Development and Validation of Wind-Farm Blockage and Wake Models

ERCOFTAC Autumn Festival
Liège, 12–13 October 2023

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Department of Mechanical Engineering

Climate Changed

Offshore Wind Gets a Warning From Its Biggest Developer

By Will Mathis and Christian Wienberg

October 29, 2019, 1:28 PM GMT+1 *Updated on October 29, 2019, 4:26 PM GMT+1*

- Danish wind farm builder overestimated time turbines can spin
- Cost of technology has plunged, boosting pace of installations

The world's biggest developer of offshore wind farms issued a reality check to the industry, saying it has overestimated the amount of time its turbines are generating electricity.

Copenhagen-based Orsted A/S announced that offshore wind farms

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Wind farm blockage

energies

Article

Wind Farm Blockage and the Consequences of Neglecting Its Impact on Energy Production

James Bleeg [1,*], Mark Purcell [2], Renzo Ruisi [1,3] and Elizabeth Traiger [1]

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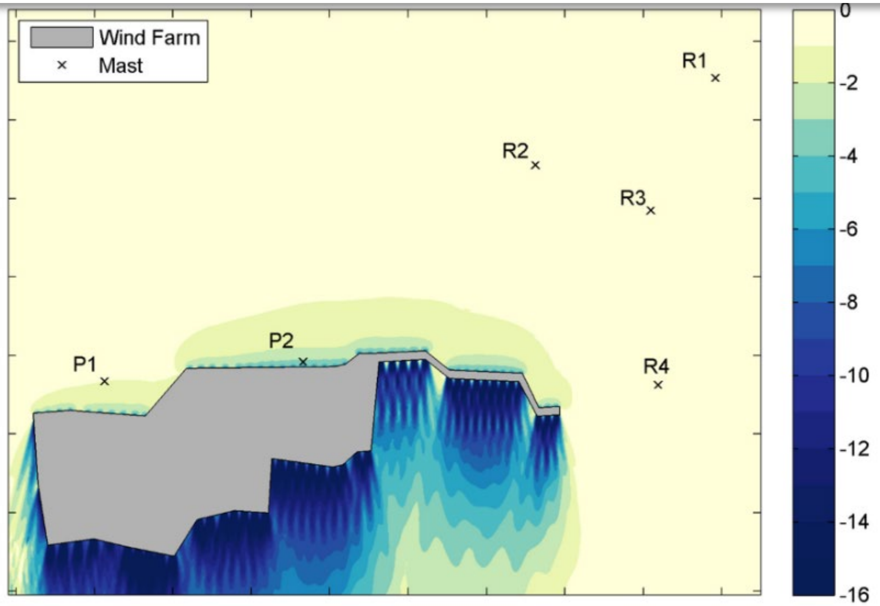


J. Fluid Mech. (2017), *vol.* 814, *pp.* 95–130. 95
doi:10.1017/jfm.2017.11

Boundary-layer development and gravity waves in conventionally neutral wind farms

Dries Allaerts[1,†] and Johan Meyers[1]

Boundary-Layer Meteorol (2018) 166:269–299
https://doi.org/10.1007/s10546-017-0307-5
CrossMark

RESEARCH ARTICLE

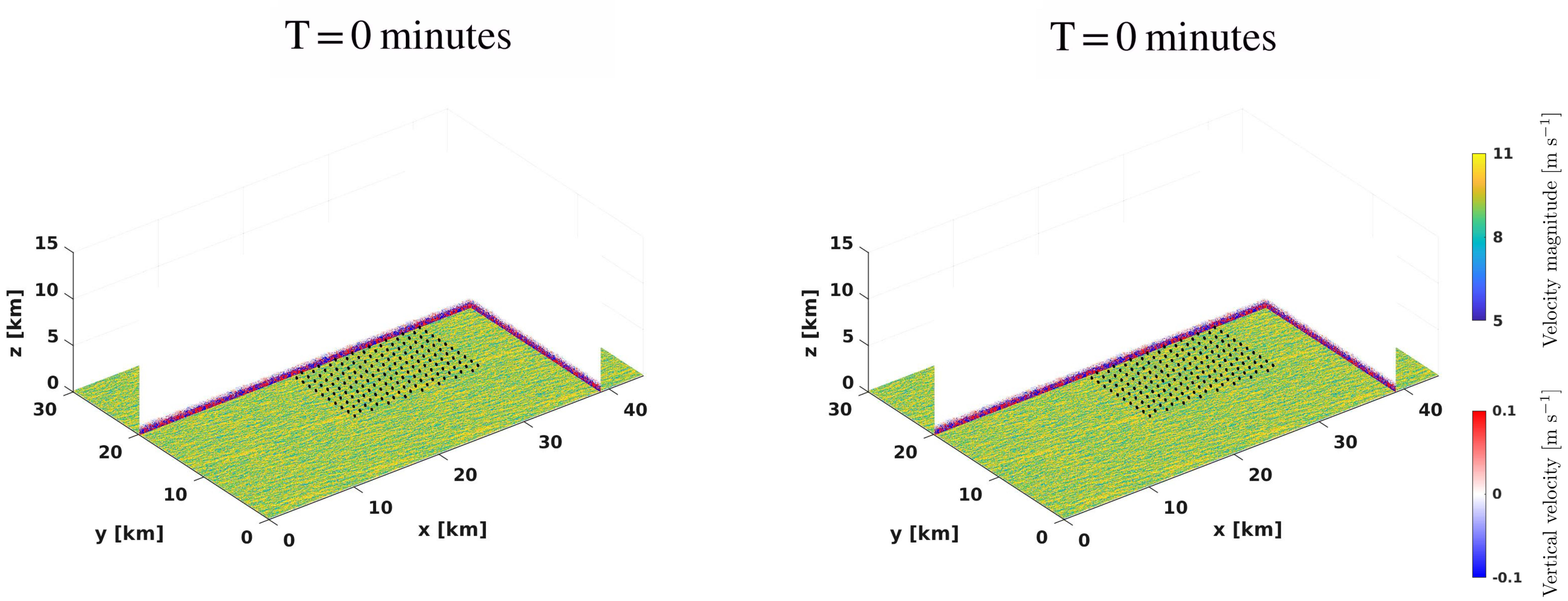
Gravity Waves and Wind-Farm Efficiency in Neutral and Stable Conditions

Dries Allaerts[1] · Johan Meyers[1]

- ➔ Gravity waves excited by wind farms
- ➔ Leads to significant upstream slow-down in semi-infinite wind farm LES

No gravity waves, negligible blockage

Gravity waves & resulting blockage



NBL

H500-$\Delta\theta$5-Γ4

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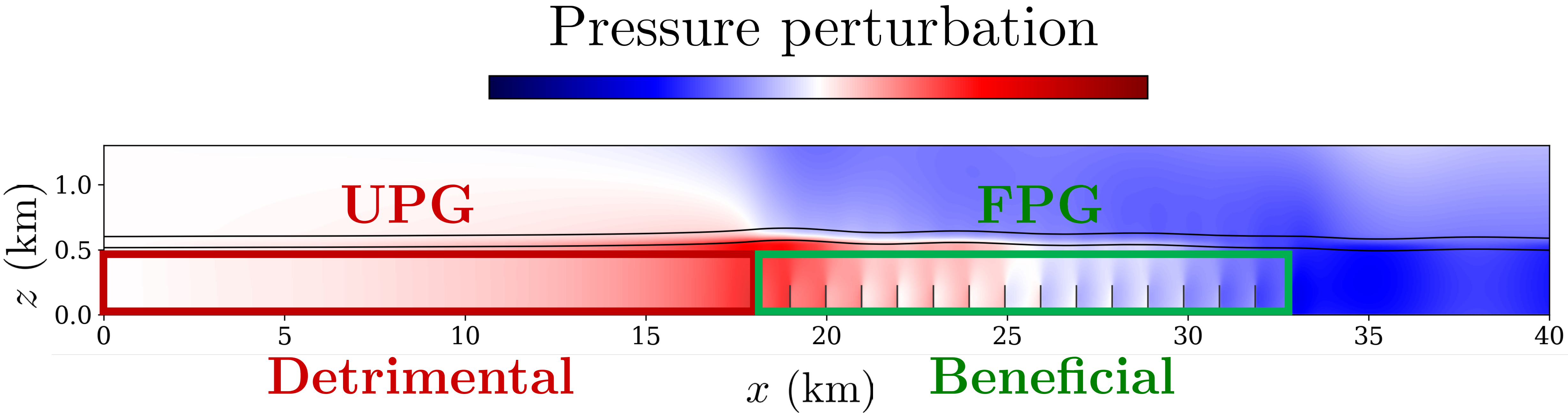
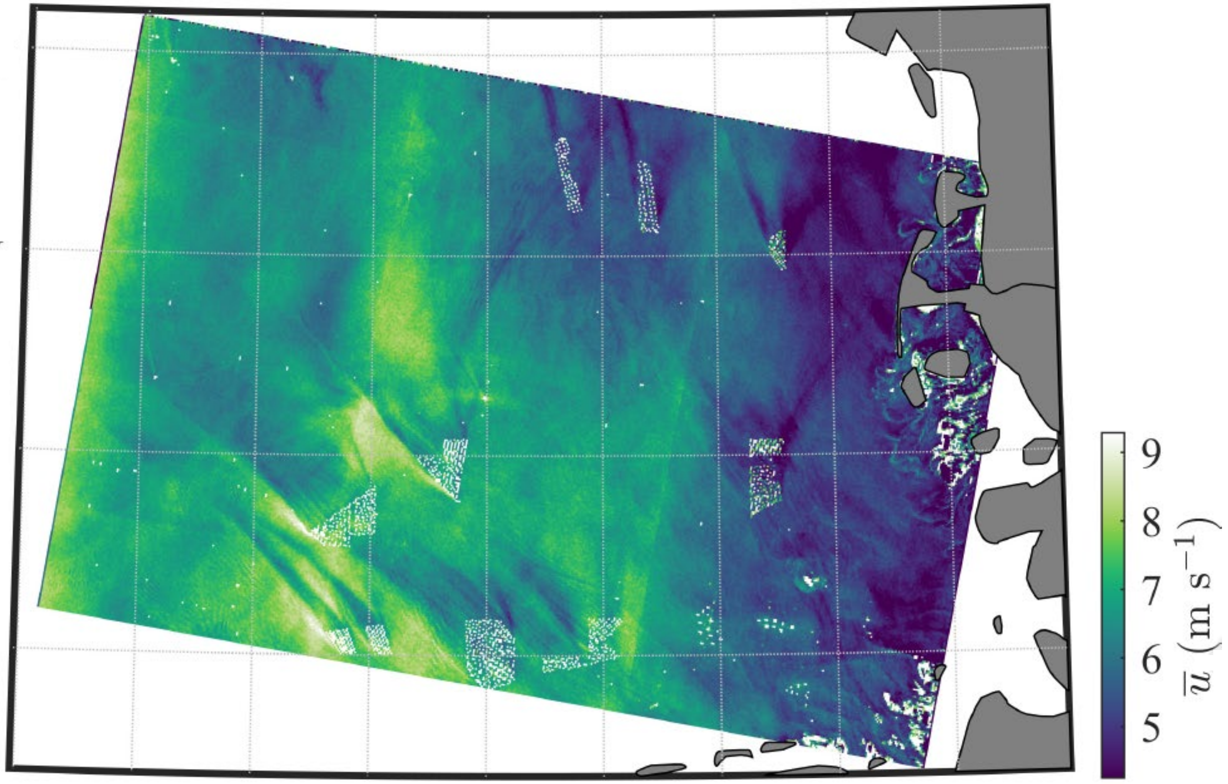
Gravity-wave induced pressure perturbation



Wind-farm–ABL interactions



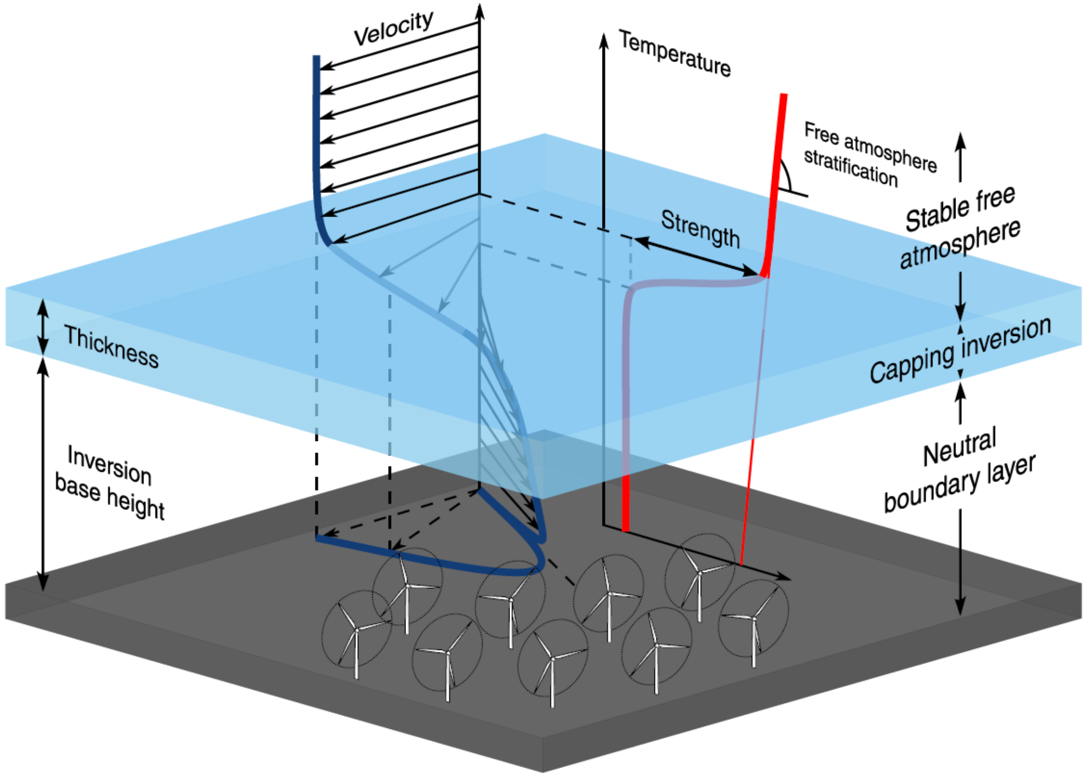
SAR image over the German Bight offshore wind-farm area
Finseras et al. (2023)

Caix, France - Photo by: Felix Vanderleenen

Outline

1. Set-up of LES database on wind-farm gravity waves and blockage
2. Effects of blockage and gravity waves on wind-farm efficiency
3. Development and validation of a fast meso–micro model for WF blockage
4. Conclusions

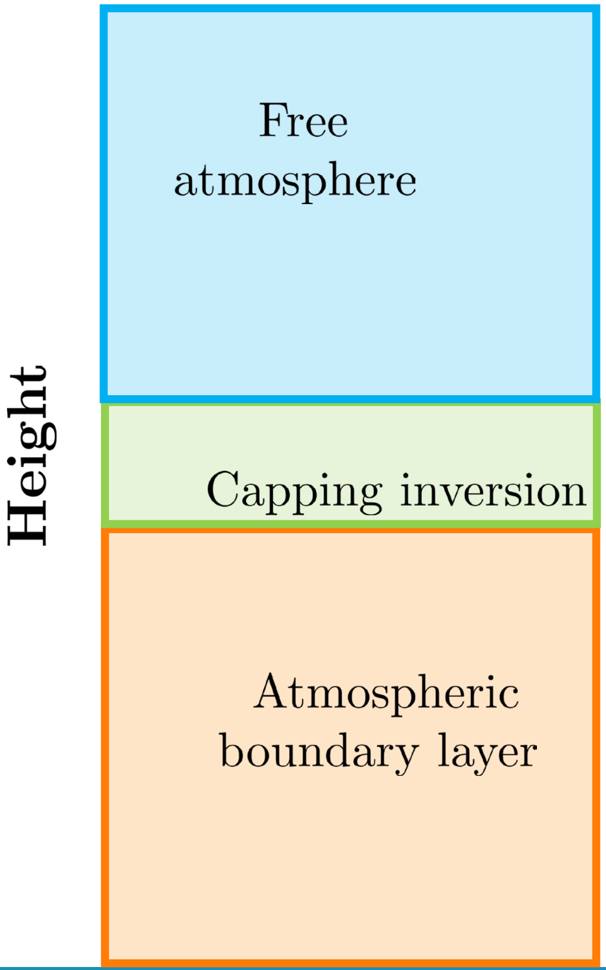
Conventionally neutral BL
(typical offshore conditions)



Allaerts, *PhD Thesis* (2016)

EXAMPLE CASE

H500-$\Delta\theta$5-Γ4



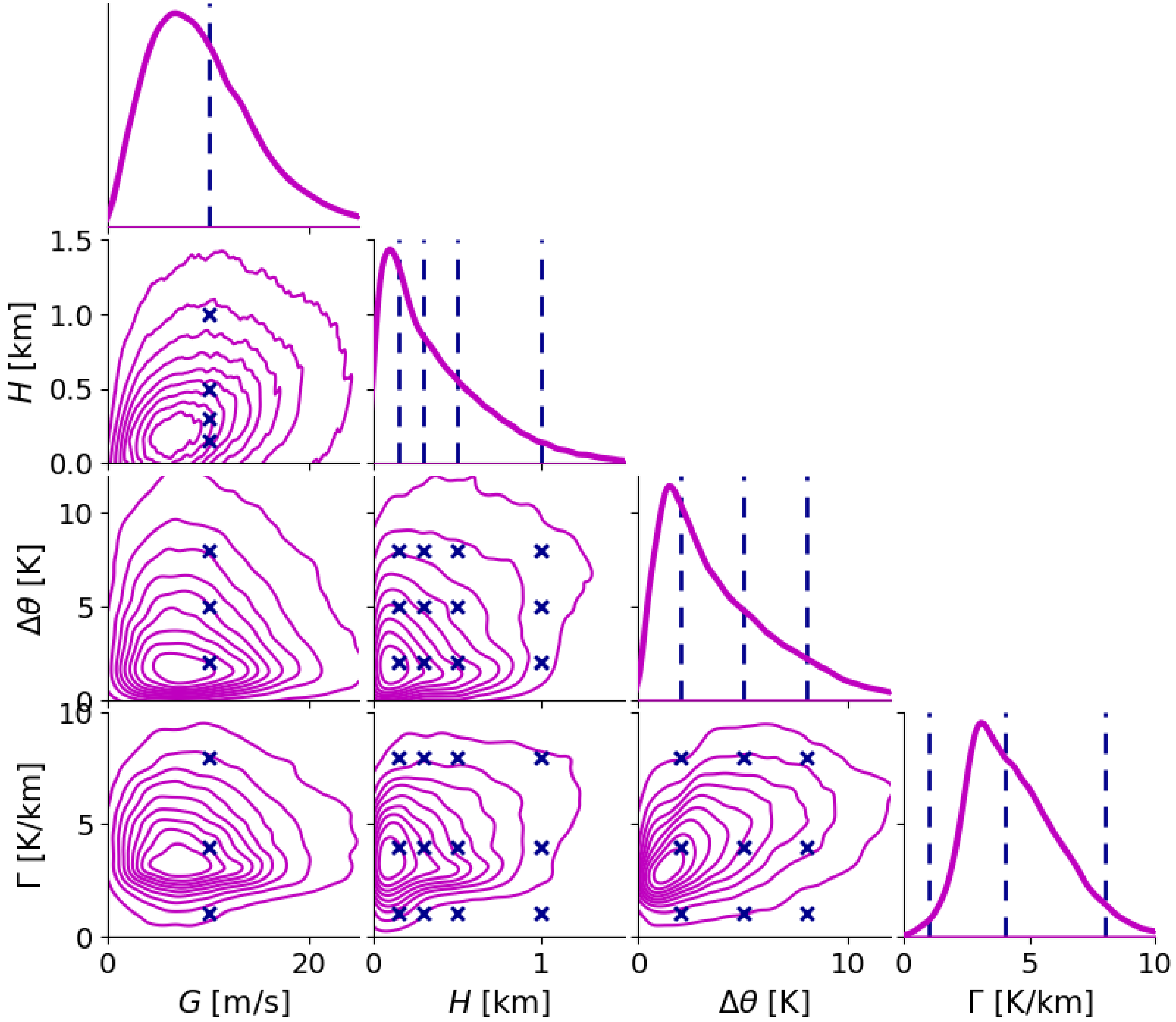
$$\frac{d\theta}{dz} = 4\ \mathrm{K/km}$$

$$\Delta\theta = 5\ \mathrm{K}$$

H=500 m

ERA5 data from 1988 to 2018

Point in Belgian North Sea, derived parameters using Rampanalli & Zardi fitting



G: 10 m/s

H: 150, 300, 500, 1000 m

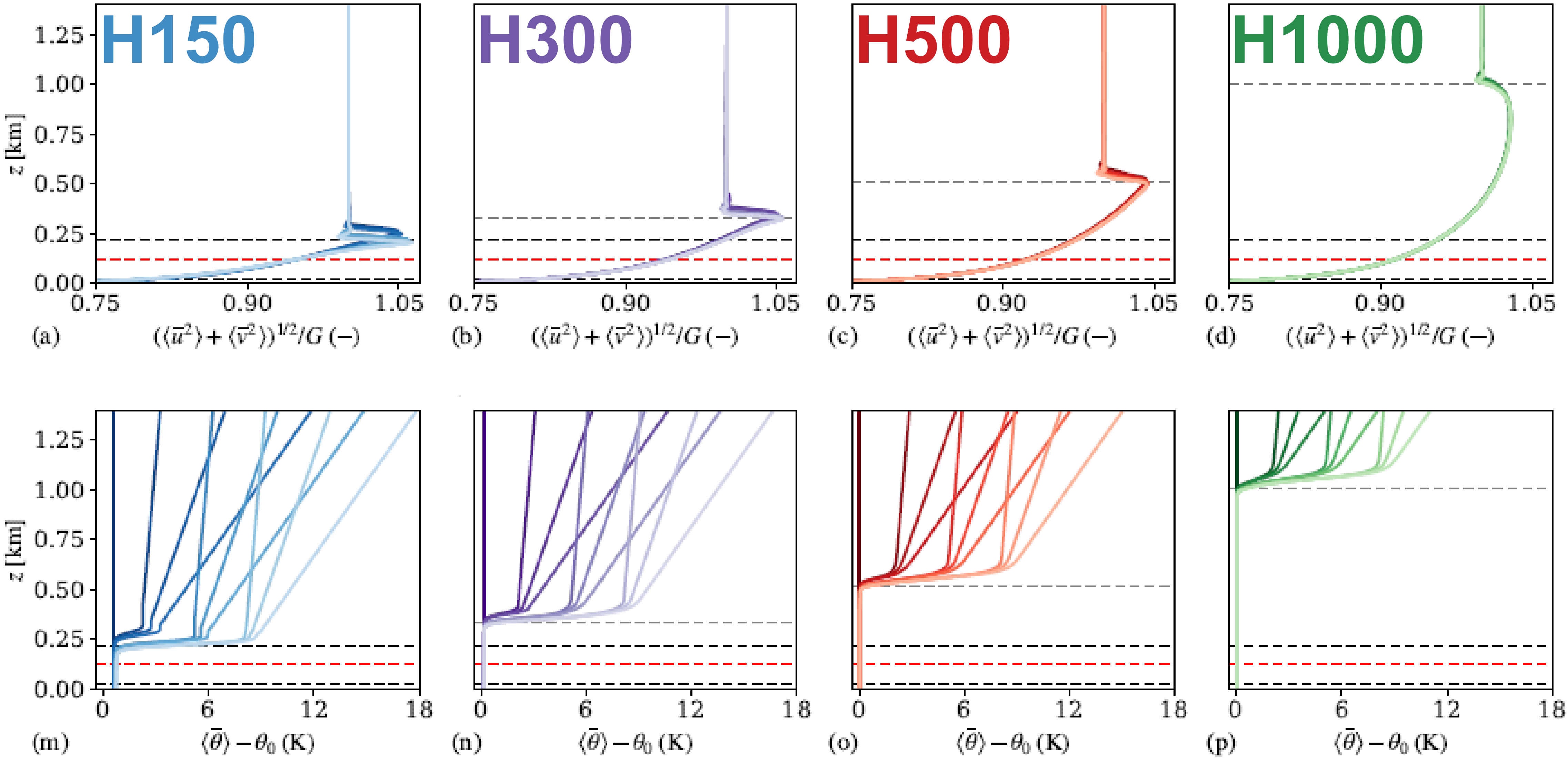
$\Delta\theta$: 2, 5, 8 K

Γ: 1, 4, 8 K/km

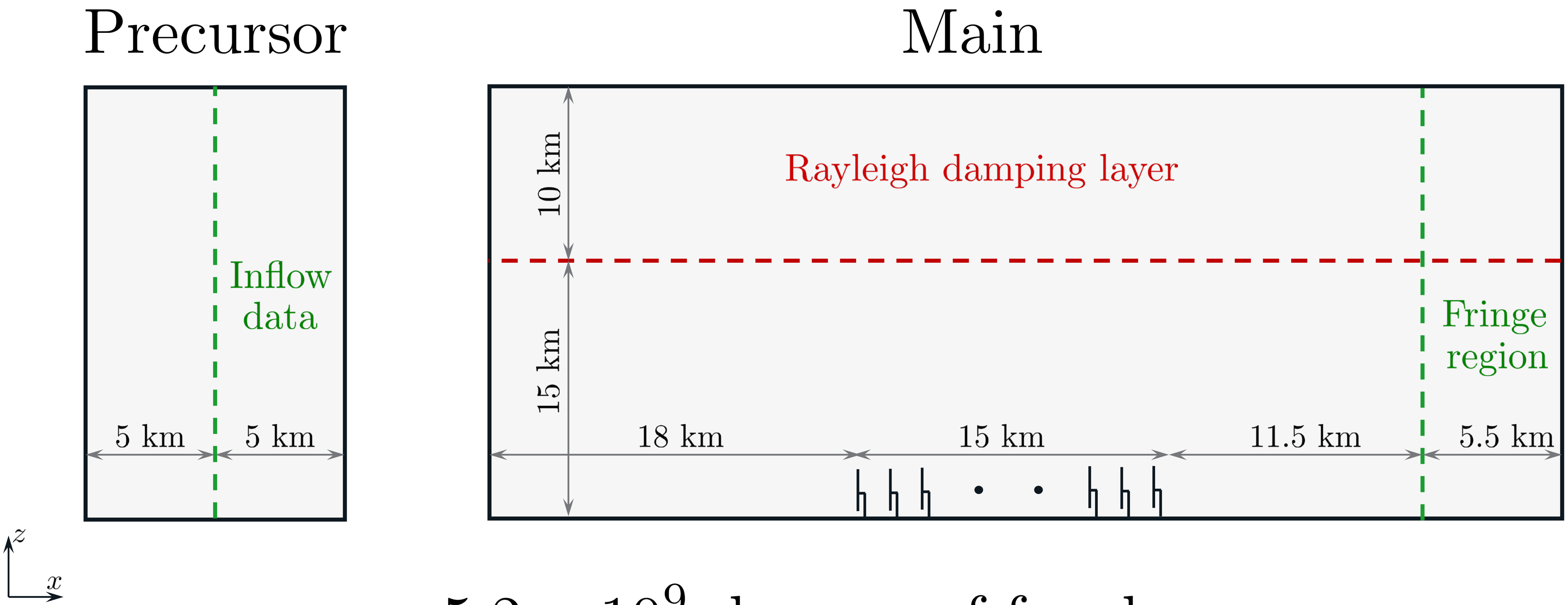
36 inflow cases

Rampanelli and Zardi, *JAM* (2004)

Wind-farm LES database: 40 cases – inflow



SP-Wind: pseudo-spectral LES solver



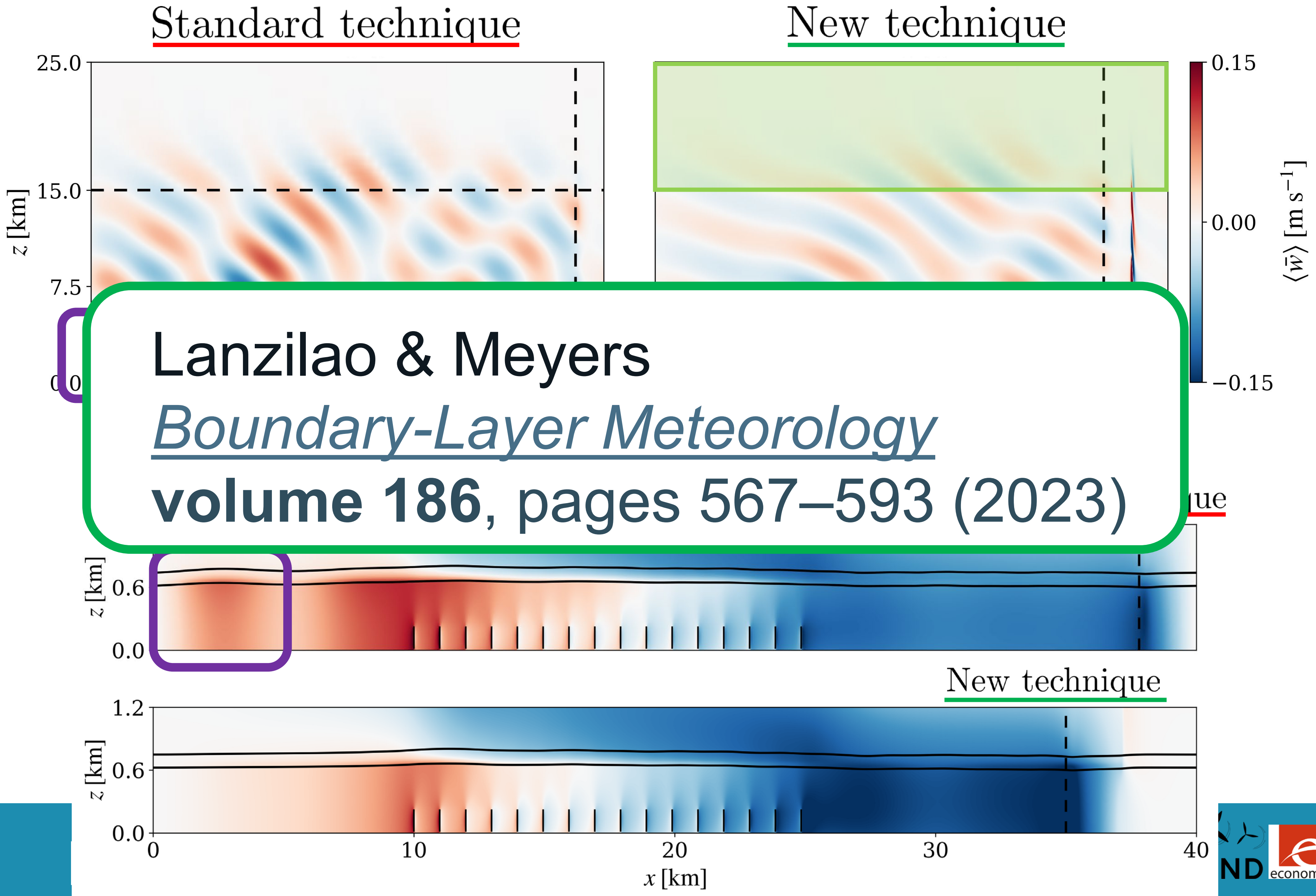
5.2×10^9 degrees of freedom

Lanzilao and Meyers, *BLM* (2023)

Wave-free fringe-region technique

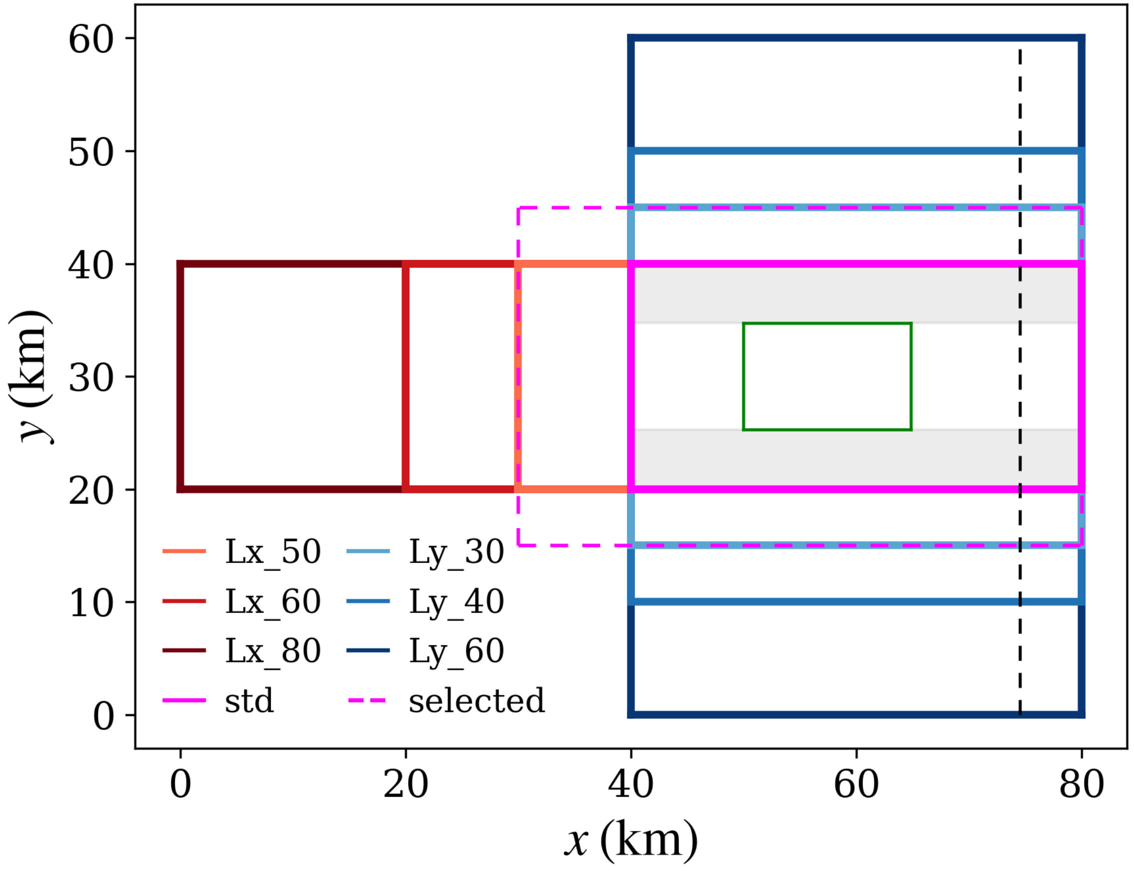
Vertical velocity

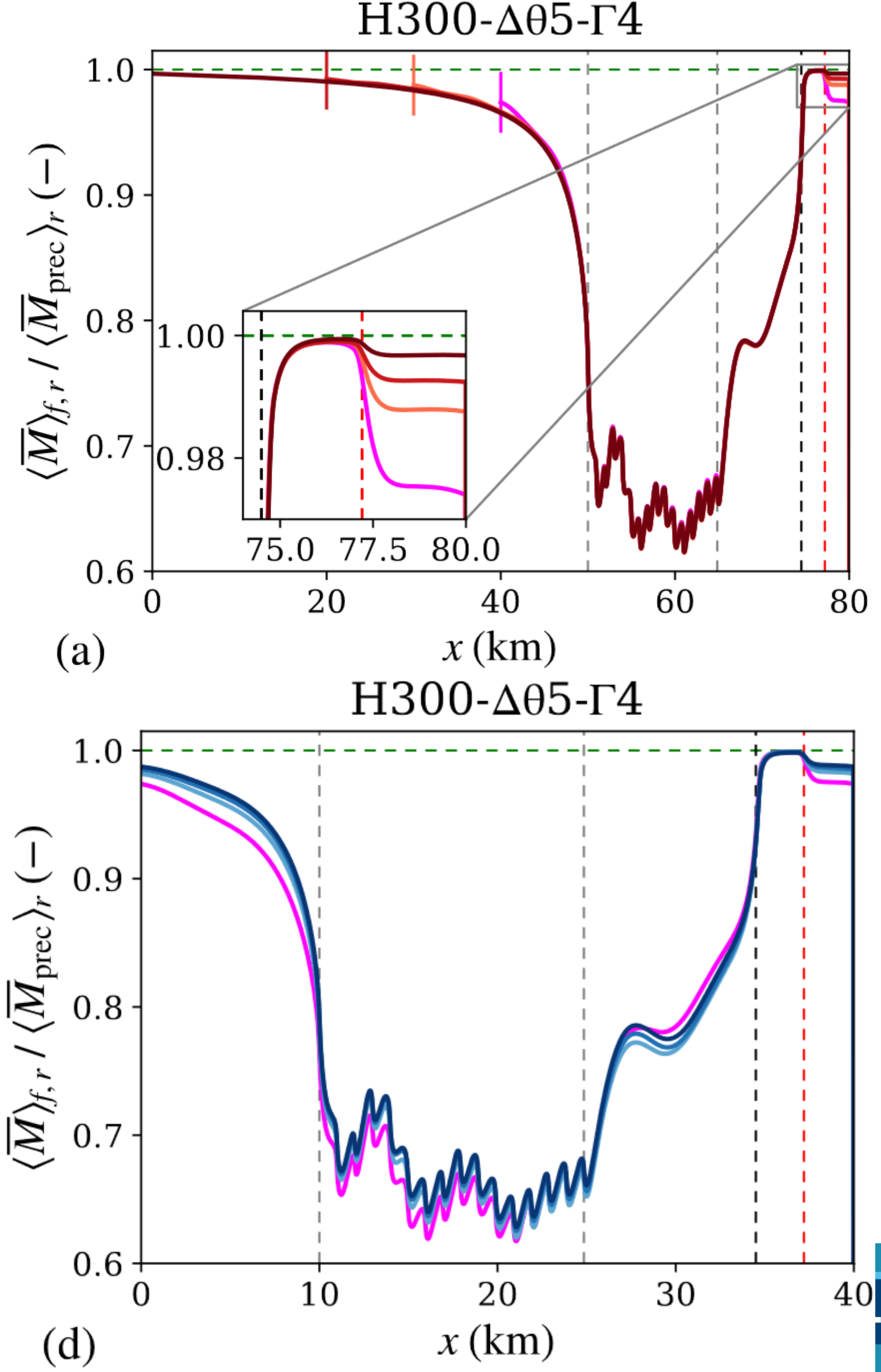
Pressure



Lanzilao & Meyers
Boundary-Layer Meteorology
volume 186, pages 567–593 (2023)

Domain sensitivity





For details: see Lanzilao & Meyers, submitted to JFM
Preprint: https://arxiv.org/pdf/2306.08633.pdf

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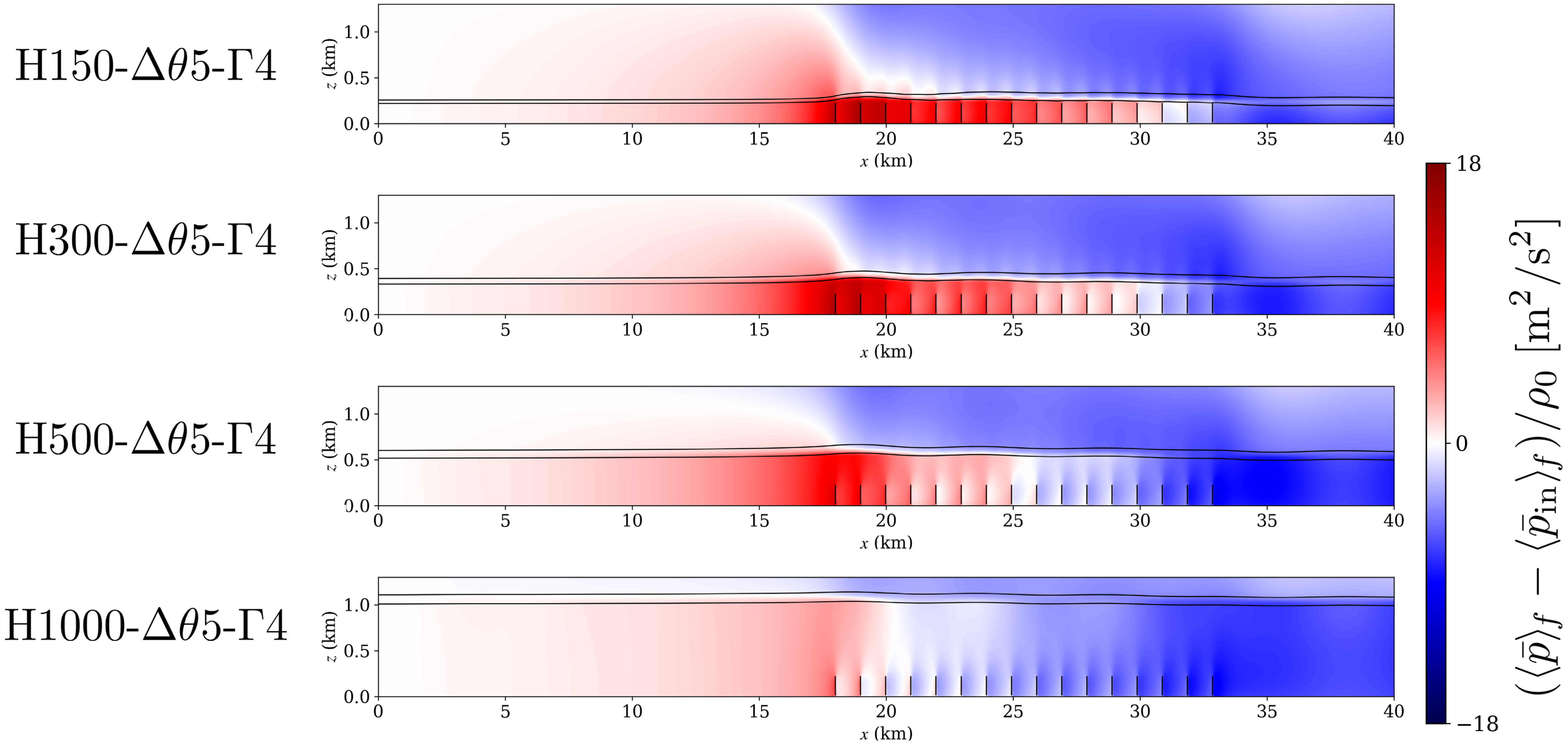
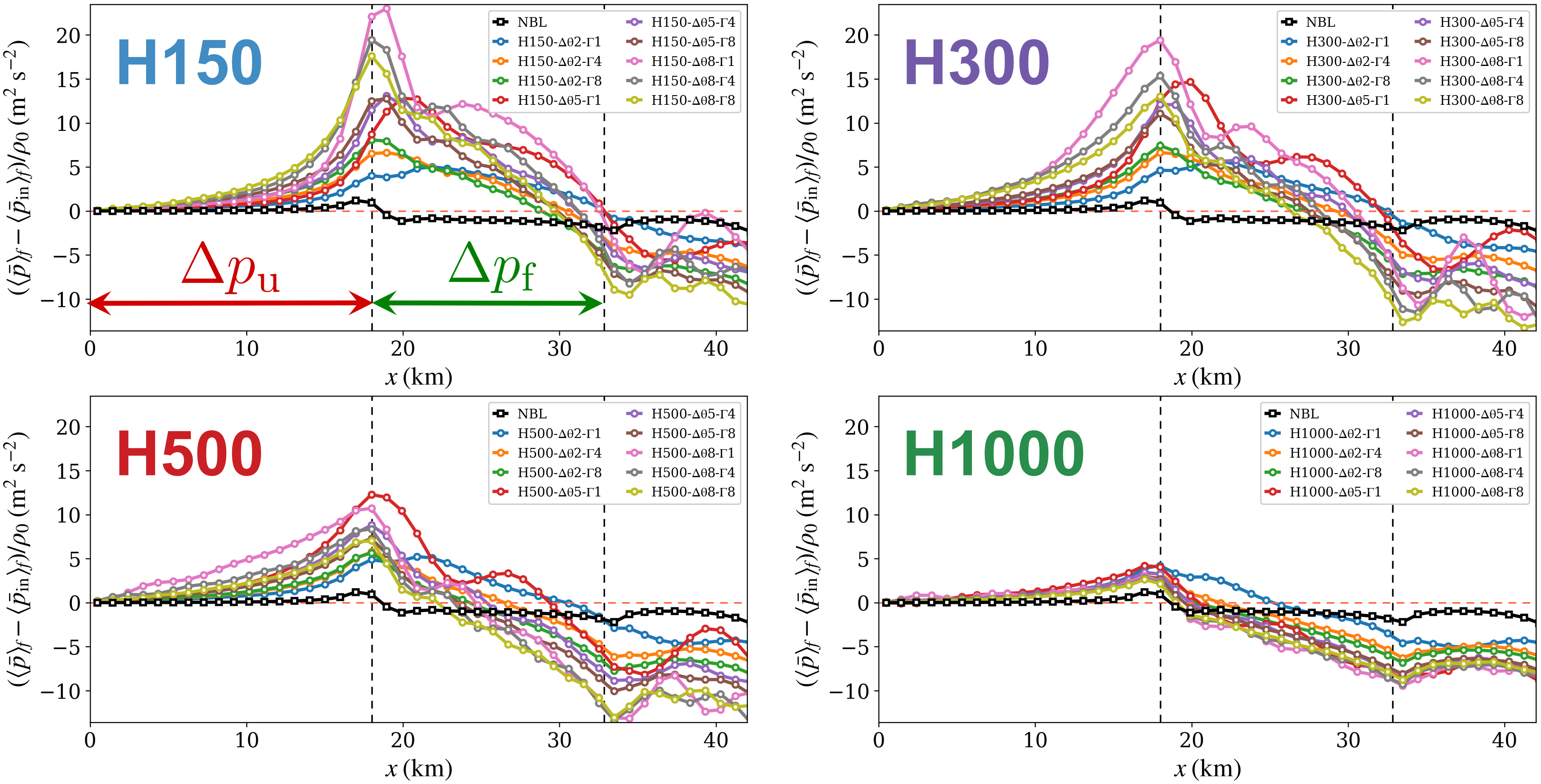

H150-Δθ5-Γ4
H300-Δθ5-Γ4
H500-Δθ5-Γ4
H1000-Δθ5-Γ4
z (km)
0.0
0.5
1.0
x (km)
0
5
10
15
20
25
30
35
40
18
0
−18
$(\langle\bar{p}\rangle_f - \langle\bar{p}_{\mathrm{in}}\rangle_f)/\rho_0$ [$\mathrm{m}^2/\mathrm{s}^2$]

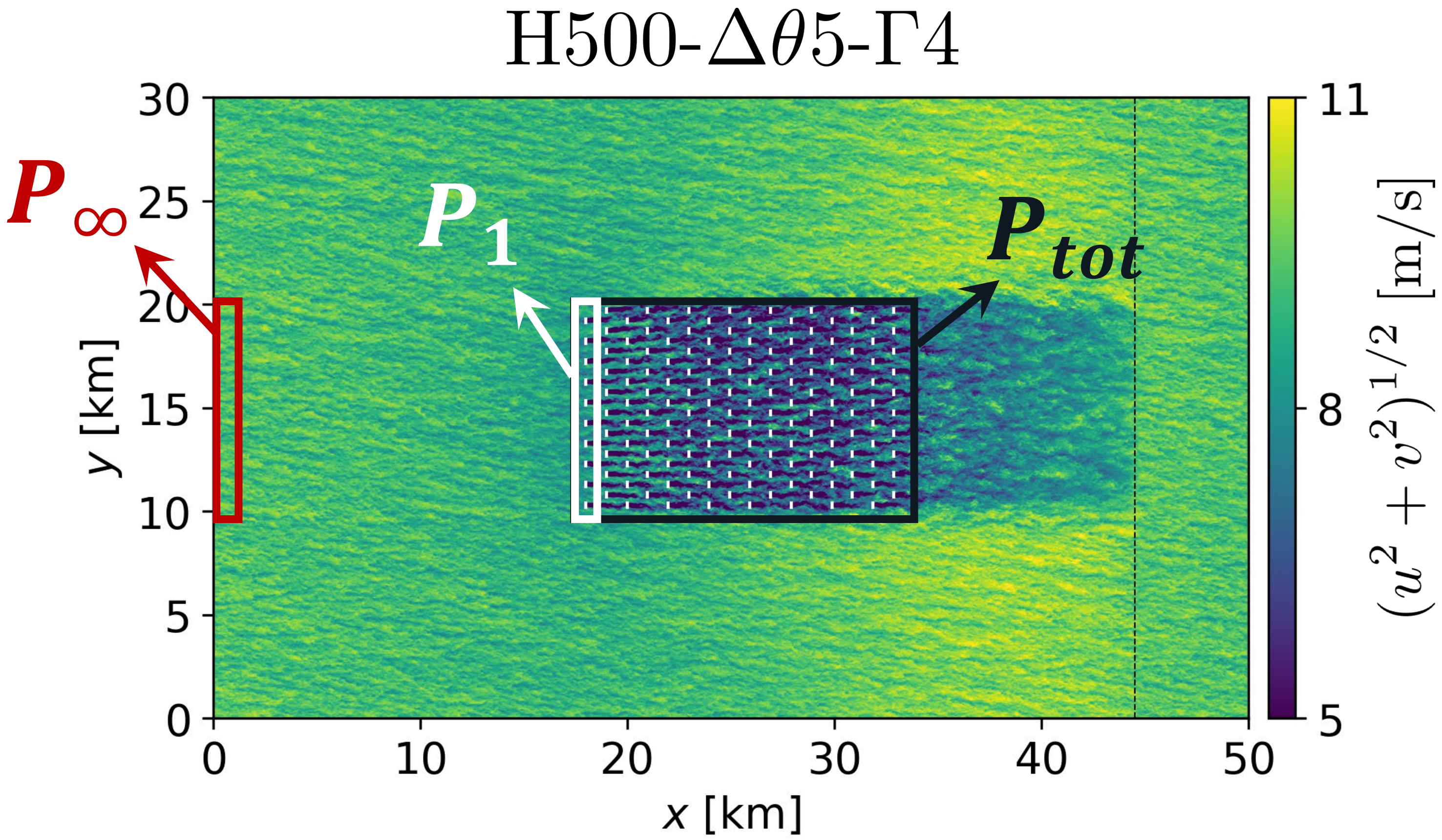

H150
H300
H500
H1000
Δp_u
Δp_f
$(\langle\bar{p}\rangle_f - \langle\bar{p}_\mathrm{in}\rangle_f)/\rho_0$ (m^2 s^{-2})
x (km)
NBL
H150-Δθ2-Γ1
H150-Δθ2-Γ4
H150-Δθ2-Γ8
H150-Δθ5-Γ1
H150-Δθ5-Γ4
H150-Δθ5-Γ8
H150-Δθ8-Γ1
H150-Δθ8-Γ4
H150-Δθ8-Γ8
H300-Δθ2-Γ1
H300-Δθ2-Γ4
H300-Δθ2-Γ8
H300-Δθ5-Γ1
H300-Δθ5-Γ4
H300-Δθ5-Γ8
H300-Δθ8-Γ1
H300-Δθ8-Γ4
H300-Δθ8-Γ8
H500-Δθ2-Γ1
H500-Δθ2-Γ4
H500-Δθ2-Γ8
H500-Δθ5-Γ1
H500-Δθ5-Γ4
H500-Δθ5-Γ8
H500-Δθ8-Γ1
H500-Δθ8-Γ4
H500-Δθ8-Γ8
H1000-Δθ2-Γ1
H1000-Δθ2-Γ4
H1000-Δθ2-Γ8
H1000-Δθ5-Γ1
H1000-Δθ5-Γ4
H1000-Δθ5-Γ8
H1000-Δθ8-Γ1
H1000-Δθ8-Γ4
H1000-Δθ8-Γ8

Farm efficiency

$$\eta_{\mathrm{farm}} = \eta_{\mathrm{w}} \eta_{\mathrm{nl}}$$

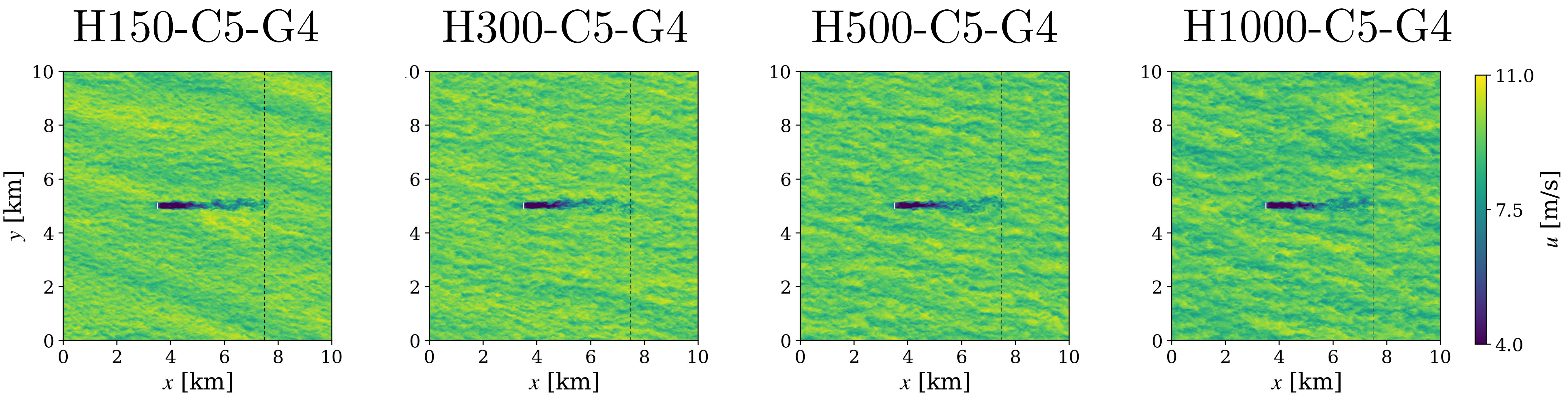
$$\eta_{\mathrm{w}} = \frac{P_{\mathrm{tot}}}{N_{\mathrm{t}} P_1}$$

$$\eta_{\mathrm{nl}} = \frac{P_1}{P_{\infty}}$$



Definitions from Allaerts & Meyers, BLM 2018

Single-turbine simulations

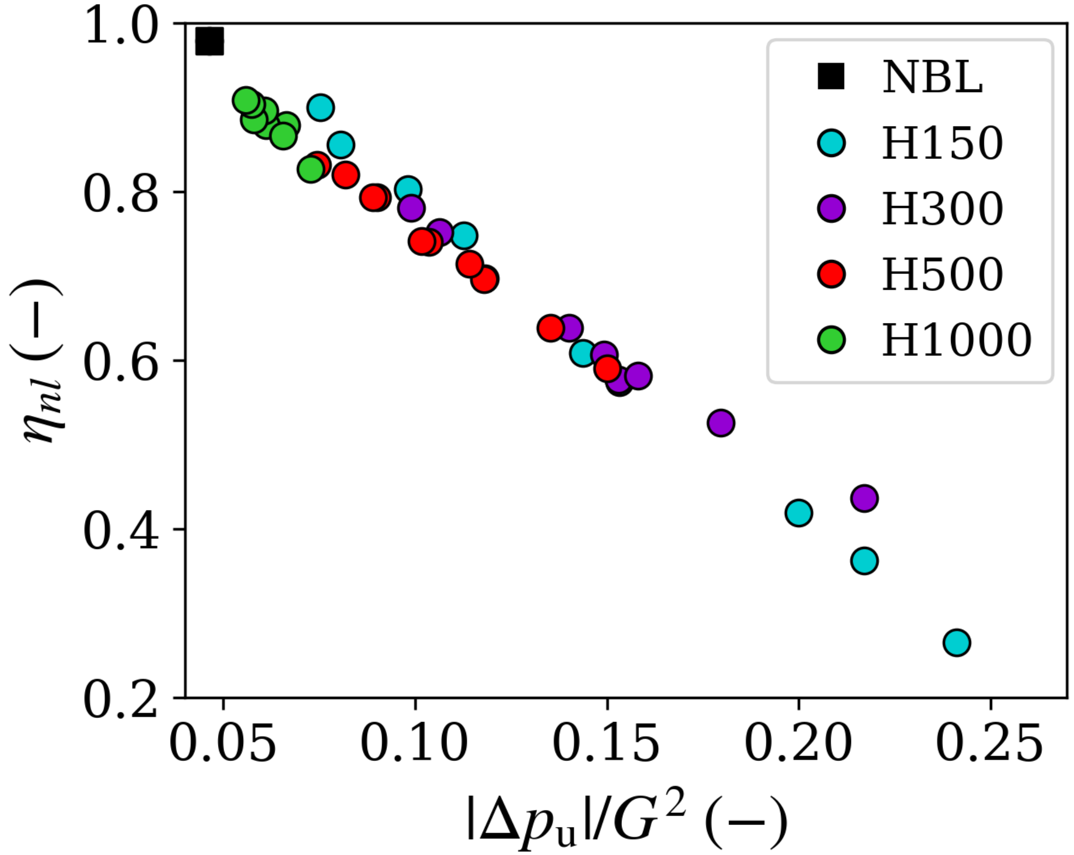


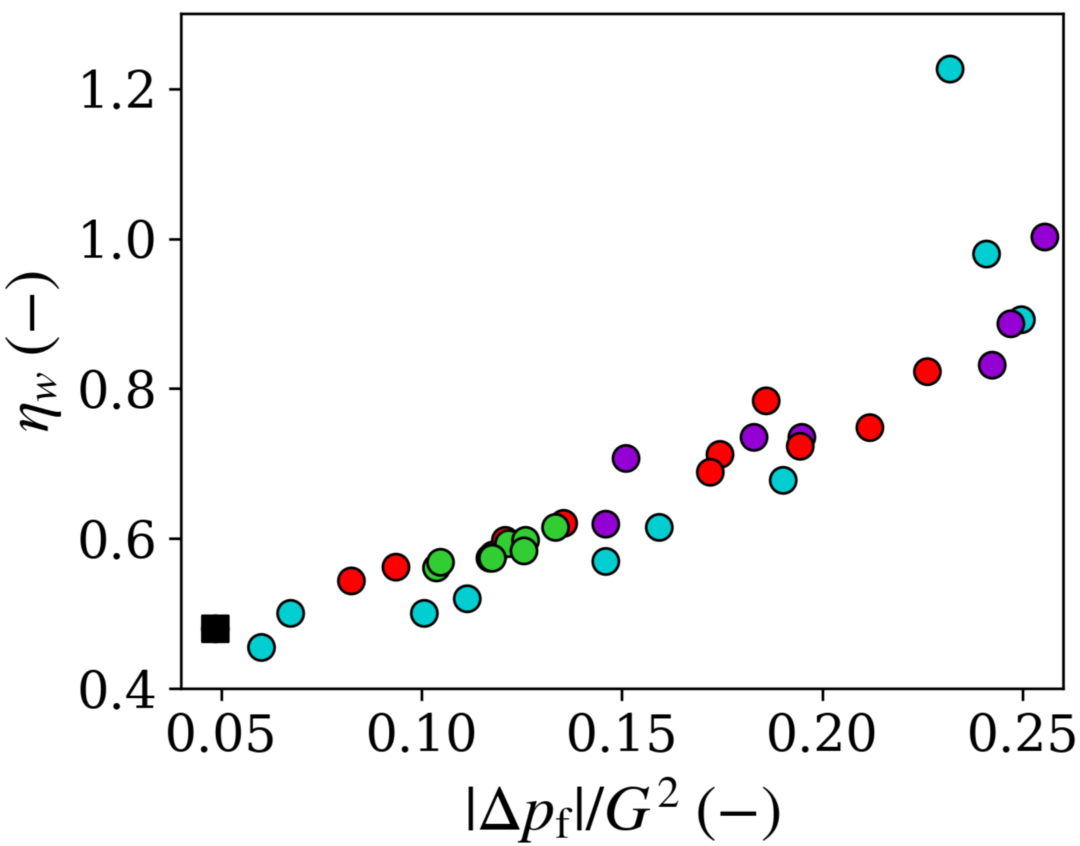
Evaluate P_∞

Non-local and wake efficiency

$$\eta_{\mathrm{nl}} = \frac{P_1}{P_\infty}$$

$$\eta_{\mathrm{w}} = \frac{P_{\mathrm{tot}}}{N_{\mathrm{t}} P_1}$$





For details: see Lanzilao & Meyers, submitted to JFM
Preprint: https://arxiv.org/pdf/2306.08633.pdf

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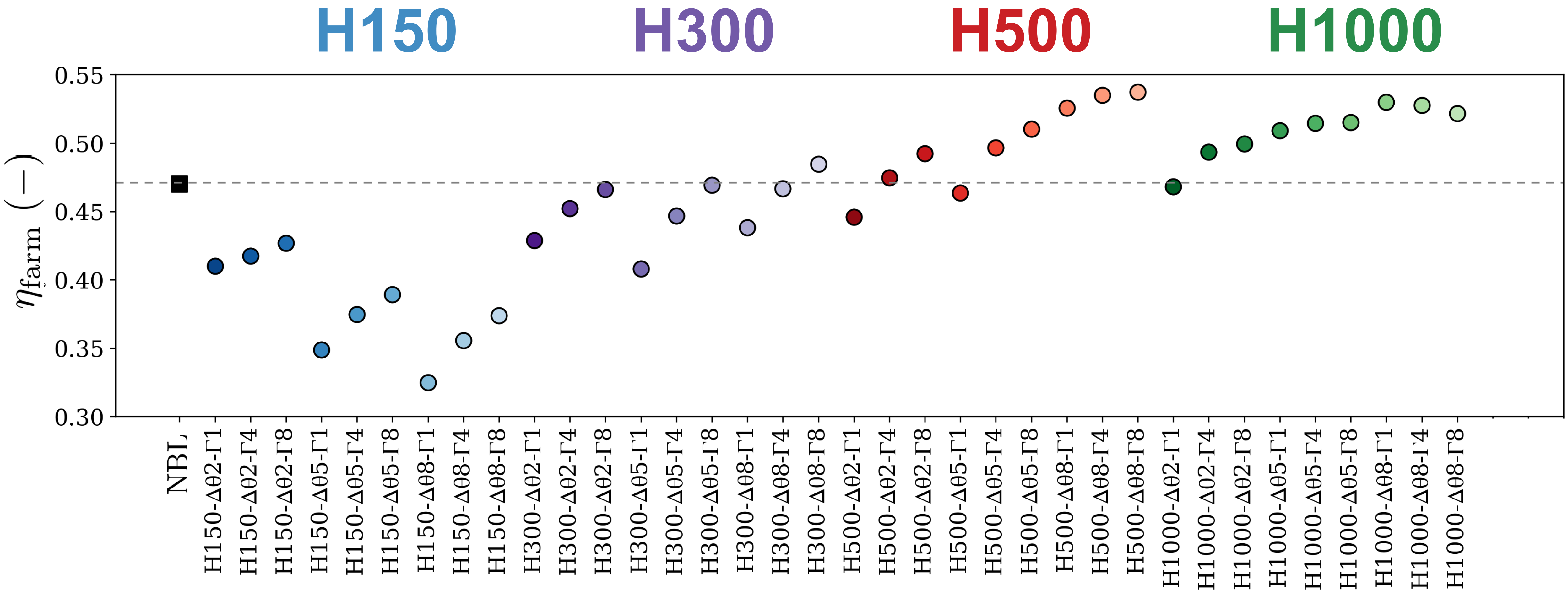
Farm efficiency



$$\eta_{\mathrm{farm}} = \eta_{\mathrm{w}}\eta_{\mathrm{nl}}$$

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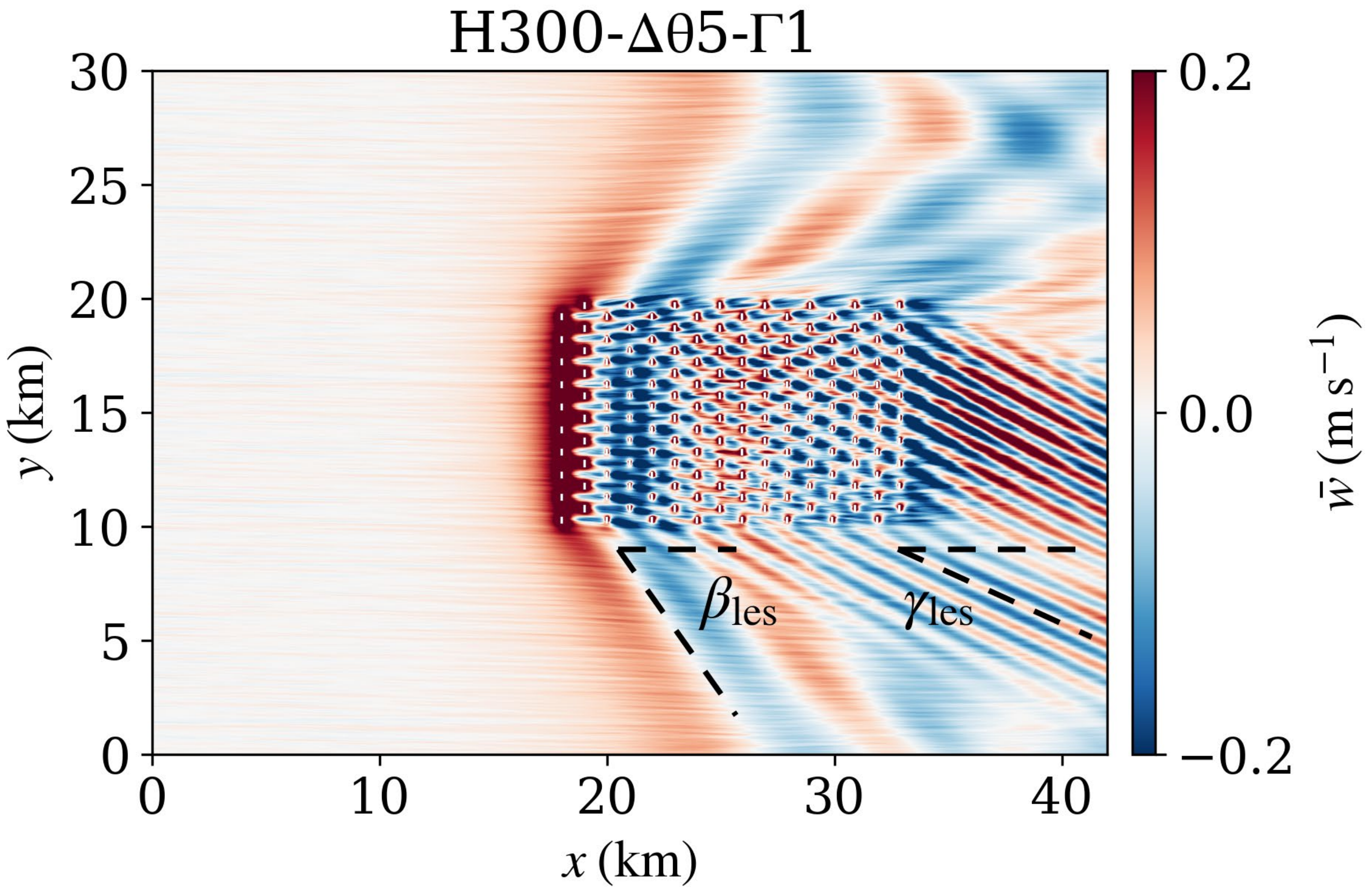
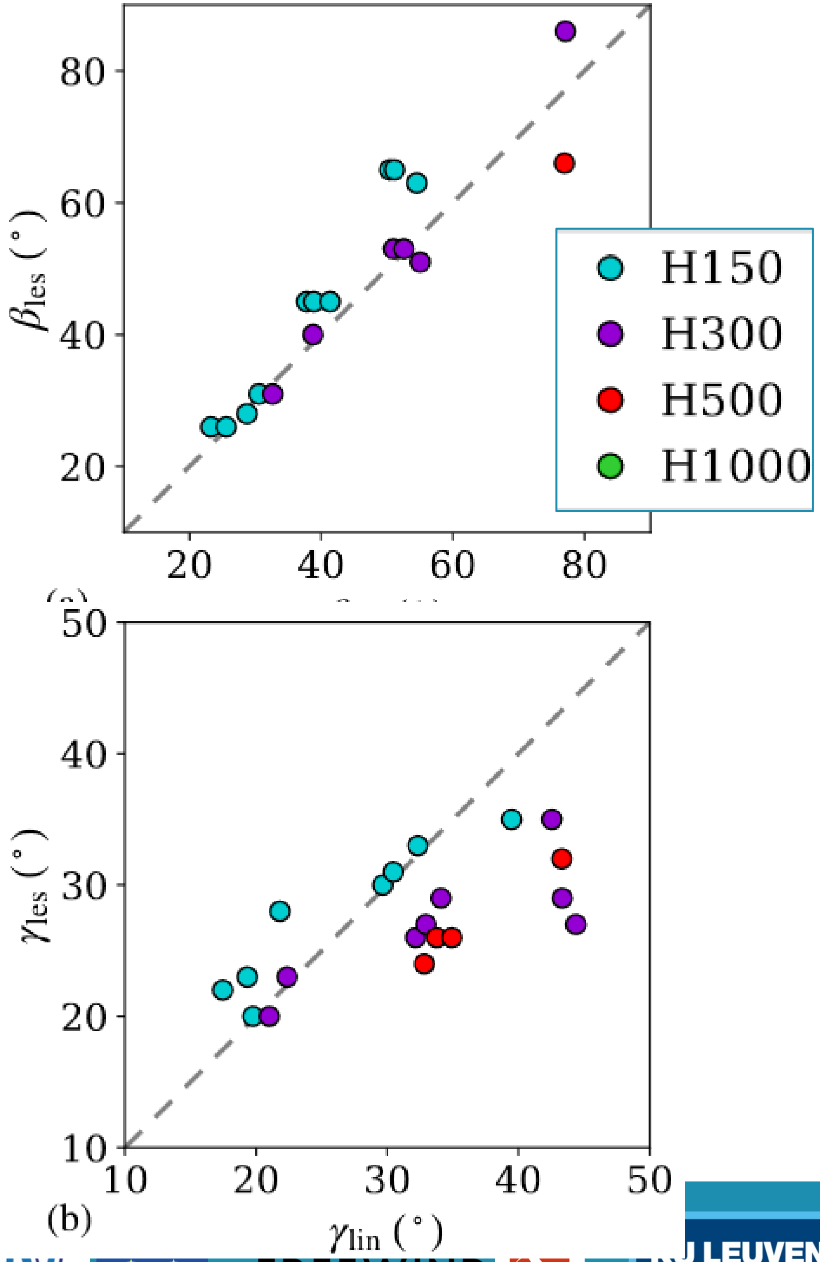
Comparison with linear theory





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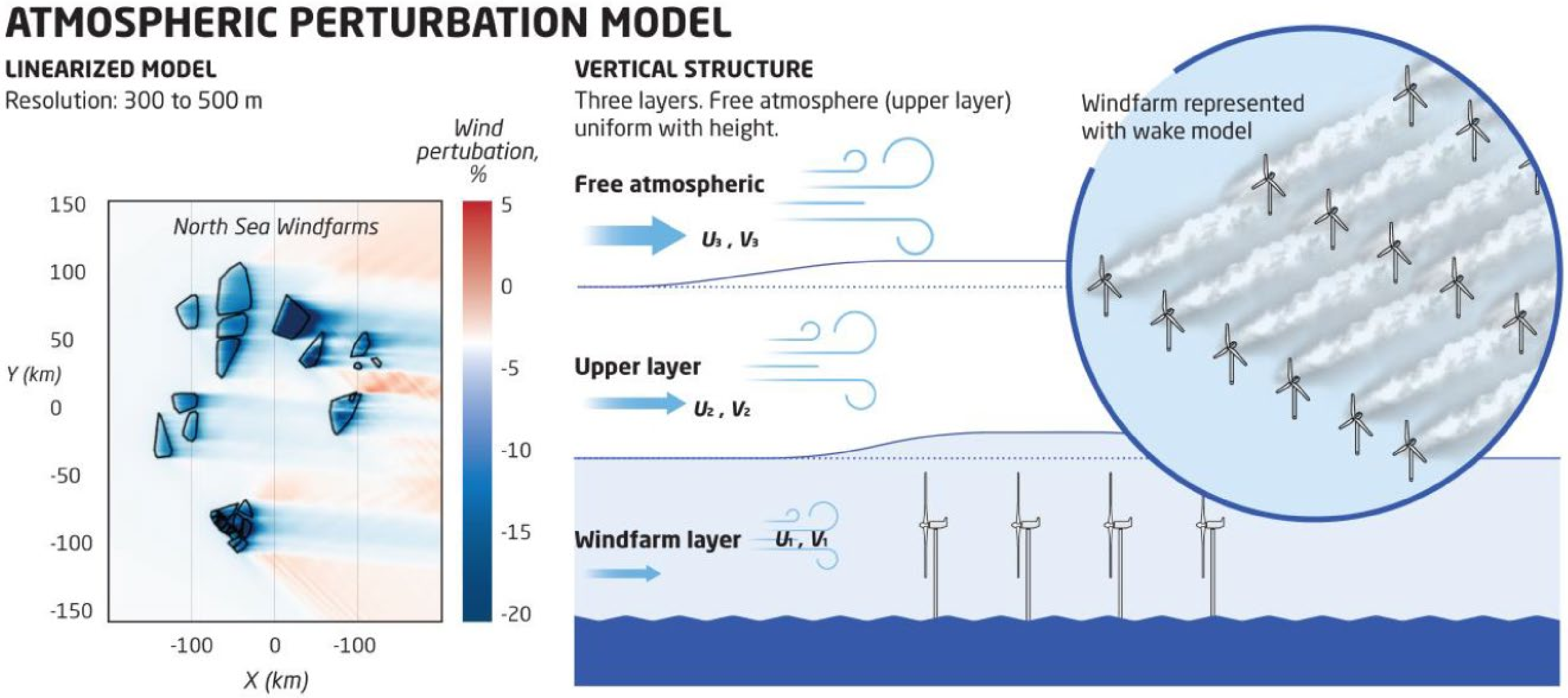
Wayve [Wind-fArm GravitY-waVe and BlockagE]

V1 now open source: https://gitlab.kuleuven.be/TFSO-software/wayve



Allaerts & Meyers, J. Fluid Mech 2019

Devesse et al. Wind Energy Science 2022

Model equations: meso-scale level

I. Start from steady RANS equations + horizontal filter

$$\overline{\phi}(x,y) = \int_0^{L_x}\int_0^{L_y} \underline{G(x-x',y-y')}\,\phi(x',y')\,\mathrm{d}x'\mathrm{d}y', \qquad \phi = \overline{\phi} + \phi''$$

Gauss kernel with filter width O(1 km)

II. Define pliant surfaces $z_1(x,y)$ above wind farm and $z_2(x,y)$ above boundary layer (using filtered properties)

$$\overline{w}(x,y,z_1) = \overline{\boldsymbol{u}}_h(x,y,z_1)\cdot\boldsymbol{\nabla}_h z_1,$$
$$\overline{w}(x,y,z_2) = \overline{\boldsymbol{u}}_h(x,y,z_2)\cdot\boldsymbol{\nabla}_h z_2,$$

II. Height-integrate between the pliant surfaces

$$\overline{\phi}_1 = \frac{1}{z_1}\int_0^{z_1}\overline{\phi}(z)\mathrm{d}z,$$
$$\overline{\phi}_2 = \frac{1}{z_2-z_1}\int_{z_1}^{z_2}\overline{\phi}(z)\mathrm{d}z$$

For details: Devesse, Lanzilao & Meyers, preprint to appear soon

Model equations: meso-scale level

Model equations in Layer 1 [Layer 2 = equivalent]

Continuity: $\boldsymbol{\nabla}_h \cdot \left(h_1 \overline{\boldsymbol{u}}_{h,1}\right) = 0,$

Momentum:

$$\overline{\boldsymbol{u}}_{h,1} \cdot \boldsymbol{\nabla}_h \overline{\boldsymbol{u}}_{h,1} = -\frac{1}{\rho_0} \boldsymbol{\nabla}_h \overline{p}_1 + \underbrace{f_c \boldsymbol{J} \cdot \left(\boldsymbol{U}_{g,h} - \overline{\boldsymbol{u}}_{h,1}\right)}_{\text{Coriolis force}} + \underbrace{\boldsymbol{\nabla}_h \cdot \overline{\boldsymbol{\tau}}_{hh,1}}_{\text{Horizontal Re stresses}} + \underbrace{\frac{\overline{\boldsymbol{\tau}}_{h3,1} - \overline{\boldsymbol{\tau}}_{h3,0}}{h_1}}_{\text{Interlayer \& wall stresses}}$$

$$+ \underbrace{\frac{\overline{\boldsymbol{f}}_{wf}}{h_1}}_{\text{Wind farm forces}} - \underbrace{\left(\boldsymbol{\nabla} \cdot \left(\boldsymbol{\tau}_{d,h}\right)\right)_1}_{\text{Dispersive stresses}} - \underbrace{\boldsymbol{f}_{ts,1}}_{\text{Taylor dispersion}} + \frac{\mathcal{R}_1}{h_1}$$

Dispersive stresses

$$\boldsymbol{\tau}_{d,h} = \overline{\boldsymbol{u}\boldsymbol{u}_h} - \overline{\boldsymbol{u}}\,\overline{\boldsymbol{u}}_h$$

For details: Devesse, Lanzilao & Meyers, preprint to appear soon

Model equations: meso-scale level

Additional steps

1. Linearization around unperturbed background state
   - allows for fast linear solve with preconditioned GMRES

2. Closure of different terms (eddy-viscosity; drag coefficients for interfaces)

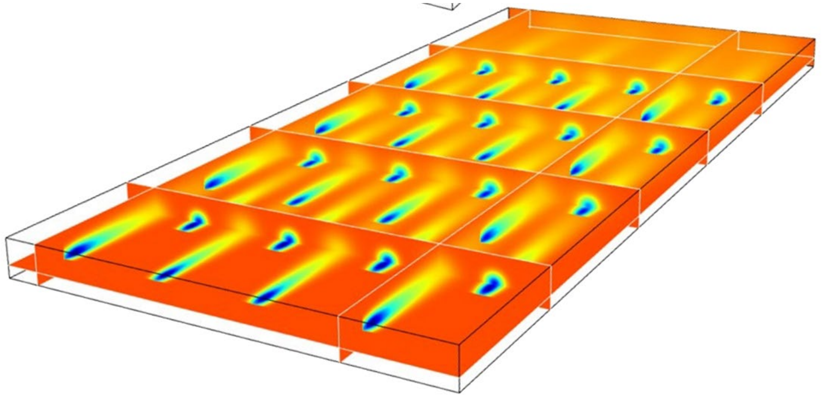
3. Pressure BC at top of BL via analytical solution to Helmholtz equation

4. Coupling to micro-scale levels (next)

For details: Devesse, Lanzilao & Meyers, preprint to appear soon

Micro-scale model

Wake model with varying background field



Background velocity (in absence of turbines)

$$\boldsymbol{u}_w(\boldsymbol{x}) = \prod_{k=1}^{N_t} \boldsymbol{A}_k(\boldsymbol{x}) \cdot \boldsymbol{U}_b(\boldsymbol{x}),$$

Wake model velocity

Tensor containing Individual wake parametrization

Details wake model – see: Lanzilao & Meyers, Wind Energy, 2022

Meso–micro coupling based on velocity matching between both levels → U_b

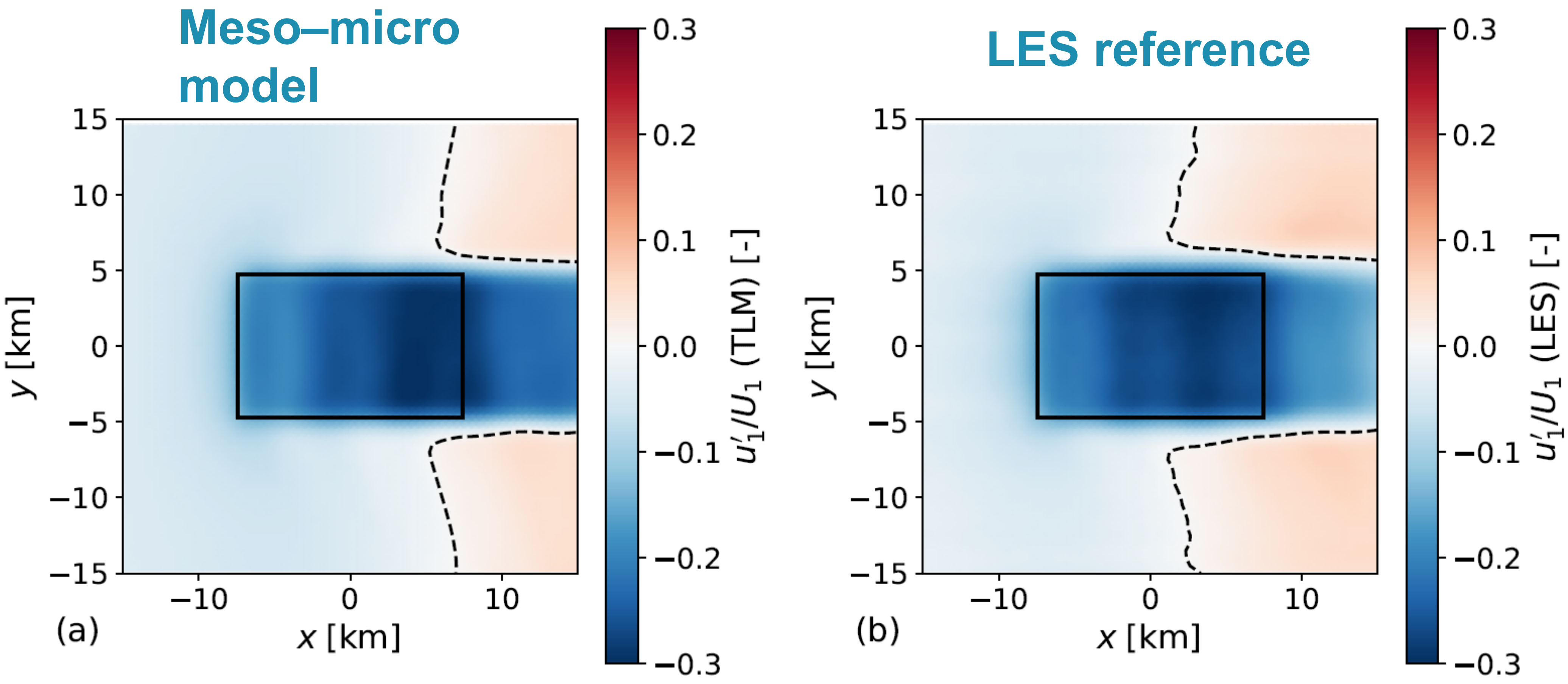
$$\frac{1}{z_1}\int_0^{z_1}\int_0^{L_x}\int_0^{L_y} G(x-x', y-y')u_w(x', y', z)\mathrm{d}x'\mathrm{d}y'\mathrm{d}z = u_1(x,y)$$

Micro — Meso

For details: Devesse, Lanzilao & Meyers, preprint to appear soon

Comparison between model and LES (meso-scale field)

H500-$\Delta\theta$5-Γ4

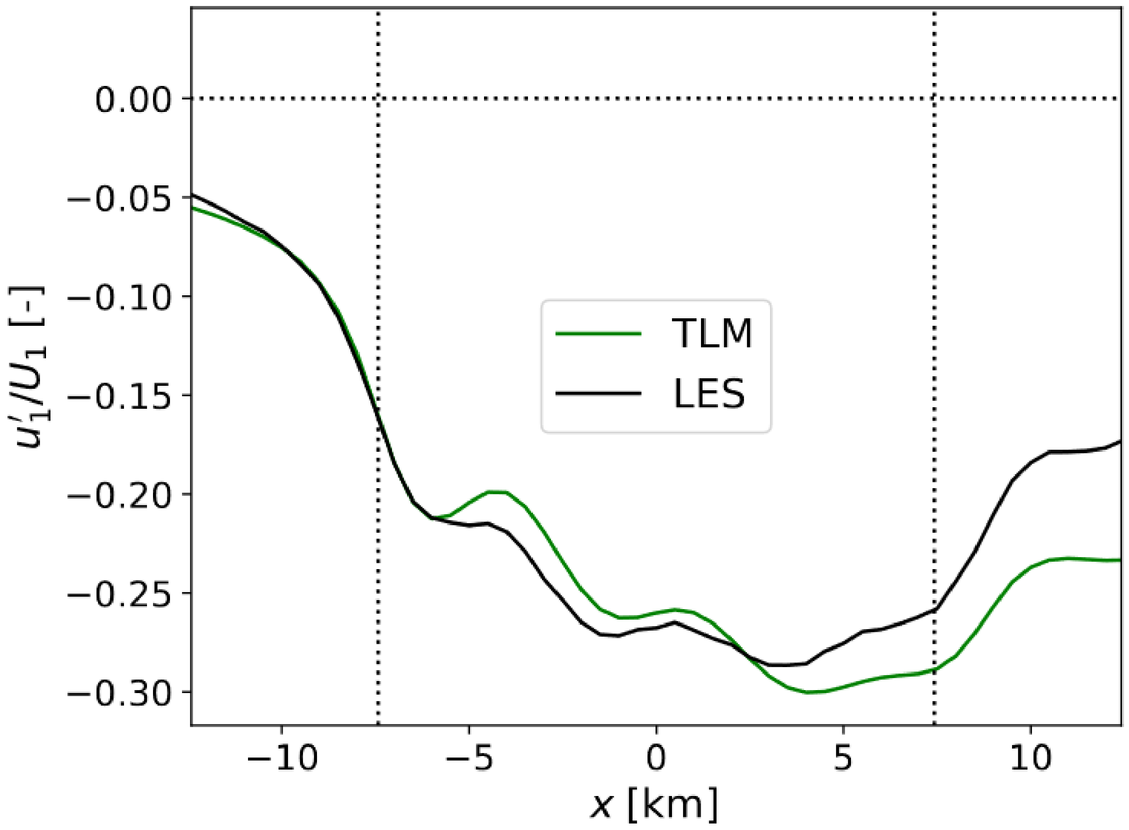


For details: Devesse, Lanzilao & Meyers, preprint to appear soon

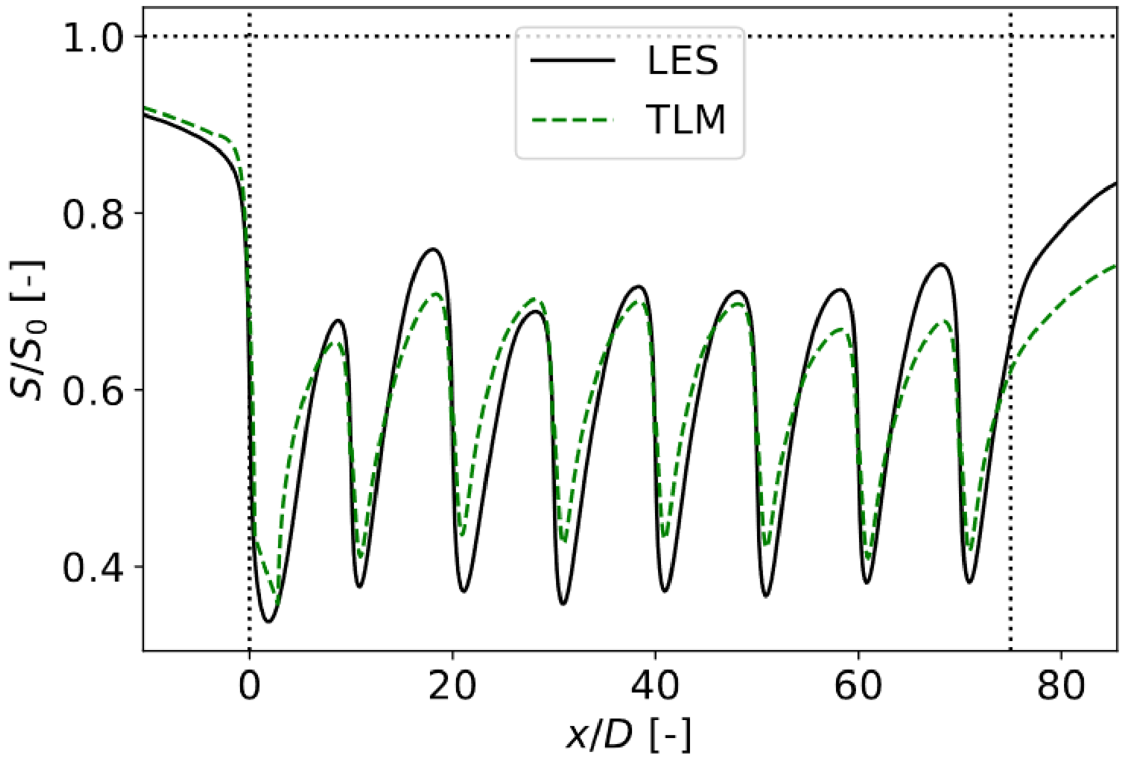
$H500\text{-}\Delta\theta 5\text{-}\Gamma 4$

Comparison between model and LES

Meso scale velocity

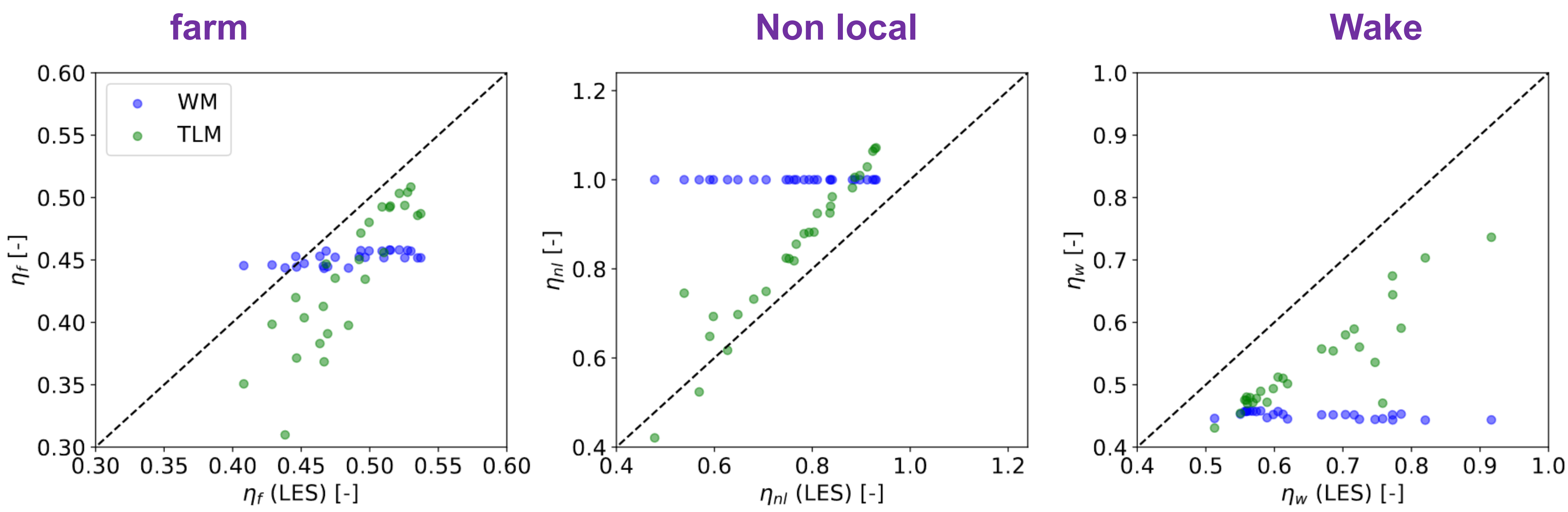


Meso + micro velocity



For details: Devesse, Lanzilao & Meyers, preprint to appear soon

Comparison of Wayve and wake models versus LES



For details: Devesse, Lanzilao & Meyers, preprint to appear soon

Conclusions

1. LES database of wind-farm gravity waves under various atmospheric conditions
   Database will become available open source soon (approx. 20TB)

2. Gravity waves lead to unfavorable pressure gradient in front of the farm; favorable pressure gradient in the farm. Strong correlations with nonlocal and wake efficiency

3. WAYVE: fast engineering model for wind farm blockage

Thank you