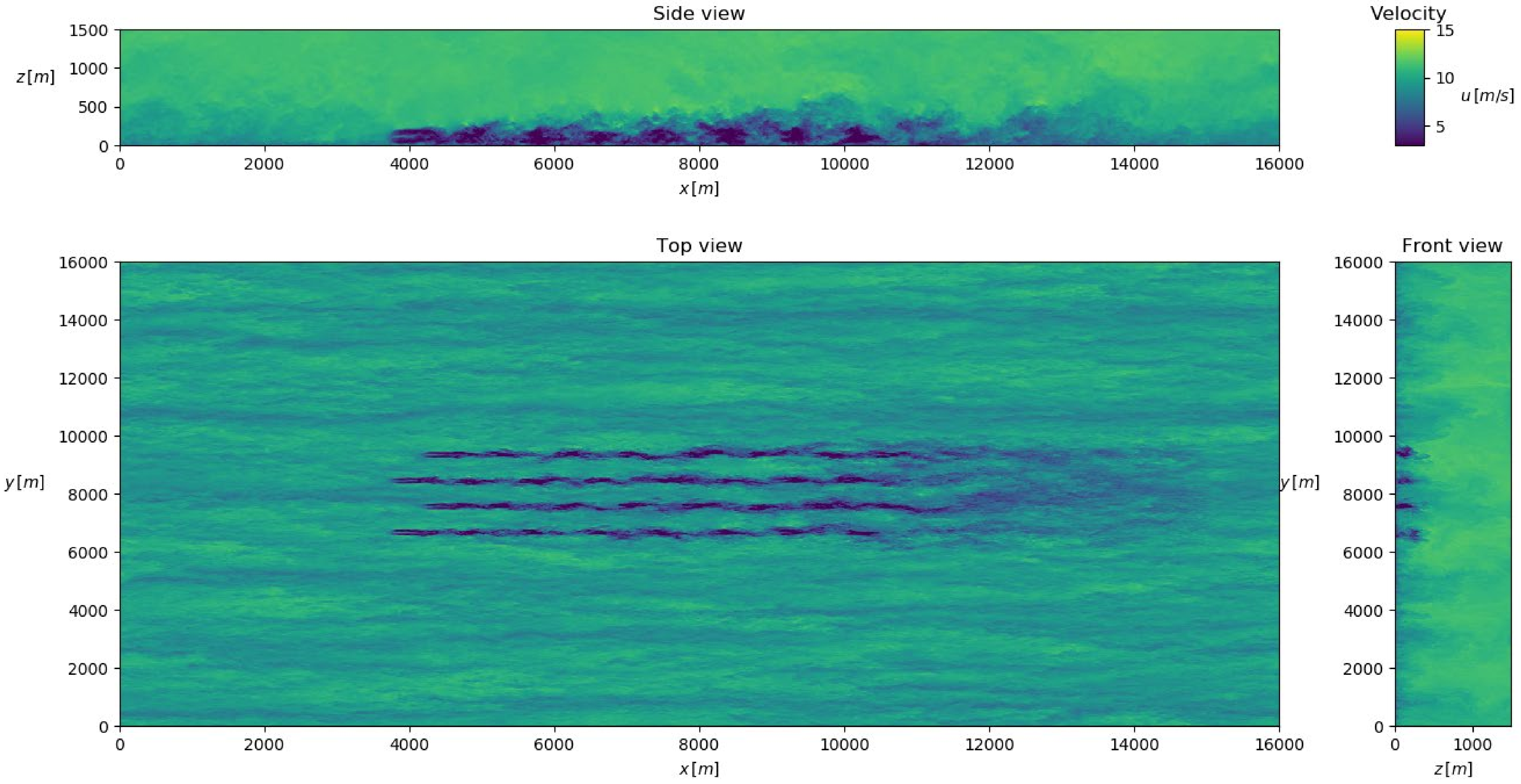
High-fidelity wind-farm simulations and data sets

PROGRESS IN THE TOTALCONTROL PROJECT

December 10, 2020, Webinar

Johan Meyers

Mechanical Engineering



Side view
Velocity
u [m/s]
z [m]
x [m]
Top view
Front view
y [m]
x [m]
z [m]

Acknowledgments

@ KU Leuven: Ishaan Sood, Wim Munters, Athanasios Vitsas, Johan Meyers

Simulations with SP-Wind

Datasets available on Zenodo

@ DTU: Søren Juhl Andersen, Niels Troldborg

Simulations with Ellipsys-3D

Datasets available on DTU server

Outline

TotalControl Reference Windfarm

Precursor simulations (PBL, CNBL)

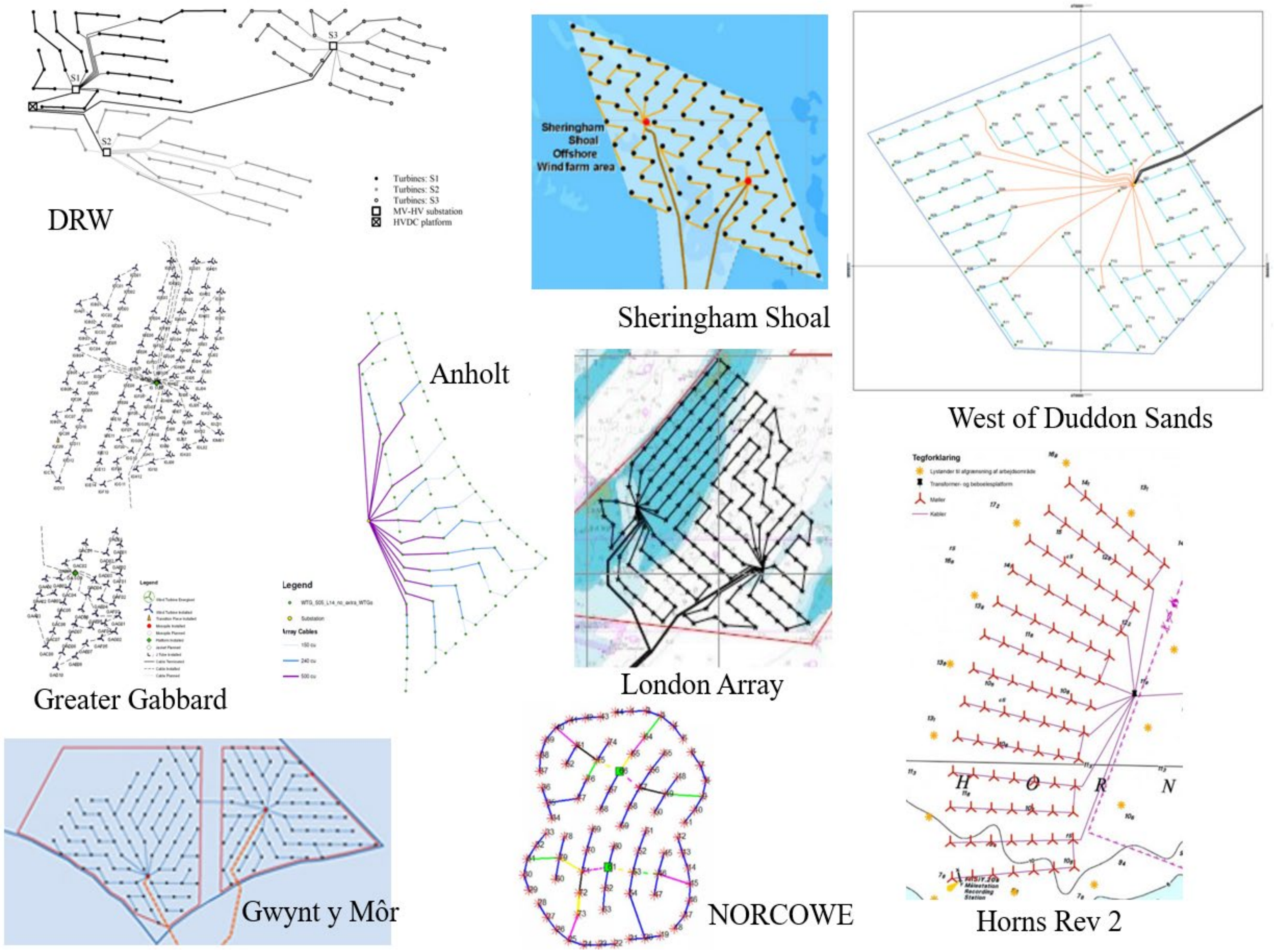
Wind-farm simulations

Data accessibility

Wind-farm layouts

Wind power plant layouts, obtained from public websites via Google Pictures. The DRW (NOWITECH) and NORCOWE plants are fictitious designs, and the others are commercial plants.

Source: Karl Merz, TotalControl D1.03



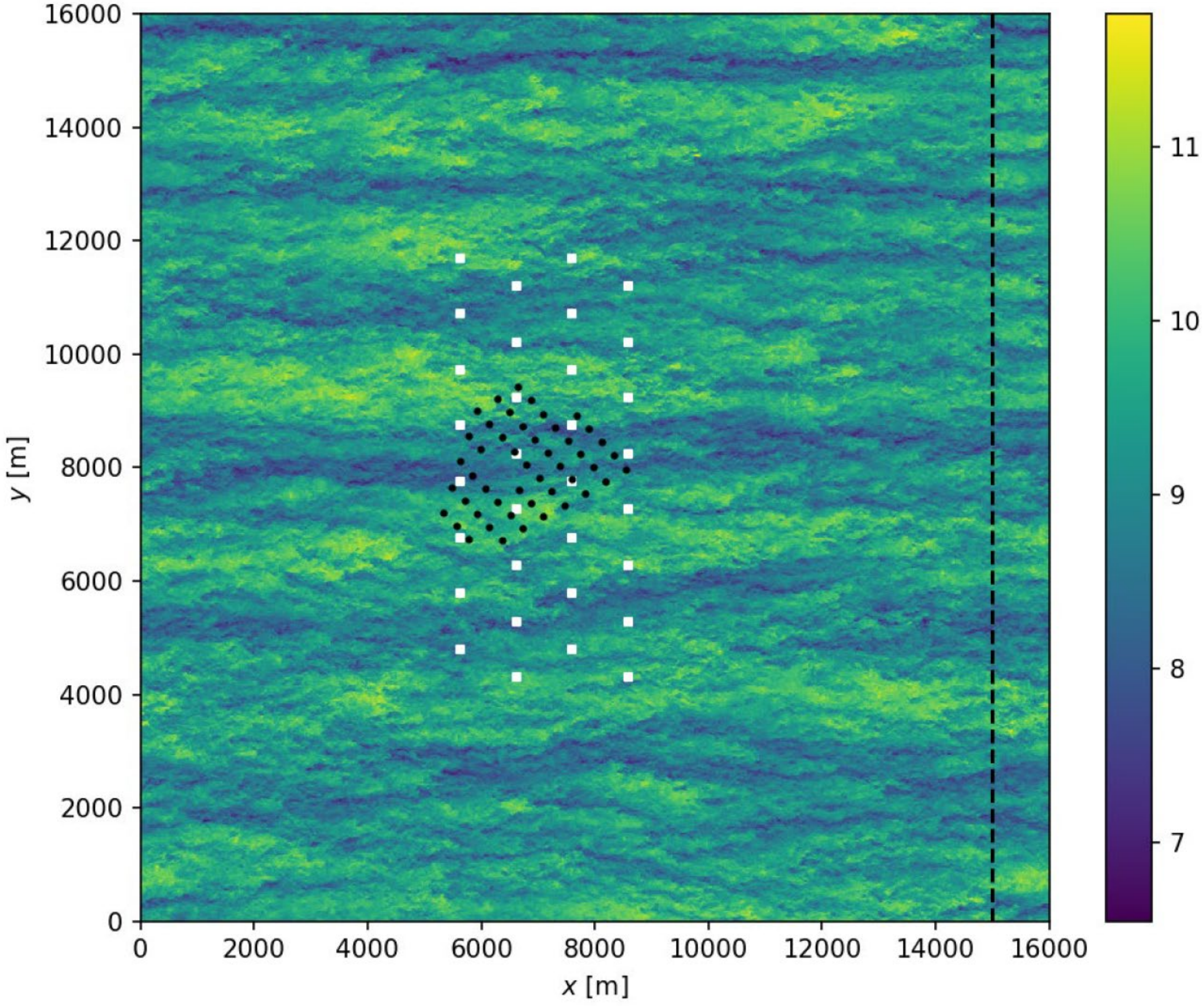
Totalcontrol reference wind farm

Black: Lillgrund layout

White: Reference WF layout

(RWF turbines: DTU 10MW)

(also detailed electrical design, etc)



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Simulation set-up

Spin-up (20h): 144000 time steps
Main simulation (75min): 9000 time steps

$N = 324 \times 10^6$

	Variable	SP-Wind	EllipSys3D
Domain size	$L_x \times L_y \times L_z$	$16 \times 16 \times 1.5$ km³	$16 \times 16 \times 1.5$ km³
Grid	$N_x \times N_y \times N_z$	$1200 \times 1200 \times 225$	$800 \times 800 \times 128$
Resolution	$\Delta_x \times \Delta_y \times \Delta_z$	$13.33 \times 13.33 \times 6.66$ m³	$20 \times 20 \times 10^*$ m³
Spinup time	T_{spin}	20 h	20 h
Precursor time	T	75 min	60 min
Time step	Δt	0.5 s	0.8 s – $1.0^{\S}$ s

Simulation set-up

Two different cases:

- PDBL: pressure-driven boundary layer (half-channel flow)
- CNBL: conventionally neutral boundary layer

Simulation parameters			
Friction velocity	u_*	$0.28\ \mathrm{m/s}$	$(u_*^2 = L_z\, \nabla p_\infty/\rho)$
Driving pressure gradient	$\nabla(p_\infty)/\rho$	$-5.2267 \times 10^{-5}\ \mathrm{m/s^2}$	
Simulation cases			
PDk	KU Leuven	$z_0 = 2 \times 10^{-4}\ \mathrm{m}$	
PDd	DTU	$z_0 = 2 \times 10^{-4}\ \mathrm{m}$	
PDkhi	KU Leuven	$z_0 = 2 \times 10^{-3}\ \mathrm{m}$	

PDBL

PDBL: rescaling of results (1)

Solution: $\boldsymbol{u}(\boldsymbol{x},t)$ (stored on zenodo – see later) **– can be rescaled !!**

Formally, two non-dimensional groups: $\boldsymbol{Re_\tau} = \frac{\boldsymbol{u_\tau h}}{\boldsymbol{\nu}}$ and $\frac{\boldsymbol{z_0}}{\boldsymbol{h}}$ $(h = L_z)$

If large scales asymptotically Reynolds independent (occurs for $\boldsymbol{Re_\tau} \rightarrow \infty$): solution scale invariant

$$\boldsymbol{u}^{\boldsymbol{new}}(\boldsymbol{x}, t^{new}) = \frac{\boldsymbol{u}(\boldsymbol{x},t)}{u_*} u_*^{new} \qquad \Delta t^{new} = \frac{\Delta t}{u_*^{new}} u_*$$

(Similarly, $\boldsymbol{x}$ can be rescaled, but ratio $\boldsymbol{z_0/h}$ needs to be kept constant)

PDBL: rescaling of results (2)

Solution: $\boldsymbol{u}(\boldsymbol{x},t)$ (stored on zenodo – see later) **– mean velocity can be shifted !!**

If we can presume inner–outer separation of scales (OK for flat terrain ABL)

$$\boldsymbol{u}(\boldsymbol{x},t) - \boldsymbol{U}_0 = f(\boldsymbol{x}/h) \neq f(z_0/h)$$

outer-layer solution is independent of inner layer and roughness sublayer

Thus

$$\boldsymbol{u}^{\boldsymbol{new}}(\boldsymbol{x},t) = \boldsymbol{u}(\boldsymbol{x},t) + u_* \Delta\boldsymbol{U}^+$$

$$\Delta\boldsymbol{U}^+ = \frac{1}{\kappa}\log\left(\frac{z_0}{z_0^{new}}\right)\boldsymbol{e}_1$$

Combination of both scalings

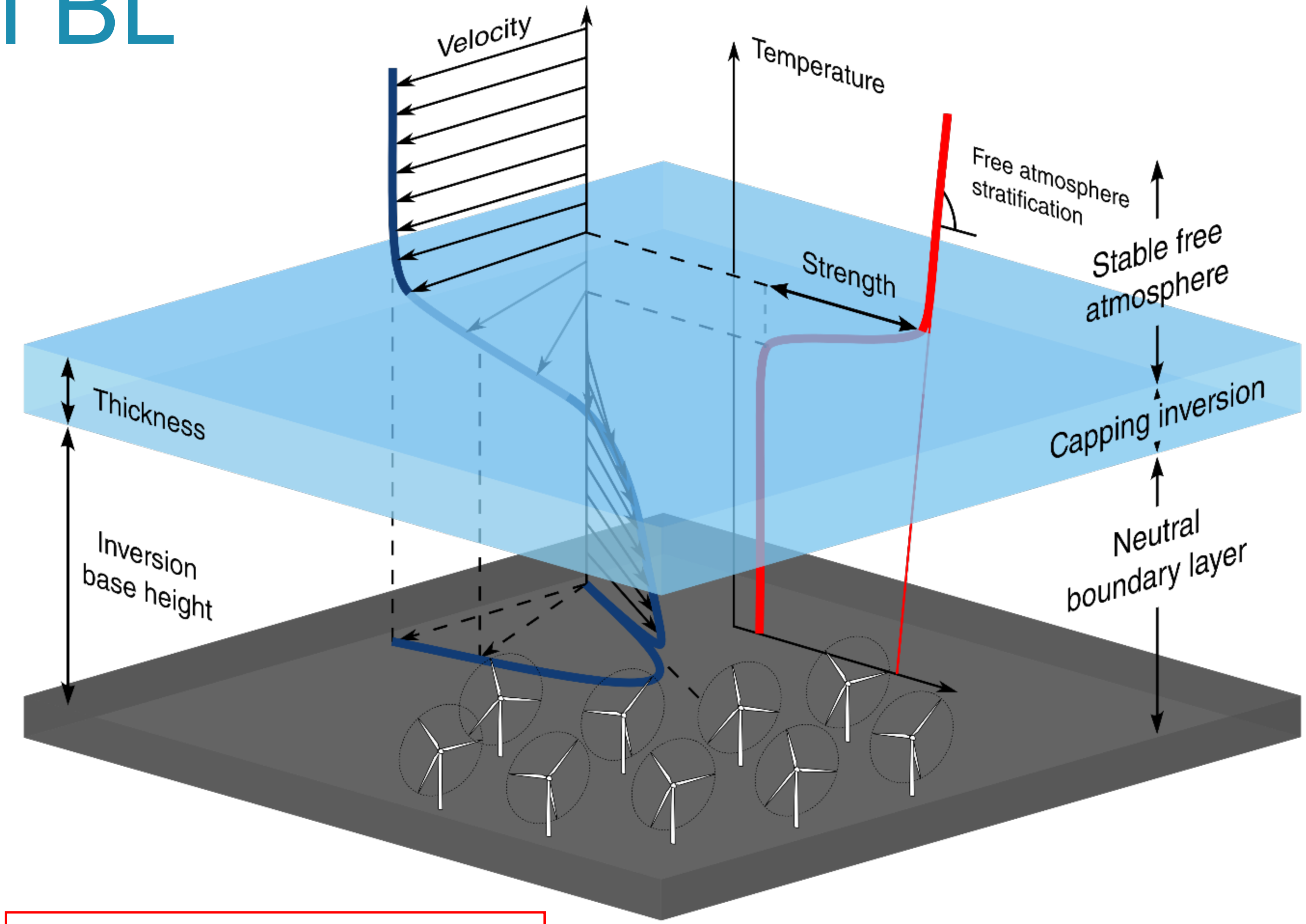
$$\boldsymbol{u}^{\boldsymbol{new}}(\boldsymbol{x},t^{new}) = u_*^{new}\left[\frac{\boldsymbol{u}(\boldsymbol{x},t)}{u_*} + \Delta\boldsymbol{U}^+\right]$$

Conventionally neutral BL

Stable free atmosphere (FA)
- Shear free flow
- Positive lapse rate
- Geostrophic balance

Capping inversion (CI)
= thin layer of strong stability
between NBL and FA

Neutral boundary layer (NBL)
- Zero surface heat flux
- Constant pot. temperature
- Turbulent flow



$$h = A \frac{\theta_0}{g\Delta\theta} u_*^2 \quad §$$

$A \approx 500$ for equilibrium

§ Csanady, *Boundary-Layer Meteorol.* 1974

CNBL: set-up

Careful initialization necessary
See: Allaerts & Meyers, POF 2015, JFM2017

$$\frac{U_G}{u_*} - \frac{1}{\kappa}\log\left(\frac{u_*}{f_c z_0}\right) = F_1(h^*, A) \qquad \text{with} \quad h^* = \frac{f_c\, h}{u_*} \quad (\sim 1/Ro), \qquad A = \frac{g\Delta\theta}{\theta_0}\frac{h}{u_*^2}$$

$$\frac{V_G}{u_*} = F_2(h^*, A)$$

Simulation parameters

Geostrophic wind	G	$12\ \mathrm{m/s}$
Coriolis parameter	f_c	$10^{-4}\ \mathrm{s}^{-1}$

$$-\frac{1}{\rho}\frac{\partial p}{\partial x} = -f_c V_G$$
$$-\frac{1}{\rho}\frac{\partial p}{\partial y} = +f_c U_G$$

Simulation cases

CNk2	KU Leuven	$z_0 = 2\times10^{-4}\ \mathrm{m}, \Delta\theta = 2\mathrm{K}\ (h = 500\ \mathrm{m})$
CNk4	KU Leuven	$z_0 = 2\times10^{-4}\ \mathrm{m}, \Delta\theta = 4\mathrm{K}\ (h = 250\ \mathrm{m})$
CNd	DTU	$z_0 = 2\times10^{-4}\ \mathrm{m}, \Delta\theta = 2\mathrm{K}\ (h = 500\ \mathrm{m})$

CNBL: rescaling of results

Rescaling via u_*: implies change of latitude (for h constant) & $\Delta\theta/\theta_0$

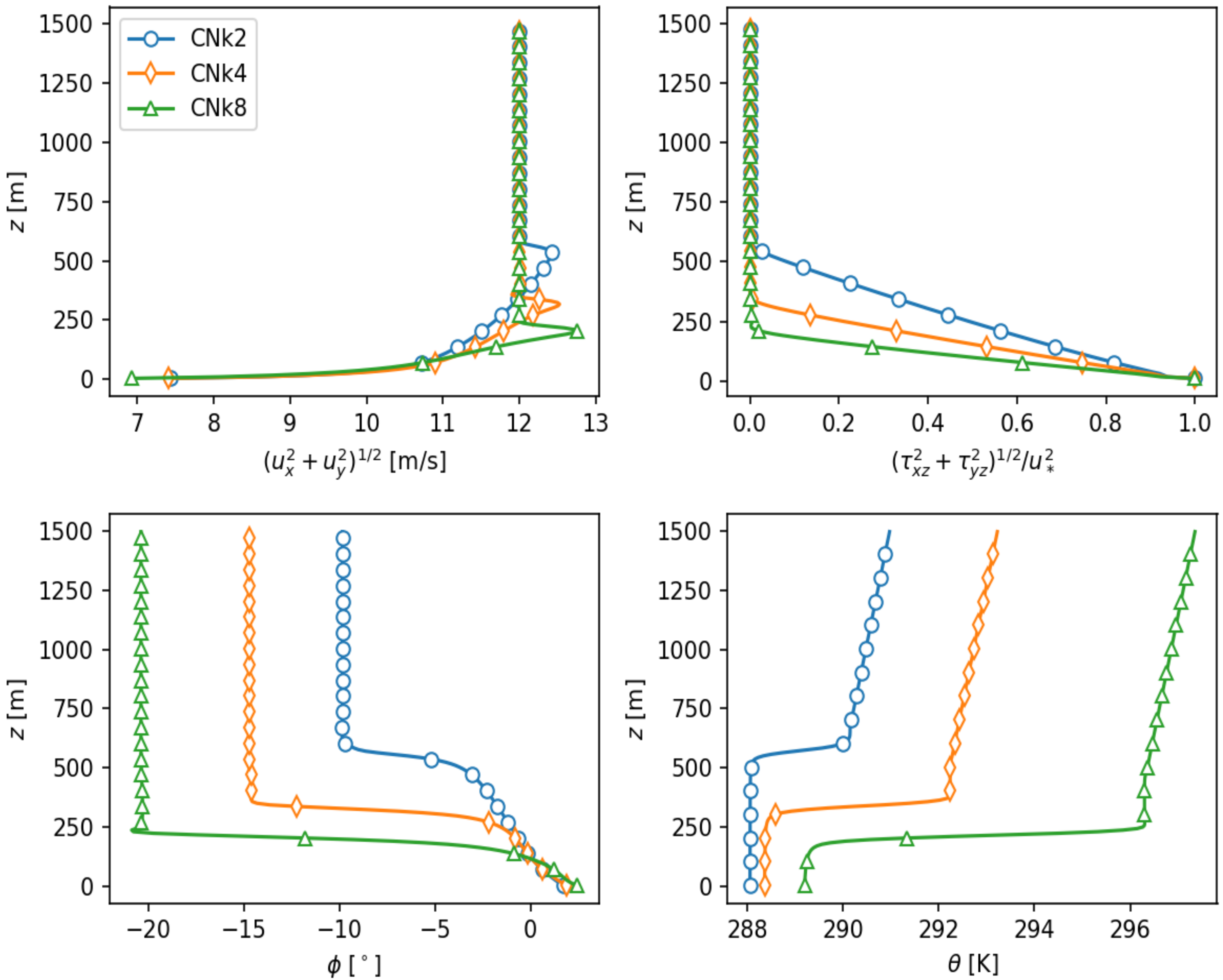
Shifting

$$\boldsymbol{u}^{new}(\boldsymbol{x},t) = \boldsymbol{u}(\boldsymbol{x},t) + u_*\Delta\boldsymbol{U}^+$$

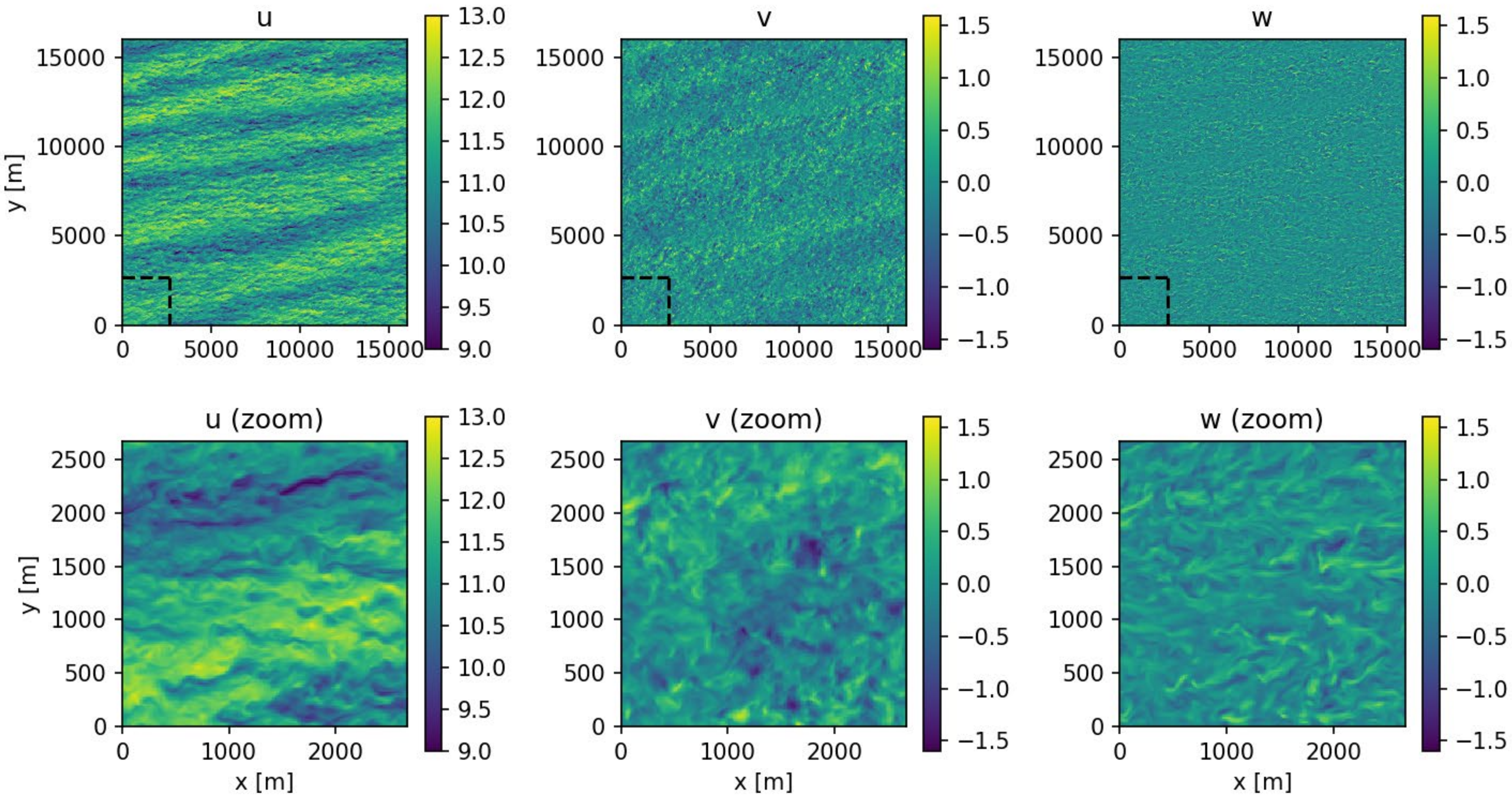
$$-\frac{1}{\rho}\frac{\partial p^{new}}{\partial y} = +\boldsymbol{f}_c(\boldsymbol{U}_G + u_*\Delta\boldsymbol{U}^+)$$

$$\Delta\boldsymbol{U}^+ = \frac{1}{\kappa}\log\left(\frac{z_0}{z_0^{new}}\right)\boldsymbol{e}_1$$

CNBL: results



CNBL: results – case CNk4



Distance metrics

Using database to reconstruct Lillgrund inflc

- Distance between mean profiles

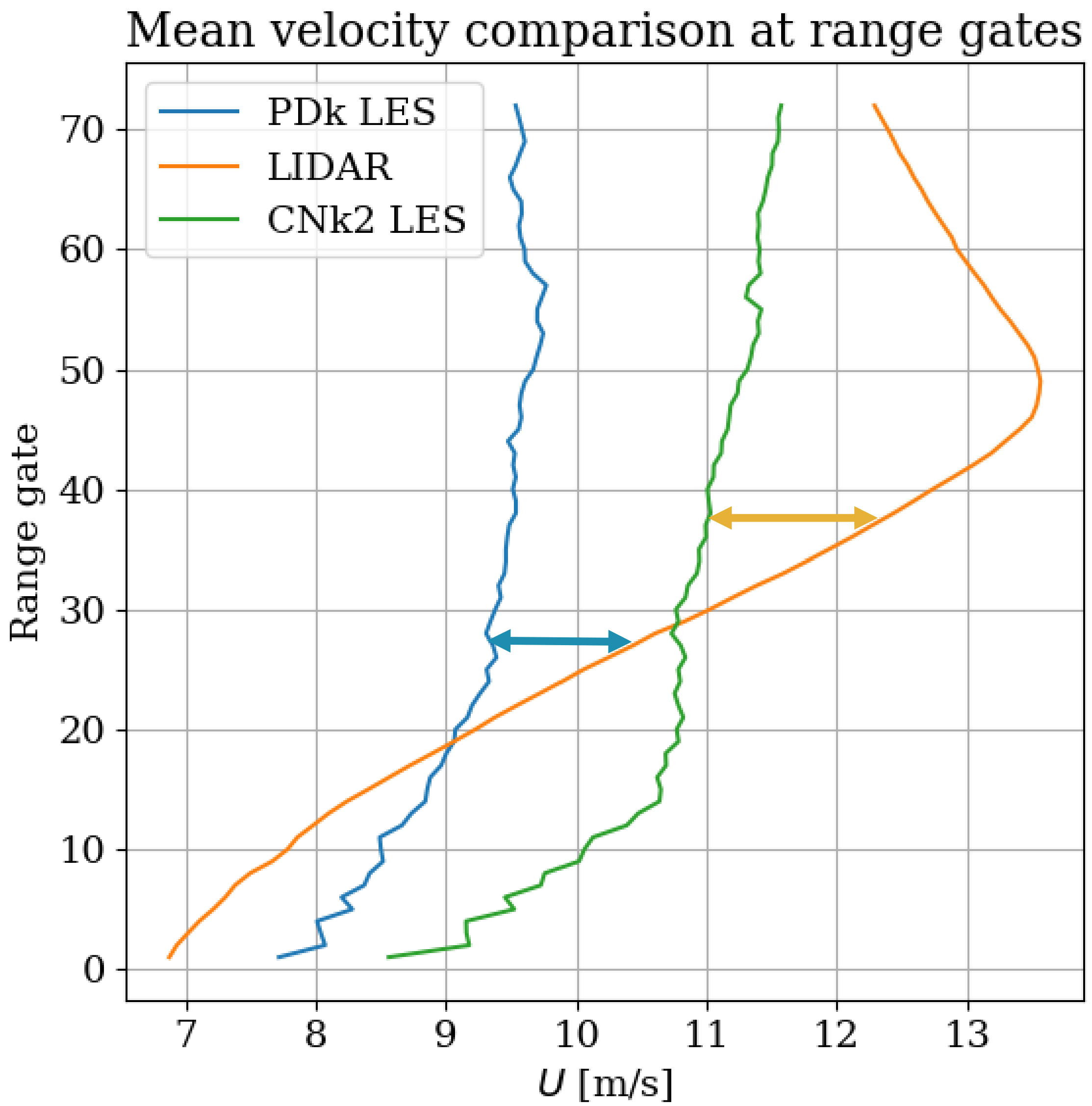
$$d_1(A,B) = \sqrt{\sum \left(\bar{x}_{A_i} - \bar{x}_{B_i}\right)^2}$$

- Distance between covariance matrices

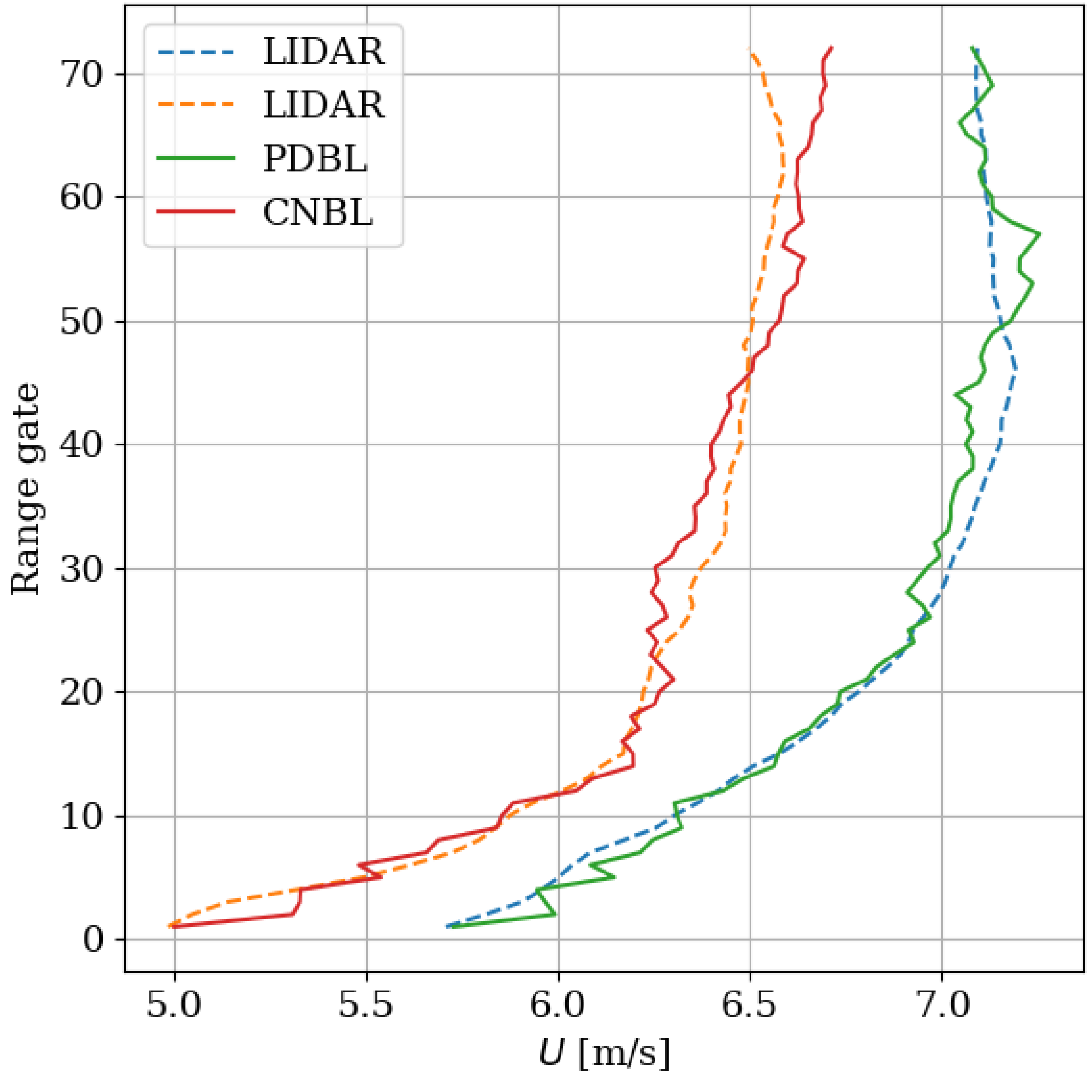
$$d_2(A,B) = \sqrt{\sum\sum \left(\sigma_{A_{ij}} - \sigma_{B_{ij}}\right)^2}$$

$$\min \; J(A,B) = d_1 + d_2$$

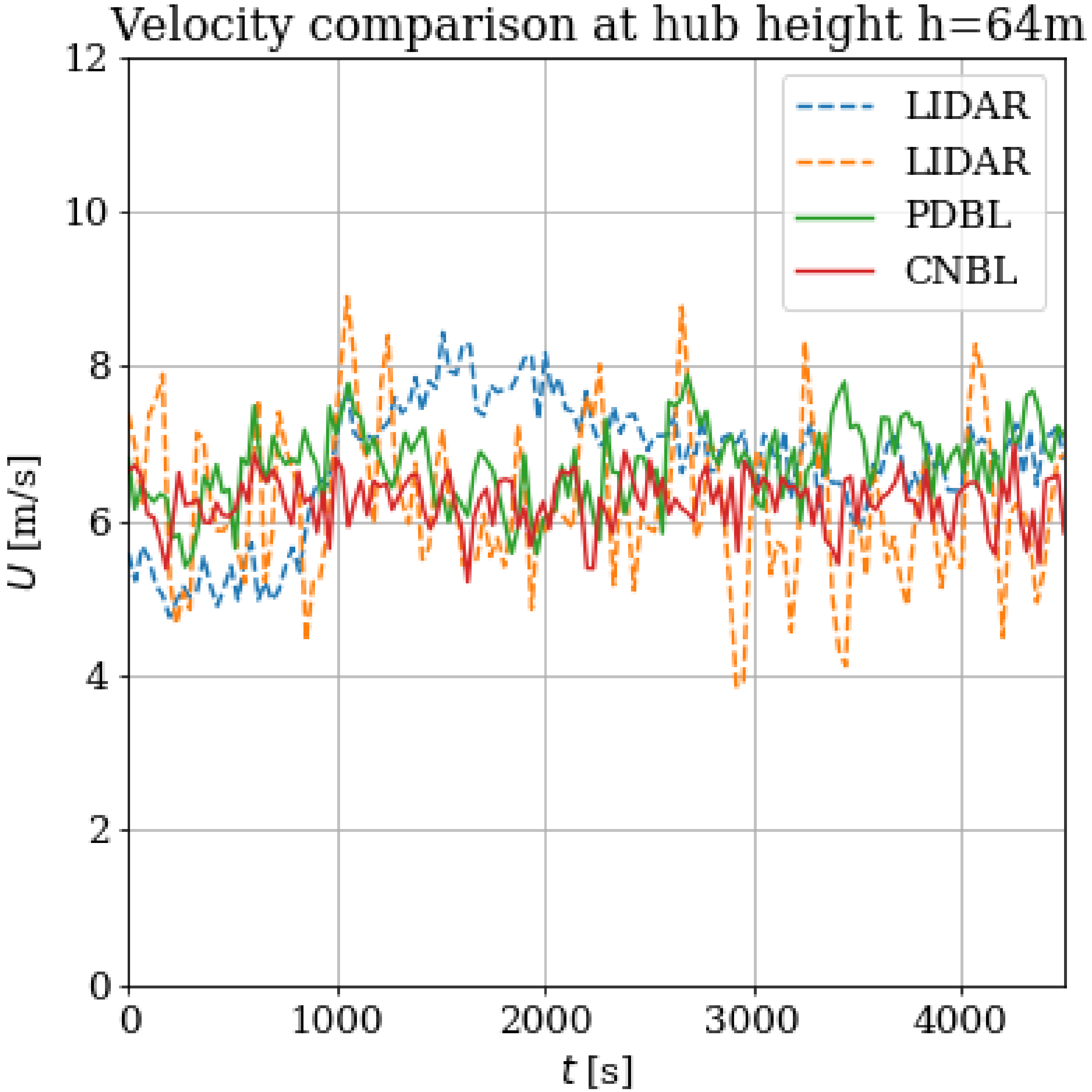
A = Lidar Data, B = Scaled LES DATA



$$\min \; J(A,B) = d_1$$

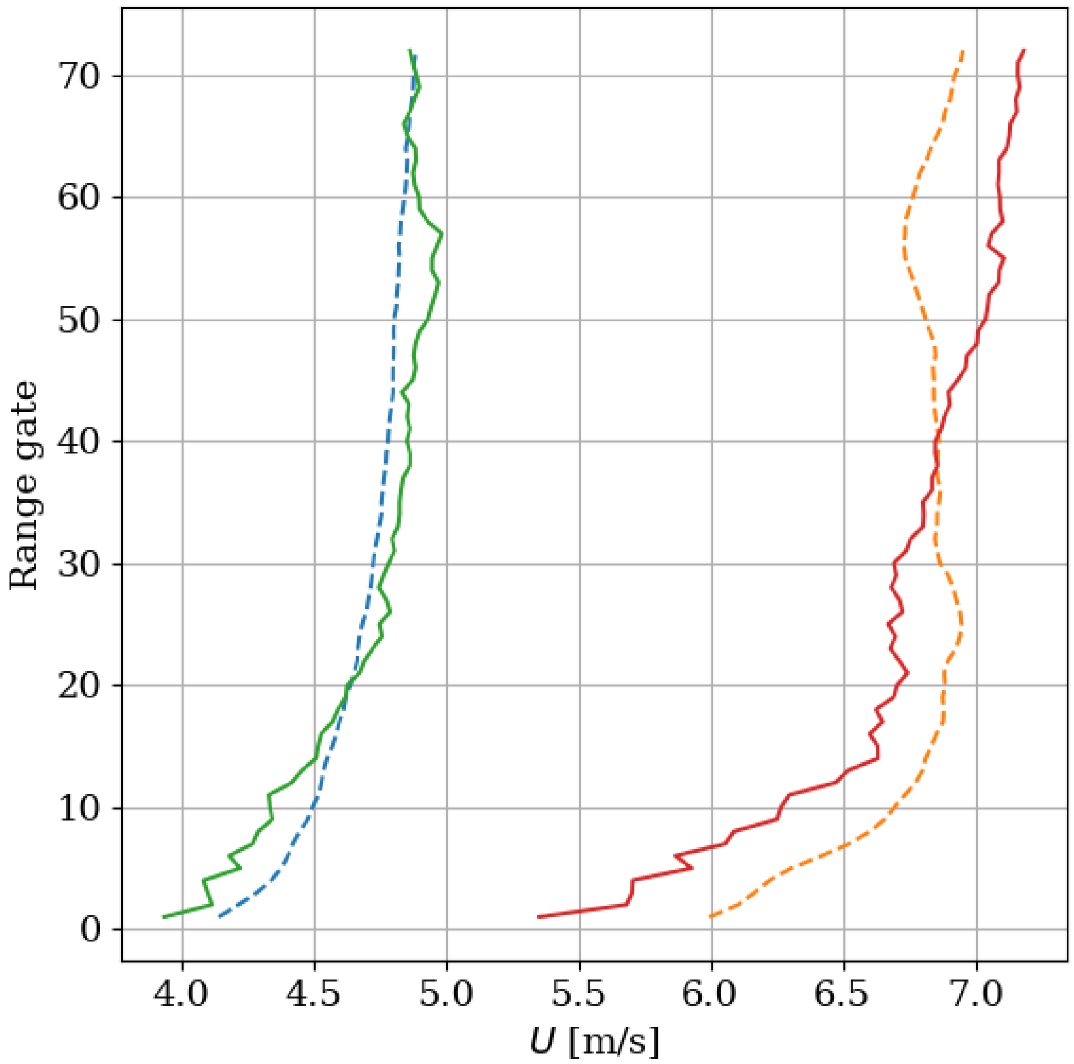


LIDAR
LIDAR
PDBL
CNBL
Range gate
0
10
20
30
40
50
60
70
5.0
5.5
6.0
6.5
7.0
U [m/s]

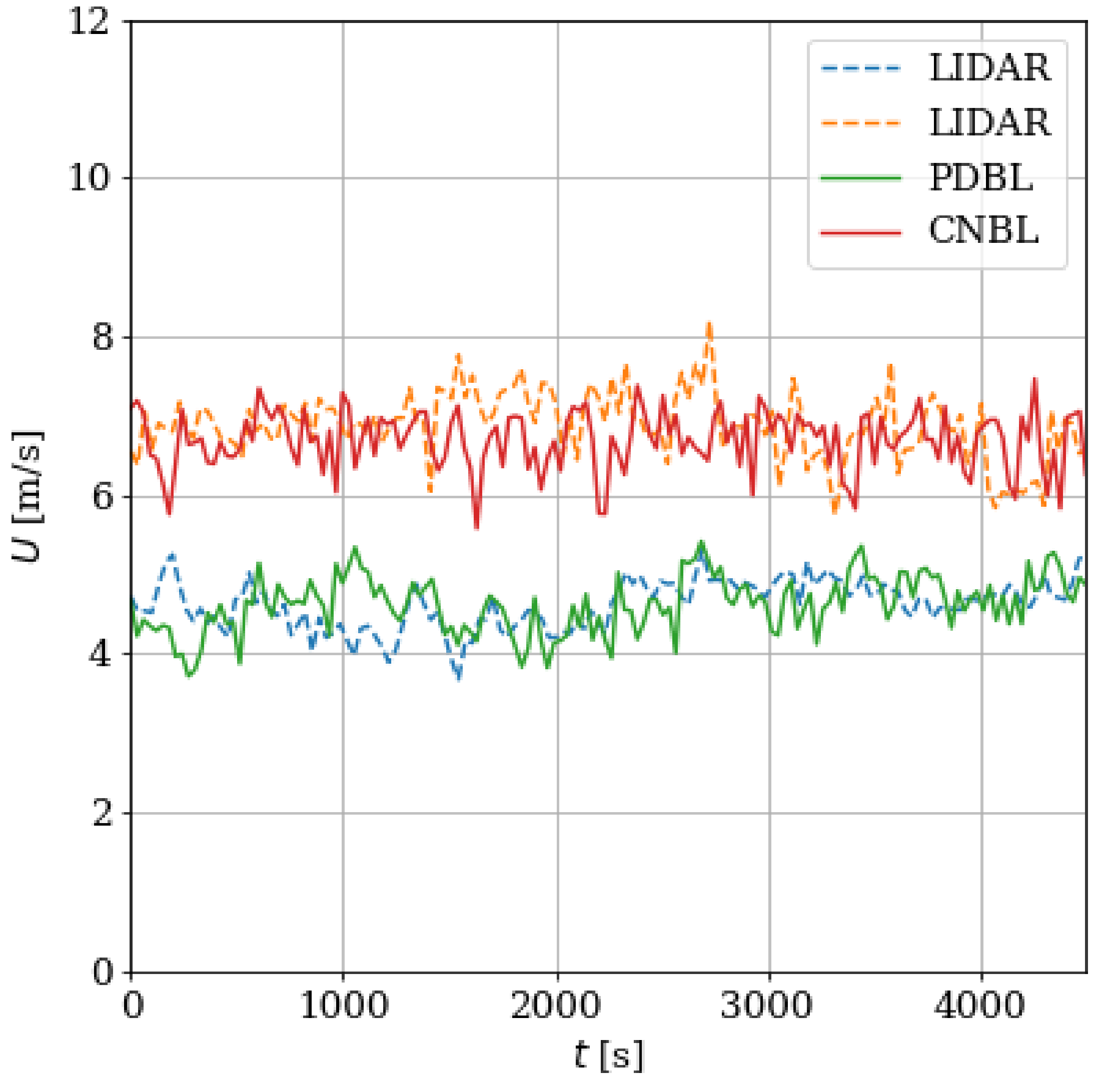


Velocity comparison at hub height h=64m
LIDAR
LIDAR
PDBL
CNBL
U [m/s]
0
2
4
6
8
10
12
0
1000
2000
3000
4000
t [s]

$$\min \; J(A,B) = d_1 + d_2$$



Range gate
70
60
50
40
30
20
10
0
4.0
4.5
5.0
5.5
6.0
6.5
7.0
U [m/s]



LIDAR
LIDAR
PDBL
CNBL
U [m/s]
12
10
8
6
4
2
0
1000
2000
3000
4000
t [s]

Outline

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Wind-farm simulations

Data accessibility

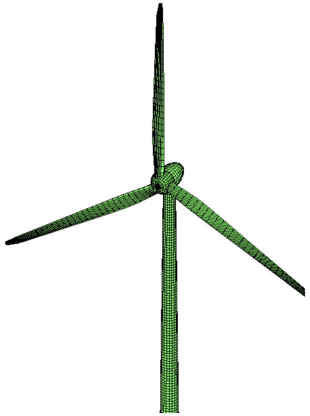
Aeroelastic actuator sector model

Multibody dynamics/EOM:

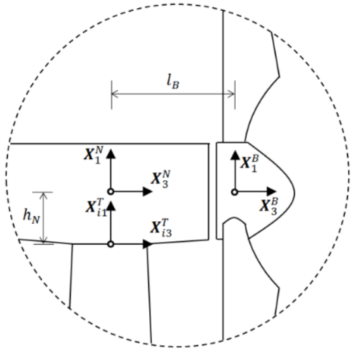
$$\underbrace{\overbrace{\boldsymbol{M}(\boldsymbol{q})}^{\text{non-linear mass matrix}}\ddot{\boldsymbol{q}}}_{\text{inertial forces}}+\underbrace{\overbrace{\boldsymbol{C}}^{\text{damping matrix}}\dot{\boldsymbol{q}}}_{\text{damping forces}}+\underbrace{\overbrace{\boldsymbol{K}}^{\text{stiffness matrix}}\boldsymbol{q}}_{\text{elastic forces}}+\underbrace{\overbrace{\boldsymbol{\Phi}_{\boldsymbol{q}}^{T}}^{\text{Jacobian of constraints}}\boldsymbol{\lambda}}_{\text{constraint forces}}=\underbrace{\boldsymbol{Q_{air}}}_{\text{aerod. forces}}+\underbrace{\boldsymbol{Q_g}}_{\text{gravity forces}}+\underbrace{\boldsymbol{Q_v}(\boldsymbol{q},\dot{\boldsymbol{q}})}_{\text{Coriolis \& gyroscopic forces}}$$

Constraint equations: $\Phi(q,t)=0$

FE model reduced with modal transformation



FEM

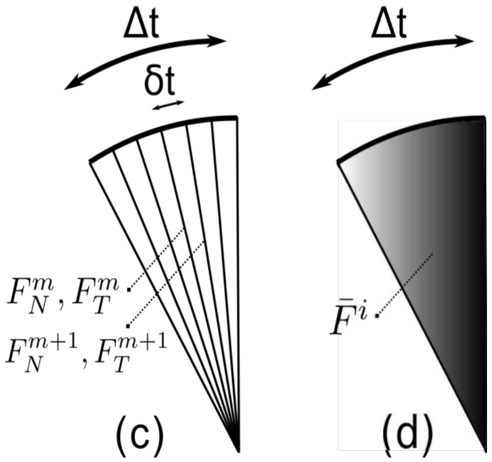


Constraints

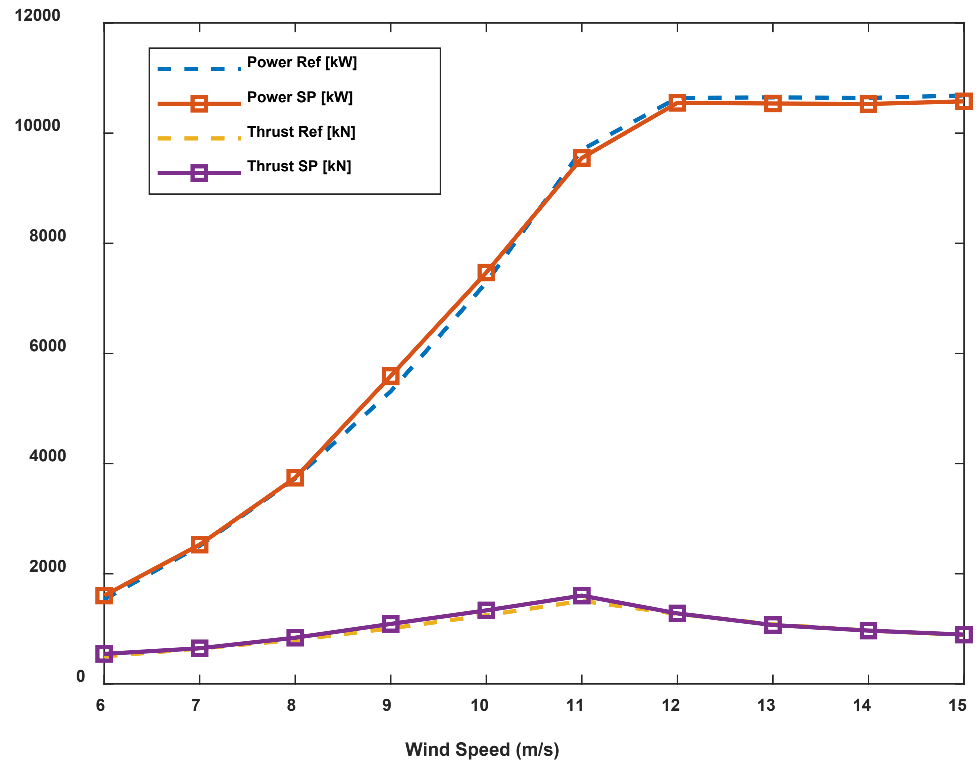
Actuator sector model:

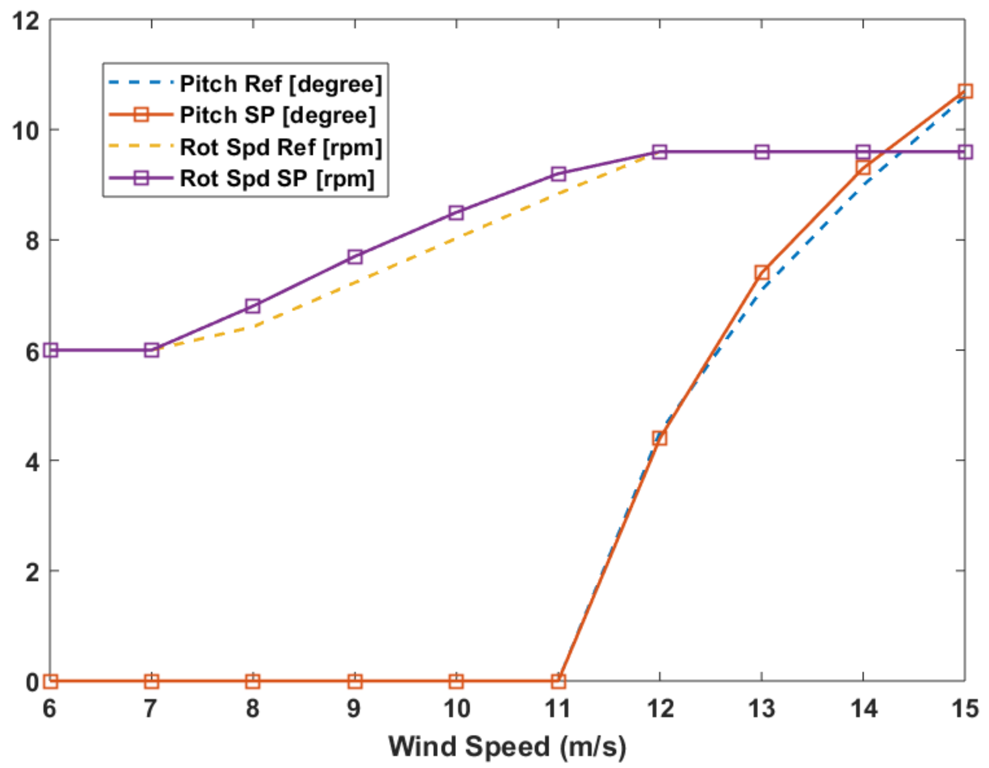
- Forces are time filtered over the swept sector
- Subsequently are spatially (Gaussian) filtered

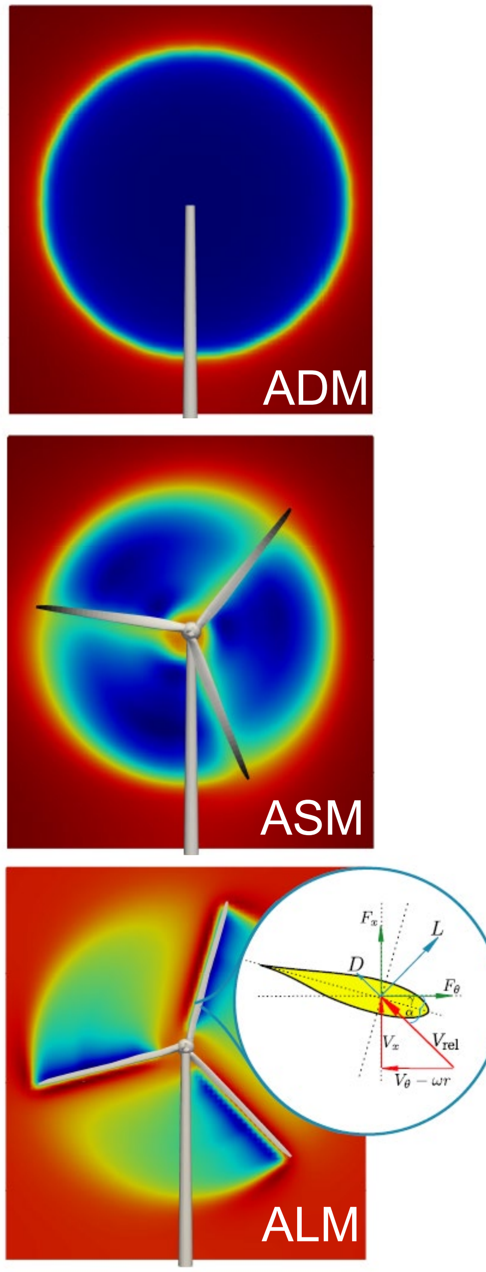
$$\hat{F}(\mathbf{x})=\sum_{n=1}^{N_t}\sum_{j=1}^{N_b=3}\int_0^R F(\hat{u},q,r)G_n(\|\mathbf{x}-r\mathbf{e_j}\|)dr$$



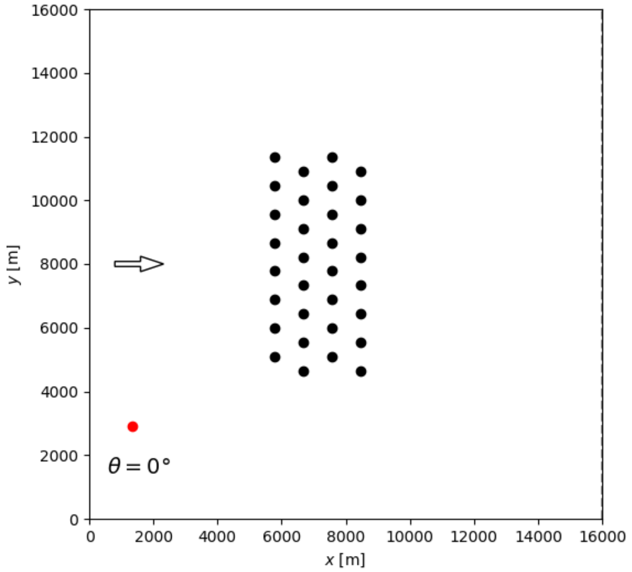
Aeroelastic actuator sector model

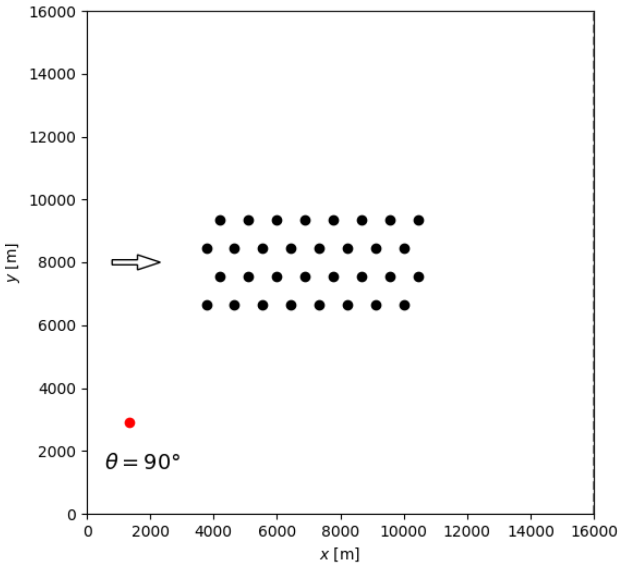


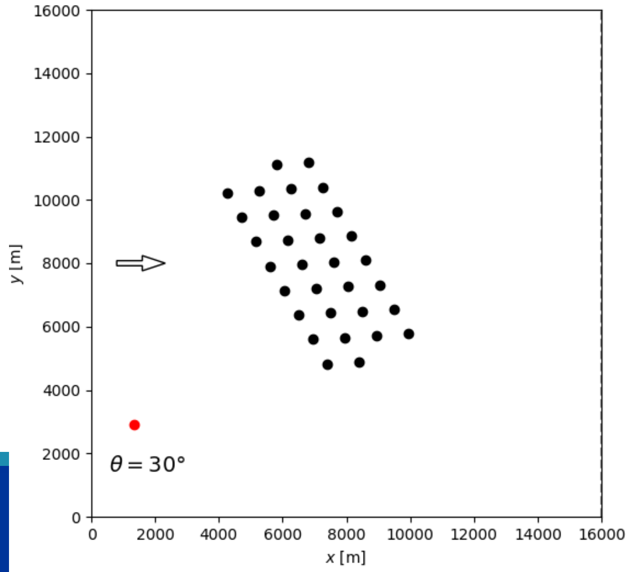


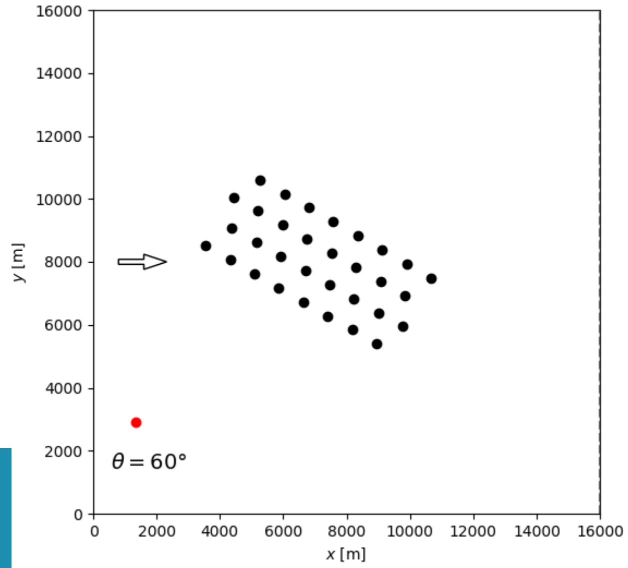


Example wind-farm orientations









TotalControl

Simulation cases

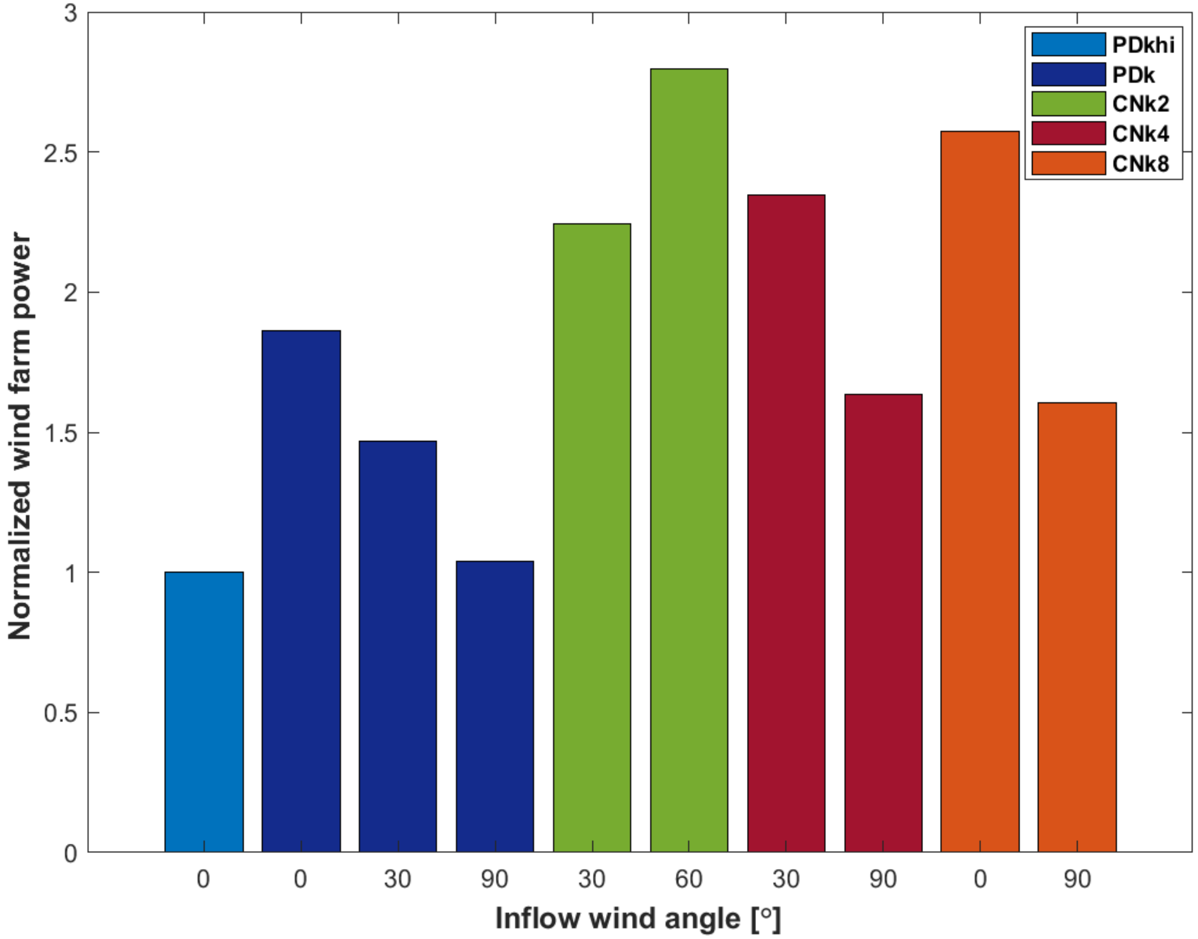
KU Leuven Simulations

Inflow	Angle (degrees)	Hub ht wind speed (m/s)	Region
PDBL_2m3	0	7.8	2
PDBL_2m4	0	9.4	2
PDBL_2m4	30	9.4	2
PDBL_2m4	90	9.4	2
CNBL_2_2m4	30	11	2.5 – 3
CNBL_2_2m4	60	11	2.5 – 3
CNBL_4_2m4	30	11.3	2.5 – 3
CNBL_4_2m4	90	11.3	2.5 – 3
CNBL_8_2m4	0	11.4	2.5 – 3
CNBL_8_2m4	90	11.4	2.5 – 3

DTU Simulations

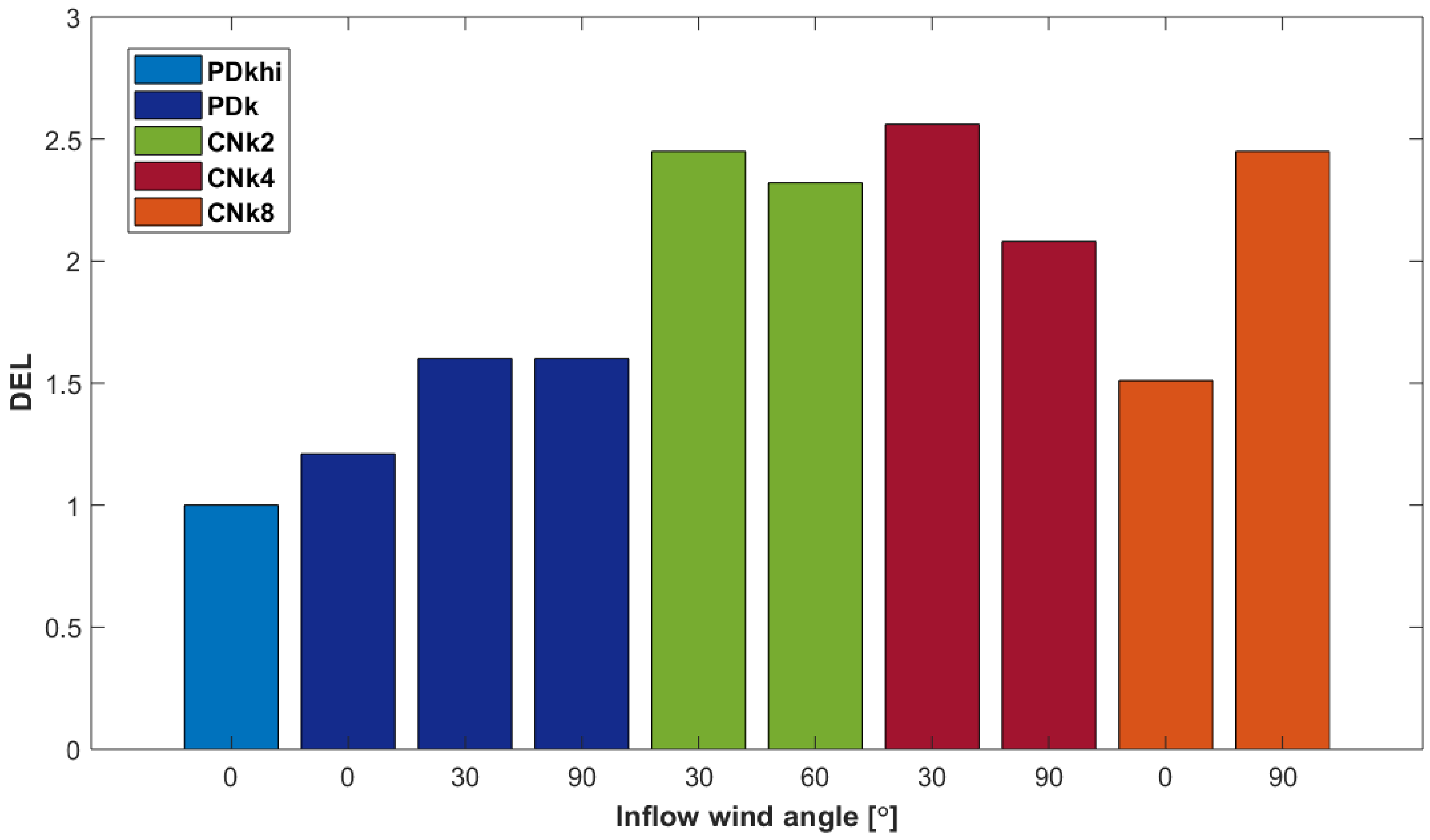
Inflow	Angle (degrees)	Hub ht Speed (m/s) mesh	Region
CNBL_2_2m3	0	10.5	2
CNBL_2_2m3	90	10.5	2
CNBL_2_2m4	0	11	2.5 – 3
CNBL_2_2m4	30	11	2.5 – 3
CNBL_2_2m4	45	11	2.5 – 3
CNBL_2_2m4	60	11	2.5 – 3
CNBL_2_2m4	90	11	2.5 – 3
CNBL_2_2m5	0	11.6	2.5 – 3
CNBL_2_2m5	90	11.6	2.5 – 3

Results – Total farm power

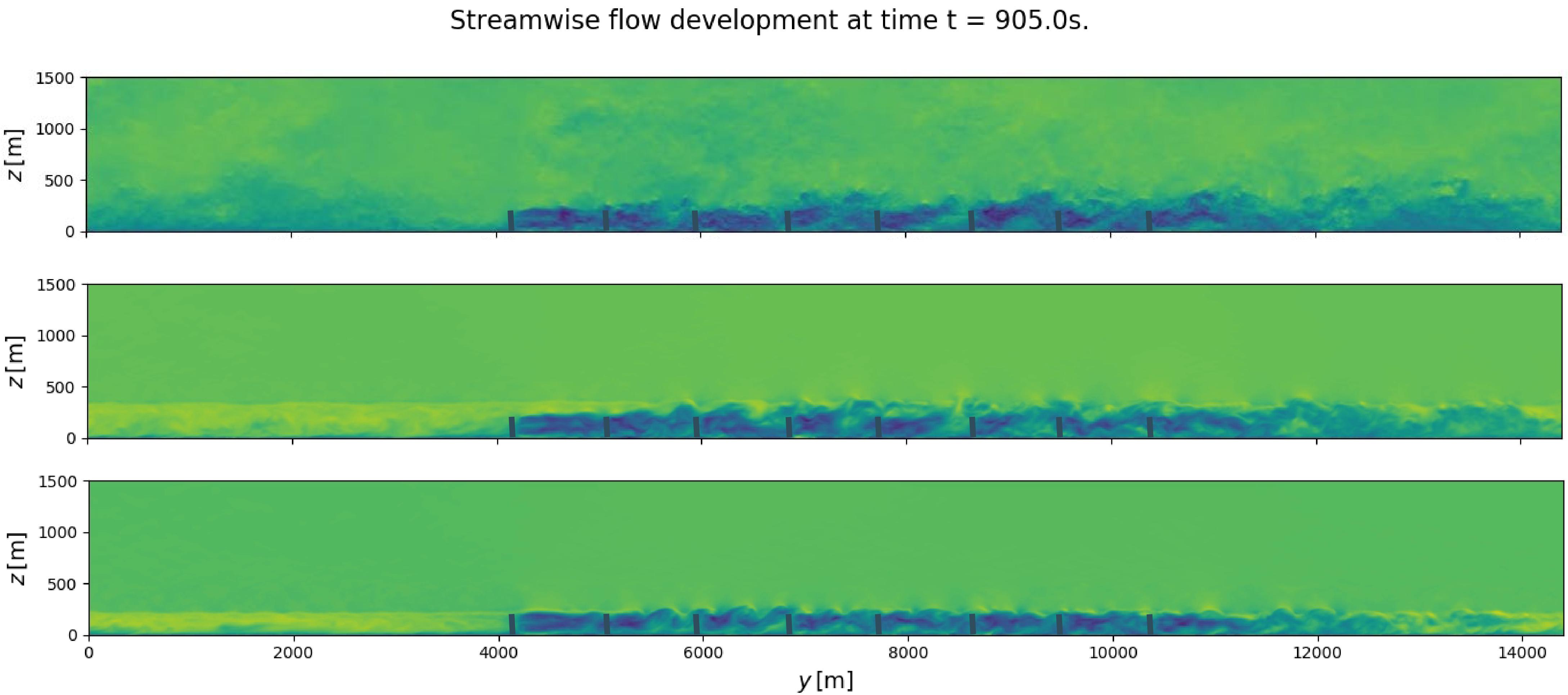


Case	ΔPower
PDk 0°	86.0%
PDk 30°	46.7%
PDk 90°	3.9%
CNk2 30°	124.2%
CNk2 60°	179.5%
CNk4 30°	134.5%
CNk4 90°	63.5%
CNk8 0°	157.5%
CNk8 90°	60.5%

Results – Fatigue loading



Visualization – Flow time series



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Wind-farm simulations

Data accessibility

Dataset availability - Zenodo

(All) Research. Shared.

— your one stop research shop!

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Communities

— create your own repository

Zenodo allows you to create your own collection and accept or reject uploads submitted to it. Creating a space for your next workshop or project has never been easier. Plus, everything is citeable and discoverable!

Max data set size : 50 GB. > >> Different data sets can be combined into communities

Precursor data : https://zenodo.org/communities/totalcontrolflowdatabase/

Windfarm data : https://zenodo.org/communities/totalcontrolwindfarmdatabase/

Reference Windfarm database CNk8 90

Ishaan Sood; Johan Meyers;

Dataset for TotalControl reference windfarm database simulation of a conventionally neutral boundary layer flow with 90 degree inflow wind direction angle (Casename CNk8 90) Included Python files for loading and visualizing the data. Use the plot_*.py files. Further information, includin

Uploaded on February 28, 2020

February 27, 2020 (1) Dataset Open Access

View

Reference Windfarm database CNk4 90

Ishaan Sood; Johan Meyers;

Dataset for TotalControl reference windfarm database simulation of a conventionally neutral boundary layer flow with 90 degree inflow wind direction angle (Casename CNk4 90) Included Python files for loading and visualizing the data. Use the plot_*.py files. Further information, includin

Uploaded on February 28, 2020

February 27, 2020 (1) Dataset Open Access

View

Reference Windfarm database CNk8 0

Ishaan Sood; Johan Meyers;

Dataset for TotalControl reference windfarm database simulation of a conventionally neutral boundary layer flow with 0 degree inflow wind direction angle (Casename CNk8 0) Included Python files for loading and visualizing the data. Use the plot_*.py files. Further information, inclu

Uploaded on February 28, 2020

February 27, 2020 (1) Dataset Open Access

View

Reference Windfarm database CNk4 30

Files (30.1 GB)

Name	Size
3D_box.h5 md5:c400443c2ab2aabe8bd84e992821566d	1.8 GB
cross_sections_timeseries.h5 md5:a1a1571294a0de1249ba60b354a4209e	17.7 GB
field_snapshot.h5 md5:6ac59c926e07d0699c623335f8038448	10.4 GB
import_dataset.py md5:1c7ea8f7fa85c32d95dba0b450321776	2.2 kB
plot_3D_box.py md5:04b372c10168967bca07ea156b129003	2.4 kB
plot_cross_sections.py md5:735b457d3508d6d54706250600f89223	2.4 kB
plot_field.py md5:aea27605993fcc307dc33c334043809e	3.5 kB
plot_performance.py md5:a5ad336407432ccd3c12da1cdaf219f9	1.8 kB
turb_performance.h5 md5:c1153a0e030d534b2aa34da1ba8c5e16	191.0 MB
visualize_dataset.py md5:babd02a1f1e8a4f602705dad9cc377e1	6.2 kB

Thank you