EERA DeepWind Conference 2021

Wake properties and power output of very large wind farms for different meteorological conditions and turbine spacings: A large-eddy simulation case study for the German Bight

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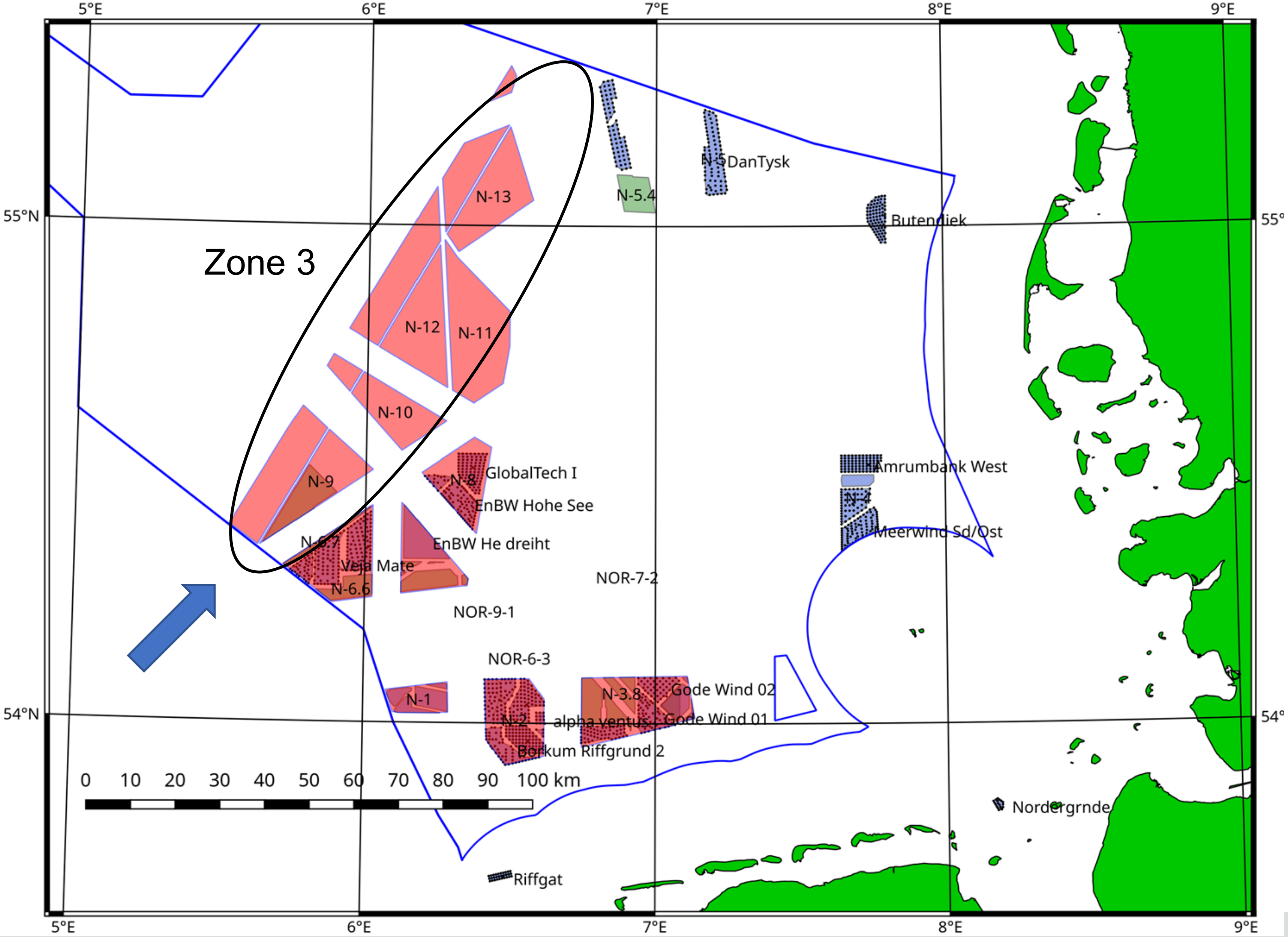
Motivation

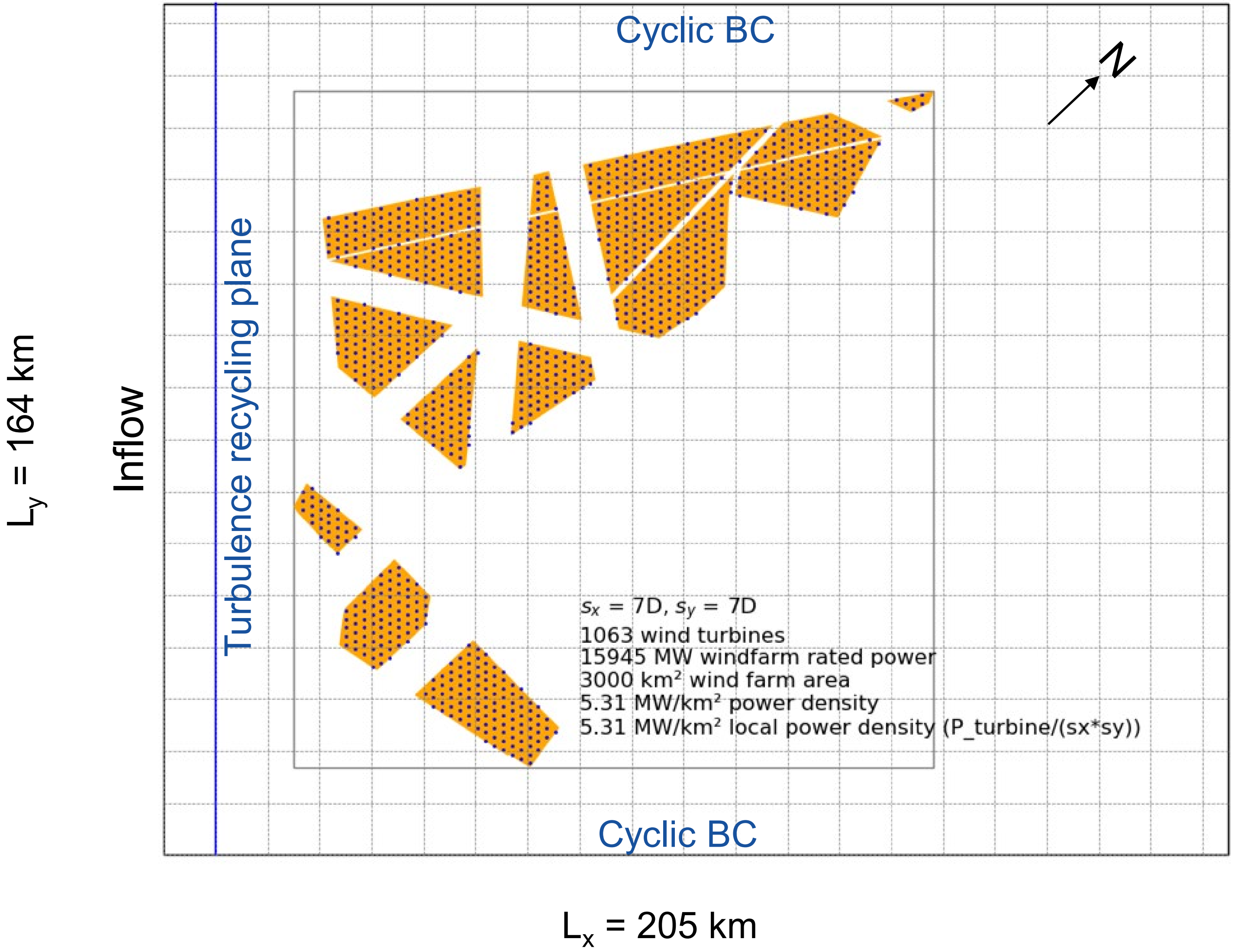


5°E
6°E
7°E
8°E
9°E
55°N
55°
54°N
54°
Zone 3
N-13
N-12
N-11
N-10
N-9
N-8
GlobalTech I
EnBW Hohe See
EnBW He dreiht
N-6.7
Veja Mate
N-6.6
NOR-7-2
NOR-9-1
NOR-6-3
N-1
N-2
N-3.8
Gode Wind 02
Gode Wind 01
alpha ventus
Borkum Riffgrund 2
N-5
DanTysk
N-5.4
Butendiek
Amrumbank West
N-4
Meerwind Sd/Ost
Nordergrnde
Riffgat
0 10 20 30 40 50 60 70 80 90 100 km

Questions

- How does very large wind farms affect the boundary layer flow?
- How does the power output of very large wind farms depend on the turbine spacing and the meteorological conditions?

Setup and domain layout



- LES-model: PALM
- Wind turbines: 1063 / 2088
- Initialization: precursor run
- Roughness length: 1 mm
- Grid spacing: 20 m
- Grid points: 7.4 billion
- Simulated time: 10 h (6 h + 4 h)
- CPU time: 24 – 50 h
- Cores: 5120

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

Wind turbine model

- IEA 15 MW reference wind turbine
  - D = 240 m
  - z_{hub} = 150 m
- Wind turbine model in PALM
  - Actuator disc model
  - Including wake rotation

https://www.nrel.gov/news/program/2020/images/15-mw-reference-social-media.jpg

Simulation overview

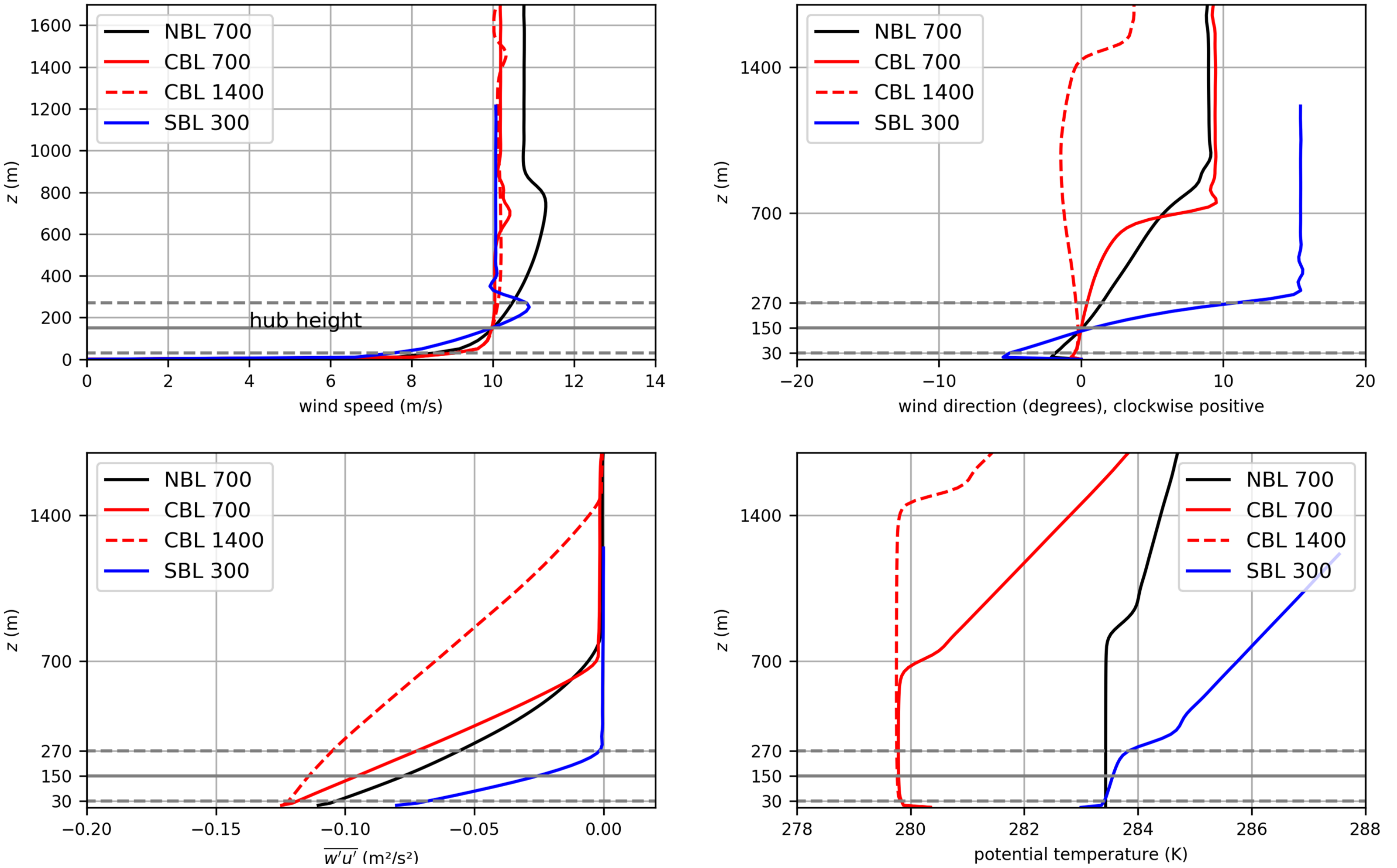
short name	Surface heating rate	Boundary layer height	turbine spacing (power density)
NBL_700_**7D**	0.00 K/h	700 m	7D (5.3 MW/km²)
NBL_700_**5D**	0.00 K/h	700 m	5D (10.4 MW/km²)
CBL_**700**_7D	0.05 K/h	700 m	7D (5.3 MW/km²)
CBL_**1400**_7D	0.025 K/h	1400 m	7D (5.3 MW/km²)
SBL_300_7D	-0.05 K/h	300 m	7 D (5.3 MW/km²)

Neutral boundary layer (**NBL**):
Variation of turbine spacing

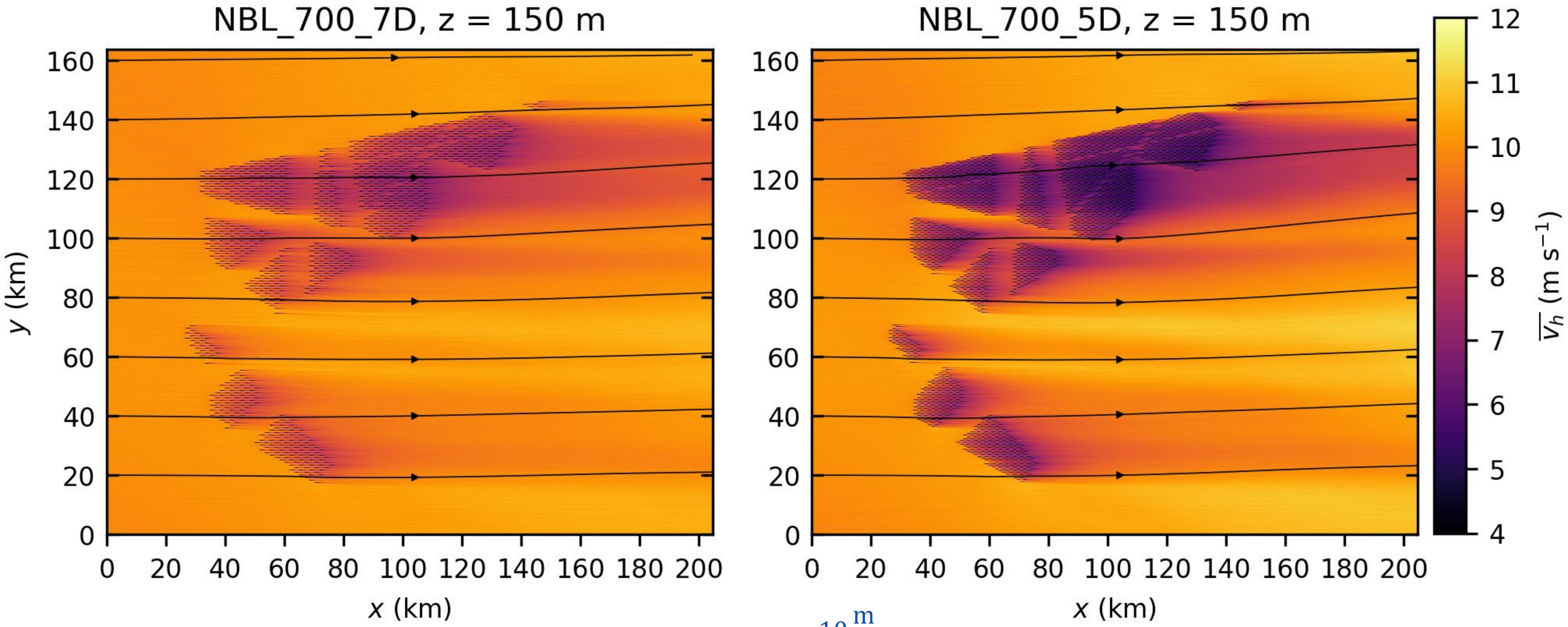
Convective boundary layer (**CBL**):
Variation of boundary layer (BL) height

Stable boundary layer (**SBL**)

Inflow profiles

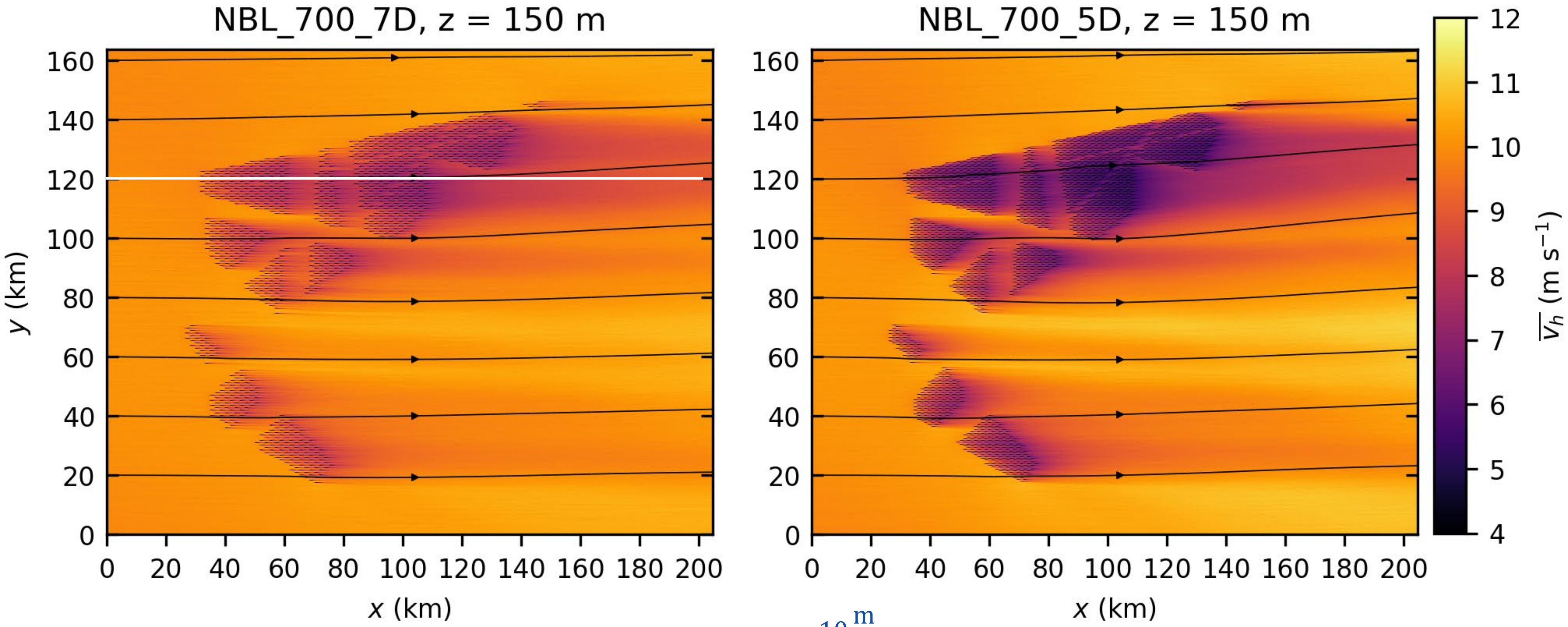


NBL: Variation of turbine spacing



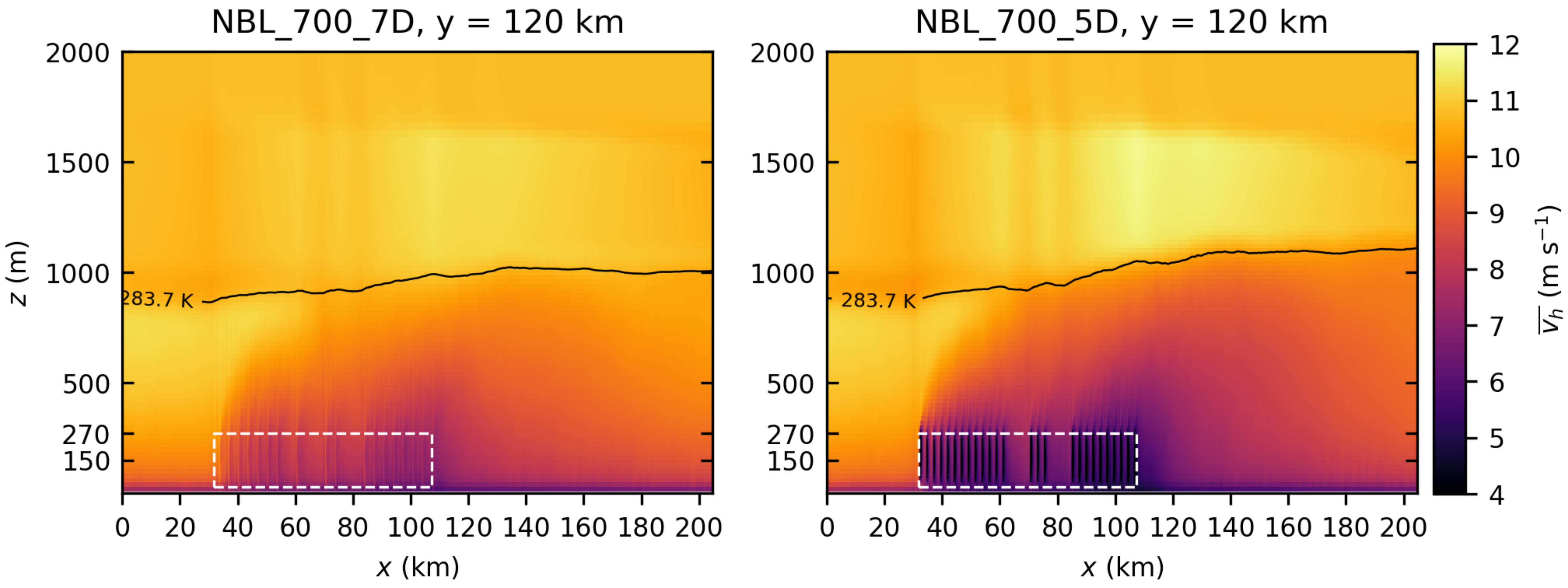
$$\mathrm{Ro} = \frac{v_h}{L * f_c} \approx \frac{10\,\frac{\mathrm{m}}{\mathrm{s}}}{100\ \mathrm{km}\ 10^{-4}\mathrm{s}^{-1}} = 1$$

NBL: Variation of turbine spacing

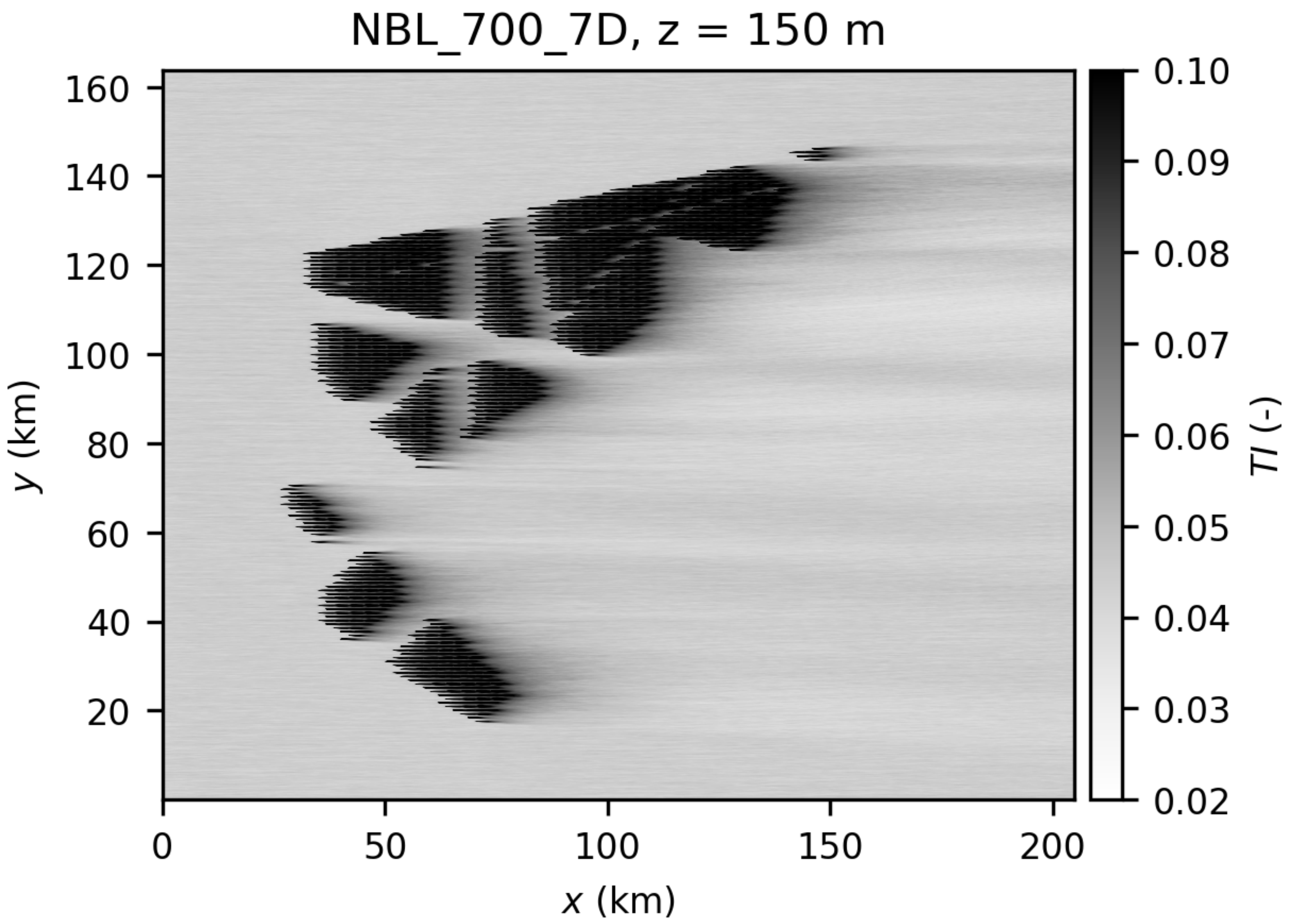


$$\mathrm{Ro} = \frac{v_h}{L * f_c} \approx \frac{10\,\frac{\mathrm{m}}{\mathrm{s}}}{100\ \mathrm{km}\ 10^{-4}\mathrm{s}^{-1}} = 1$$

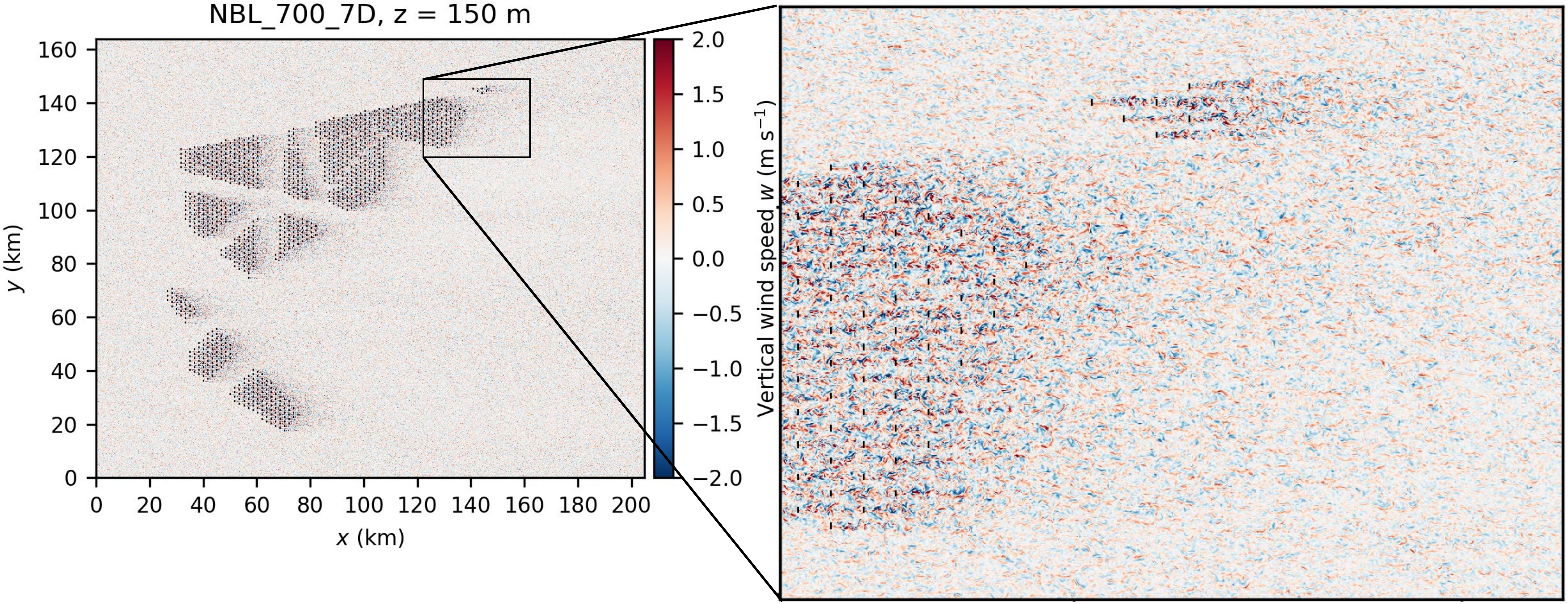
NBL: Variation of turbine spacing



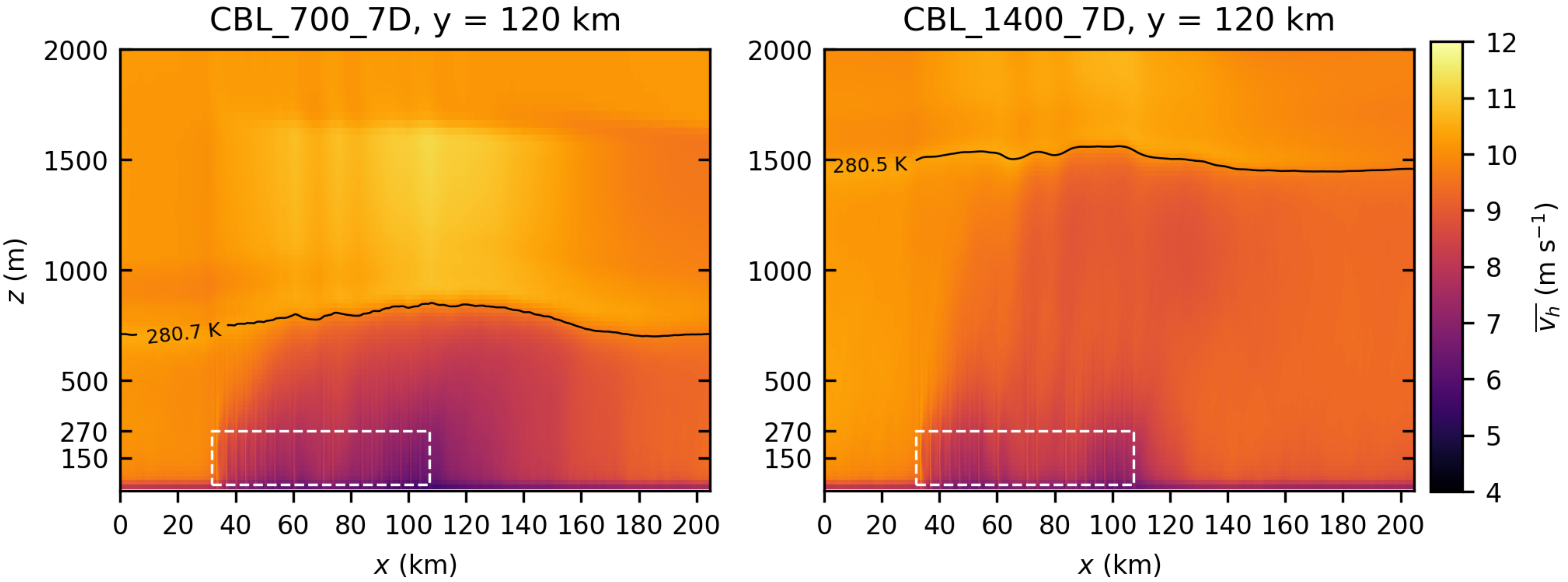
Turbulence intensity in the wake



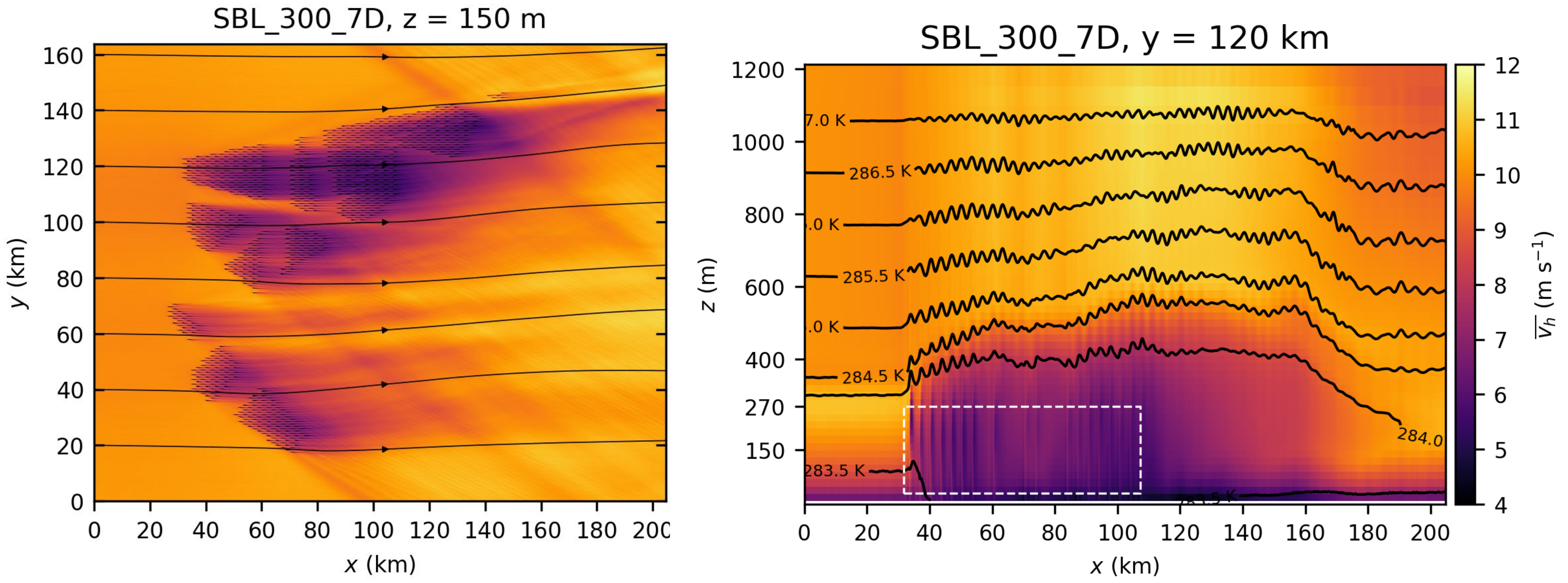
Instantaneous vertical velocity

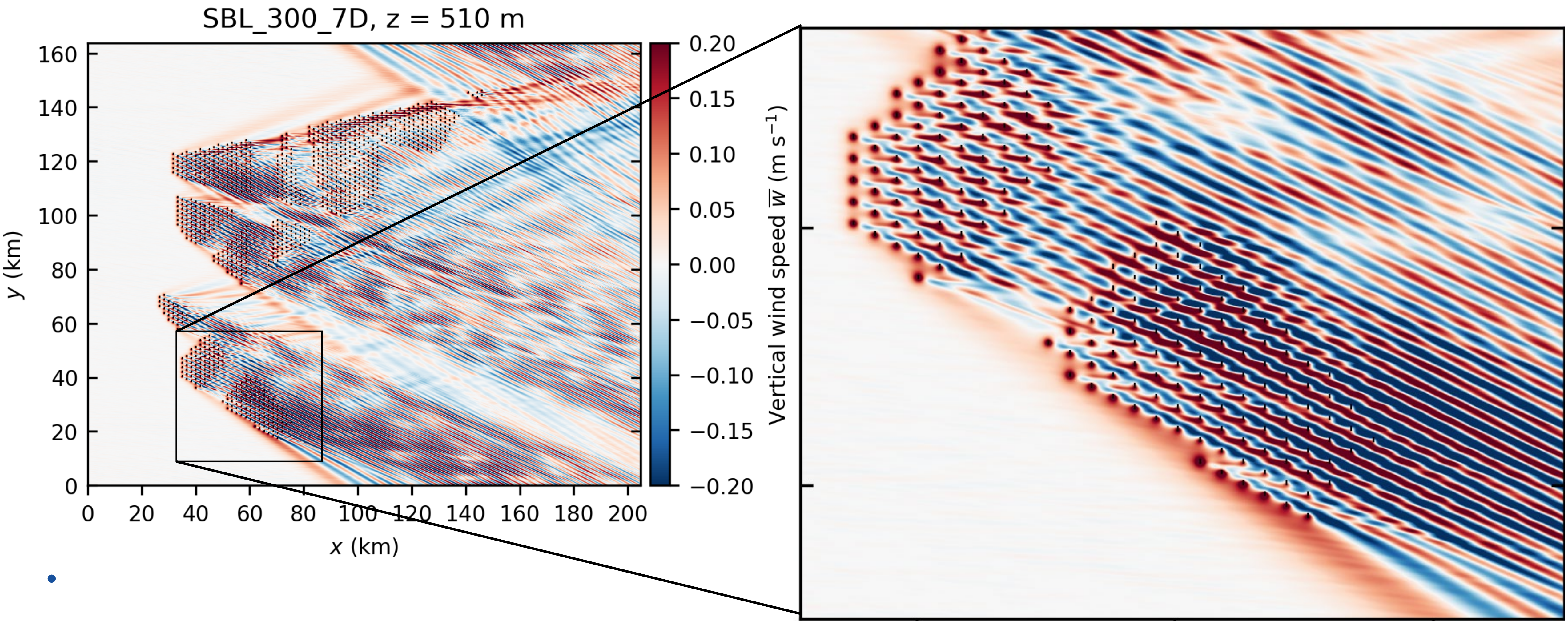


CBL: Variation of boundary layer height



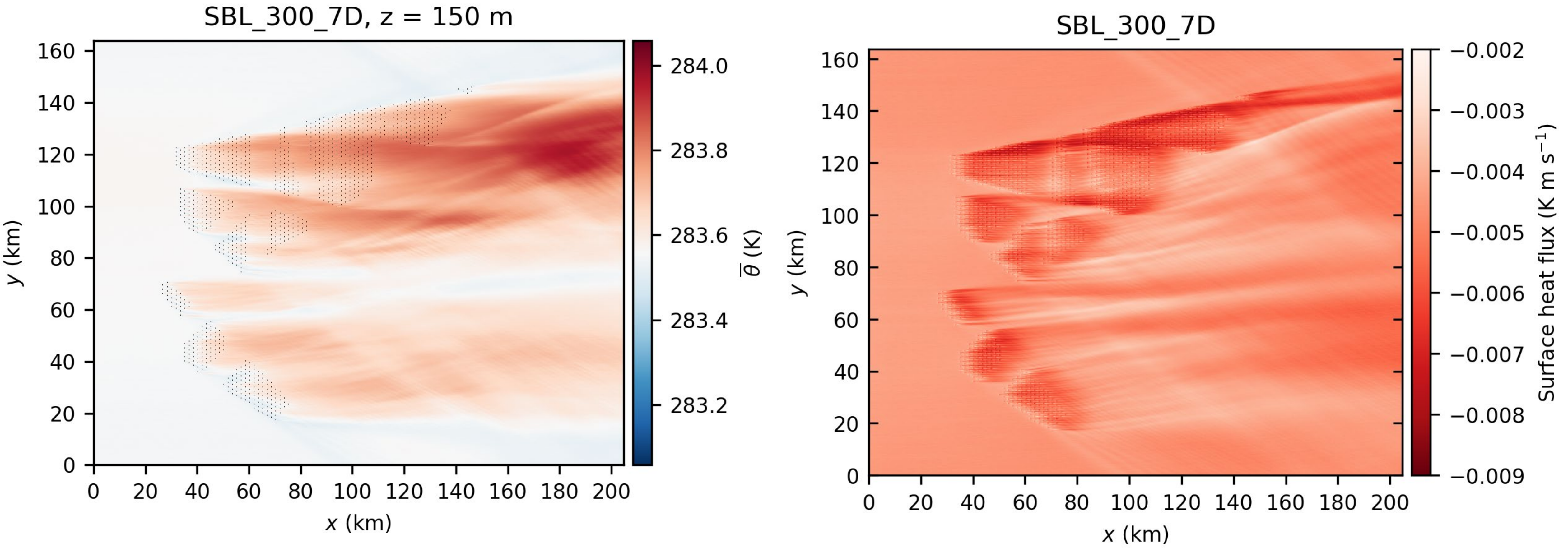
SBL: Wake deflection and gravity waves



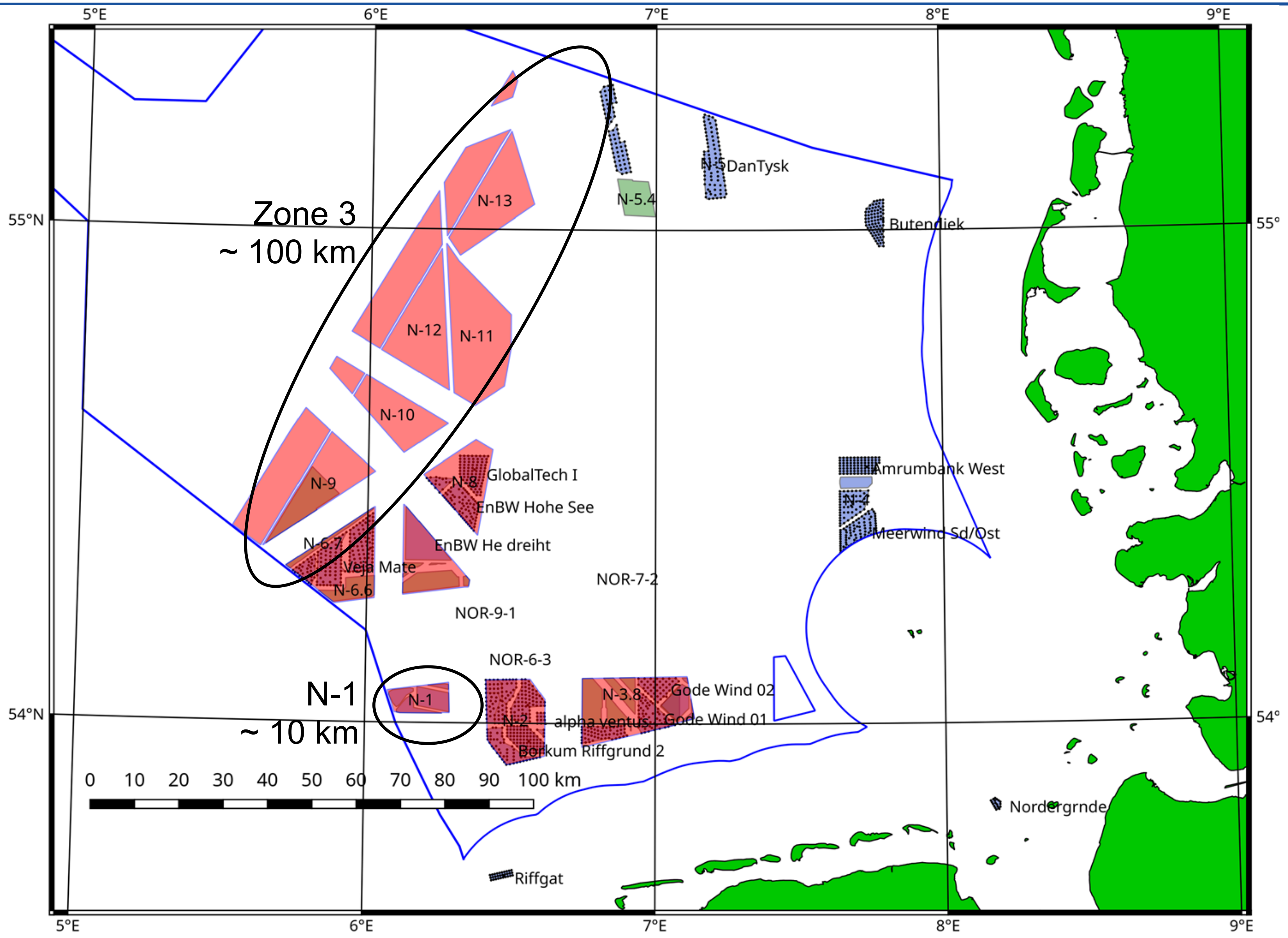

SBL_300_7D, z = 510 m
160
140
120
100
80
60
40
20
0
y (km)
0
20
40
60
80
100
120
140
160
180
200
x (km)
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
Vertical wind speed $\overline{w}$ (m s^{-1})

-

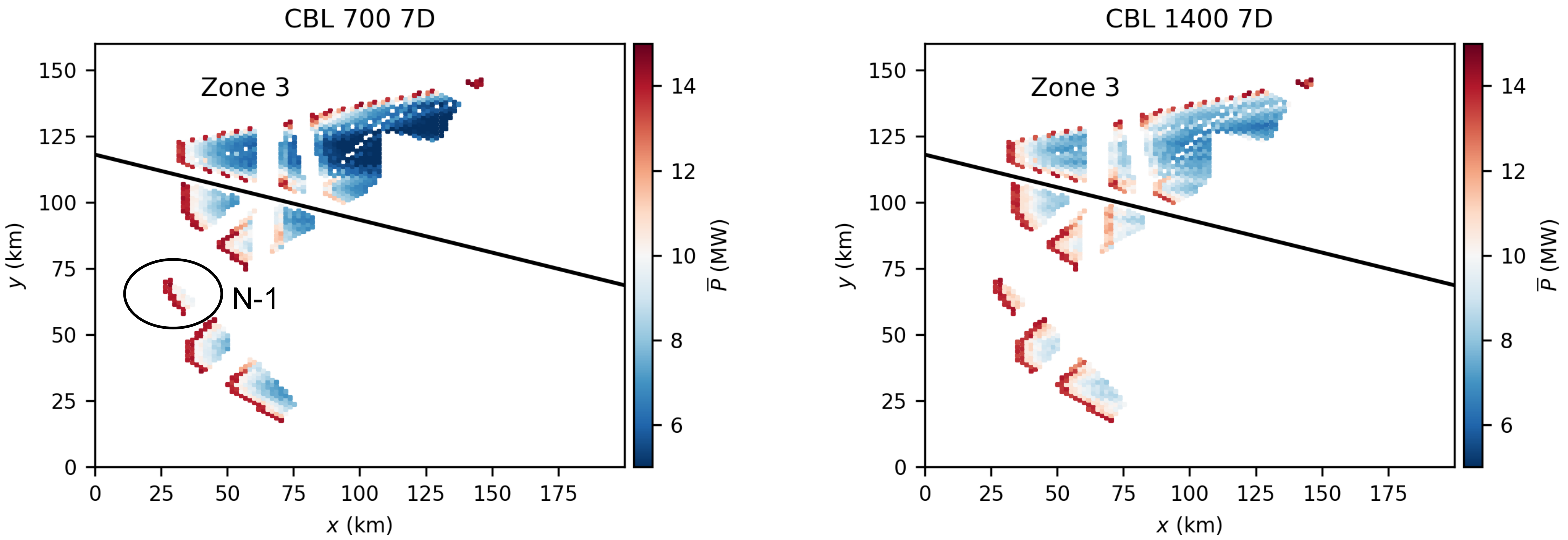
SBL: Entrainment of warm air, surface heat flux



Power output: Comparison between small and large wind farms



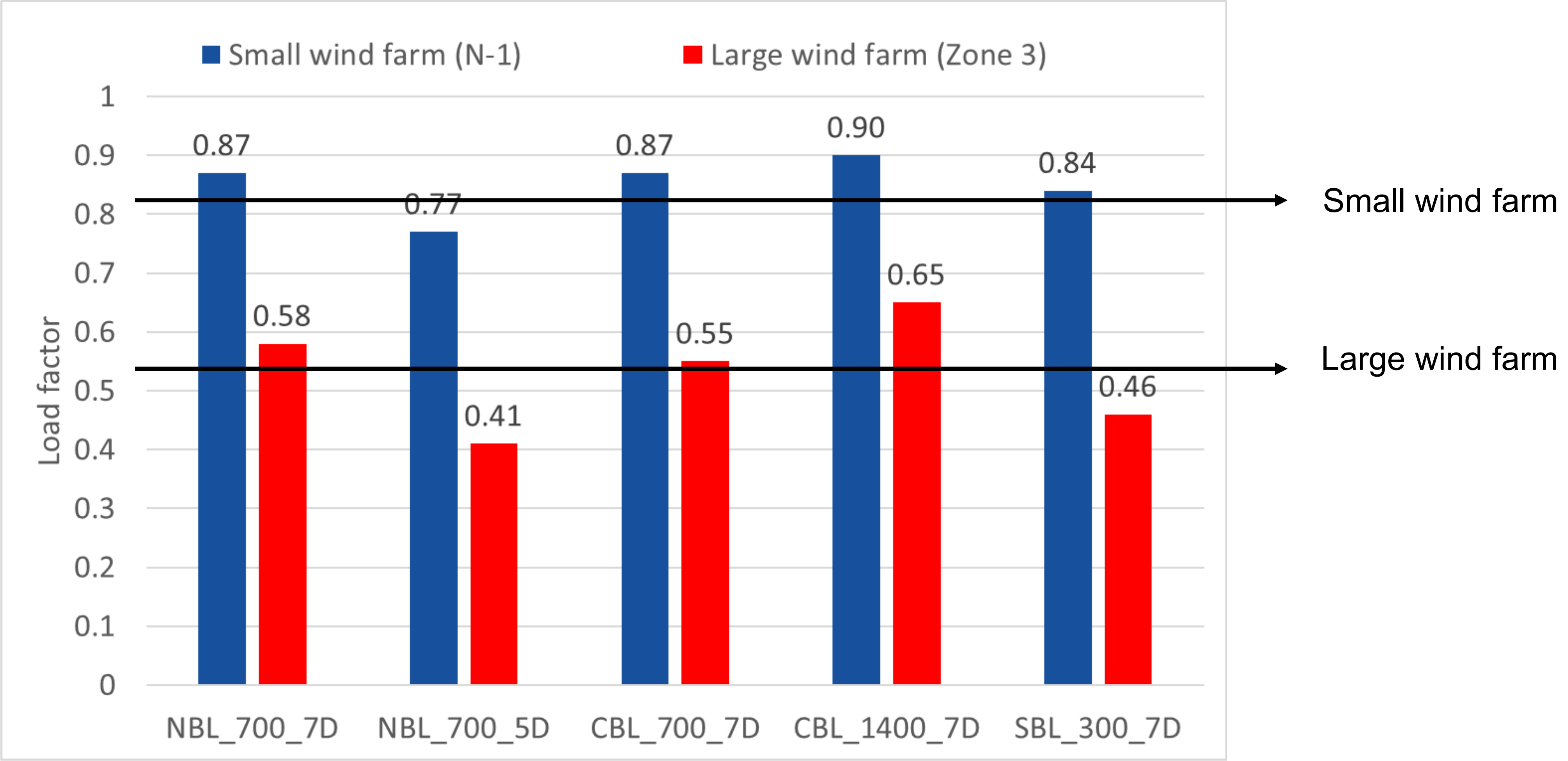
Wind turbine power output



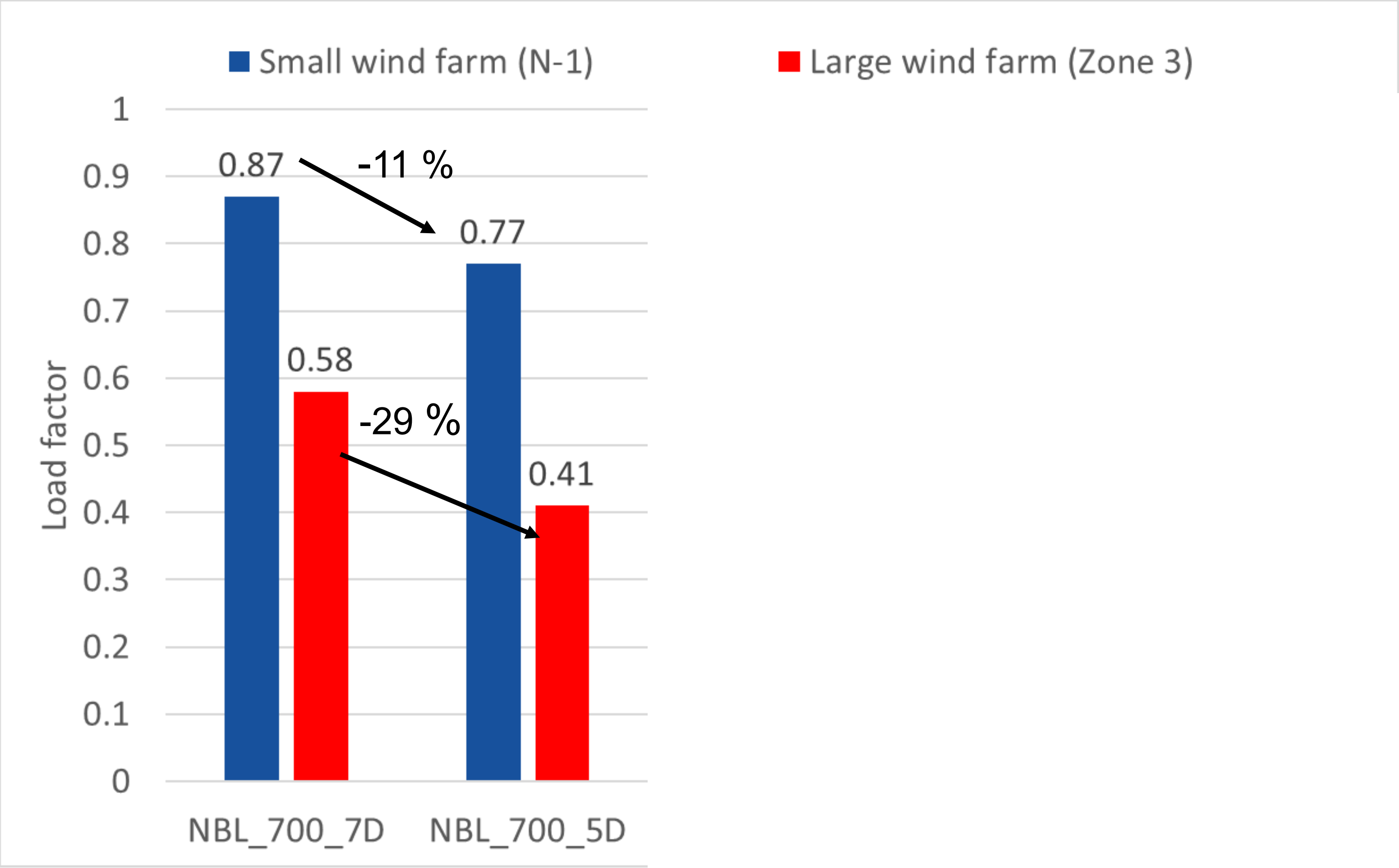
- Load factor = Mean turbine power / first row turbine power

Load factors: Wind farm size

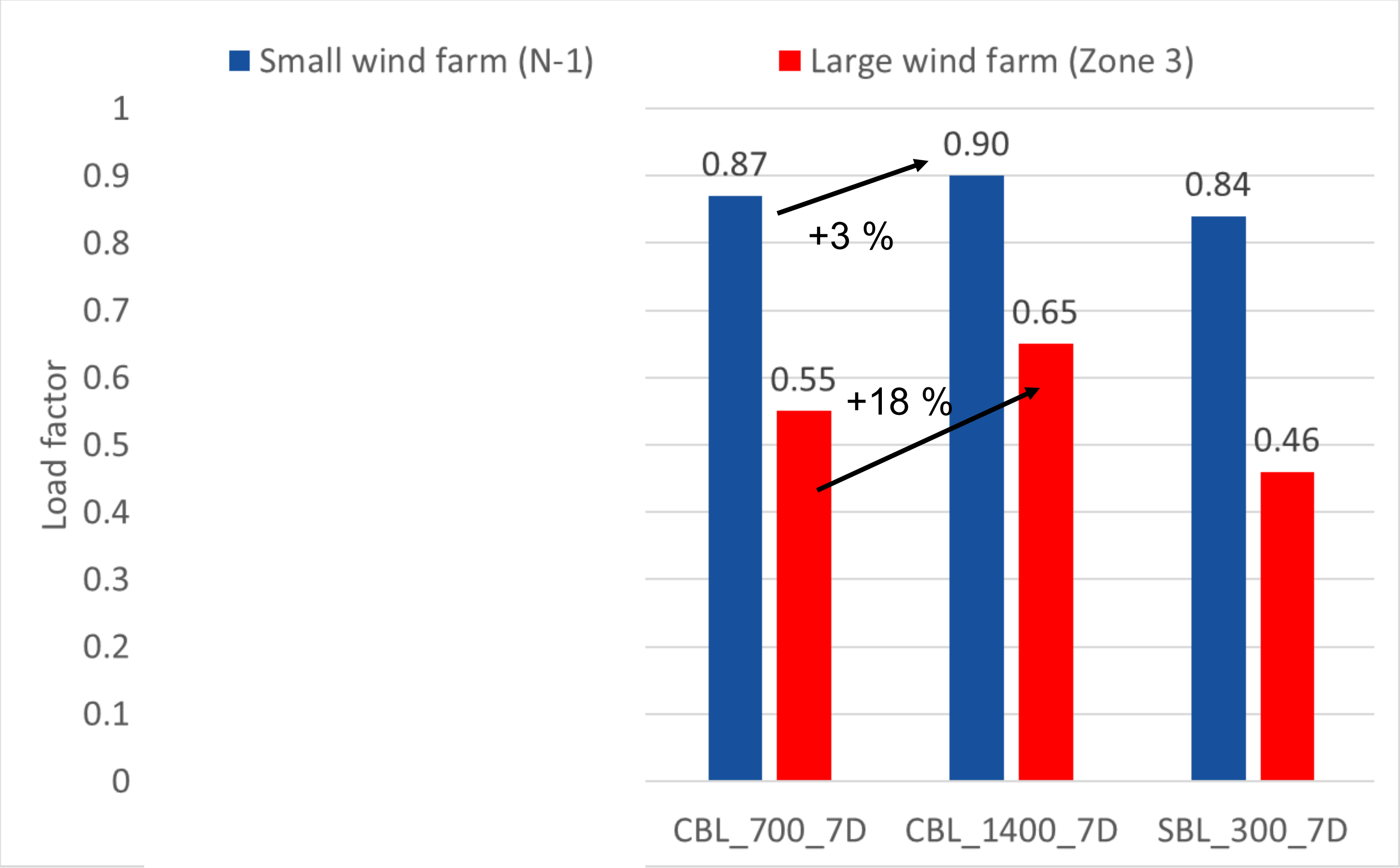
- Load factor = Mean turbine power / first row turbine power



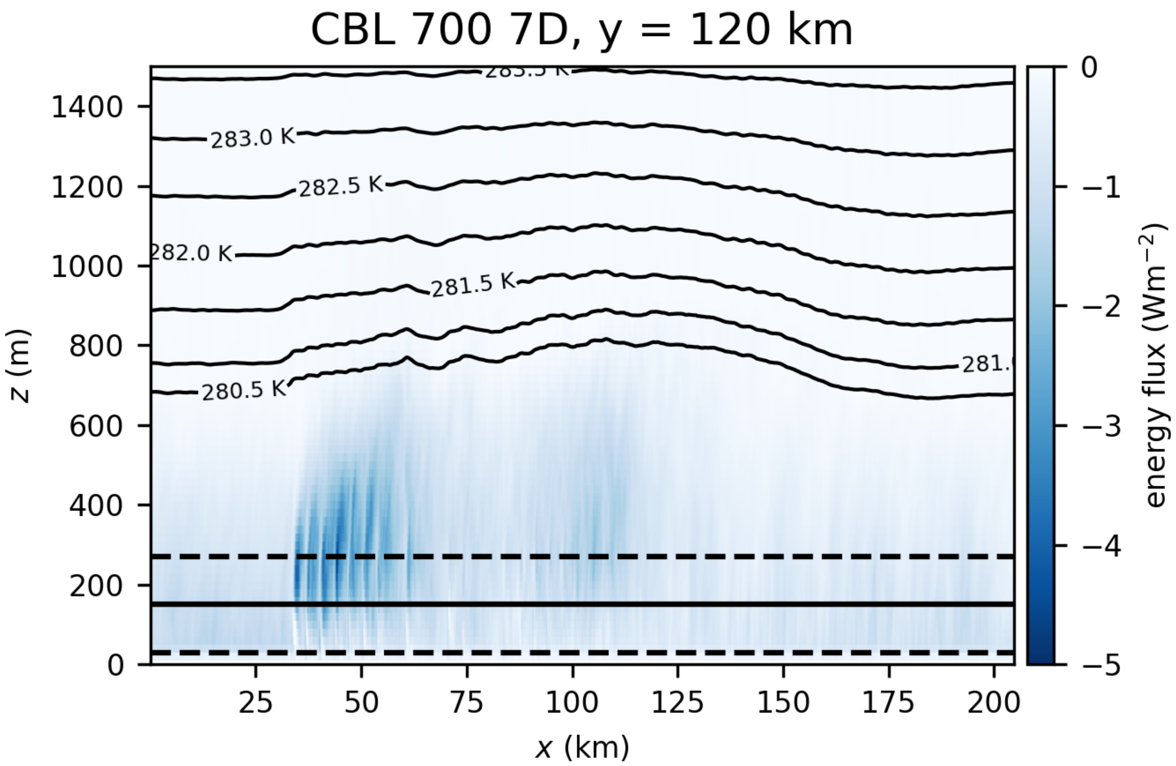
Load factors: Turbine spacing

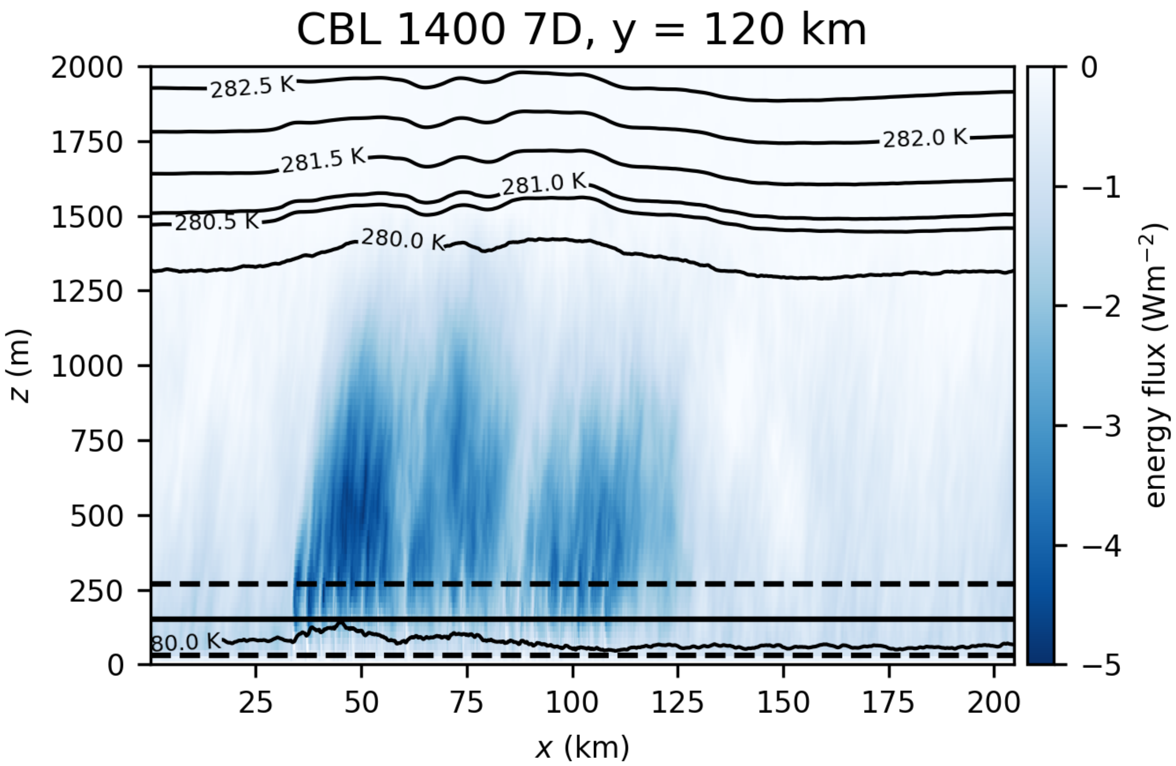


Load factors: Boundary layer height

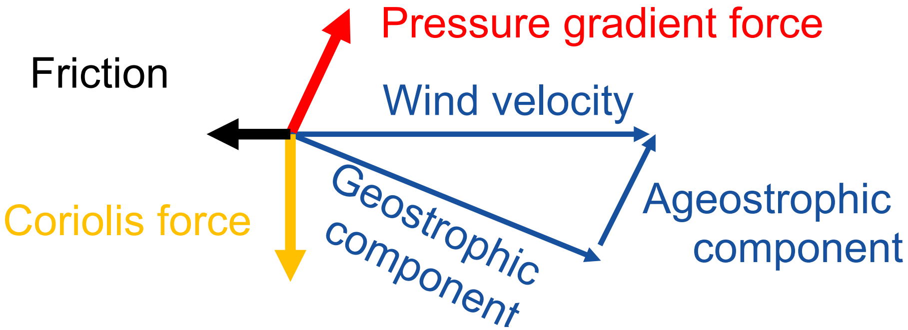


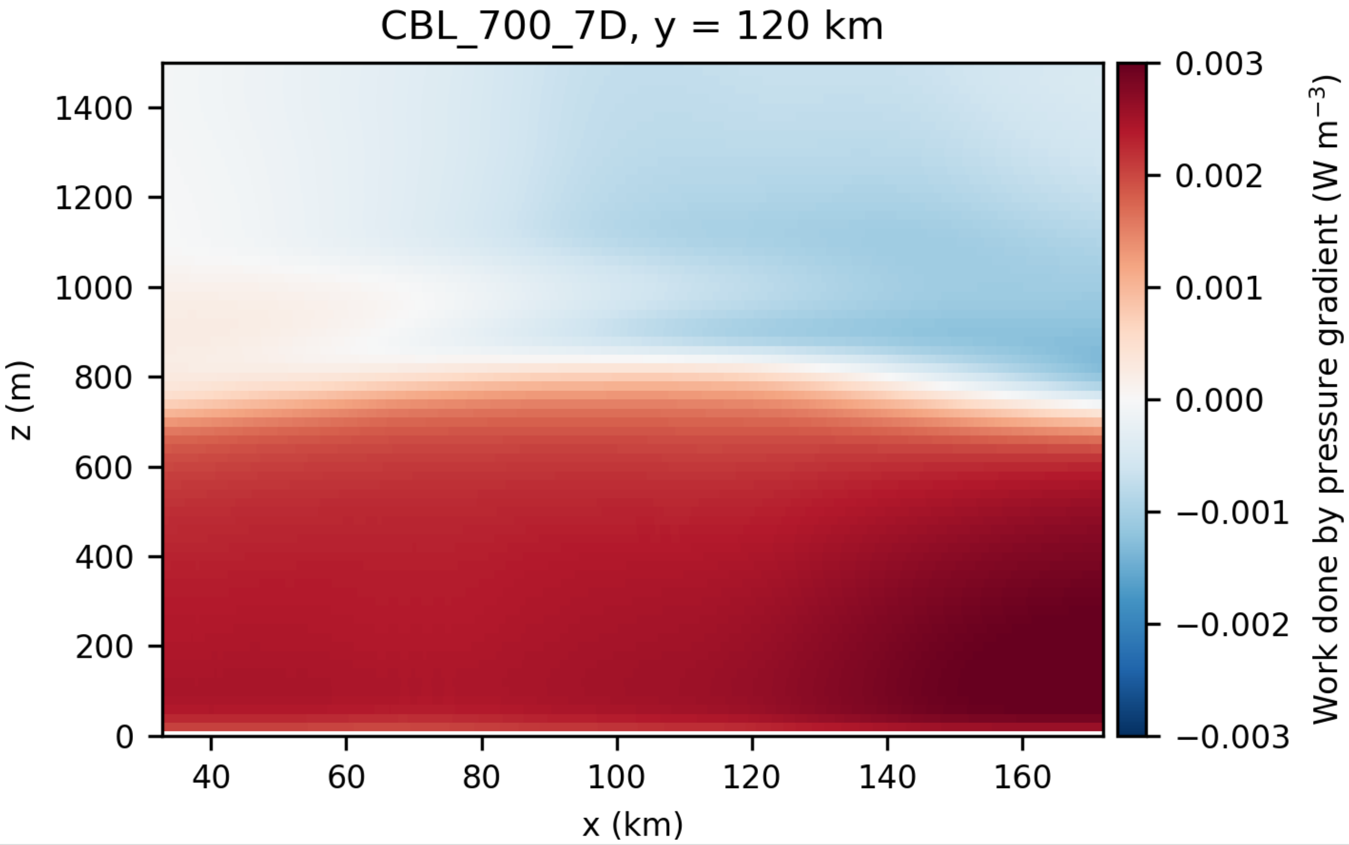
Turbulent vertical kinetic energy flux

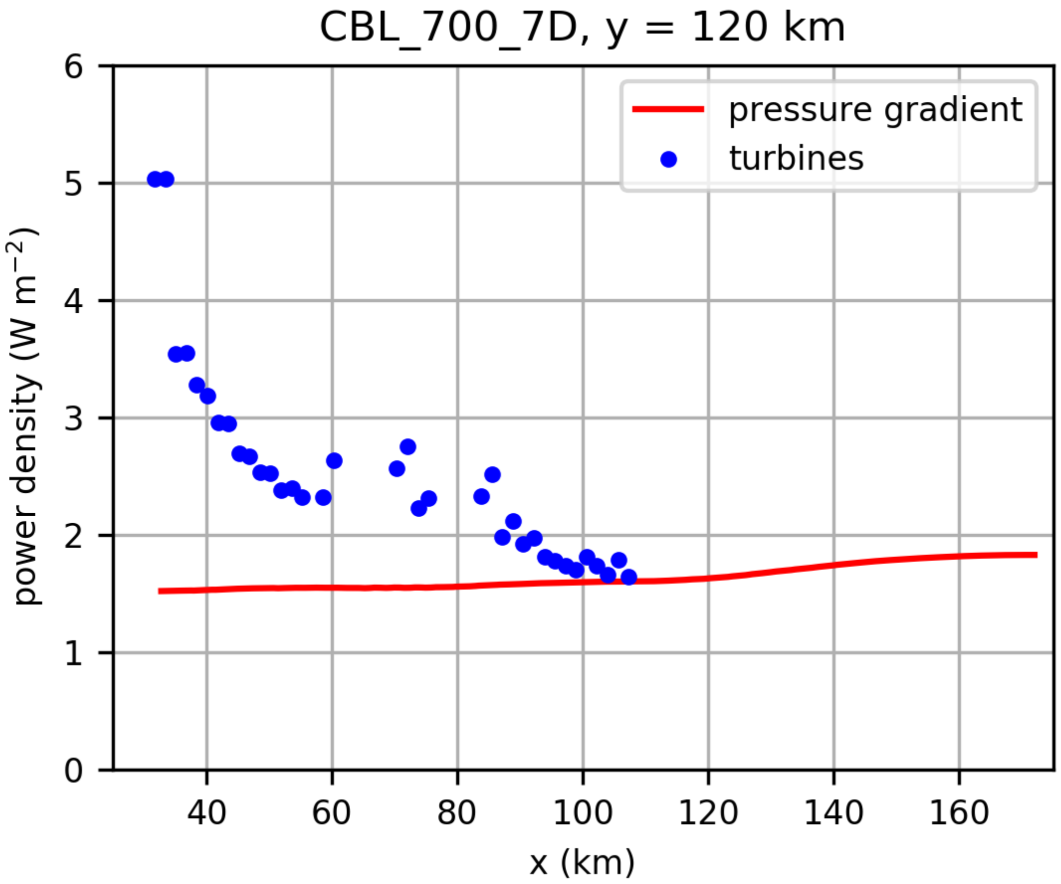




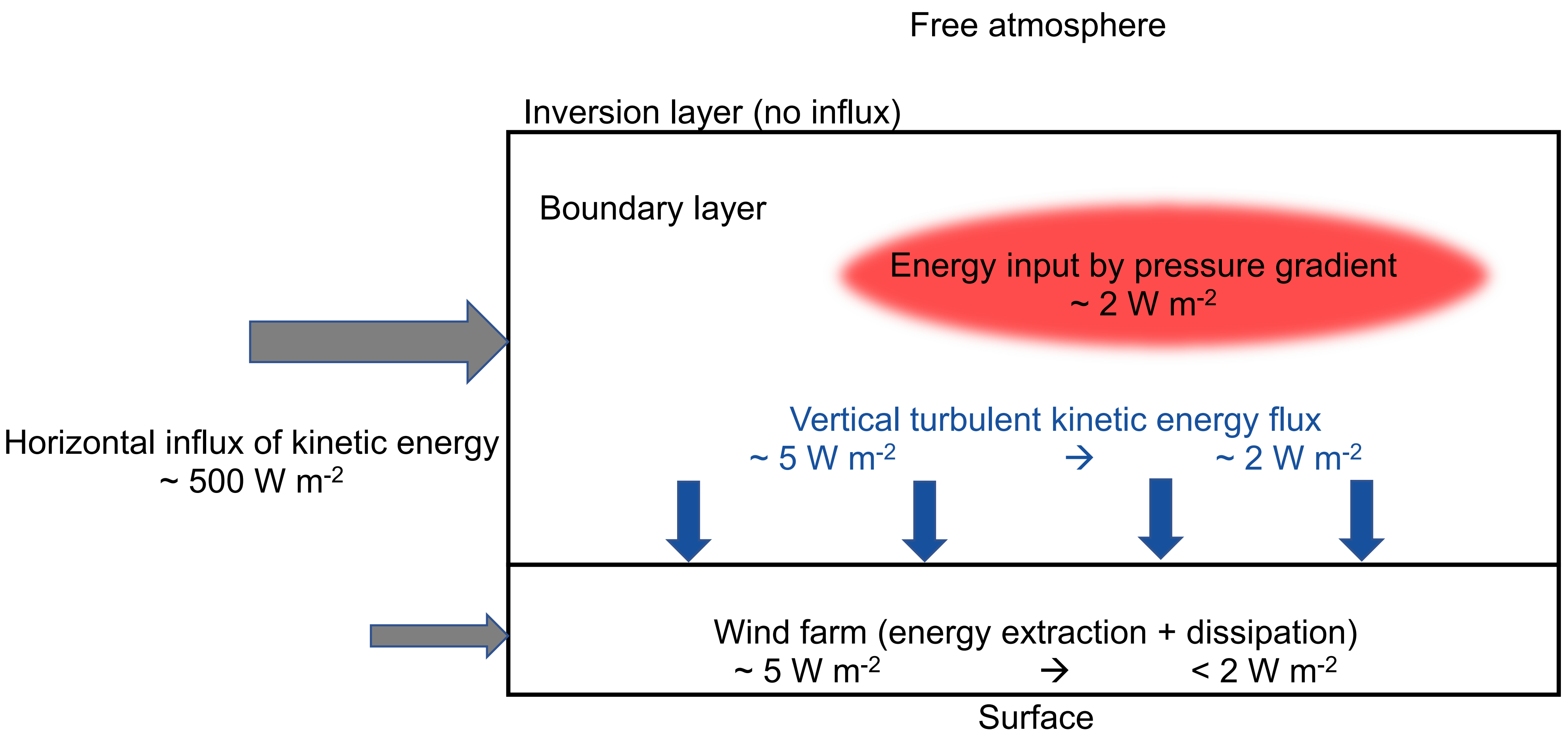
Energy input by pressure gradient force







Energy source model



Conclusions

- How does very large wind farms affect the boundary layer flow?
  - All cases:
    - Boundary layer growth due to flow deceleration and mass flow conservation
    - Counterclockwise wake deflection due to reduced Coriolis force
    - Long wake (> 100 km) in terms of speed deficit, but short (~ 10 km) in terms of turbulence intensity
    - Stronger speed deficit for shallower boundary layers
  - SBL:
    - Short wake, wind speed in far wake is even higher than inflow wind speed
    - Excitation of gravity waves in the free atmosphere
    - Entrainment of warm air into the boundary layer
    - Modified surface heat flux
- How does the power output of very large wind farms depend on the turbine spacing and the meteorological conditions?
  - Mean turbine power (load factor) of large wind farms is much smaller than that of small wind farms.
  - Smaller turbine spacing leads to strong reduction of the load factor.
  - The boundary layer height has a significant influence on the load factor.
  - Main energy source for very large wind farms is the energy input by the pressure gradient.
  - Wake deflection to lower pressure enhances energy input by pressure gradient.