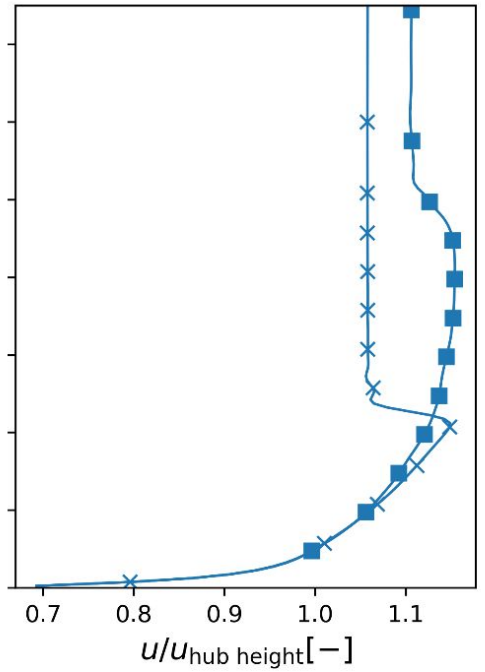


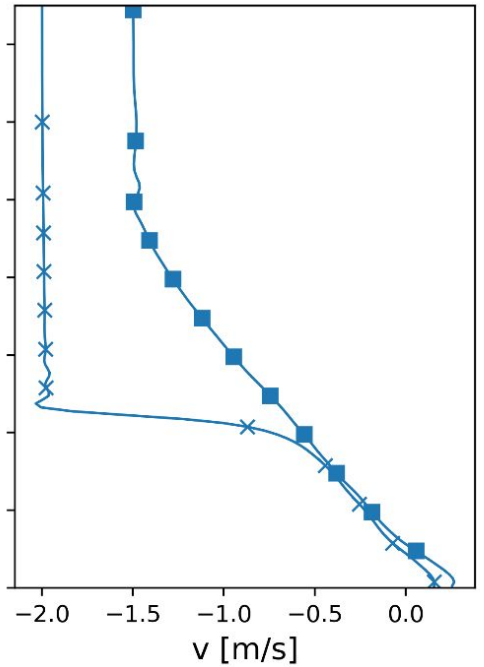
LES setup 2

Precursors and inflow profiles









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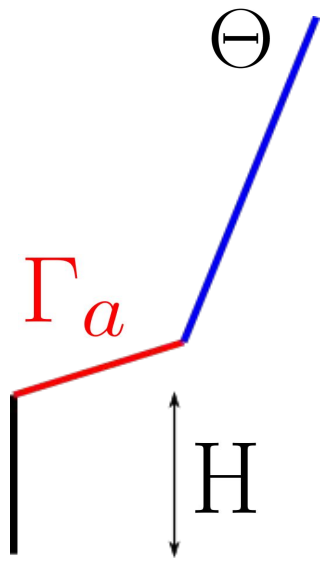

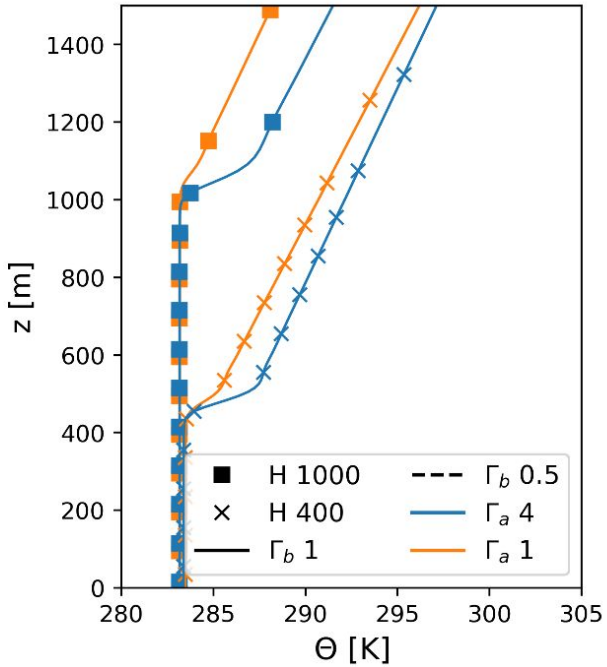

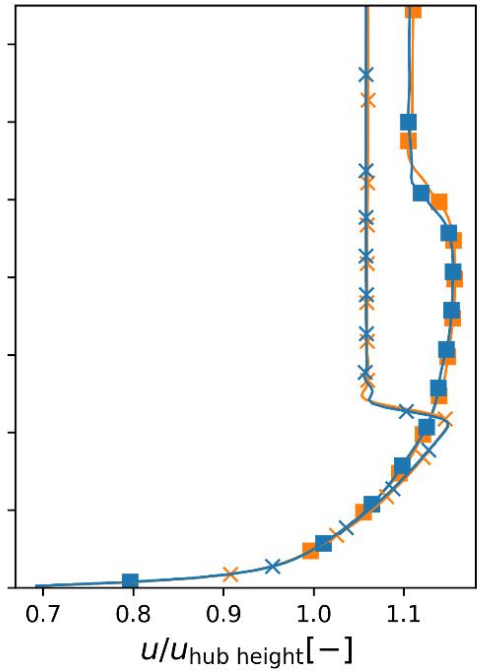

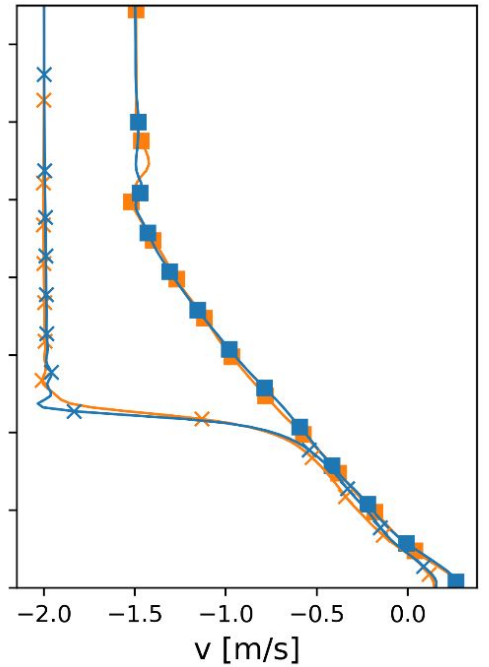

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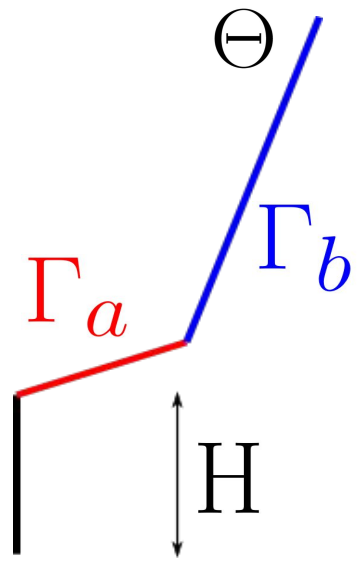

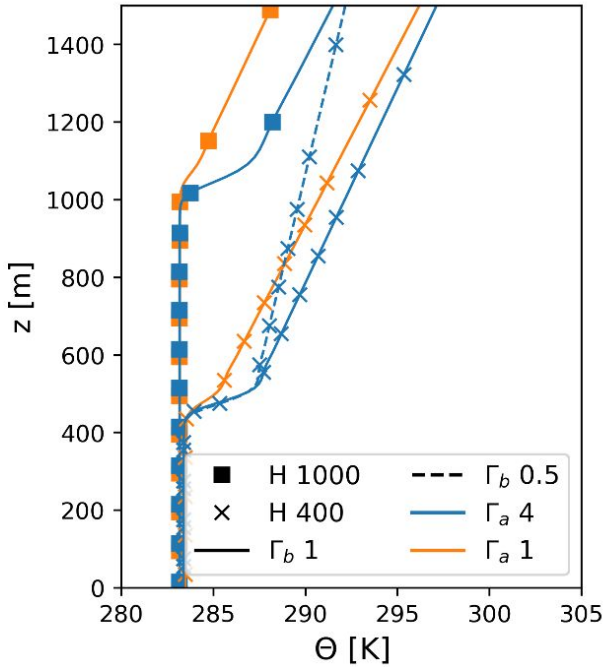

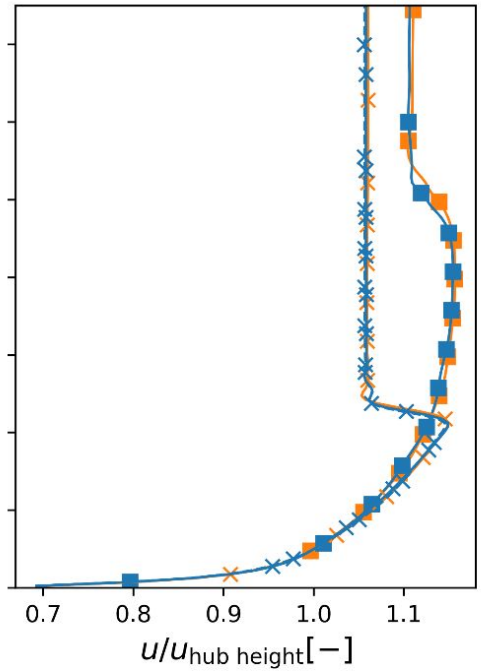

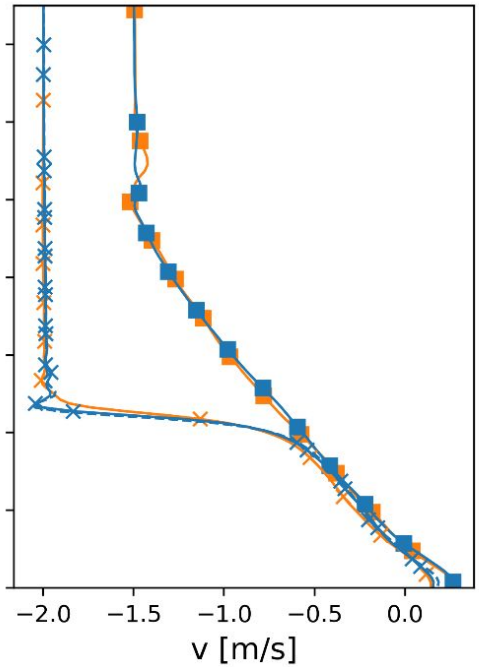

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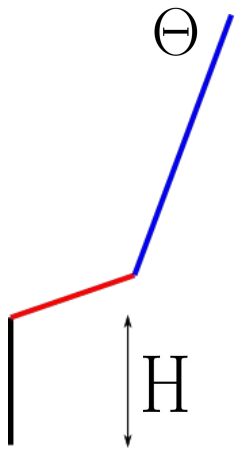
Simulation results:

Velocity deficit

- Sensitivity to height of inversion layer



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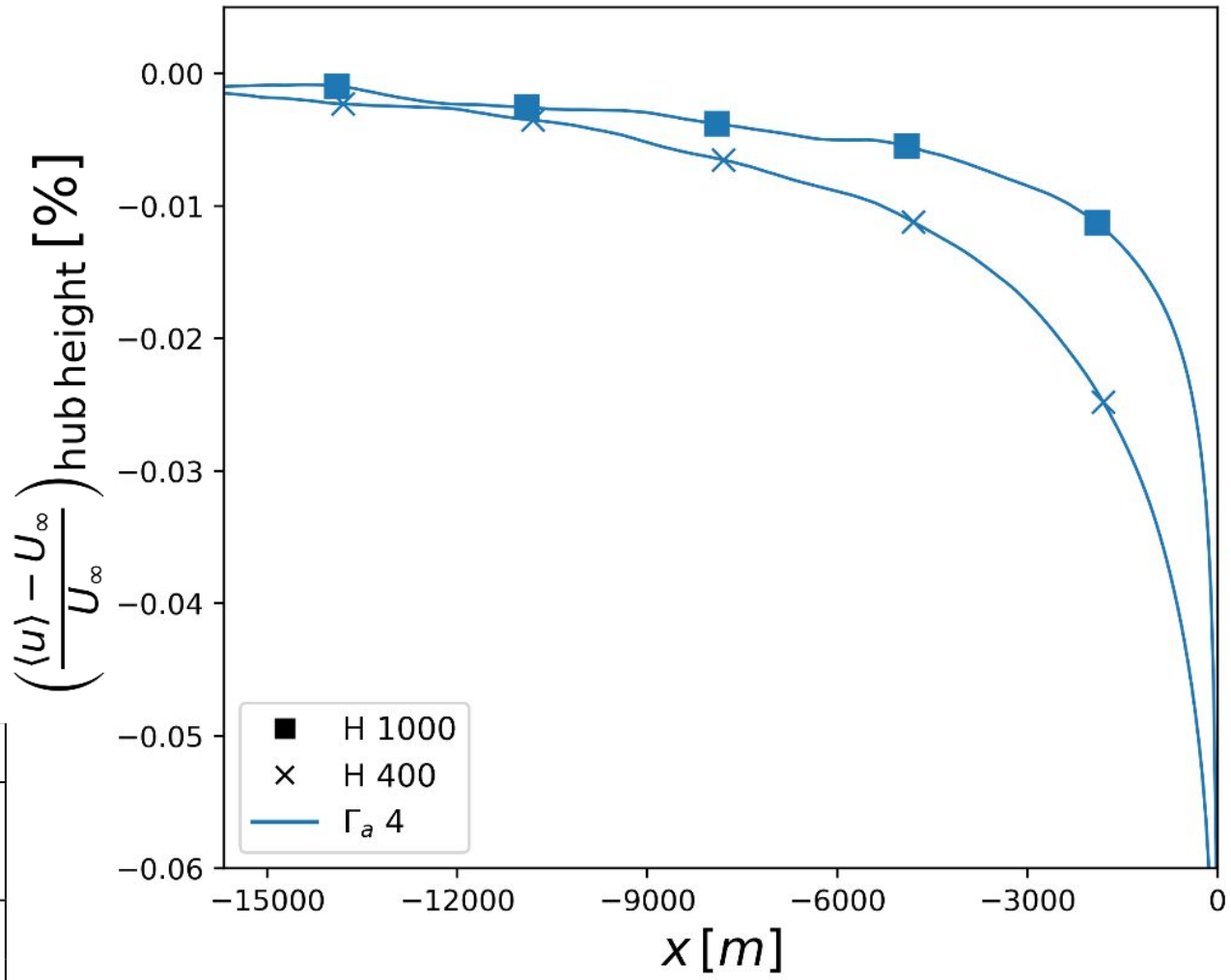
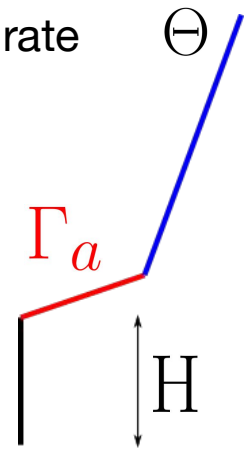


Simulation results

Velocity deficit

- Sensitivity to height of inversion layer
- Sensitivity to inversion lapse rate



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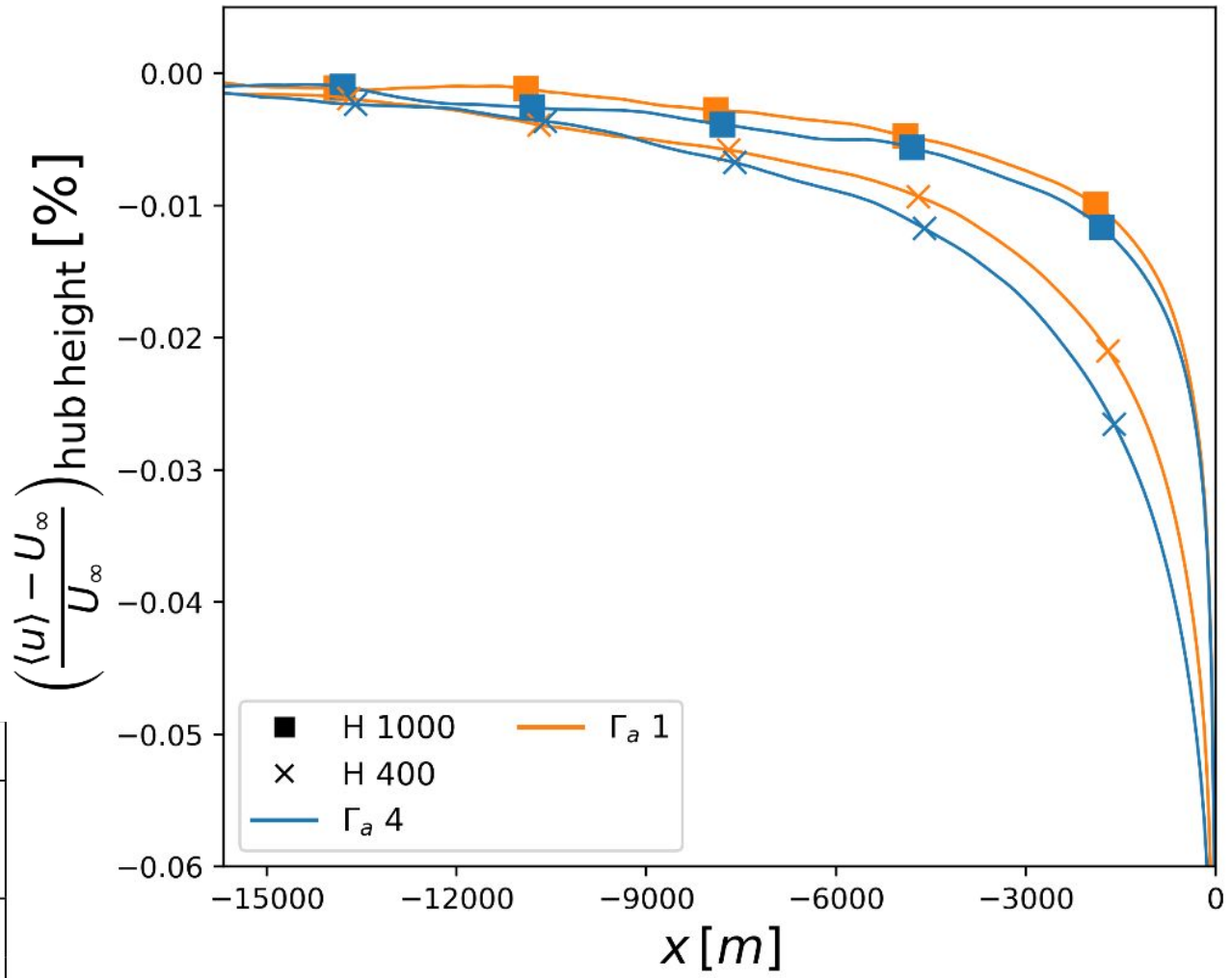
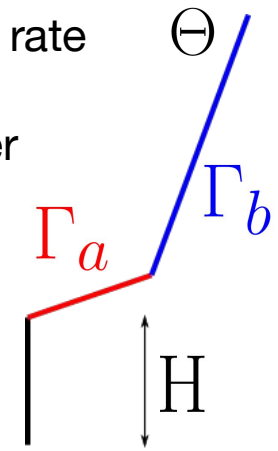


Simulation results

Velocity deficit

- Sensitivity to height of inversion layer
- Sensitivity to inversion lapse rate
- Sensitivity also to upper layer stratification



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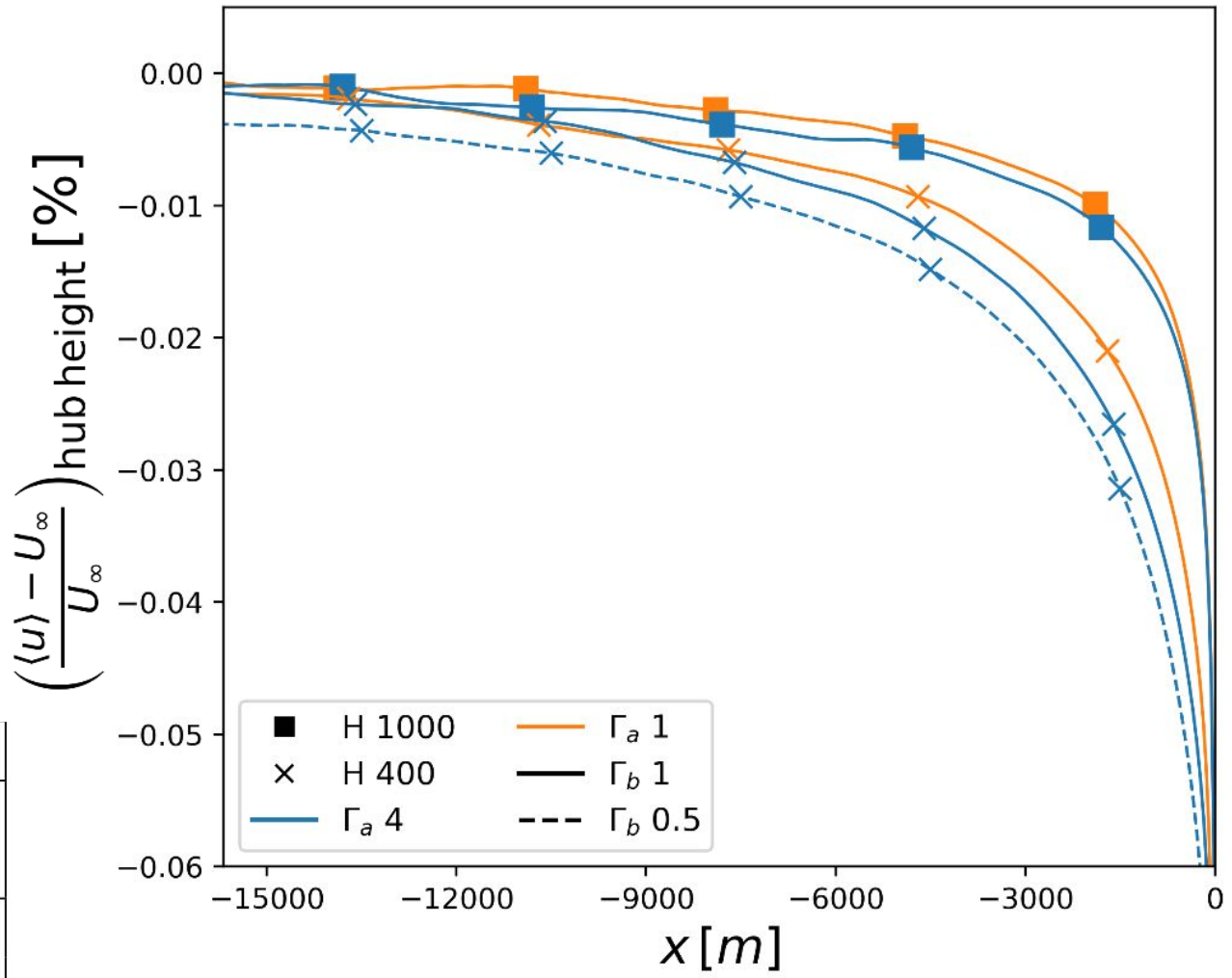


Towards model improvements

Developing a parametrization

$$u_{x,\mathrm{loss}} = f(\vec{x}, \rho, U_\infty, D, c_t, N_t, T_{\mathrm{layout}}, L_{\mathrm{farm}}, W_{\mathrm{farm}}, \Theta)$$

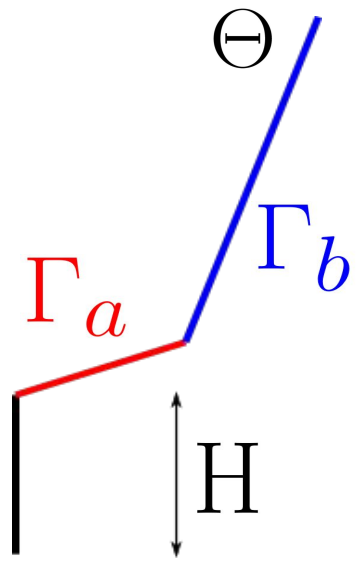
- Simplified to account only for parameters changed in the LES (neglecting the lapse rate)

$$u_{x,\mathrm{loss}} = f(x, U_\infty, L_{\mathrm{farm}}, H)$$

- Casted in dimensionless form thanks to Pi-Theorem (Buckingham)

$$\pi_u = F\left(\pi_x,\ \pi_h\right)$$

$$\pi_u = \frac{u_{x,\mathrm{loss}}}{U_{x,\infty}} \qquad \pi_x = \frac{x}{L_{\mathrm{farm}}} \qquad \pi_h = \frac{H - D}{L_{\mathrm{farm}}}$$



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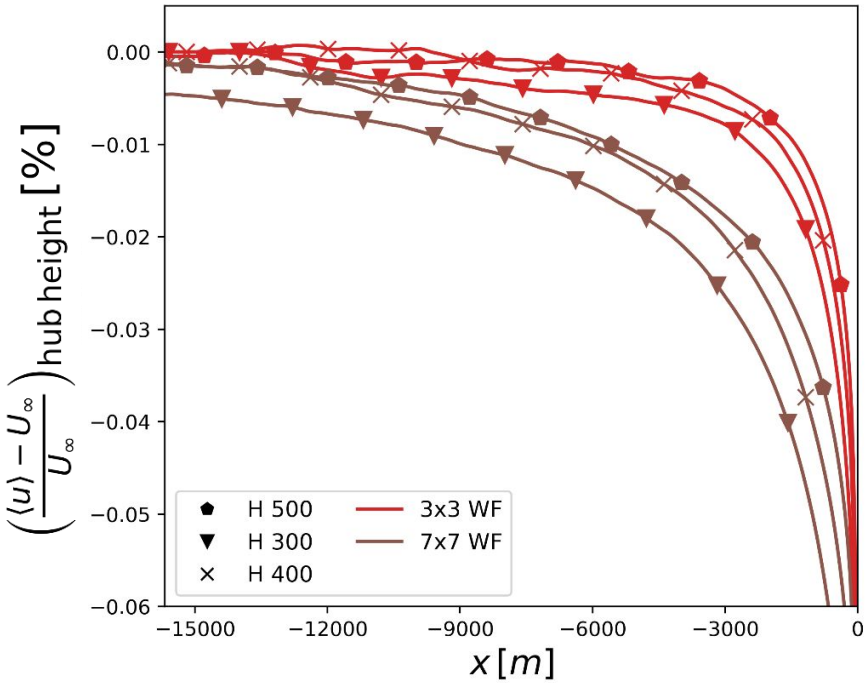


Towards model improvements

Developing a parametrization

$$u_{x,\mathrm{loss}} = f(x, U_\infty, L_{\mathrm{farm}}, H)$$

$$\pi_u = F(\pi_x, \pi_h)$$

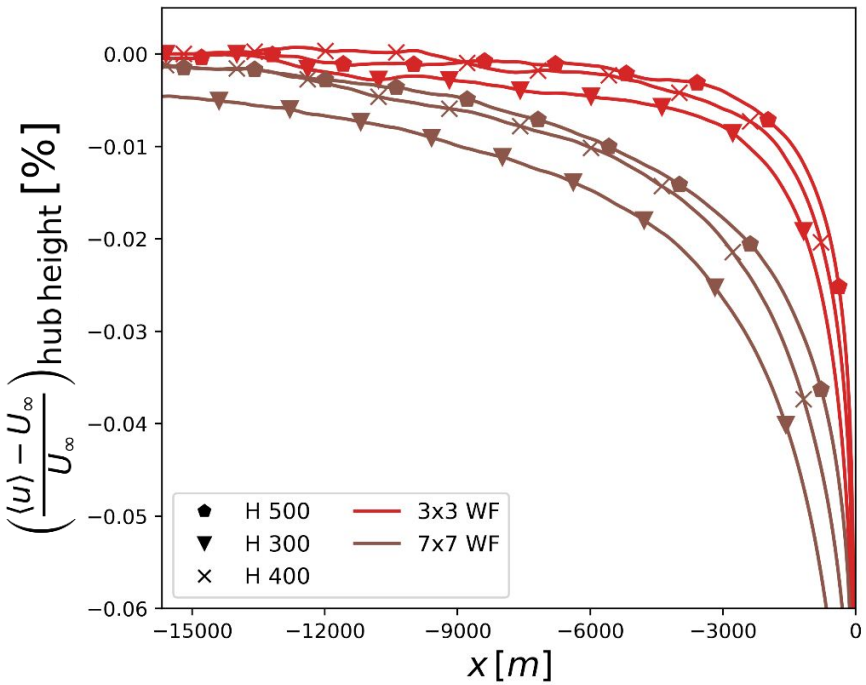
$$\frac{\pi_u}{g(\pi_h)} = G(\pi_x)$$

with

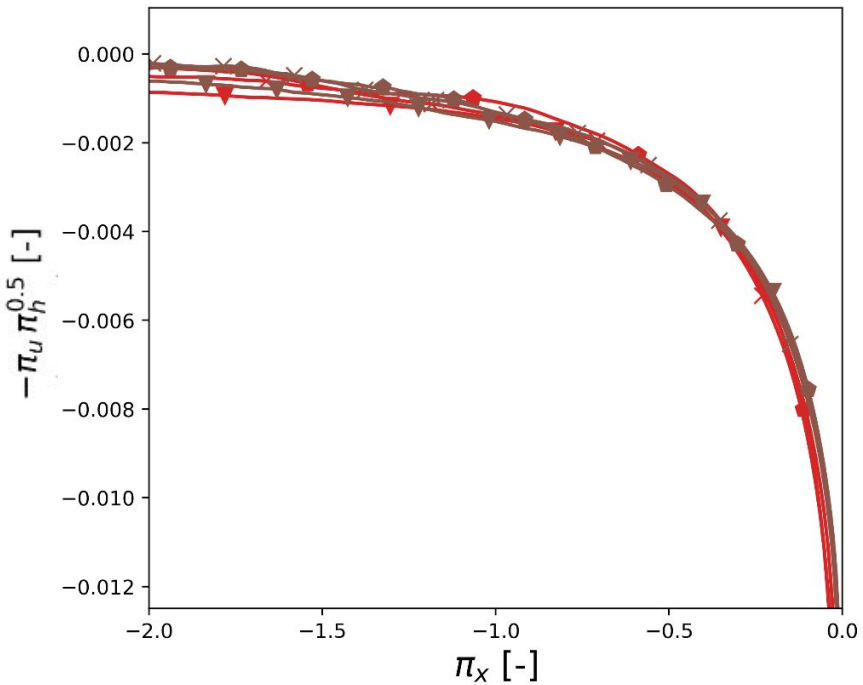
$$g(\pi_h) = \pi_h^{-0.5}$$

$$\pi_x = \frac{x}{L_{\mathrm{farm}}} \qquad \pi_h = \frac{H - D}{L_{\mathrm{farm}}}$$

Not scaled



Rescaled

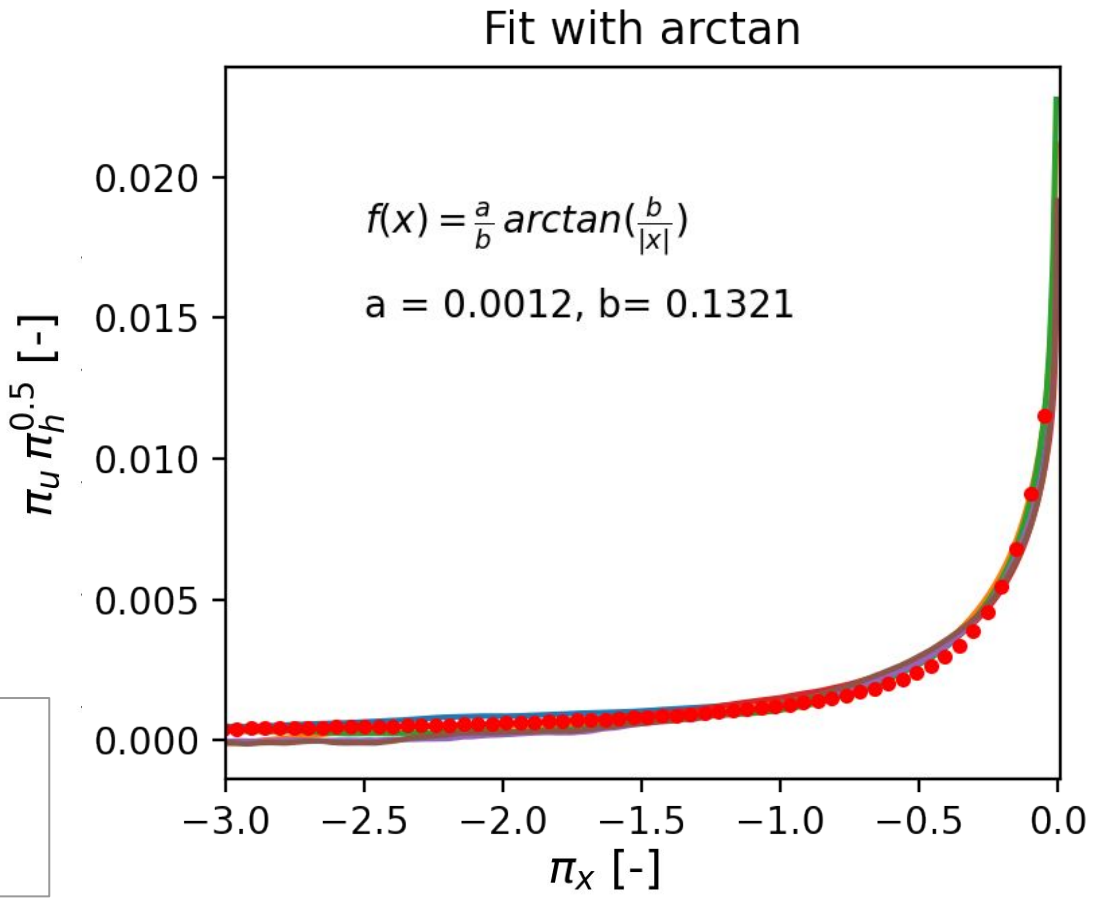


Correlation for Global Blockag?

Simple fit

- Once the curve collapse a simple fit can be used to draw a correlation
- Problems:
  - How to use it?
  - is it General enough?

$$\pi_u = \frac{u_{x,loss}}{U_{x,ref}} \qquad \pi_x = \frac{x}{L_{farm}} \qquad \pi_h = \frac{H_{abl} - D}{L_{farm}}$$



Towards model improvements

Testing the parametrization

$$u_{x,\mathrm{loss}} = f(x, U_\infty, L_{\mathrm{farm}}, H)$$

$$\pi_u = F(\pi_x, \pi_h)$$

$$\frac{\pi_u}{g(\pi_h)} = G(\pi_x)$$

with

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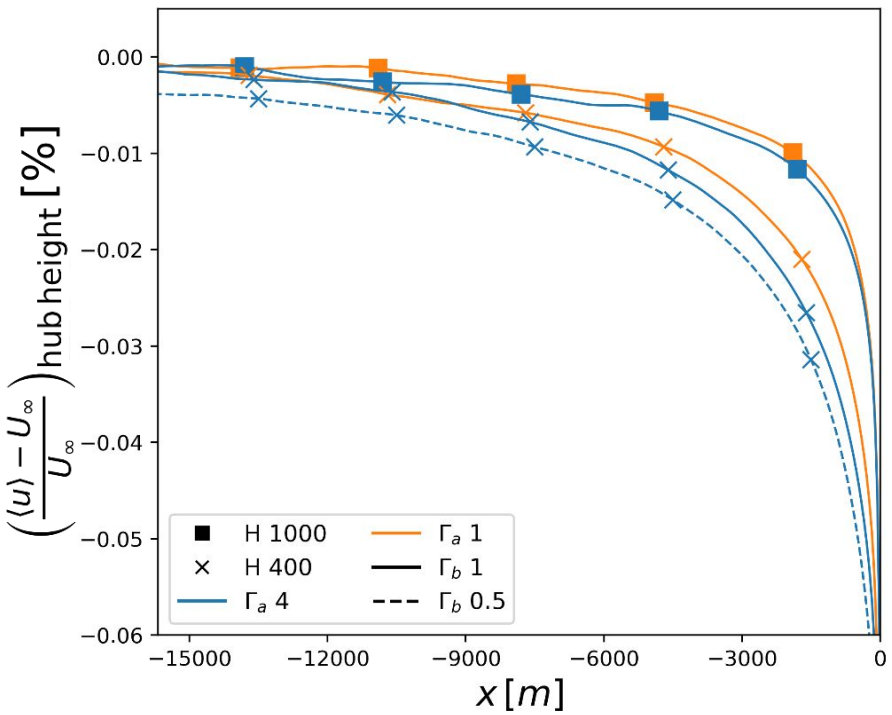
The Lapse rate should be accounted in the parametrization

Not scaled



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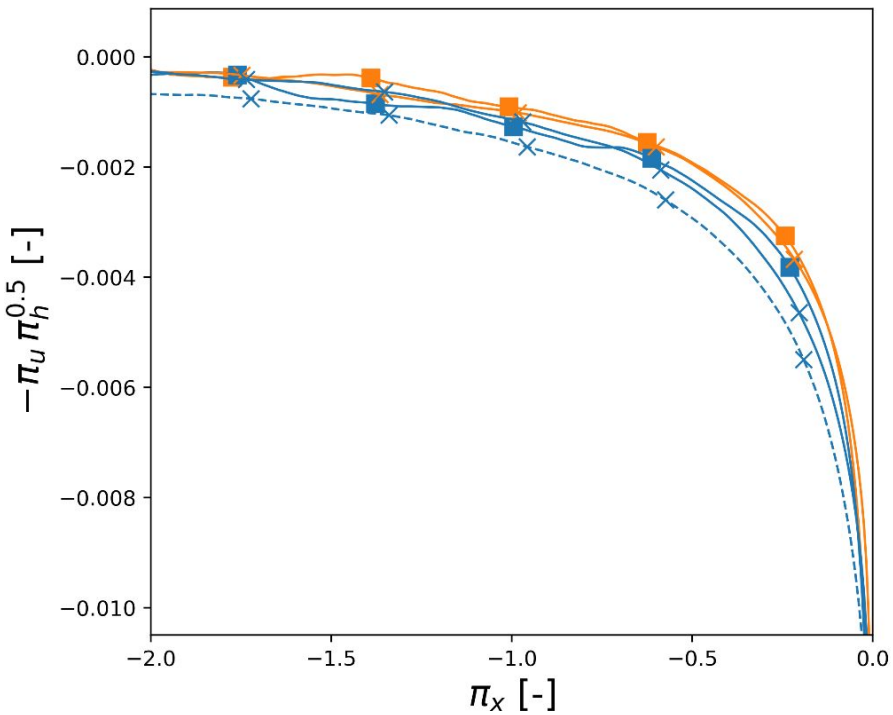


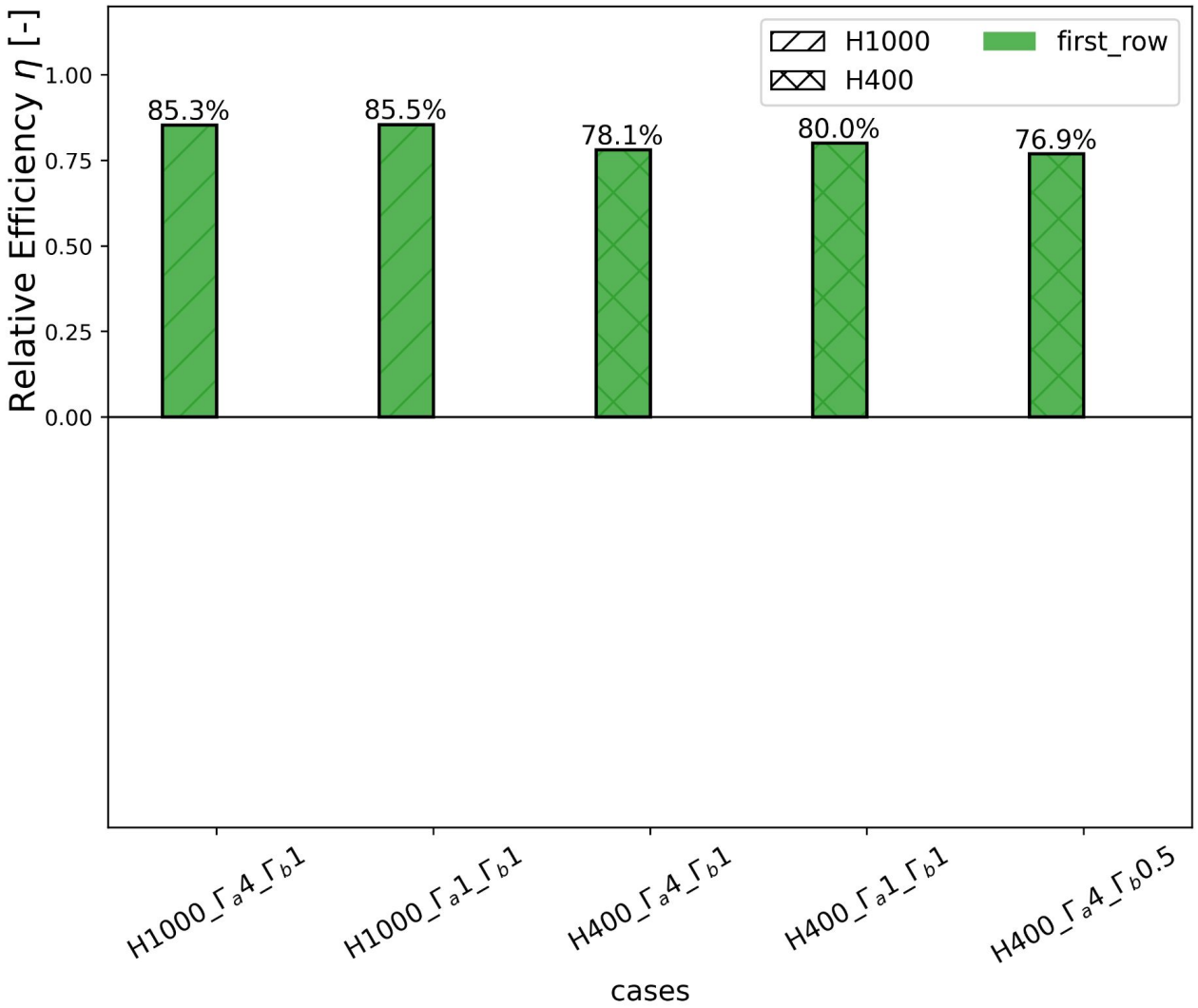
Simulation results

Impact on efficiency

- Relative efficiency:

$$\eta = \frac{\sum_{i=0}^{N_t} P_i\left(\mathrm{REWS}_i\right)}{\sum_{i=0}^{N_t} P_i\left(\mathrm{REWS}_\infty\right)}$$

$$REWS = \frac{1}{A_{\mathrm{rotor}}} \int_{A_{\mathrm{rotor}}} u_\infty(z) dA$$



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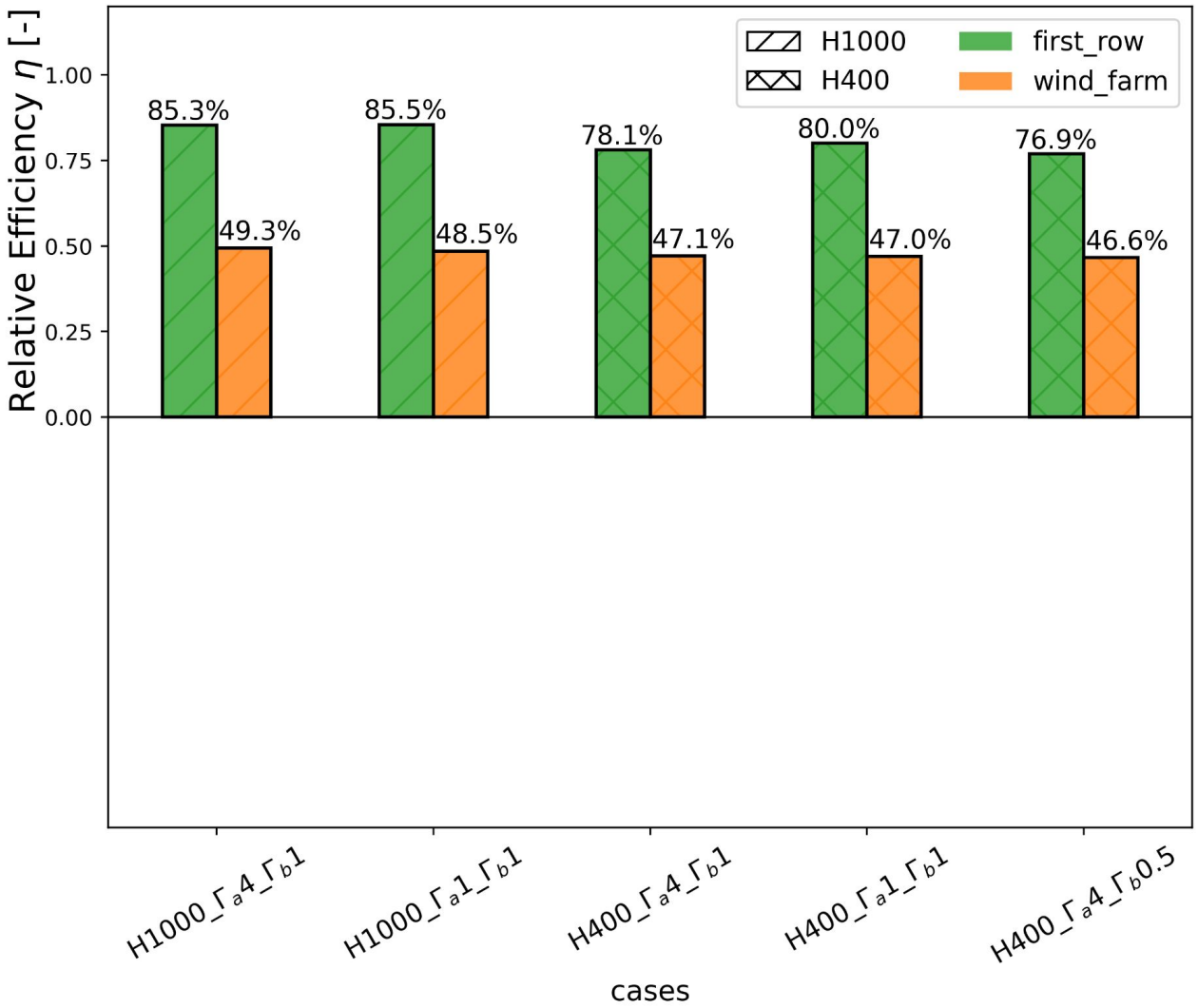

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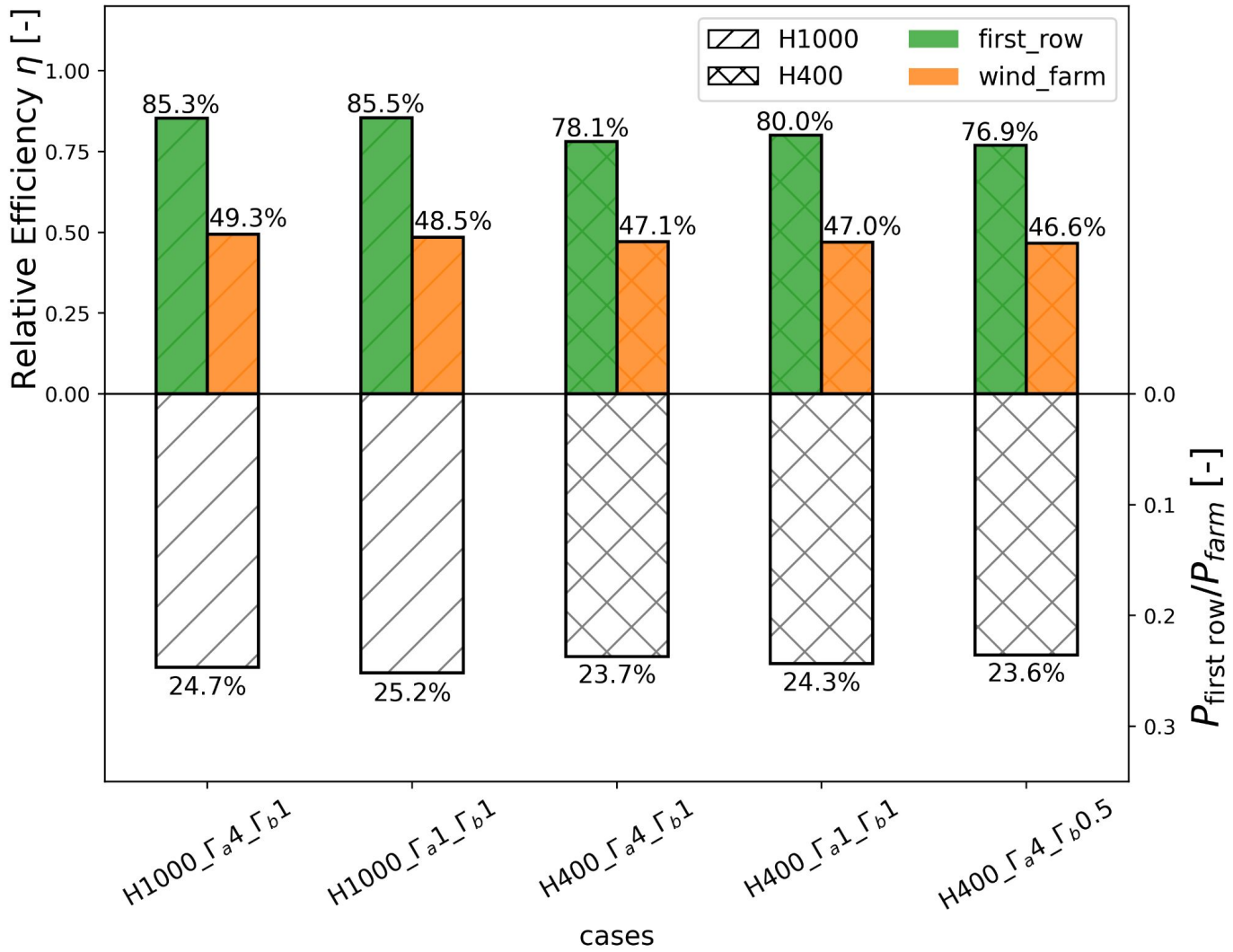
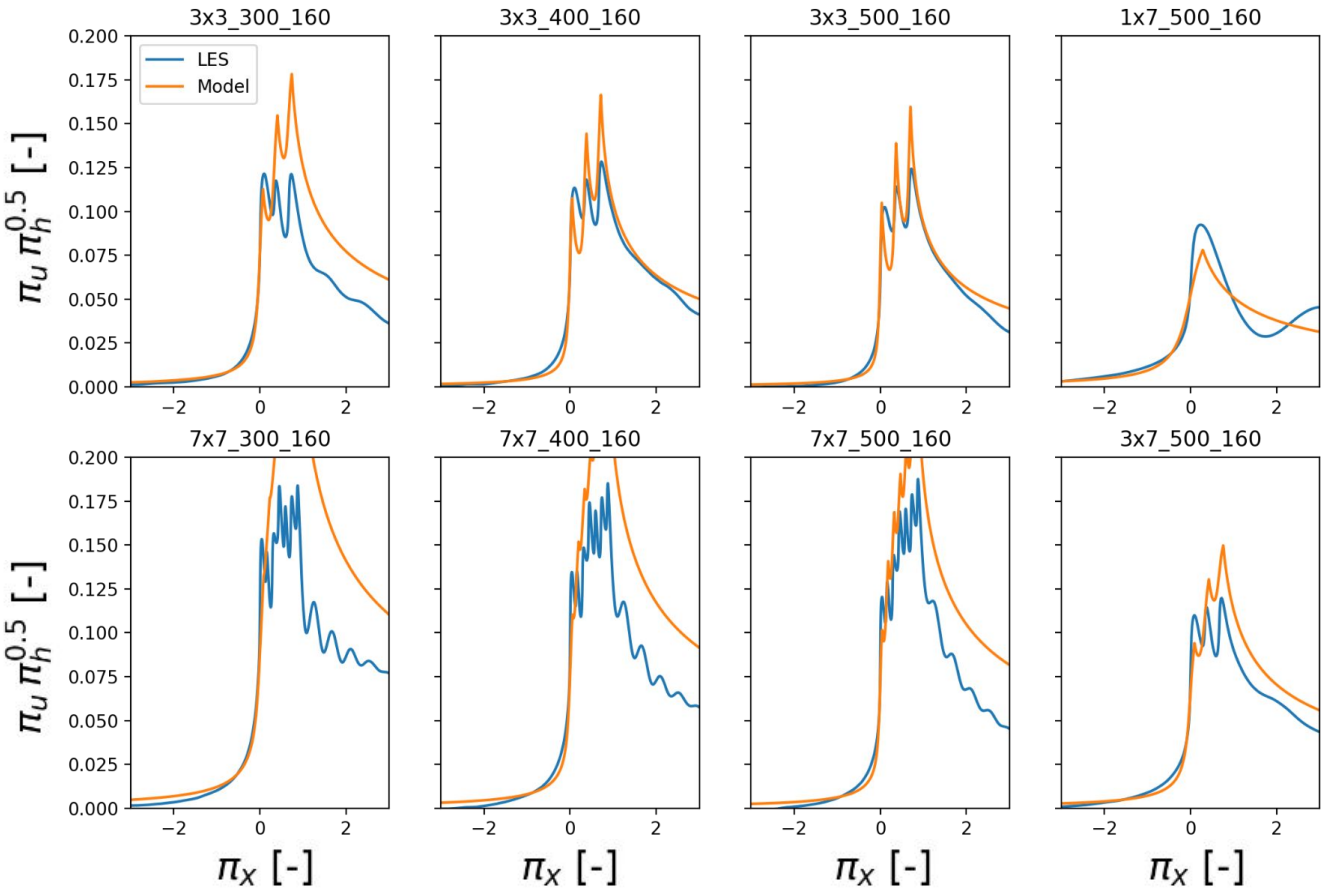
- H has a very clear effect.
  The lapse rate of the inversion and the free-atmosphere have a more subtle and complex effect



Model development

Potential flow based model

- Wind farm interpreted as a sum of wind turbine rows
- Rows are modeled as a source of mass calibrated on thrust
- Additional sources dependent on the ABL height are added to better fit LES results.
- In development: treatment of the in farm accelerations



Conclusions

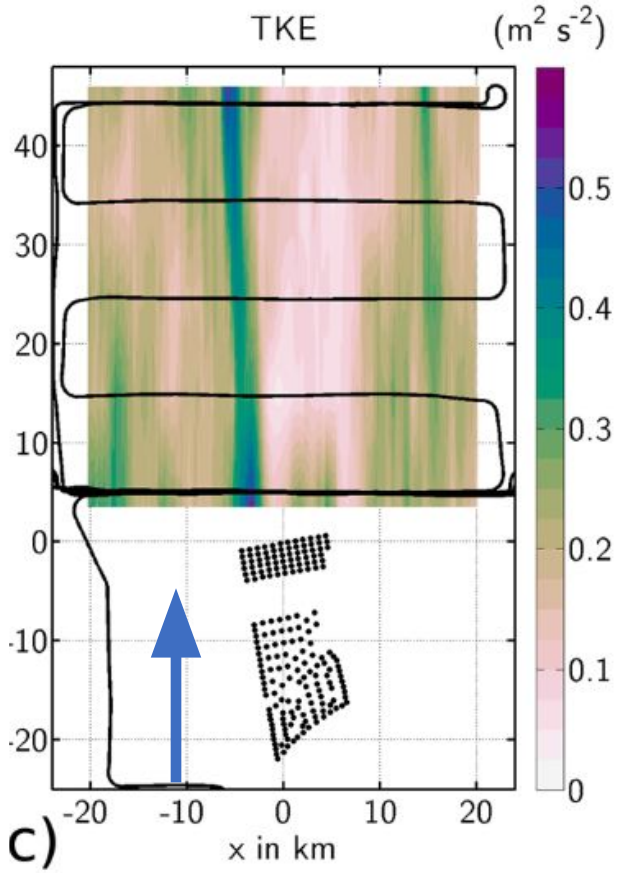
Global Blockage

- GBE depends on wind farm size, atmospheric boundary layer height, and lapse rate of capping inversion and free atmosphere
- We define a parametrization for the ABL height and wind farm size
- Currently the parametrization is being implemented in a industry model framework
- LES shown that the GBE is just a part of the interplay between wind farm and atmospheric stratification.

Outlook

Parameterization of cluster wake asymmetry in industry models

- Flight measurements in the predecessor project WIPAFF showed a zone of high TKE at the left edge of the wake of the N4 cluster when looking in downwind direction
- In satellite data an asymmetry in the wake region of a wind farm cluster is also sometimes observed



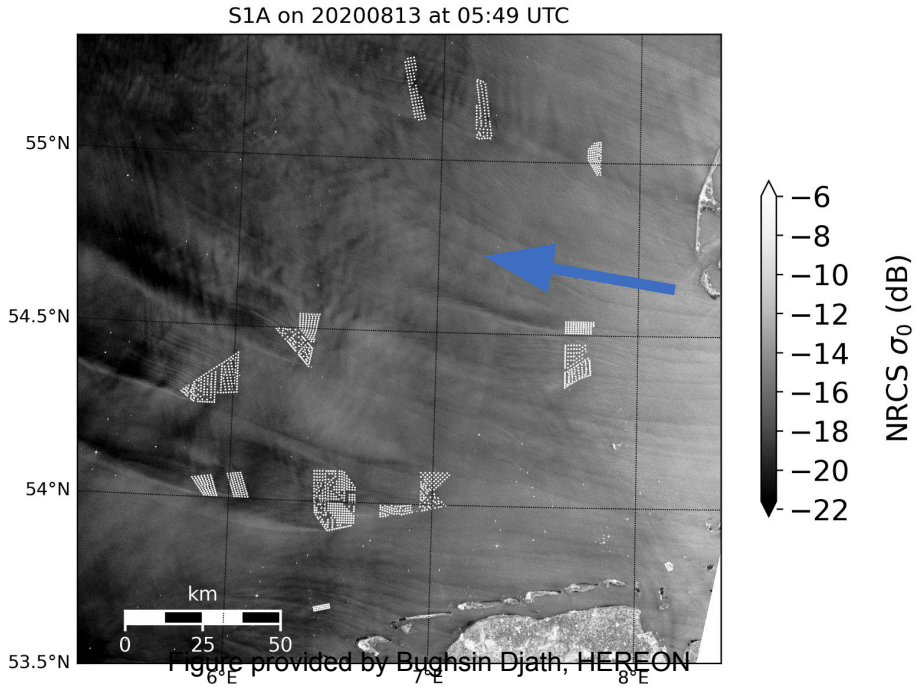


Figure provided by Bughsin Djath, HEREON

Figure from: *Platis, A., Siedersleben, S., Bange, J. et al.* First *in situ* evidence of wakes in the far field behind offshore wind farms. *Sci Rep* **8**, 2163 (2018). https://doi.org/10.1038/s41598-018-20389-y

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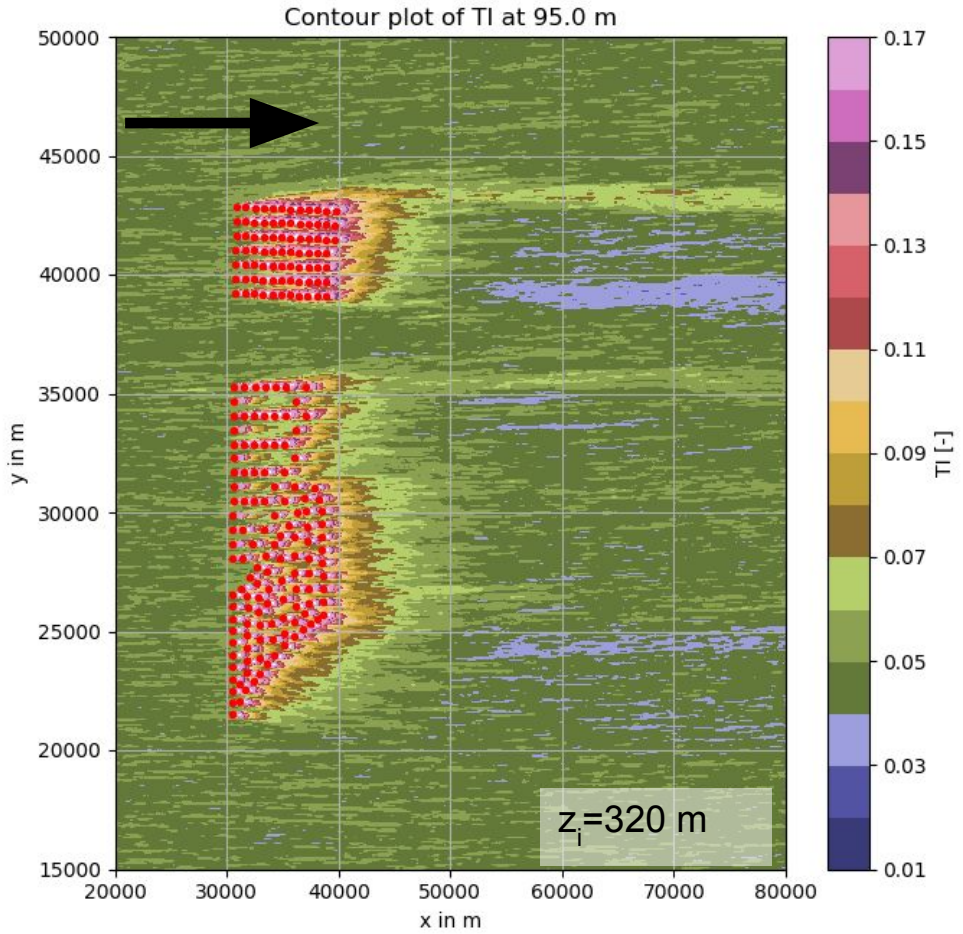
Outlook

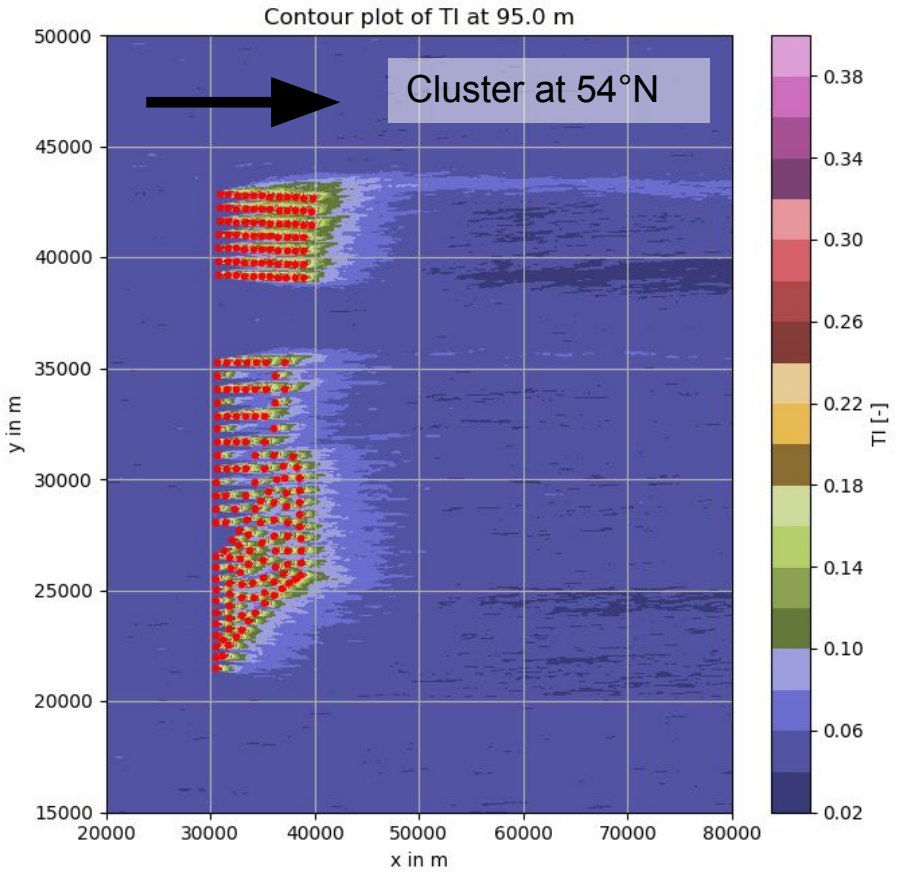
Parameterization of cluster wake asymmetry in industry models

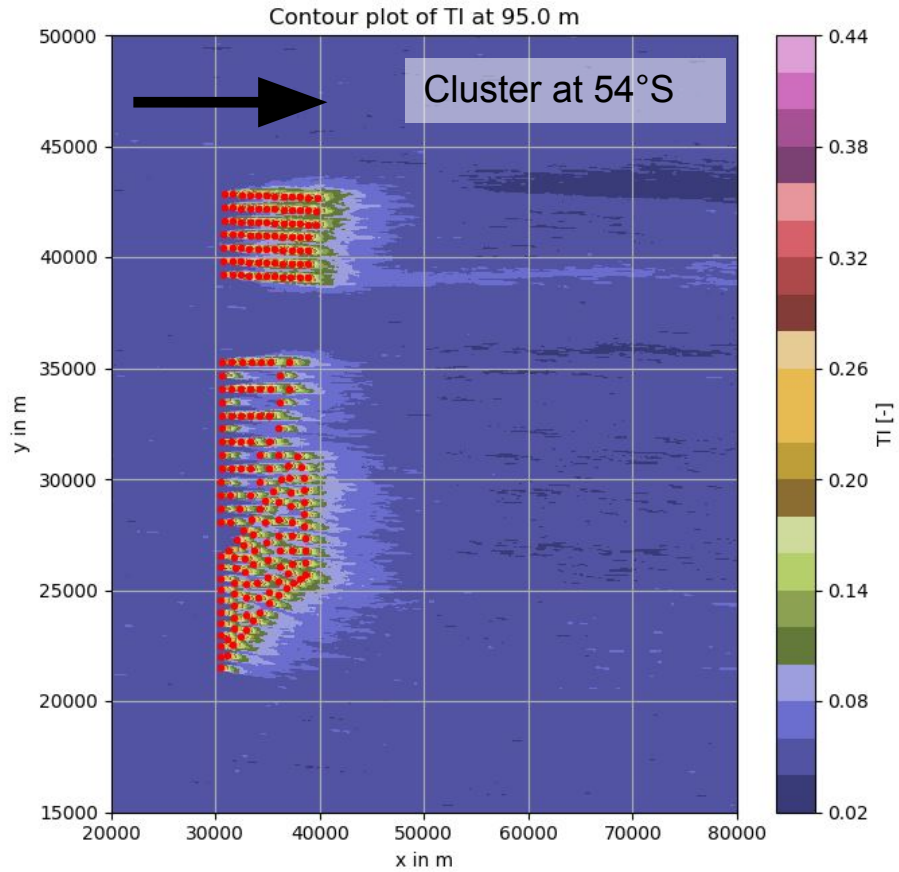
- LES in X-Wakes confirmed the existence of an asymmetry of the wake with respect of TI especially in the case of shallow boundary layers



Outlook

Parameterization of cluster wake asymmetry in industry models





- Asymmetry result of wind veer due to the Coriolis force and vertical mixing in the cluster wake
- Therefore, position of high TI streak dependent on which hemisphere the wind farm is situated

Outlook

Improvement of in industry models with LES

- Developing a parameterization for the asymmetry of the cluster wake
- Focus on intra-farm speed-up and interaction with ABL
- Further development and testing of GBE model with GLOBE dataset
- **Extensive development of these topics will be achieved in the follow-up project C²Wakes**

Acknowledgments

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