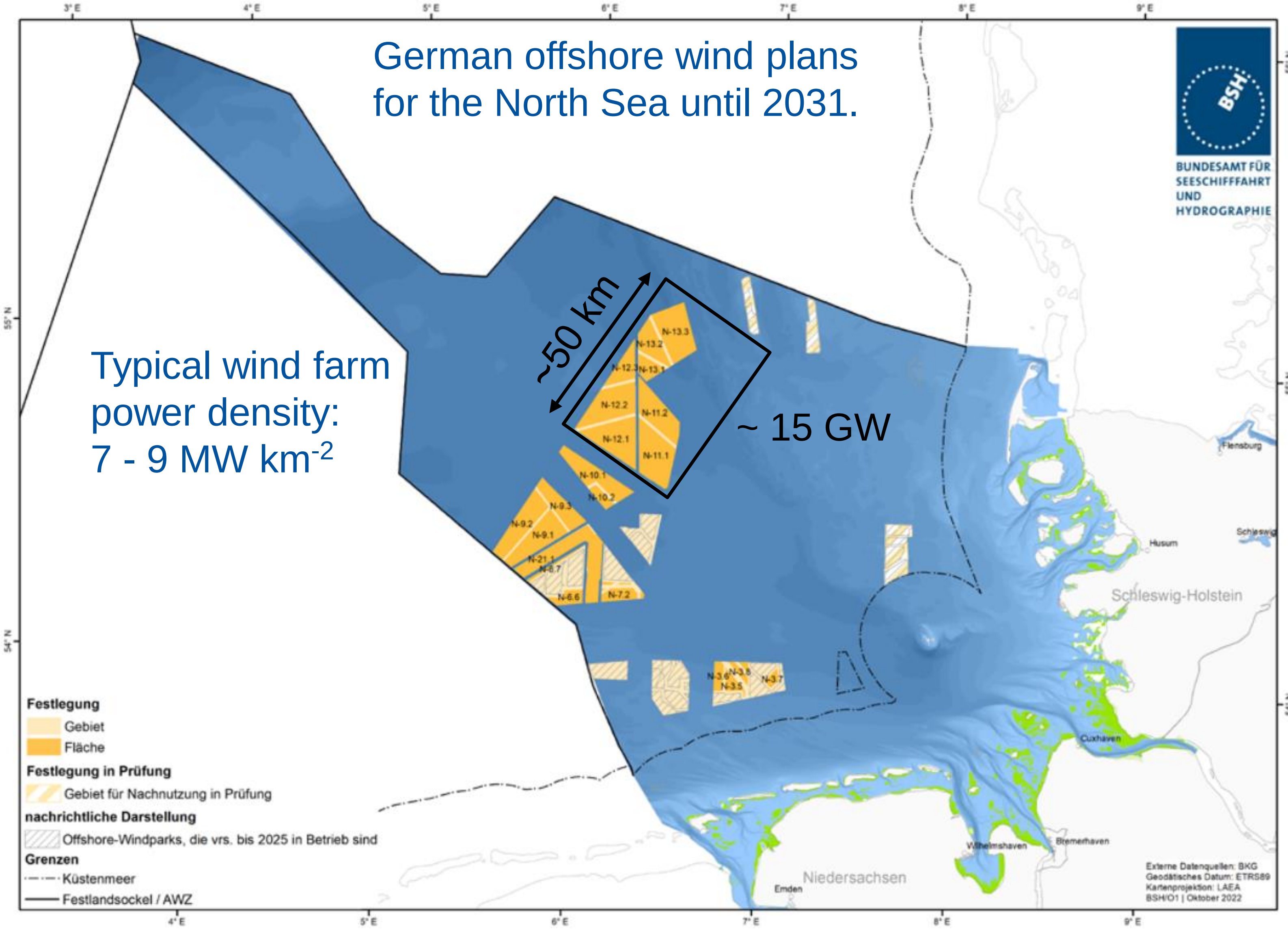
Leibniz Universität Hannover

Large-eddy simulation of a 15 GW wind farm and comparison with advanced wake models

Oliver Maas
Institute of Meteorology and Climatology
Leibniz University Hannover

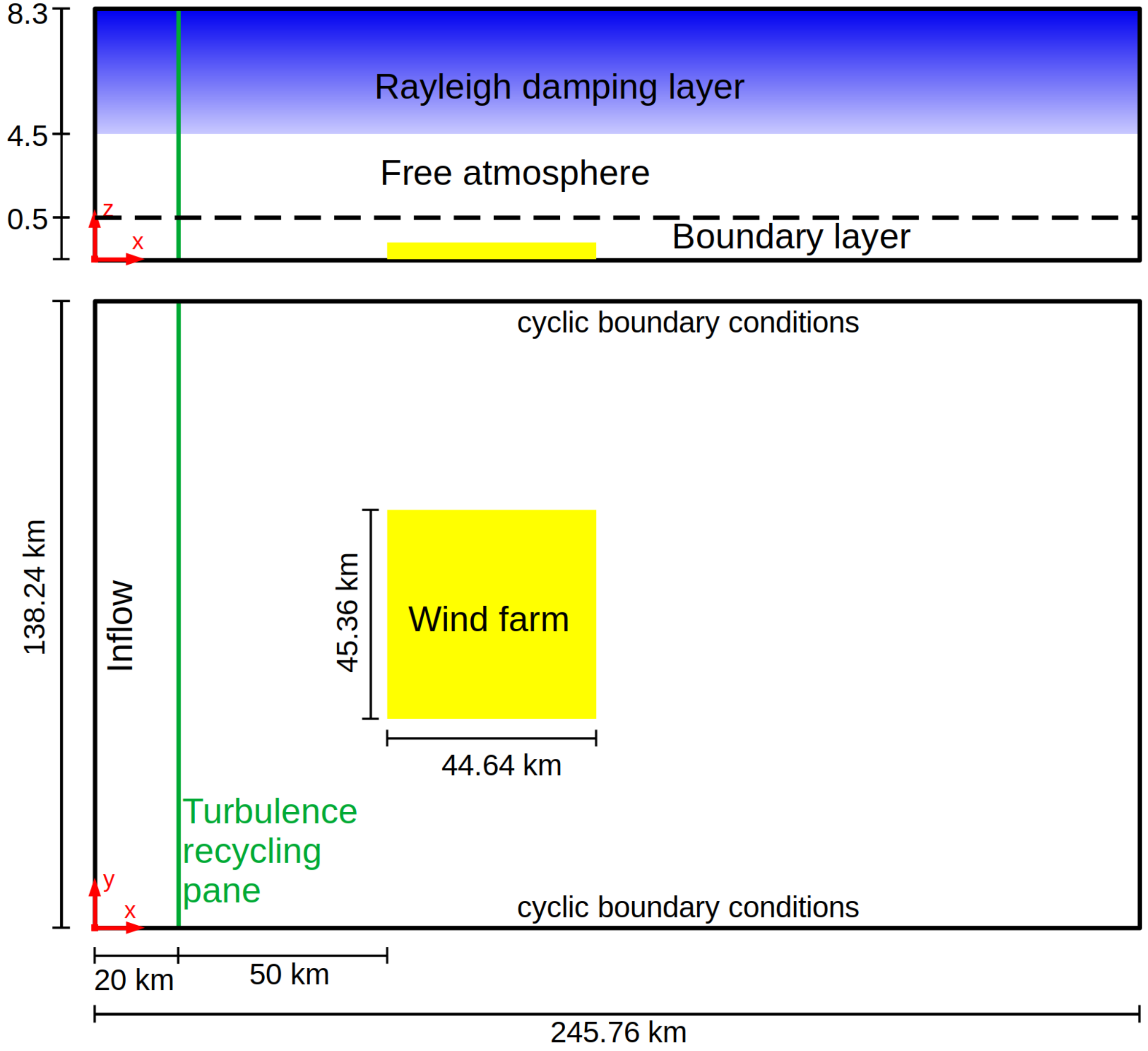
EERA DeepWind Conference 2023
Trondheim



https://www.bsh.de/DE/THEMEN/Offshore/Meeresfachplanung/Flaechenentwicklungsplan/flaechenentwicklungsplan_node.html

- How does a 15 GW wind farm modify the wind field?
- How do wake models perform for a 15 GW wind farm?
- Where does all the energy come from?

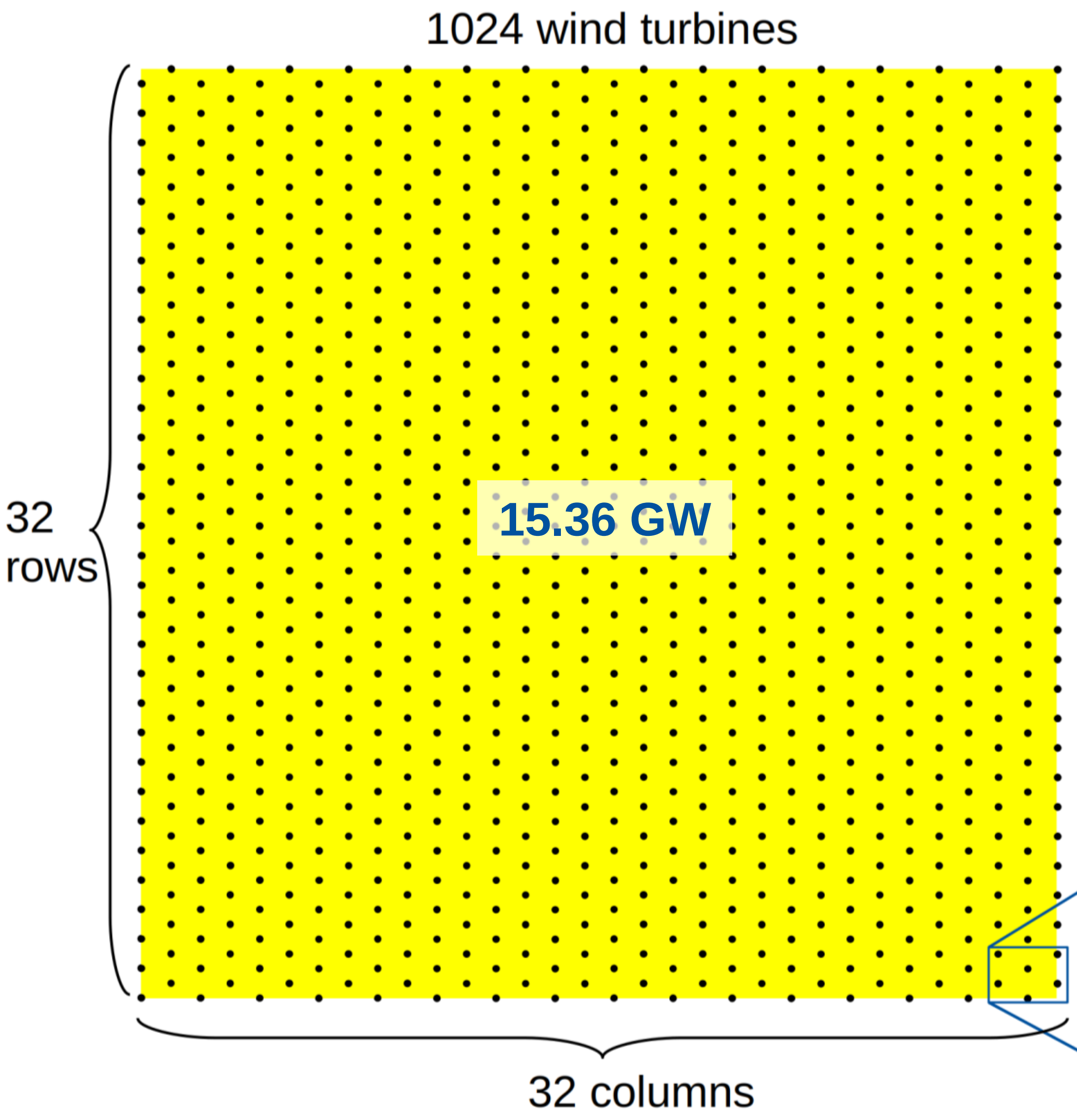
Domain layout



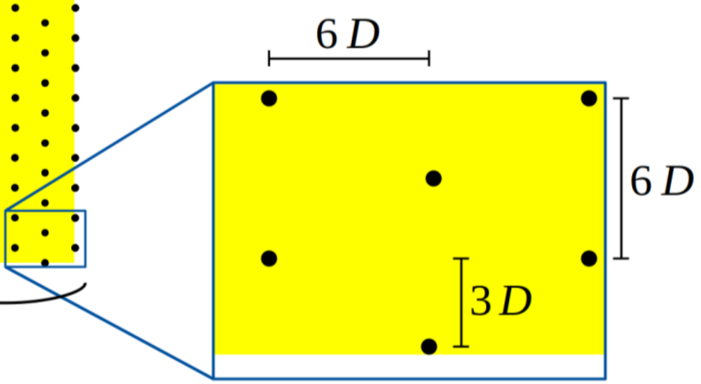
- LES model: PALM
- Grid spacing: 20 m (12 points / D)
- Grid points: 6.8 billion
- Simulated time: 24 h
- Wall-clock time: 50 h
- Cores: 5184

The work was supported by the North-German Supercomputing Alliance HLRN

Wind farm layout



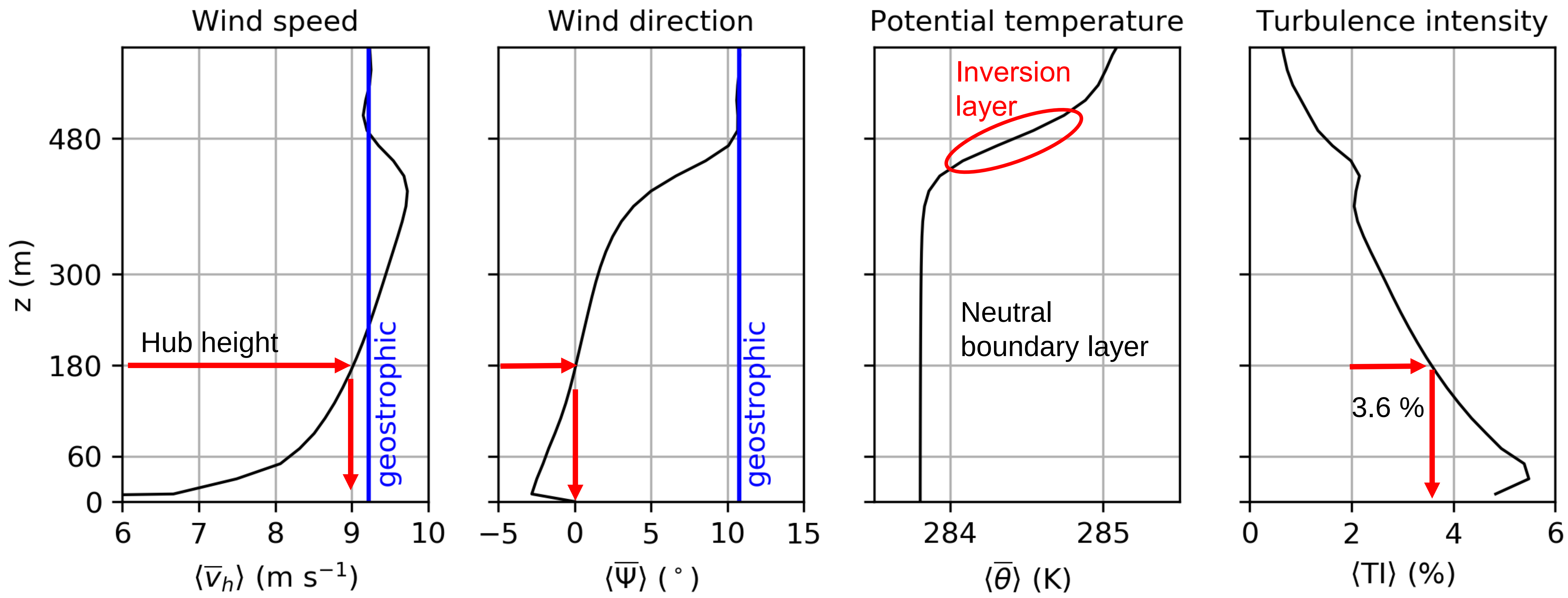
IEA 15 MW reference turbine



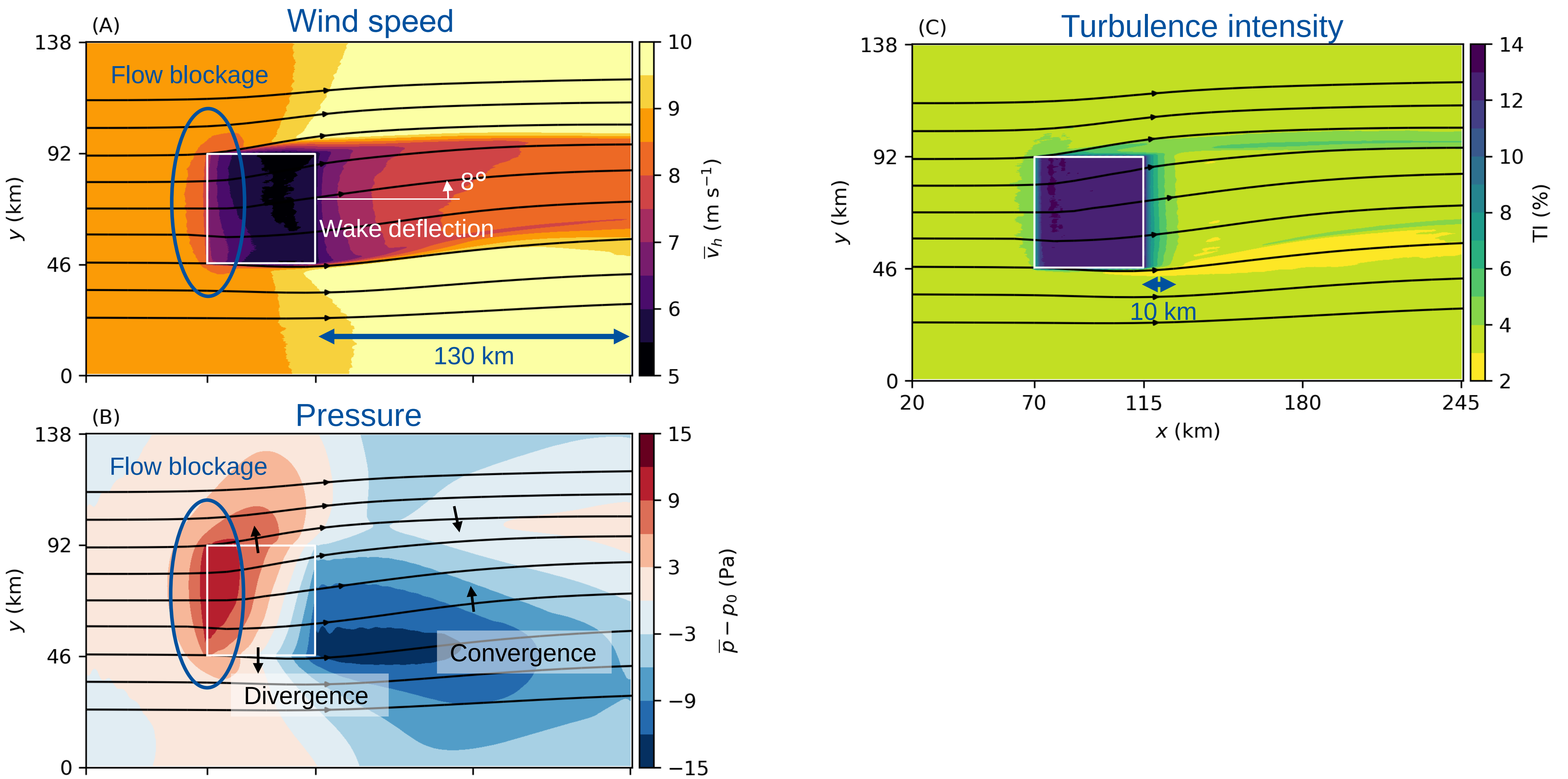
Actuator disc model with rotation

Installed power density:
7.23 MW km^{-2}

Inflow profiles

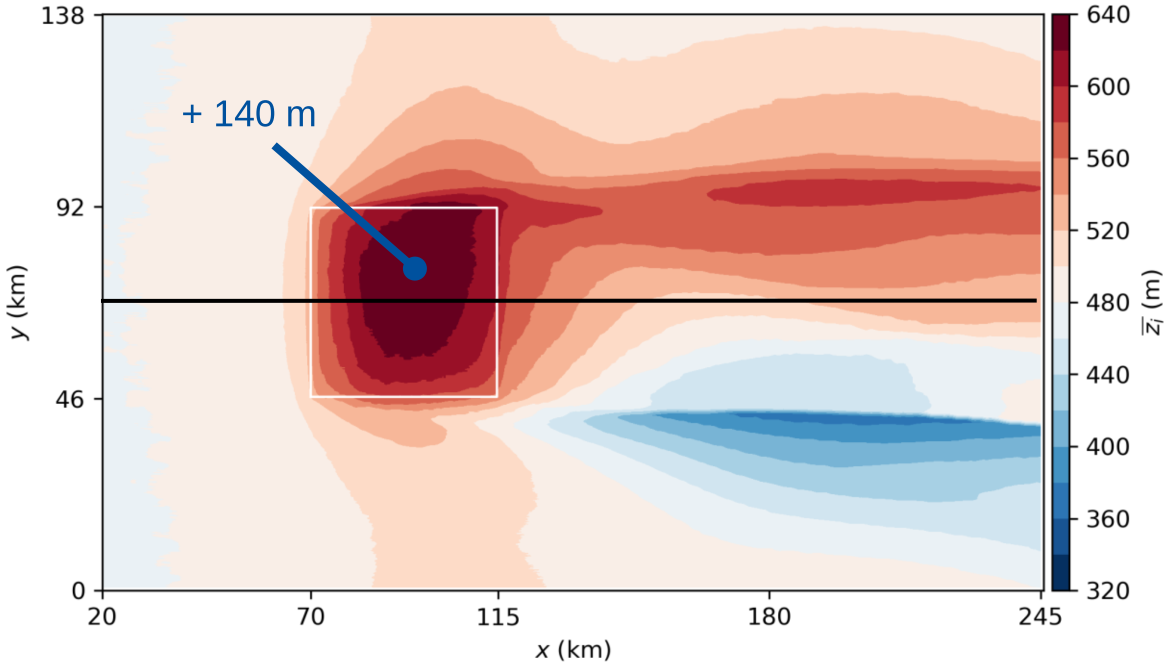


Mean flow at hub height

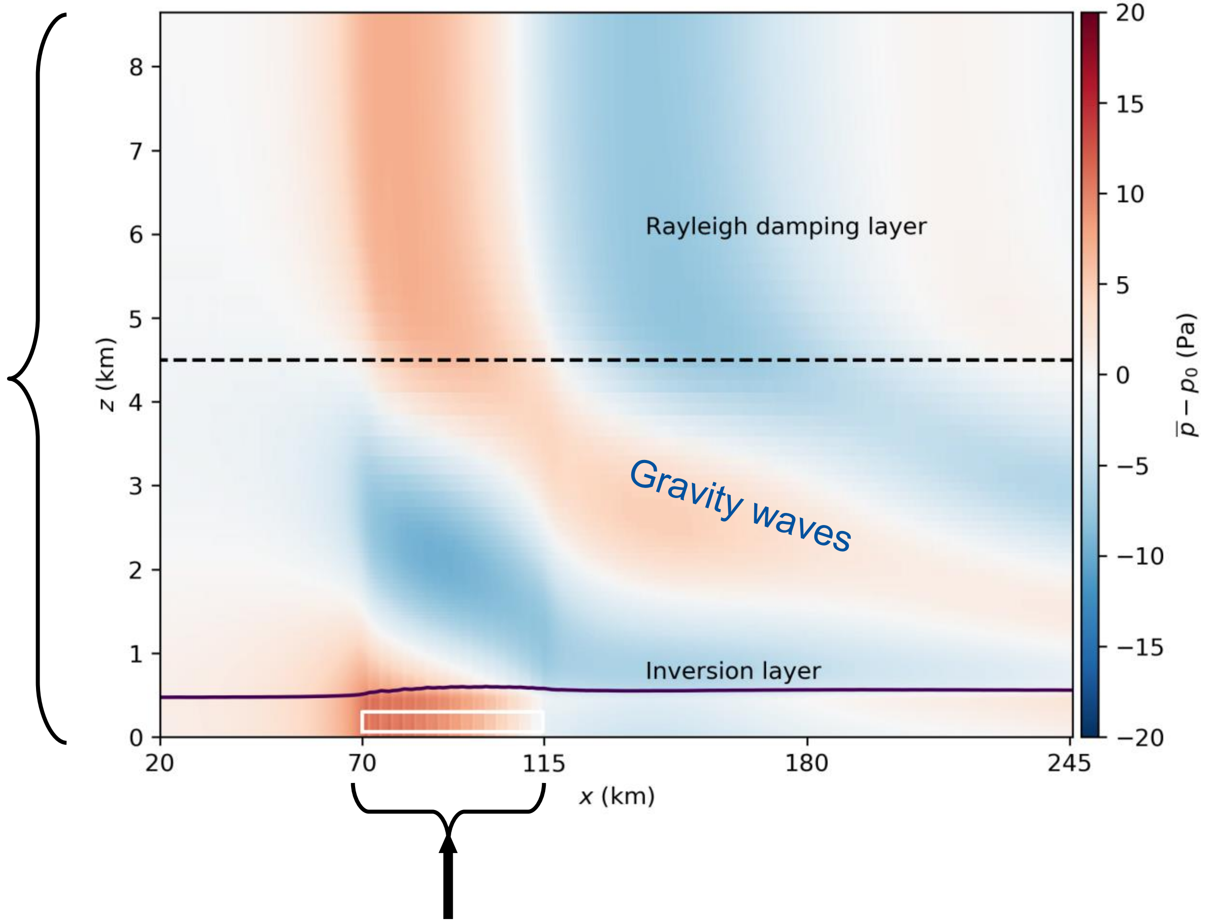


Inversion layer height and pressure distribution

Inversion layer height

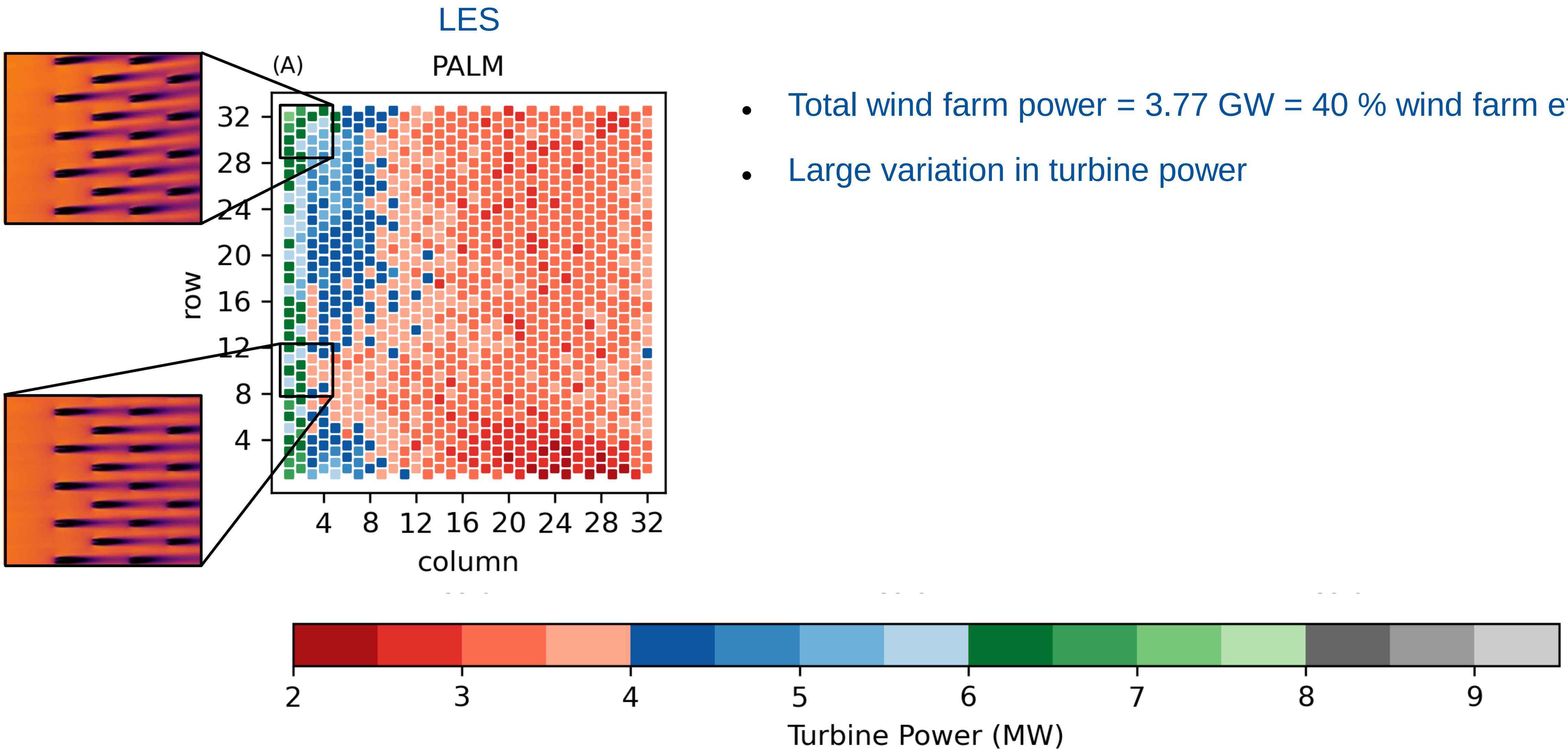


Pressure



Negative pressure gradient = acceleration

Power output



- Total wind farm power = 3.77 GW = 40 % wind farm efficiency
- Large variation in turbine power

Wake models

- NP model (Niayifar and Porté-Agel)
- TurbOPark model (Turbulence Optimized Park)

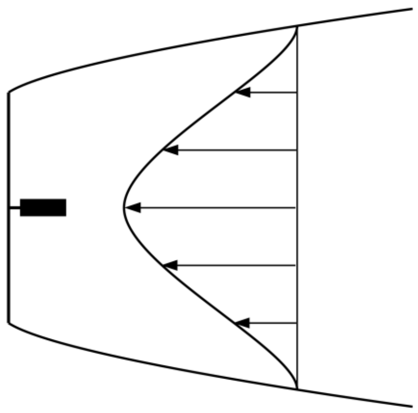
- Gaussian wake profile
- Wake expansion rate depends on local turbulence intensity (ambient + wake)
- Based on momentum-conserving velocity deficit model for single turbine wake

NP model:

- Linear superposition of velocity deficits (momentum conserving)
- No superposition of turbulence intensity
- Turbulence model of Crespo and Herna’ndez (1996)

TurbOPark model:

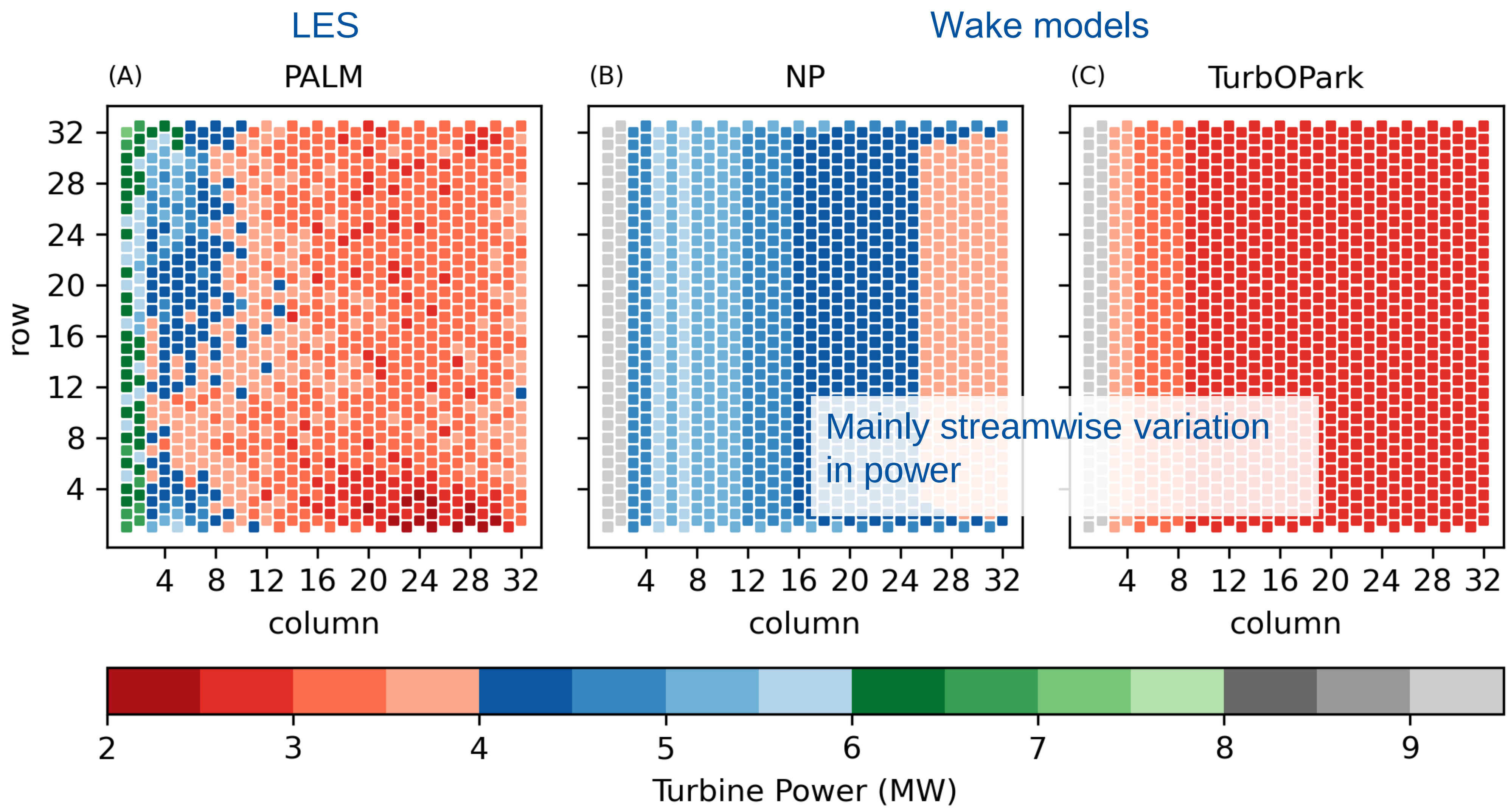
- Quadratic superposition of velocity deficits (energy conserving)
- Quadratic superposition of turbulence intensity
- Turbulence model of Frandsen (2007)



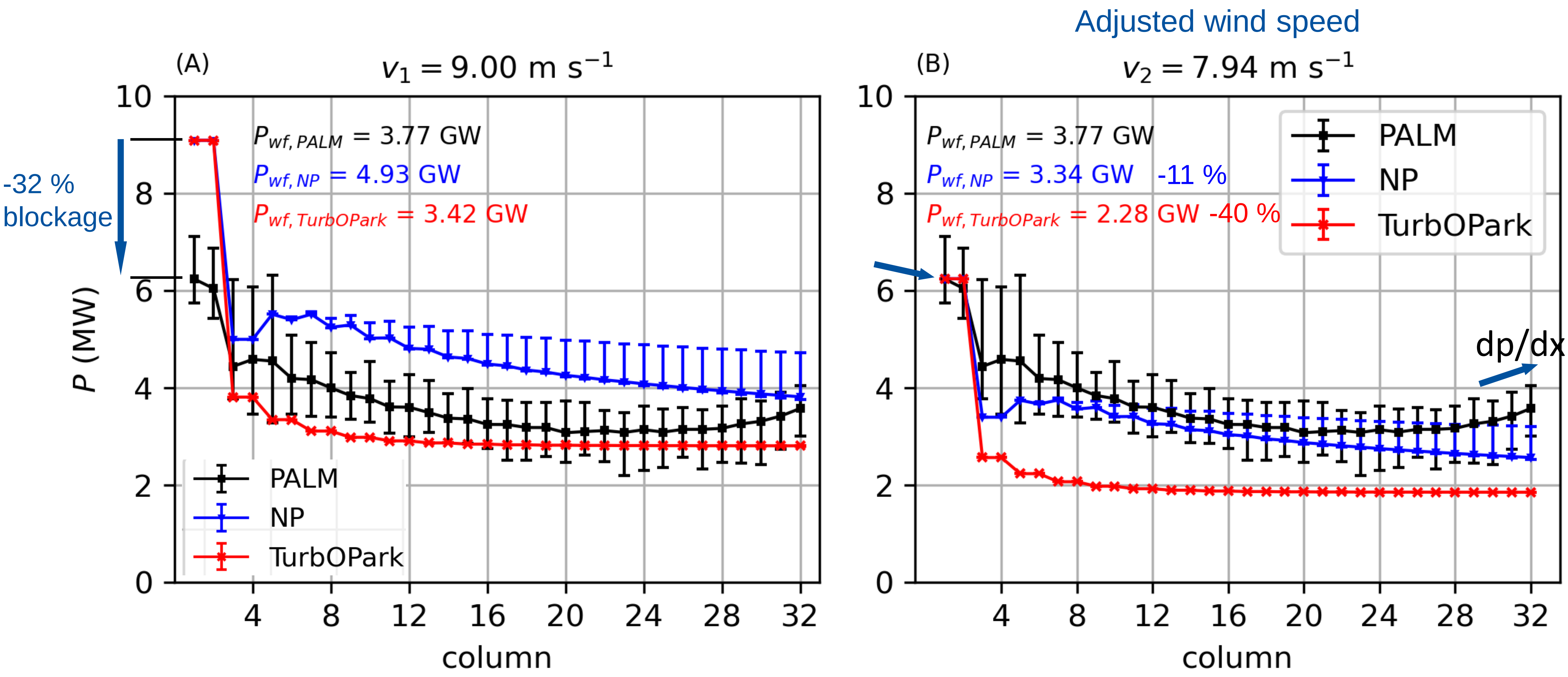
Simulations performed with

PyWake

Comparison LES – wake models

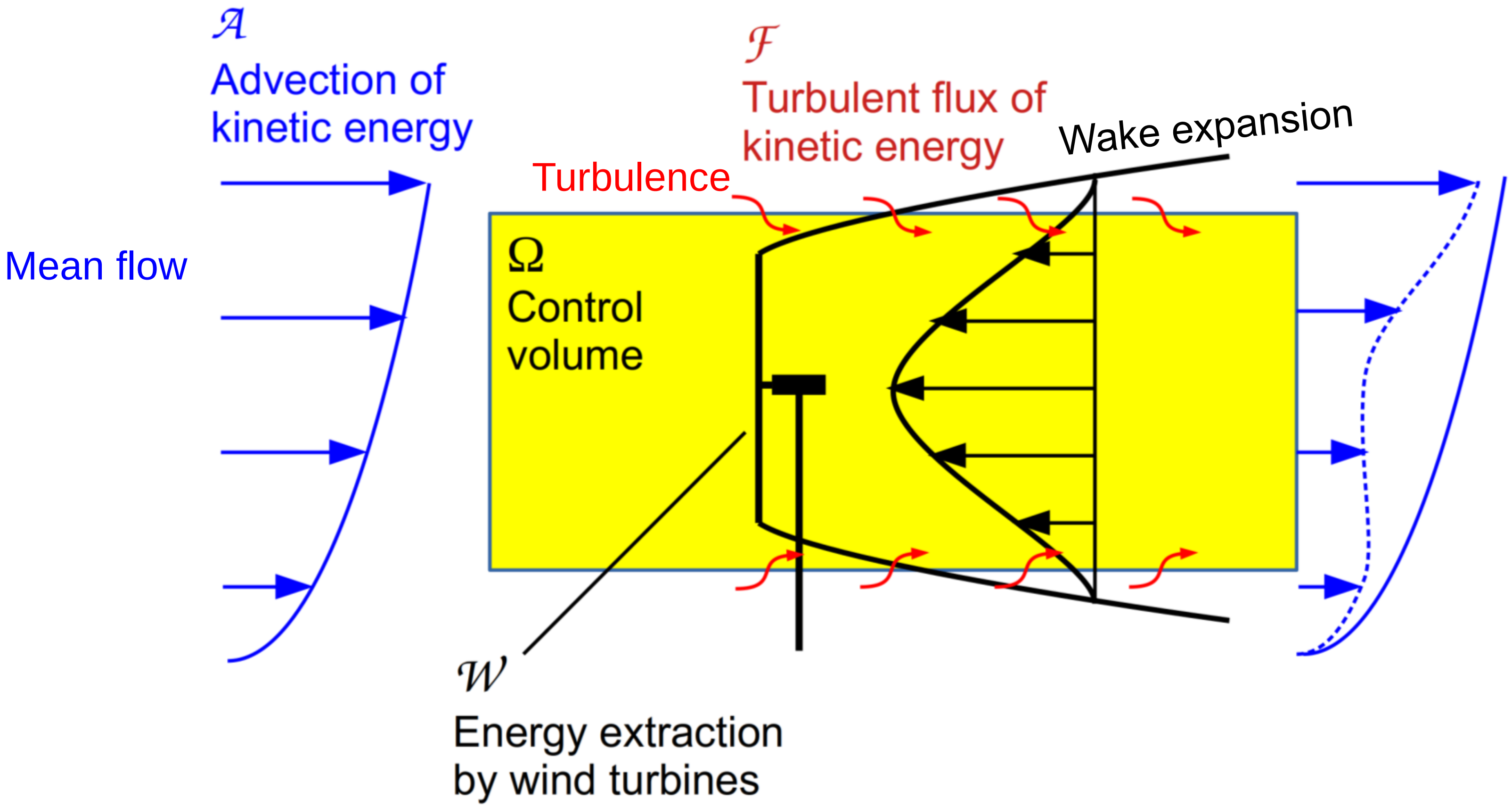


Column-wise averaged turbine power



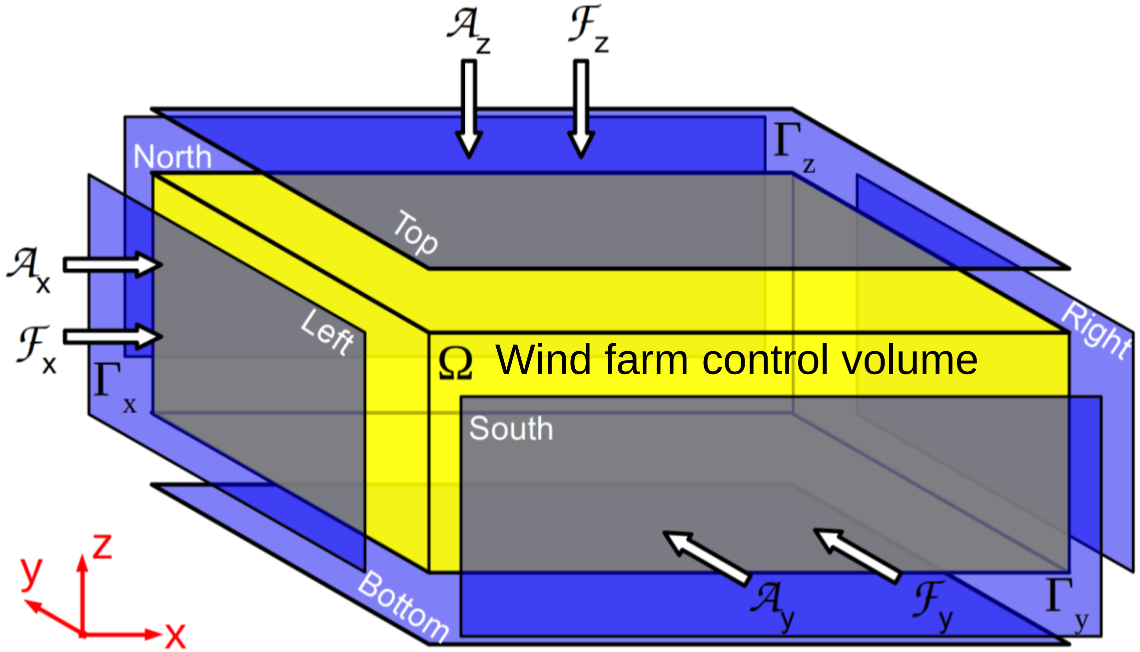
Why are there so large differences?

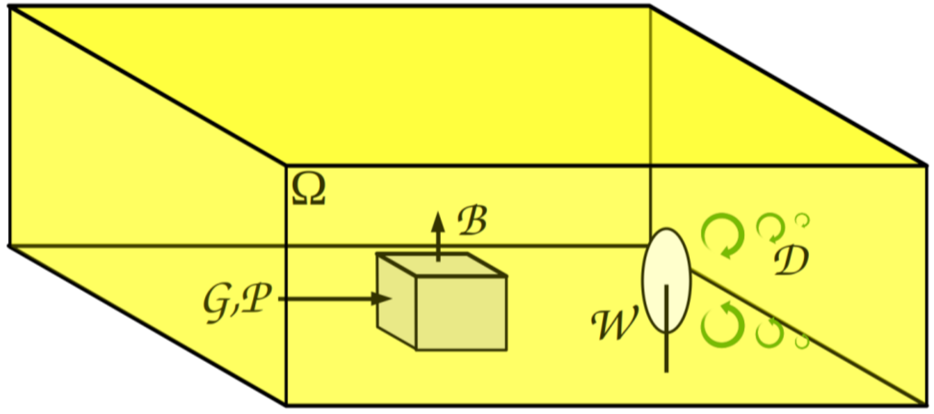
- Wake models take into account 2 energy sources and 1 energy sink:



- But maybe there are also other energy sources or sinks?

Energy budget analysis of the LES





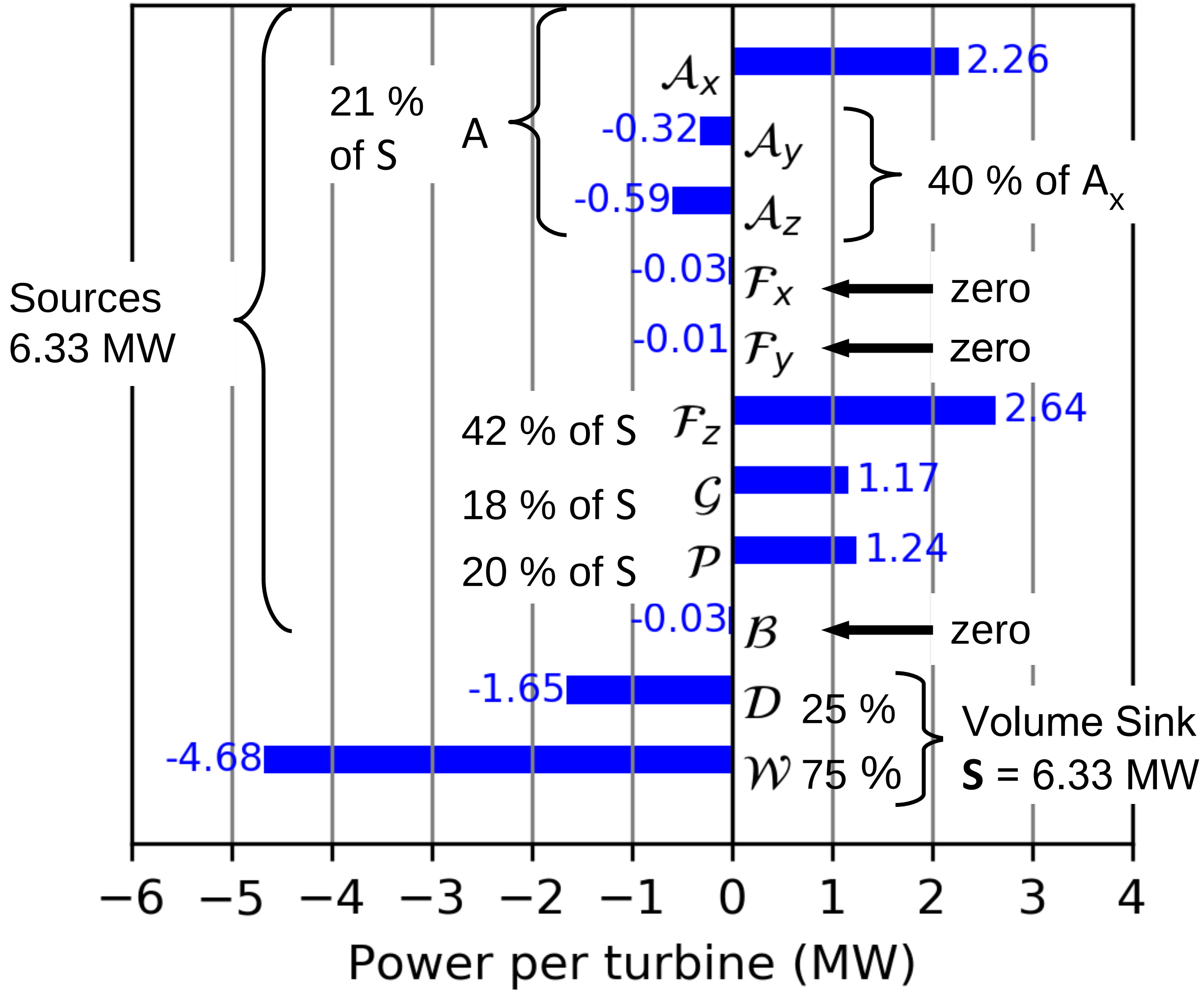
- Surface sources or sinks:
  - $\mathcal{A}$: **A**dvection of kinetic energy
  - $\mathcal{F}$: Turbulent **F**lux of kinetic energy
- Volume sources or sinks:
  - $\mathcal{G}$: **G**eostrophic forcing
  - $\mathcal{P}$: **P**ressure gradients
  - $\mathcal{B}$: **B**uoyancy forces
  - $\mathcal{D}$: **D**issipation
  - $\mathcal{W}$: **W**ind turbines

$$0 = \underbrace{-\int_\Omega \frac{\partial \bar{\tilde{u}}_j \overline{E}_k}{\partial x_j} d\Omega}_{\mathcal{A}} \underbrace{- \int_\Omega \frac{\partial}{\partial x_j} \bar{\tilde{u}}_i \overline{\tilde{u}_i' \tilde{u}_j'} d\Omega + \int_\Omega \frac{\partial}{\partial x_j} \overline{\tilde{u}_i \tau_{ij}} d\Omega - \int_\Omega \frac{\partial}{\partial x_j} \frac{1}{2} \overline{\tilde{u}_j' \tilde{u}_i' \tilde{u}_i'} d\Omega - \int_\Omega \overline{\frac{\tilde{u}_i'}{\rho_0} \frac{\partial \pi^{*\prime}}{\partial x_i}} d\Omega}_{\mathcal{F}}$$

$$+ \underbrace{\int_\Omega (\bar{\tilde{u}}_2 f_3 u_{g,1} - \bar{\tilde{u}}_1 f_3 u_{g,2}) d\Omega}_{\mathcal{G}} \underbrace{- \int_\Omega \frac{\bar{\tilde{u}}_i}{\rho_0} \frac{\partial \overline{\pi^*}}{\partial x_i} d\Omega}_{\mathcal{P}} + \underbrace{\int_\Omega \frac{g}{\theta_0} \overline{\left(\tilde{\theta} - \theta_0\right) \tilde{u}_3} d\Omega}_{\mathcal{B}}$$

$$\underbrace{- \int_\Omega \overline{\tau_{ij} \frac{\partial \tilde{u}_i}{\partial x_j}} d\Omega - \mathcal{R}}_{\mathcal{D}} + \underbrace{\int_\Omega \overline{\tilde{u}_i d_i} d\Omega}_{\mathcal{W}},$$

Wind farm energy budgets



- Surface sources or sinks:
  - $\mathcal{A}$: **A**dvection of kinetic energy
  - $\mathcal{F}$: Turbulent **F**lux of kinetic energy
- Volume sources or sinks:
  - $\mathcal{G}$: **G**eostrophic forcing
  - $\mathcal{P}$: **P**ressure gradients
  - $\mathcal{B}$: **B**uoyancy forces
  - $\mathcal{D}$: **D**issipation
  - $\mathcal{W}$: **W**ind turbines

How can the wake models be improved?

- Take pressure distribution into account
  - Advantages:
    - Blockage effect covered
    - Higher (more realistic) turbine powers inside the wind farm
  - Tasks:
    - Model gravity wave induced pressure distribution in the wind farm
    - Model the effect of this pressure distribution on the velocity field (e.g. applying Bernoulli’s principle)

Conclusions

- How does a 15 GW wind farm modify the wind field?
  - Flow blockage + divergence
  - Wake deflection
  - Inversion layer displacement + gravity wave induced pressure gradients

- What are the main energy sources?
  - Vertical turbulent fluxes + advection. But also: geostrophic forcing, pressure gradient

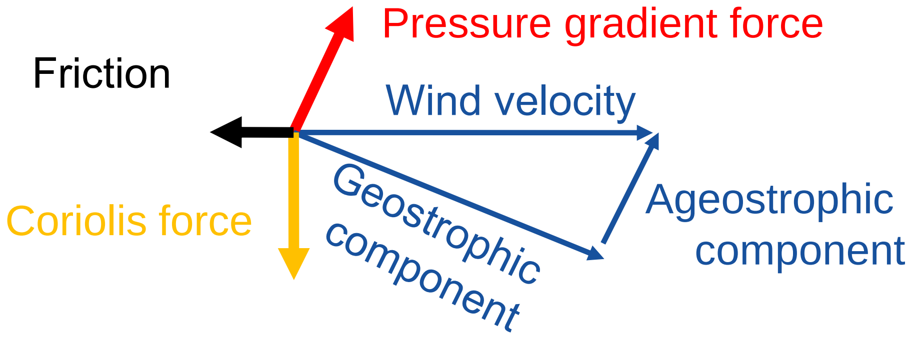
- How do analytical wake models perform for a 15 GW wind farm?
  - Not so good. They neglect important energy sources and sinks.
  - How can they be improved? Taking pressure distribution into account.

- Limitations of the LES study:
  - Only 1 wind speed, direction, BL height, stratification, wind farm layout
  - Reality is not as ideal as the simulation

References

- Maas, O. Large-eddy simulation of a 15 GW wind farm: flow effects, energy budgets and comparison with wake models. Frontiers 2023, In review.
- Bastankhah, M. and Porté-Agel, F. (2014). A new analytical model for wind-turbine wakes. Renewable Energy 70, 116–123. doi:10.1016/j.renene.2014.01.002
- Crespo, A.; Hernandez, J.; Frandsen, S. Survey of modelling methods for wind turbine wakes and wind farms. Wind Energy 1999, 2, 1–24.
- Frandsen, S. T. (2007). Turbulence and turbulence- generated structural loading in wind turbine clusters. Ph.D. thesis, Technical University of Denmark
- Pedersen, J. G., Svensson, E., Poulsen, L., and Nygaard, N. G. (2022). Turbulence Optimized Park model with Gaussian wake profile. Journal of Physics: Conference Series 2265, 022063. doi:10.1088/1742-6596/2265/2/022063

Geostrophic forcing



Energy budget equations

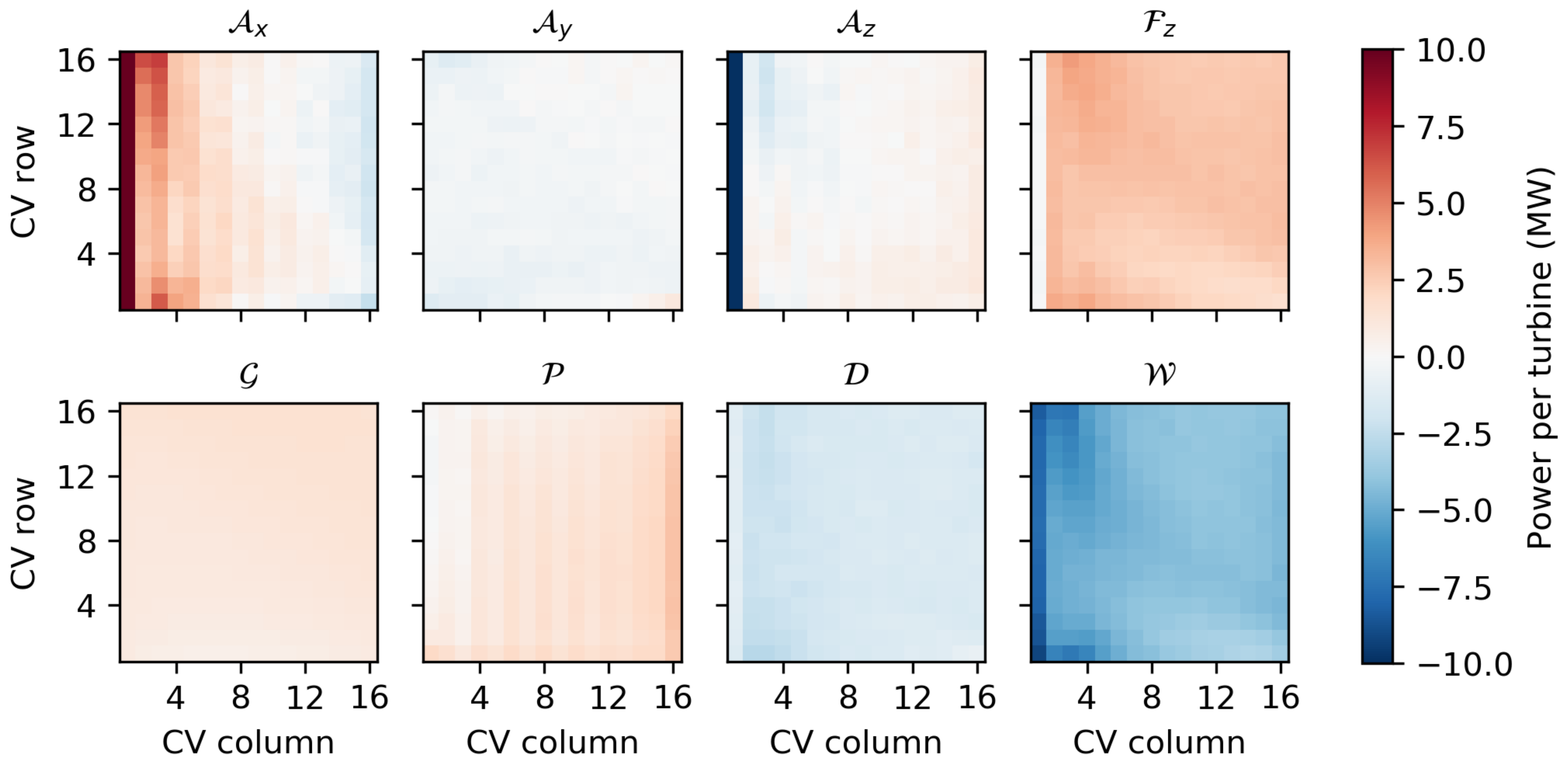
$$0 = \underbrace{-\int_\Omega \frac{\partial \overline{\tilde{u}}_j \overline{E}_k}{\partial x_j} d\Omega}_{\mathcal{A}} \underbrace{- \int_\Omega \frac{\partial}{\partial x_j} \overline{\tilde{u}}_i \overline{\tilde{u}_i' \tilde{u}_j'} d\Omega + \int_\Omega \frac{\partial}{\partial x_j} \overline{\tilde{u}_i \tau_{ij}} d\Omega - \int_\Omega \frac{\partial}{\partial x_j} \frac{1}{2} \overline{\tilde{u}_j' \tilde{u}_i' \tilde{u}_i'} d\Omega - \int_\Omega \overline{\frac{\tilde{u}_i'}{\rho_0} \frac{\partial \pi^{*\prime}}{\partial x_i}} d\Omega}_{\mathcal{F}}$$

$$\underbrace{+ \int_\Omega (\overline{\tilde{u}}_2 f_3 u_{g,1} - \overline{\tilde{u}}_1 f_3 u_{g,2}) d\Omega}_{\mathcal{G}} \underbrace{- \int_\Omega \frac{\overline{\tilde{u}}_i}{\rho_0} \frac{\partial \overline{\pi^*}}{\partial x_i} d\Omega}_{\mathcal{P}} \underbrace{+ \int_\Omega \frac{g}{\theta_0} \overline{\left(\tilde{\theta} - \theta_0\right) \tilde{u}_3} d\Omega}_{\mathcal{B}}$$

$$\underbrace{- \int_\Omega \overline{\tau_{ij} \frac{\partial \tilde{u}_i}{\partial x_j}} d\Omega - \mathcal{R}}_{\mathcal{D}} \underbrace{+ \int_\Omega \overline{\tilde{u}_i d_i} d\Omega}_{\mathcal{W}} ,$$

- Surface sources or sinks:
  - $\mathcal{A}$: **A**dvection of kinetic energy
  - $\mathcal{F}$: Turbulent **F**lux of kinetic energy
- Volume sources or sinks:
  - $\mathcal{G}$: **G**eostrophic forcing
  - $\mathcal{P}$: **P**ressure gradients
  - $\mathcal{B}$: **B**uoyancy forces
  - $\mathcal{D}$: **D**issipation by SGS model
  - $\mathcal{W}$: **W**ind turbines

Wind turbine control volume energy budgets



Column-wise averaged energy budgets