

Large-eddy simulations of the internal boundary layer and wake flow within large wind farms

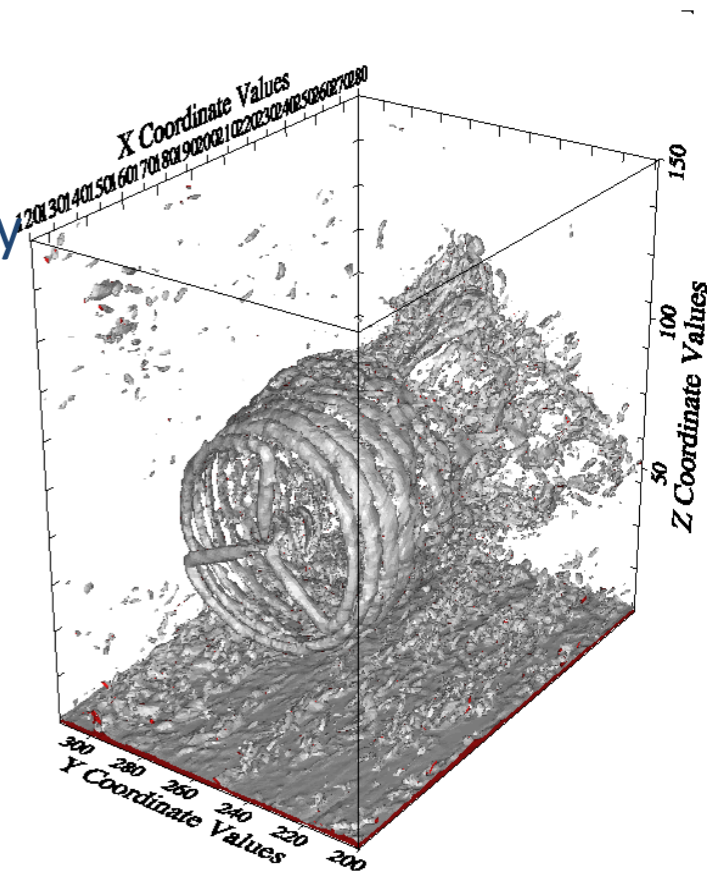
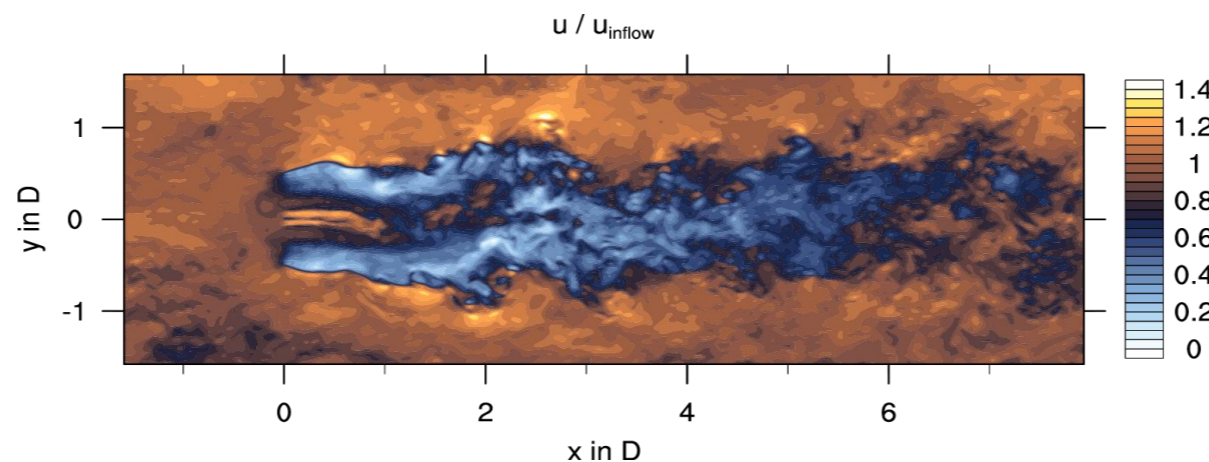


Björn Witha

G. Steinfeld, D. Heinemann

ForWind – Center for Wind Energy Research
Research Group Energy Meteorology
Carl von Ossietzky University Oldenburg, Germany

Contact: bjoern.witha@forwind.de



Motivation



Meerwind Süd/Ost wind farm – © Björn Witha

Motivation



Horns Rev wind farm – © Christian Steiness

The LES-Model PALM

A **PA**rallelized **L**arge-Eddy-Simulation-**M**odel for atmospheric and oceanic flows, developed since 1997 at IMUK, Leibniz University Hannover (Raasch & Schröter, 2001, Meteorol. Z., **10**, 363-372)



palm.muk.uni-hannover.de

Input

Wind profile, temperature profile (stability), surface roughness, surface fluxes *or* nudging

Output

All relevant atmospheric variables: mean and turbulent fluctuations, turbulent fluxes

Computational parameters

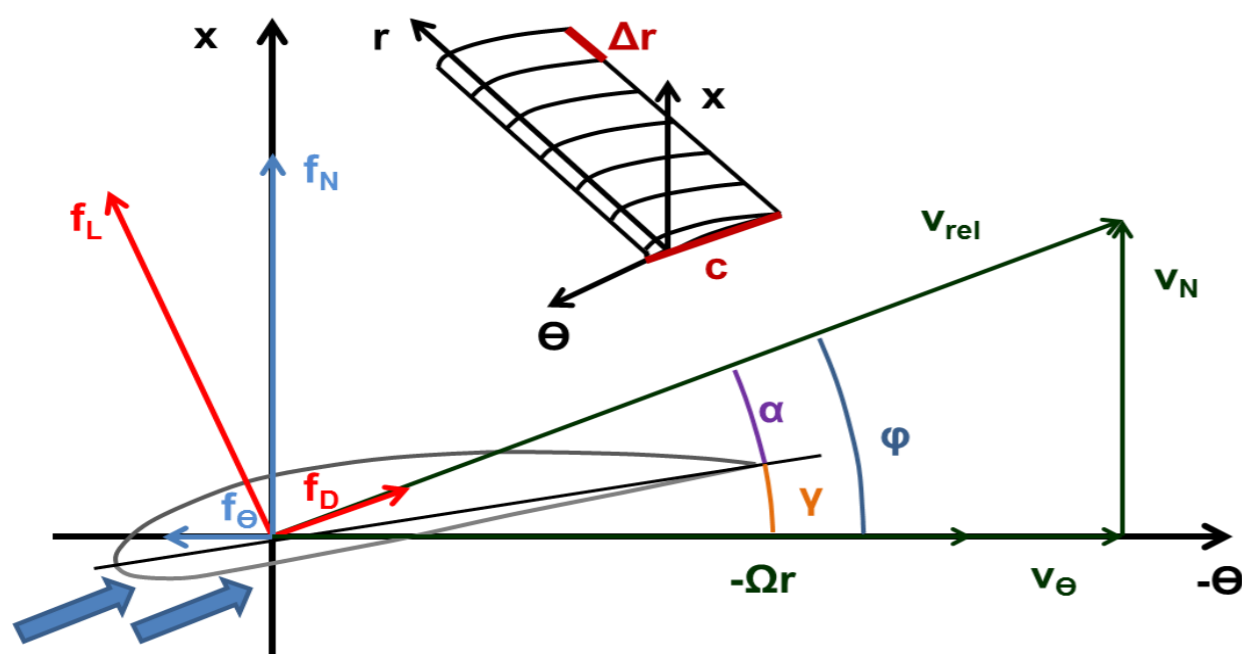
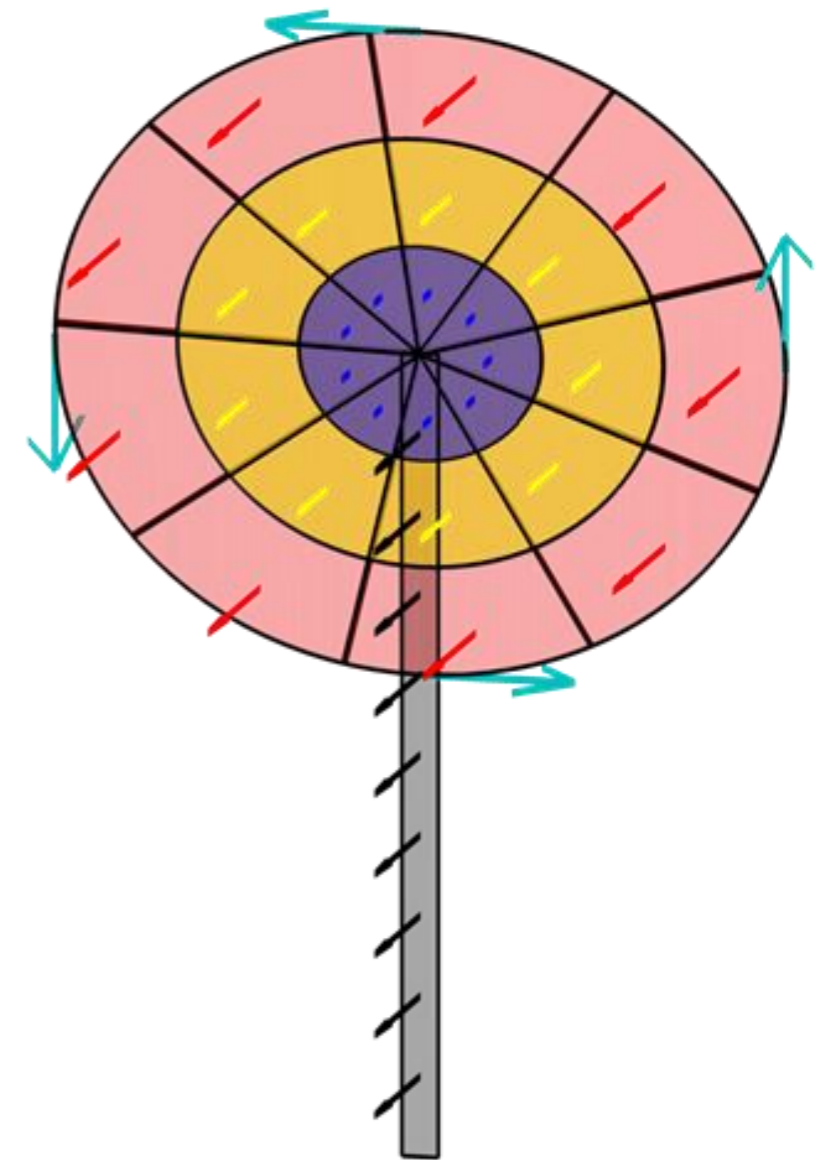
Typical domain size	10 km x 5 km x 2 km
Grid resolution	1 – 10 m
Time step	0.1 – 1 s
Grid point number	10^7 – 10^{10}
Simulation time	up to 400,000 CPU hours

Wind turbine parameterization

Enhanced actuator disk model (with BEM)

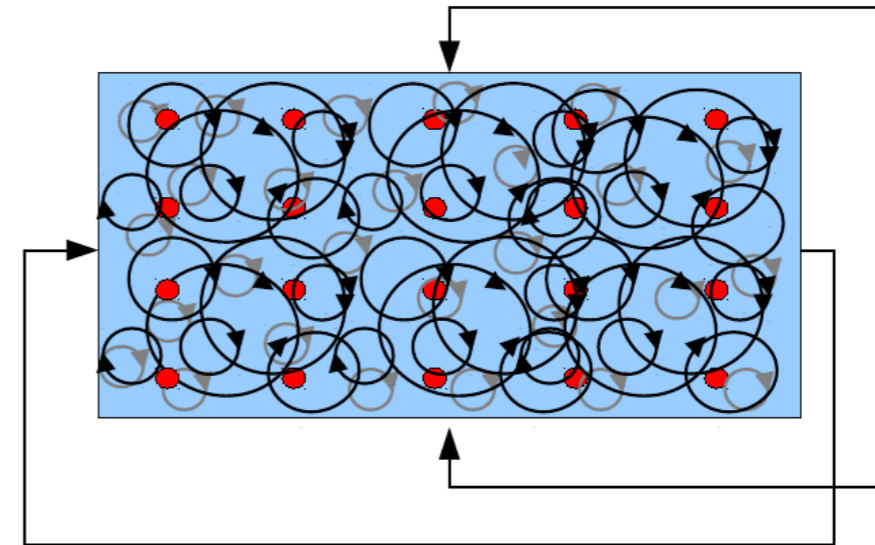
$$F_{L_{b,r}} = \frac{1}{2} \rho C_L V_{rel}^2 \frac{N_b c}{2 \pi r} \quad F_{D_{b,r}} = \frac{1}{2} \rho C_D V_{rel}^2 \frac{N_b c}{2 \pi r}$$

- ✦ considers rotation and local forces
- ✦ almost identical results compared to actuator line model but much faster

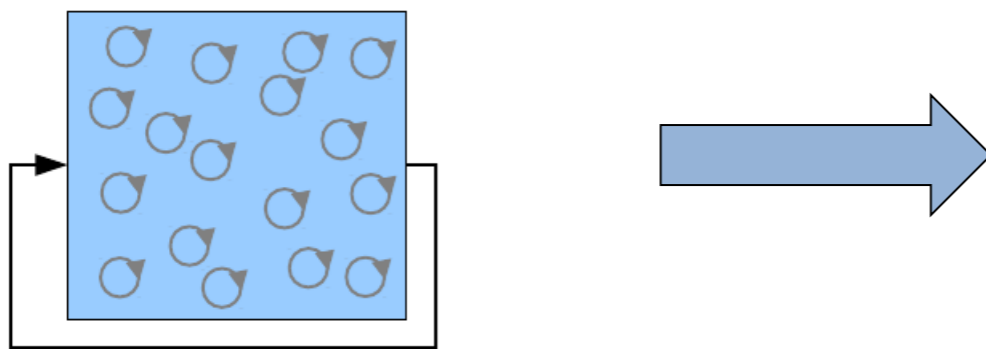


Simulation of large finite and infinite wind farms

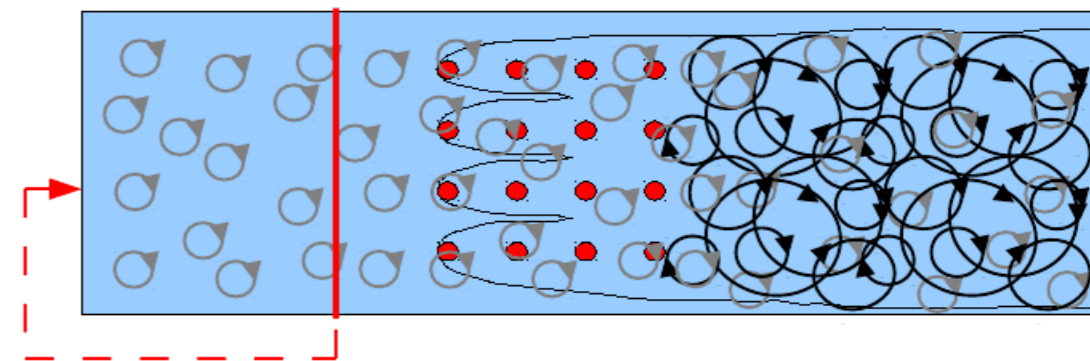
Infinite wind farm realized by periodic horizontal boundary conditions



Finite wind farm requires non-periodic boundary conditions in mean flow direction:

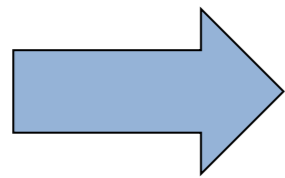


Precursor run with periodic boundary conditions to generate atmospheric turbulence



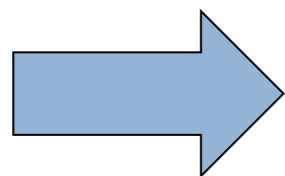
Main run initialized with results of the precursor run, **non-periodic boundary conditions and turbulence recycling**

(1) Comparison of finite and infinite wind farm simulations



Is it appropriate to simulate very large wind farms as infinite?

(2) Effect of atmospheric stability on wake flow in infinite wind farms

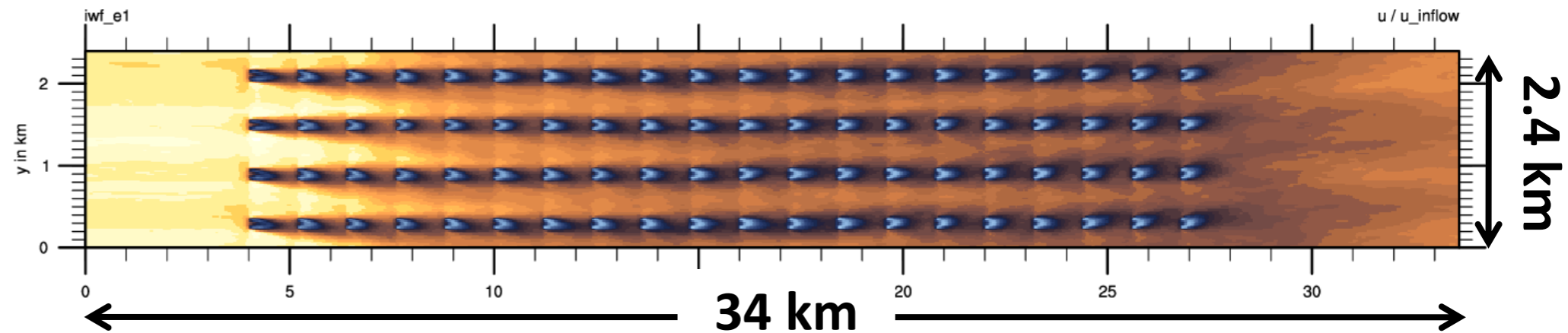


Is stability important or is it acceptable to neglect it?

(1) Finite vs. infinite wind farms – wind speed

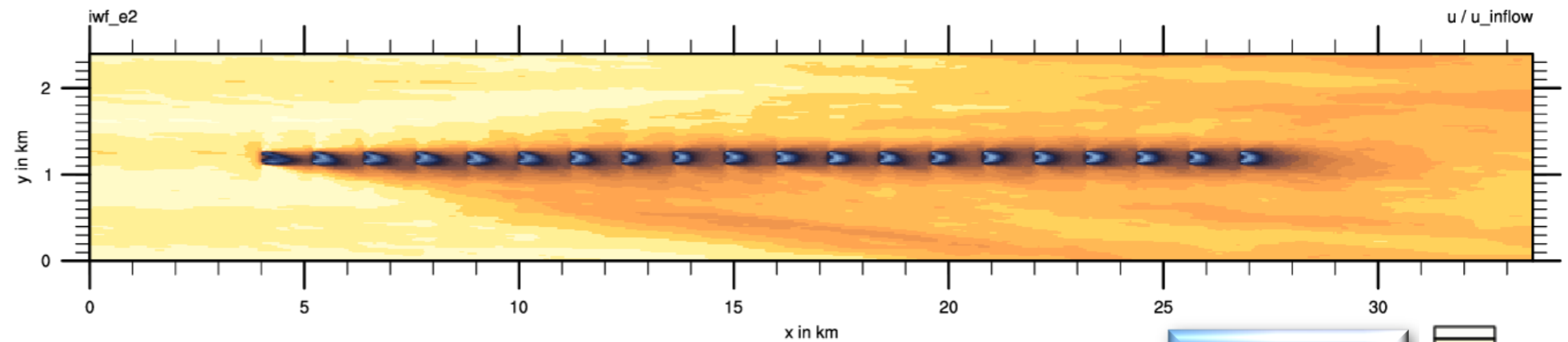
FINITE 1:

20 turbines / row
 $D_x = 1200$ m (9.5 D)
 $D_y = 600$ m (4.8 D)



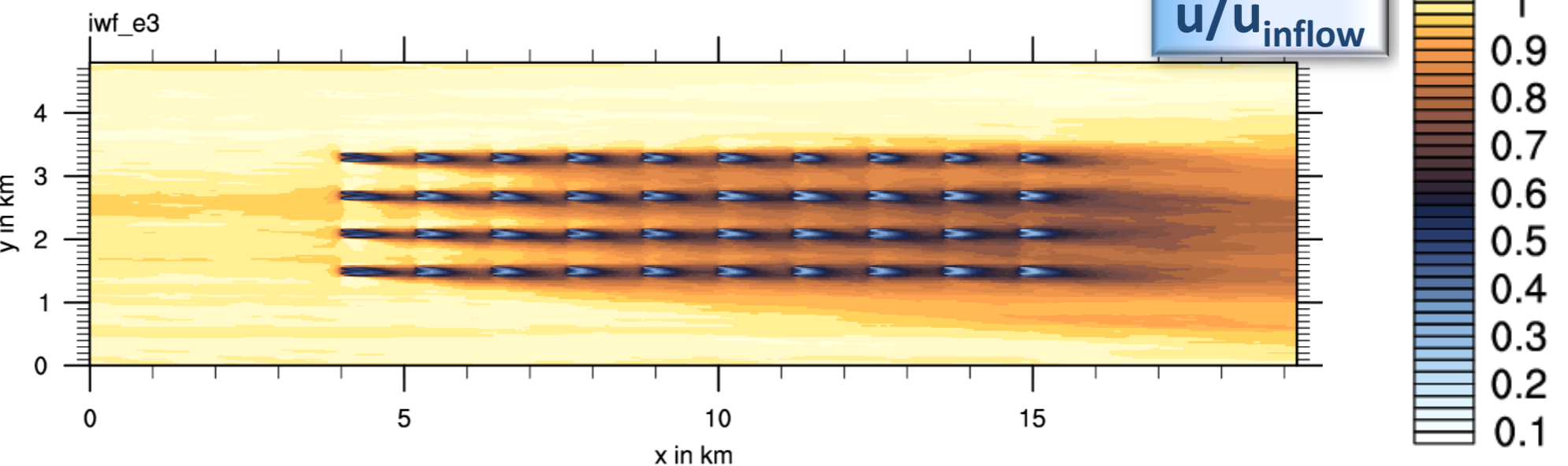
FINITE 2:

20 turbines / row
 $D_x = 1200$ m (9.5 D)
 $D_y = 2400$ m (17 D)

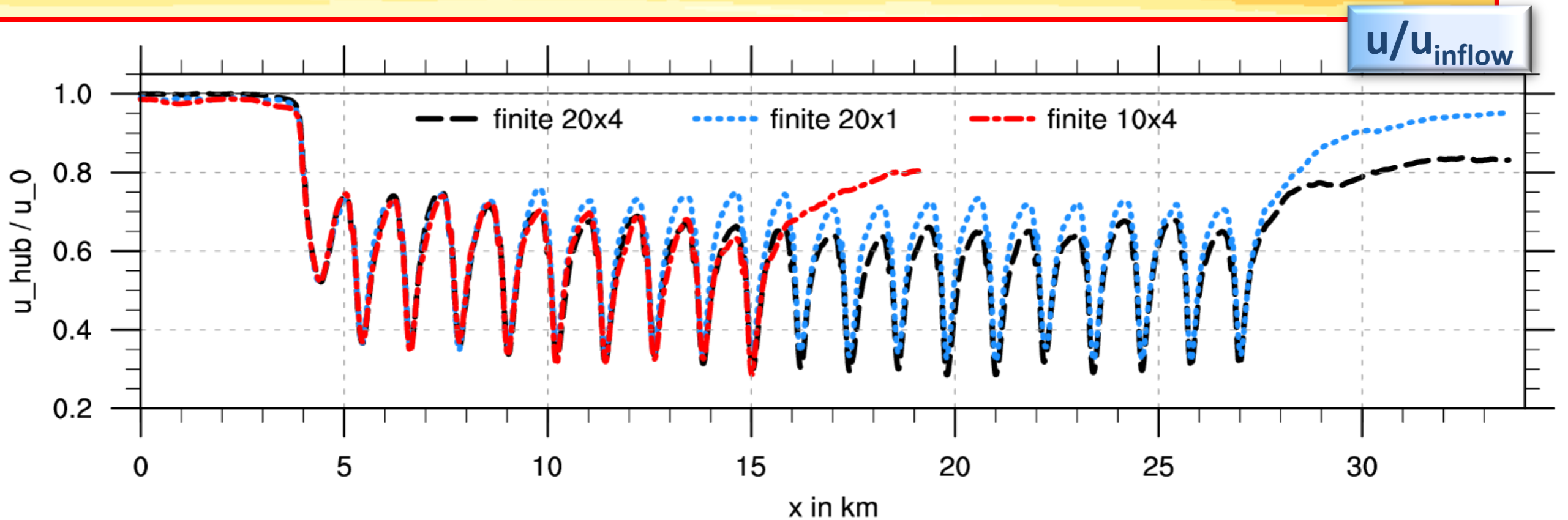
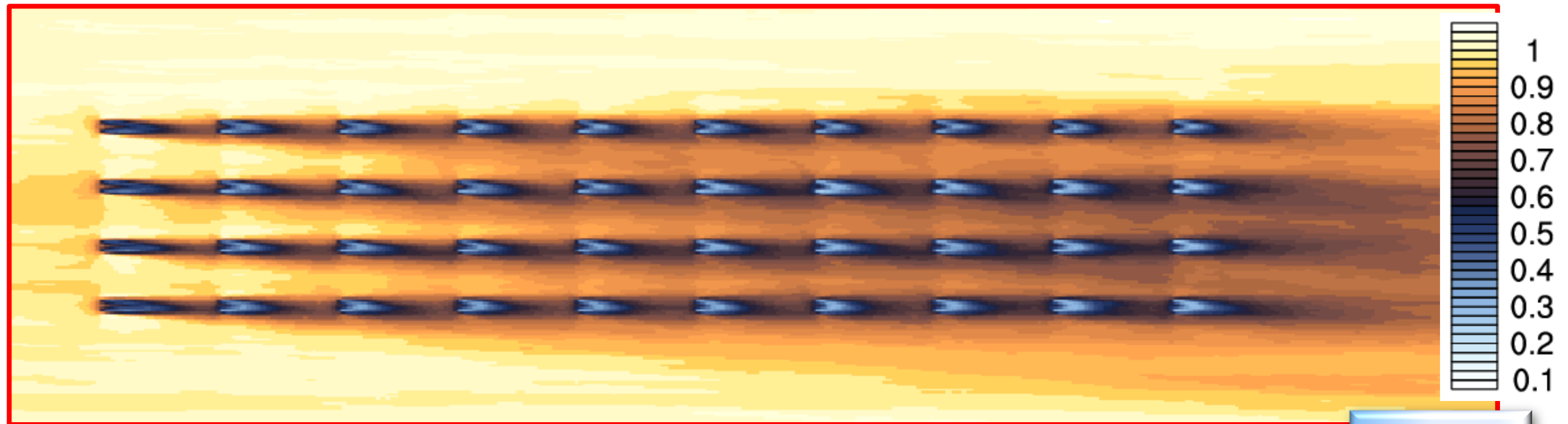


FINITE 3:

10 turbines / row
 $D_x = 1200$ m (9.5 D)
 $D_y = 600$ m (4.8 D)



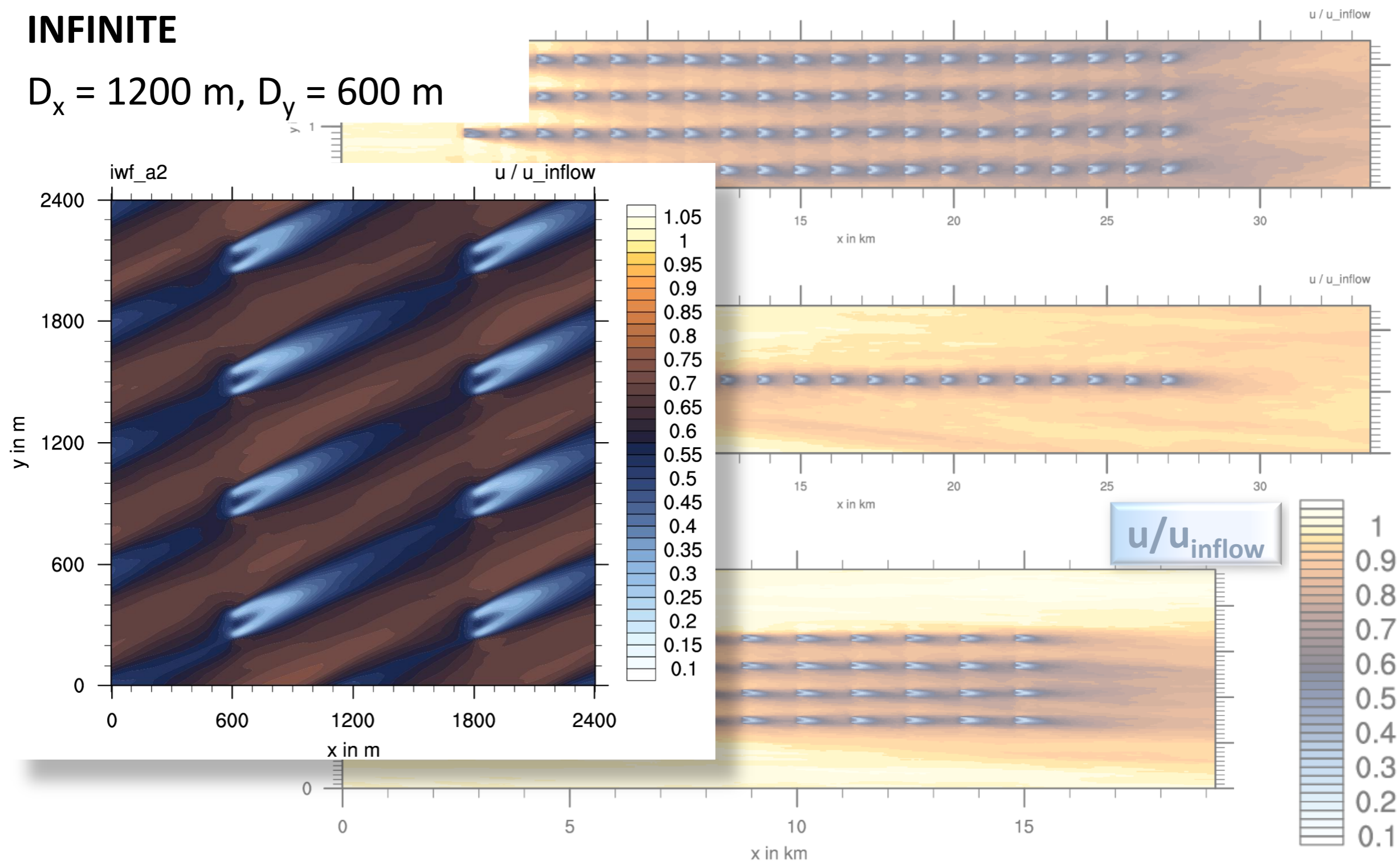
(1) Finite vs. infinite wind farms – wind speed



(1) Finite vs. infinite wind farms – wind speed

INFINITE

$D_x = 1200 \text{ m}$, $D_y = 600 \text{ m}$



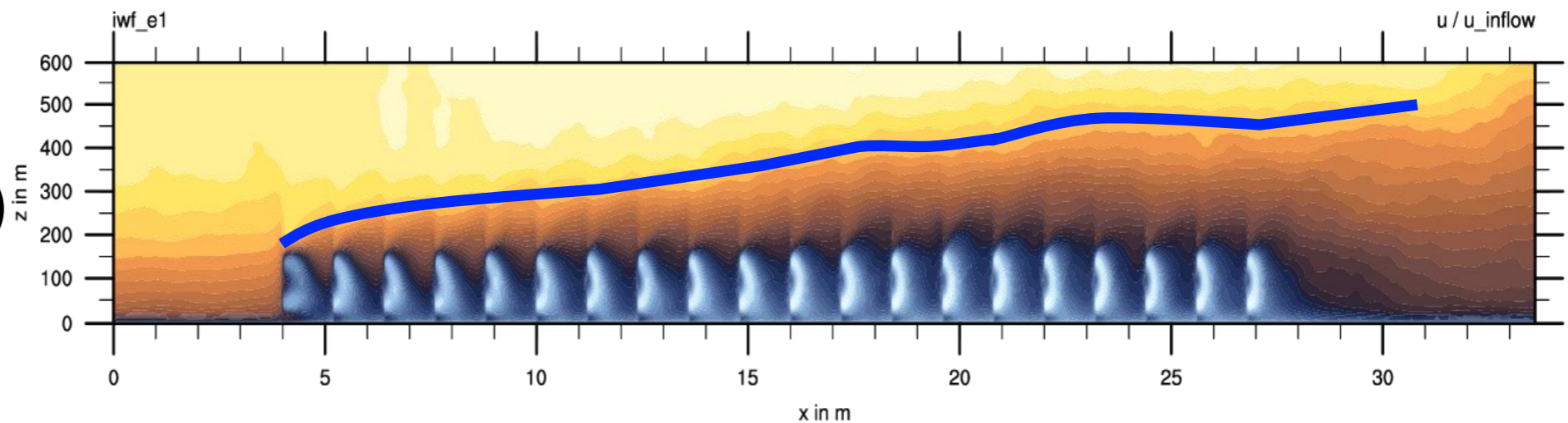
(1) Finite vs. infinite wind farms – wind speed

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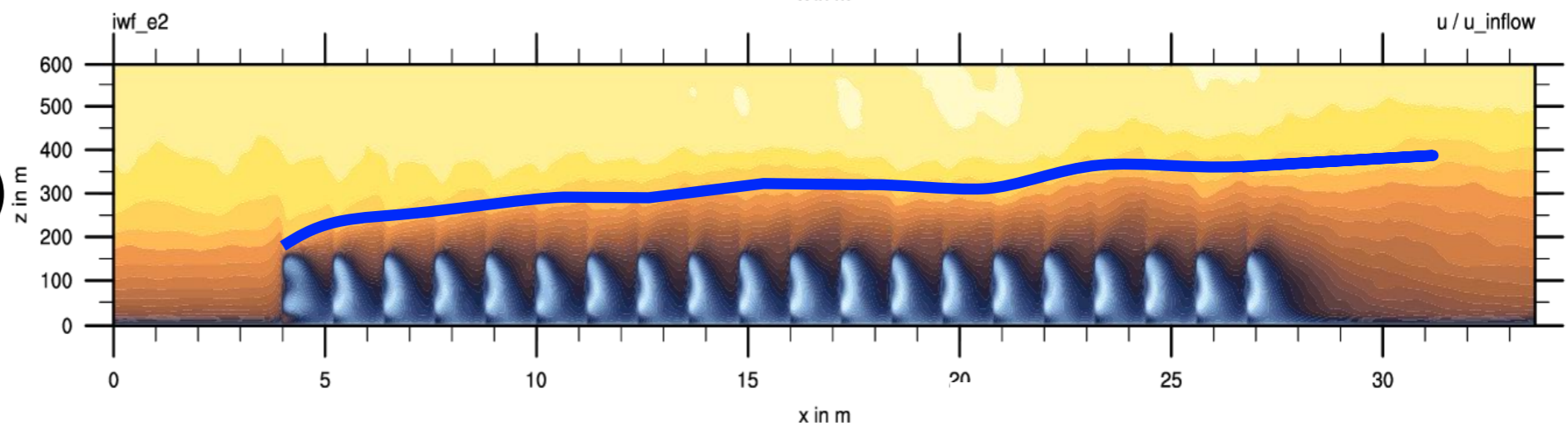


FINITE 2:

20 turbines / row

$D_x = 1200$ m (9.5 D)

$D_y = 2400$ m (17 D)

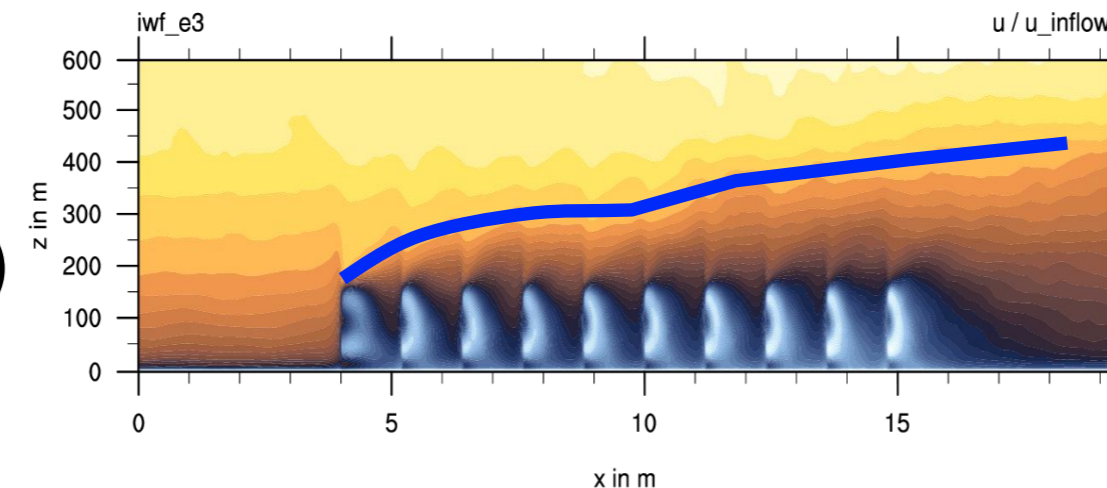


FINITE 3:

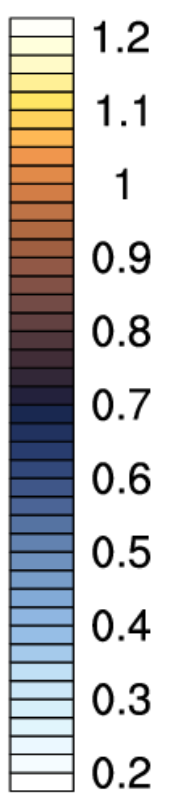
10 turbines / row

$D_x = 1200$ m (9.5 D)

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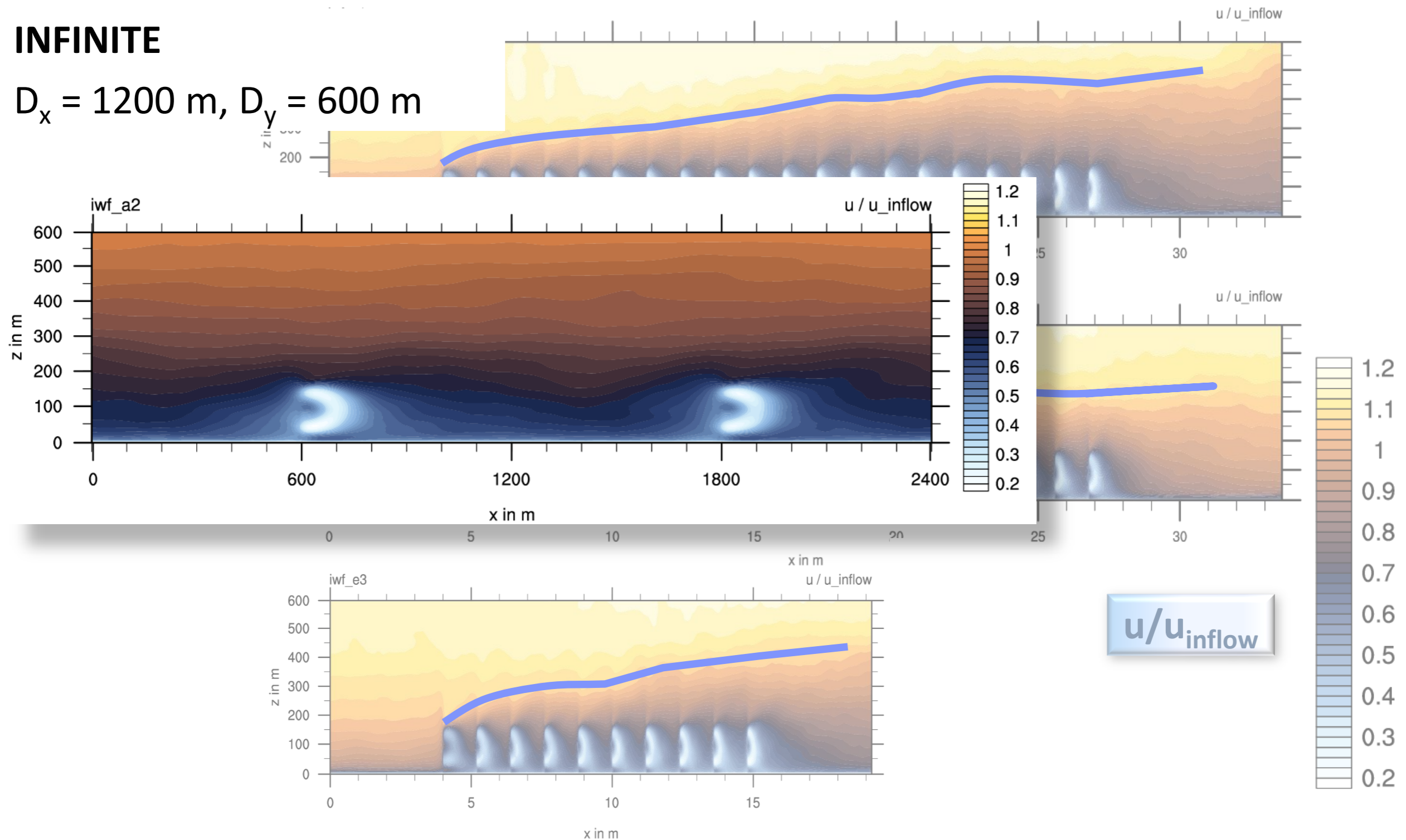
u/u_{inflow}



(1) Finite vs. infinite wind farms – wind speed

INFINITE

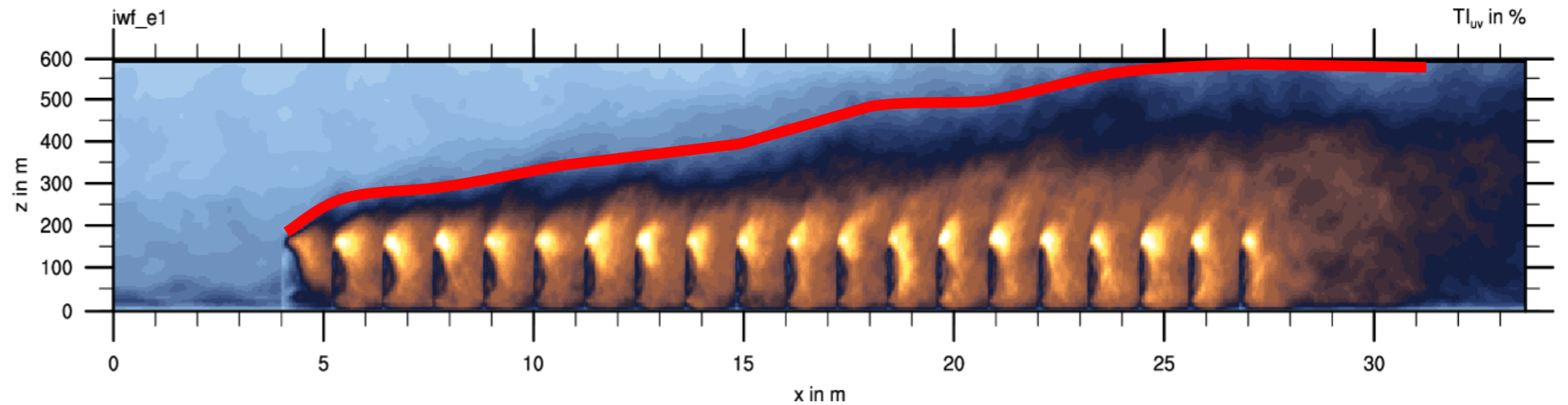
$D_x = 1200 \text{ m}$, $D_y = 600 \text{ m}$



(1) Finite vs. infinite wind farms – turbulence intensity

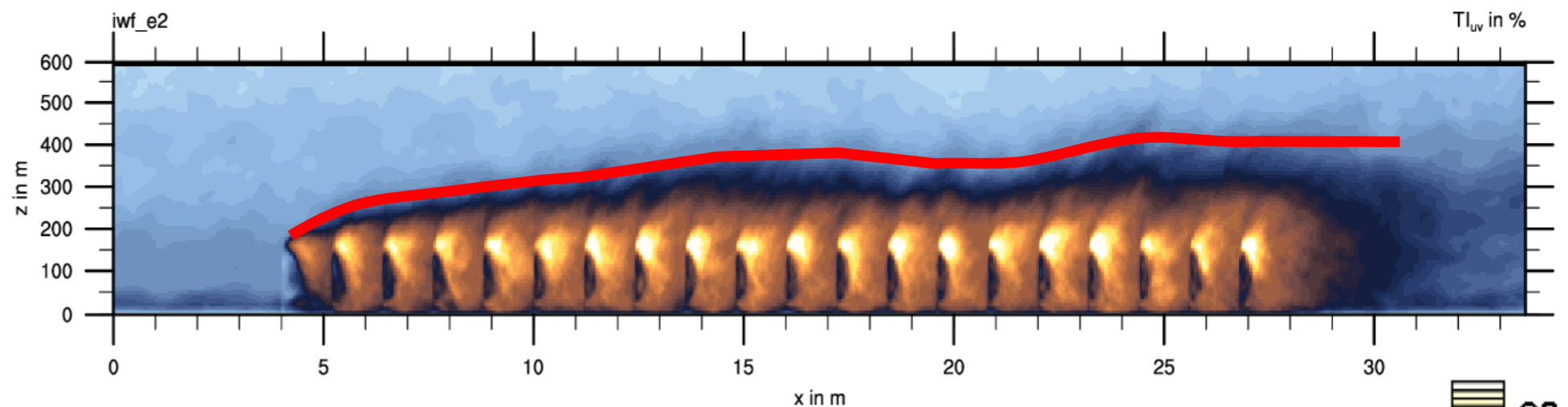
FINITE 1:

20 turbines / row
 $D_x = 1200$ m (9.5 D)
 $D_y = 600$ m (4.8 D)



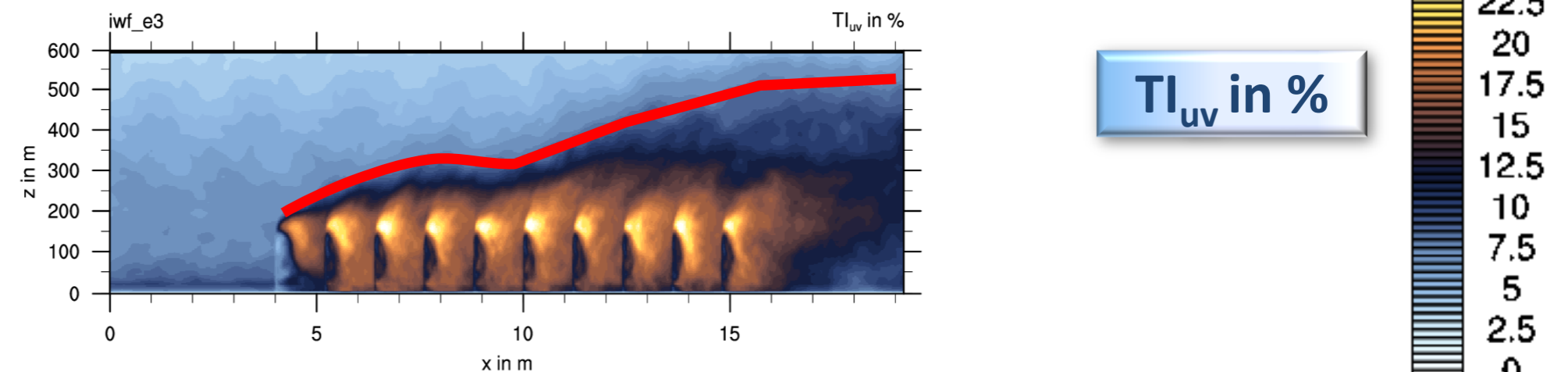
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20 turbines / row
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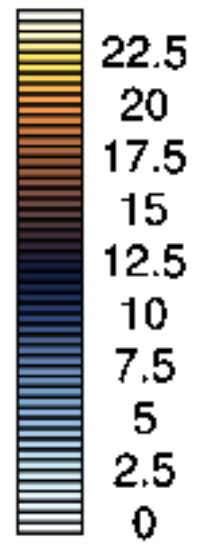


FINITE 3:

10 turbines / row
 $D_x = 1200$ m (9.5 D)
 $D_y = 600$ m (4.8 D)



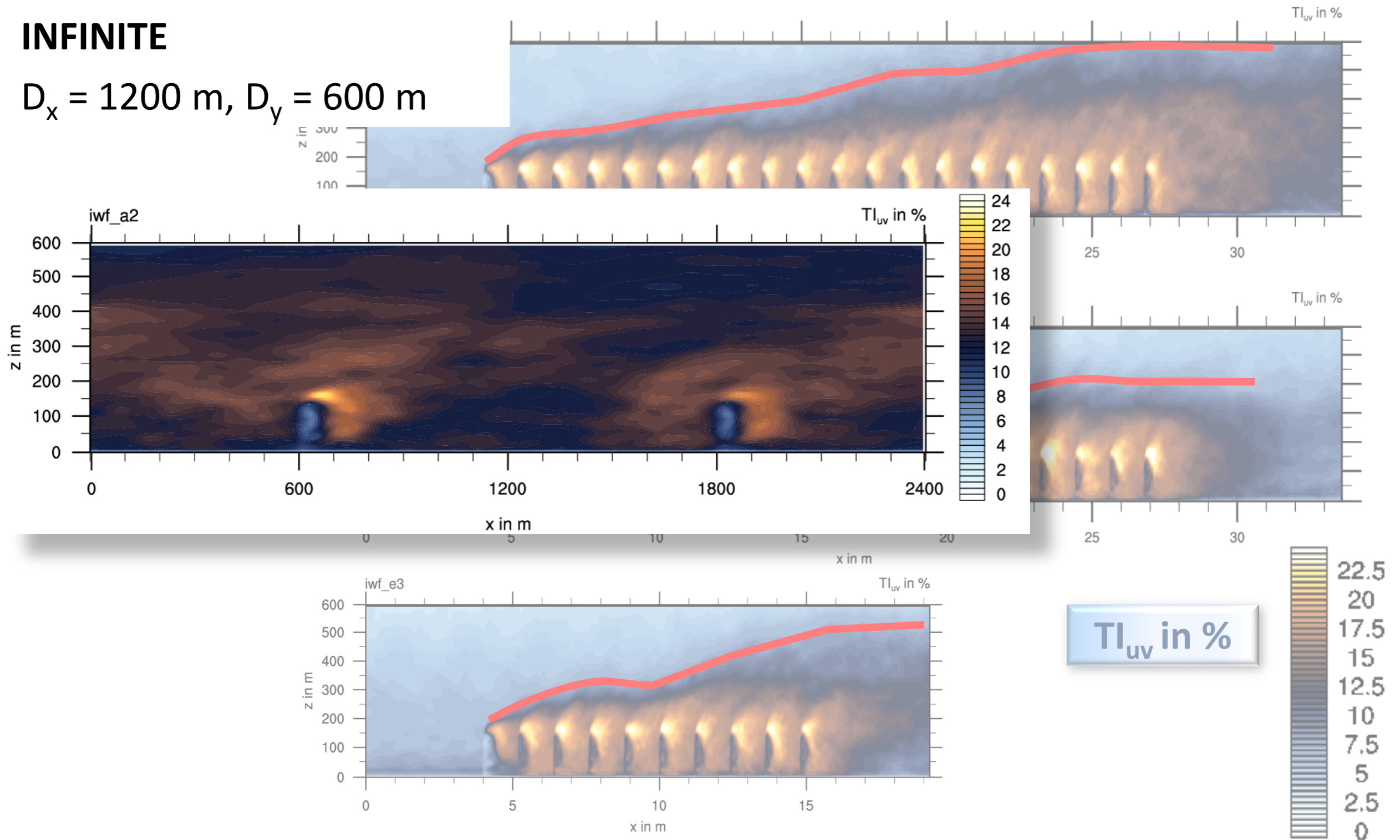
Tl_{uv} in %



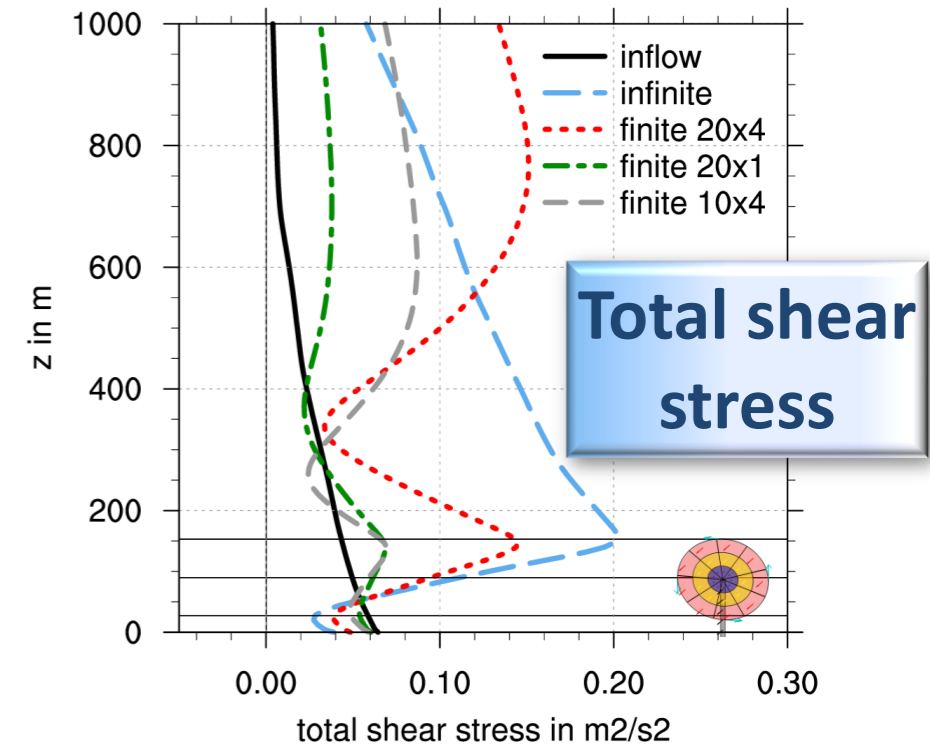
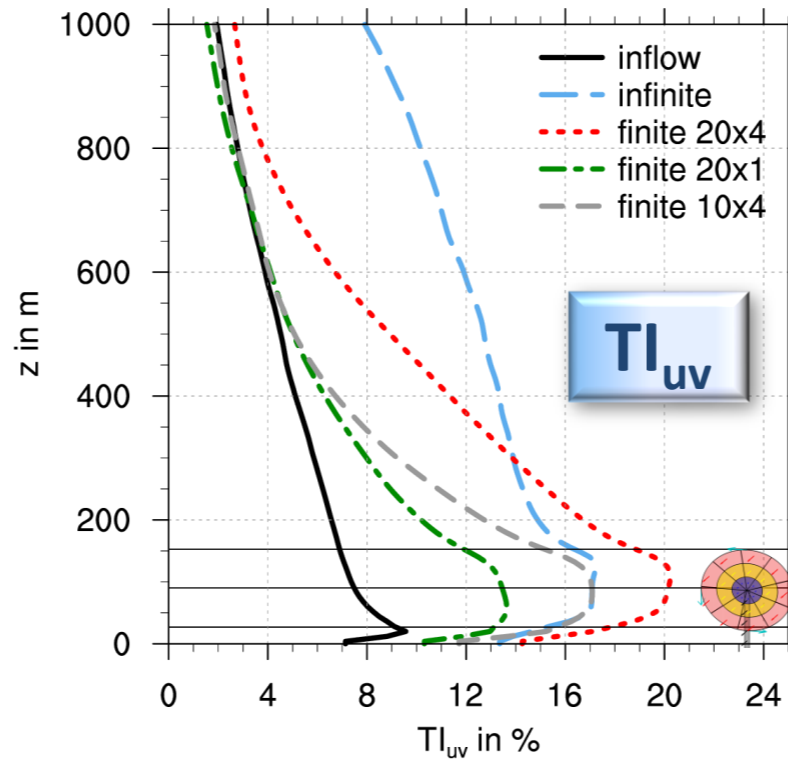
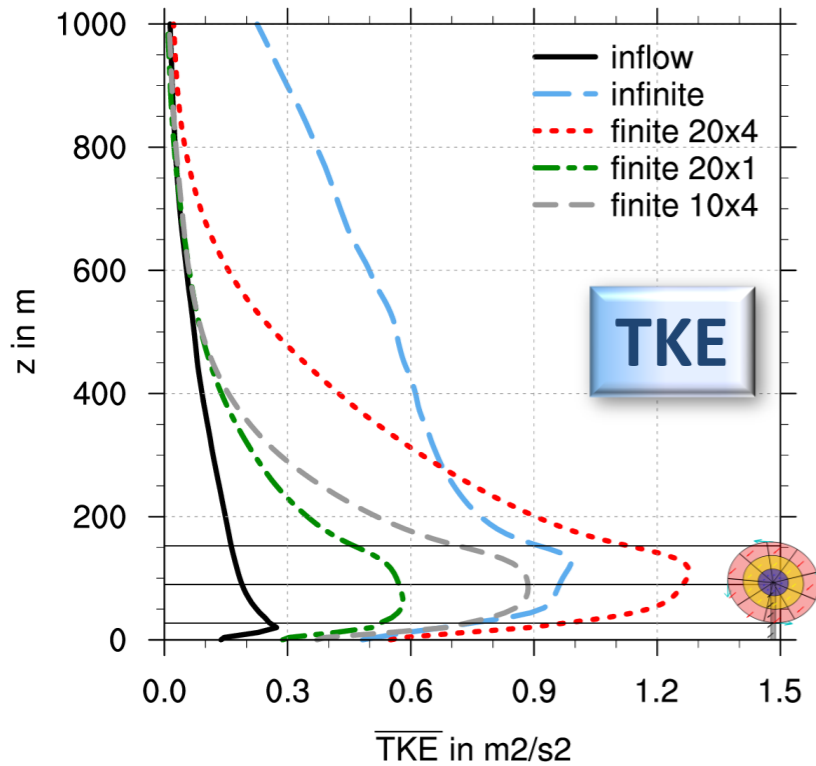
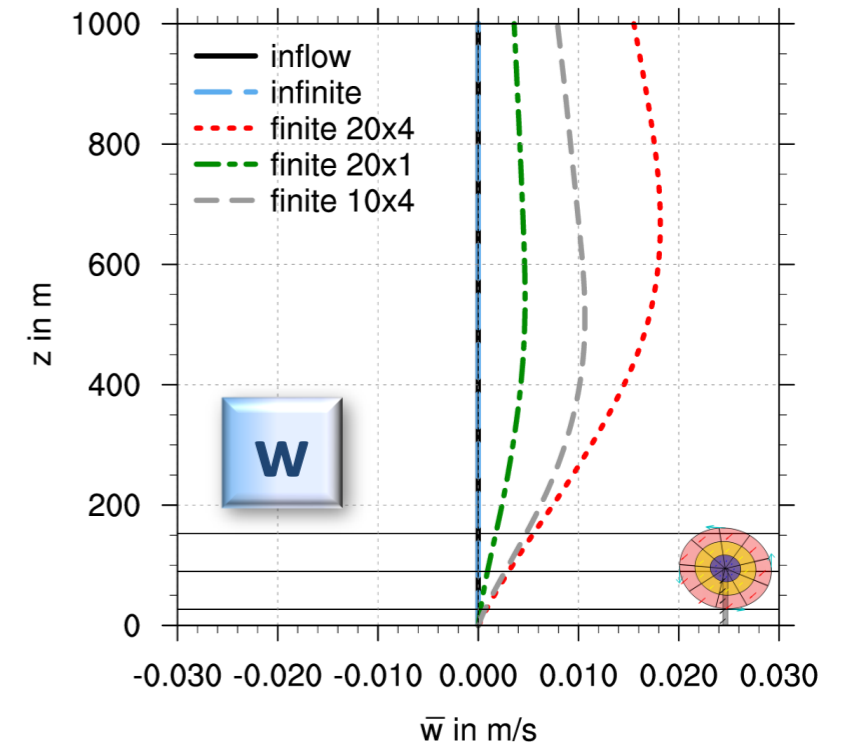
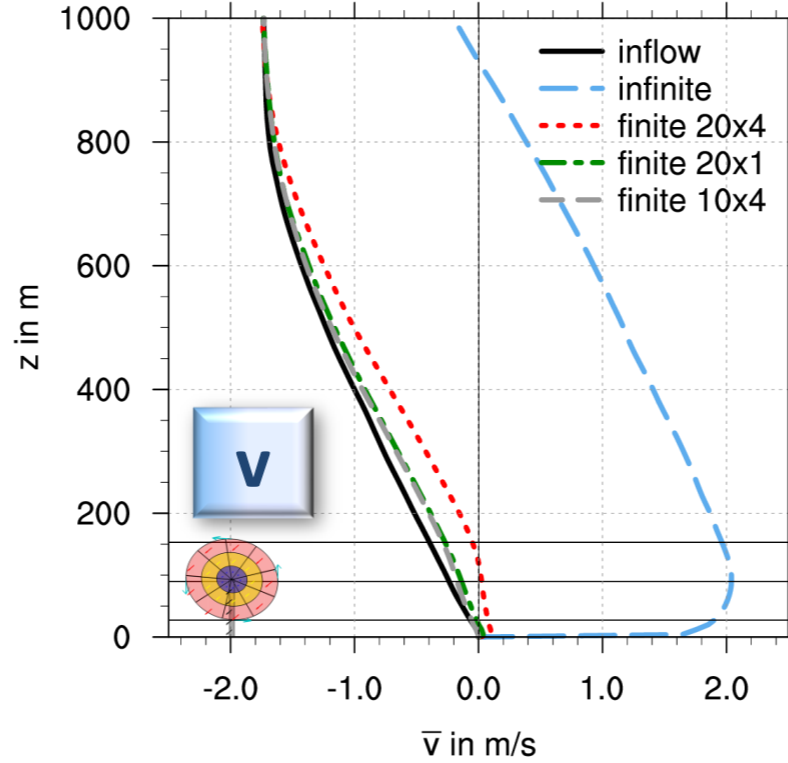
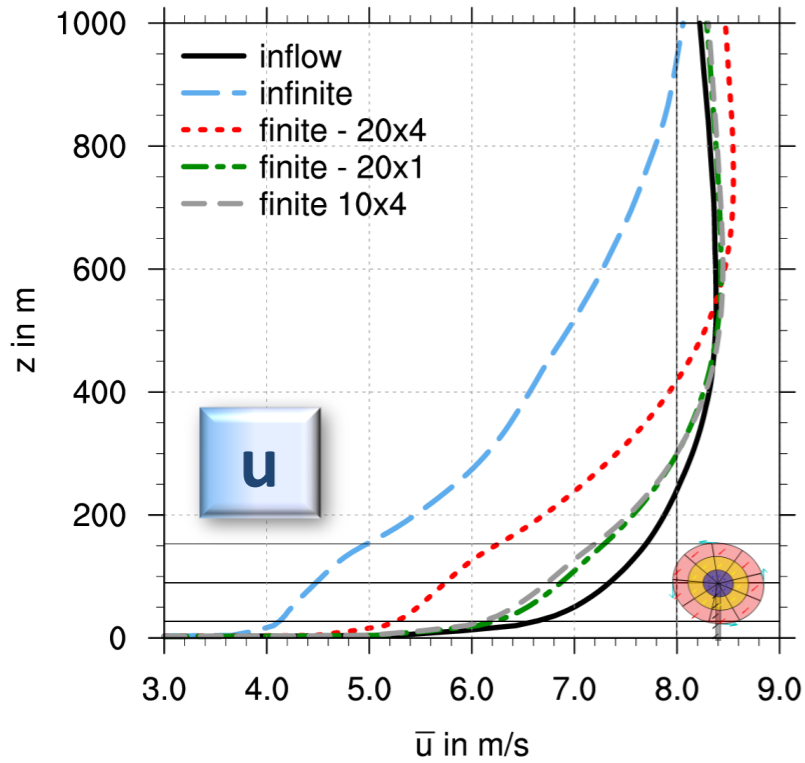
(1) Finite vs. infinite wind farms – turbulence intensity

INFINITE

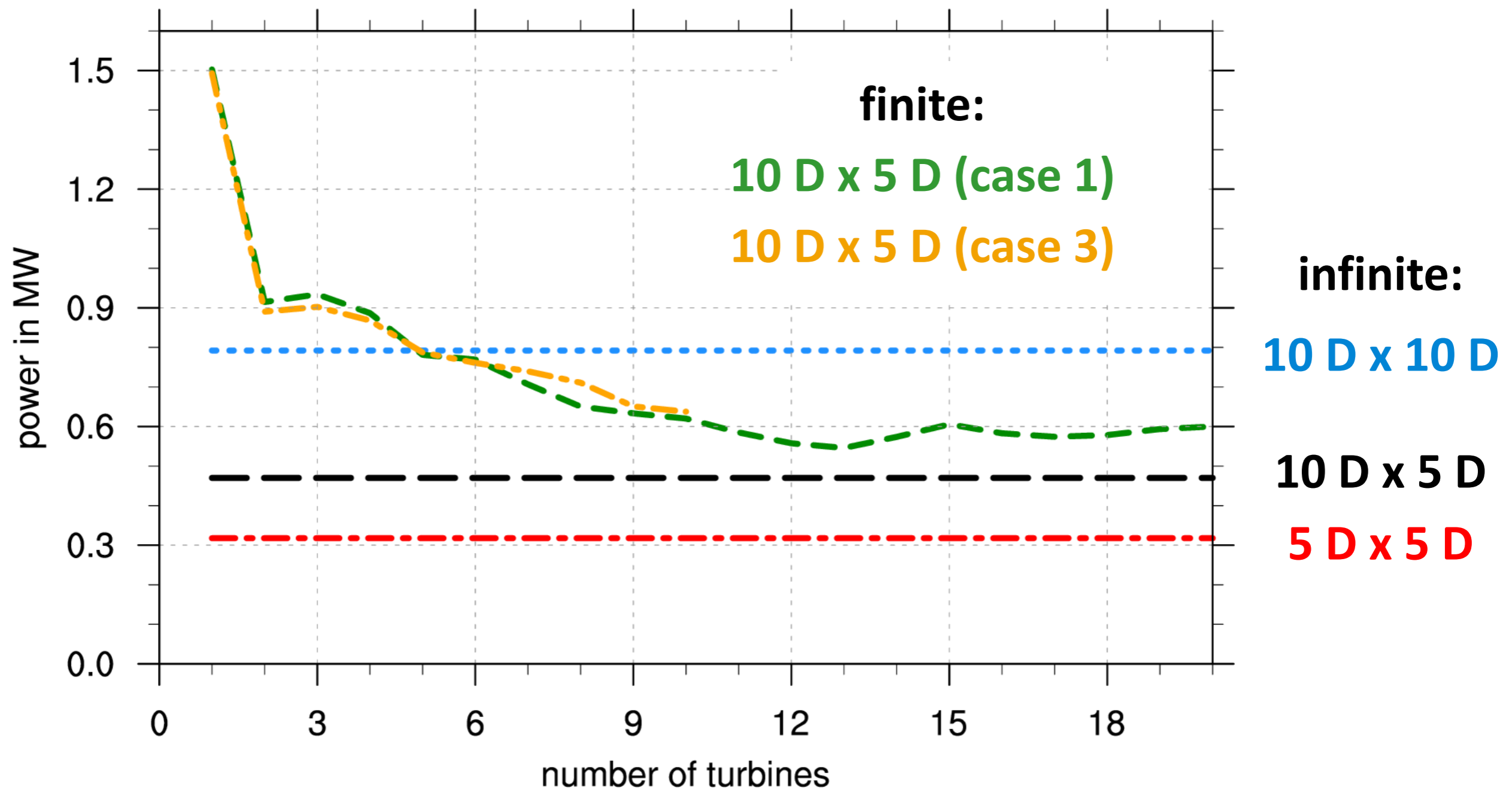
$D_x = 1200 \text{ m}, D_y = 600 \text{ m}$



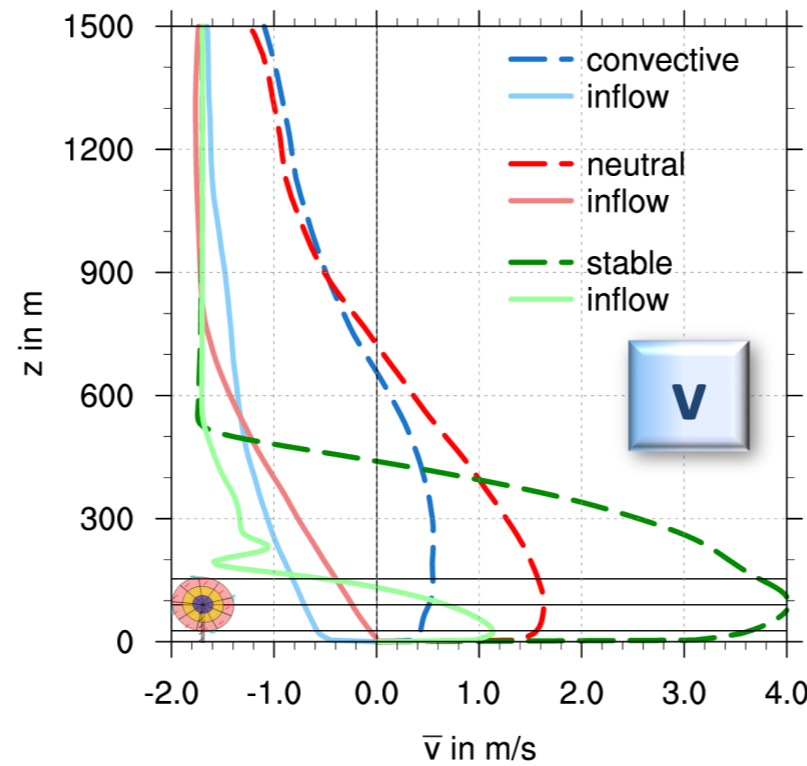
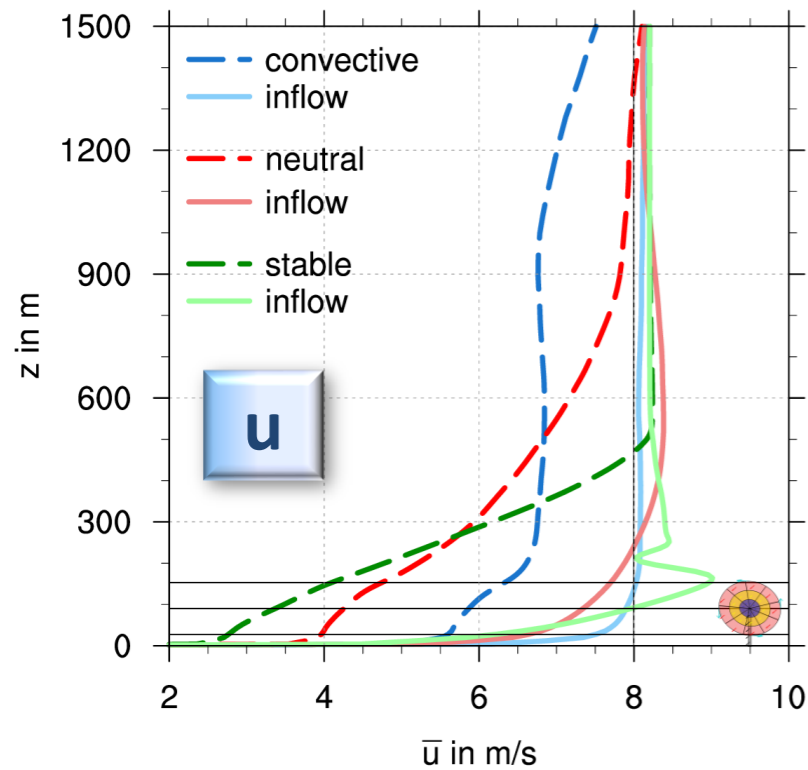
(1) Finite vs. infinite wind farms - profiles



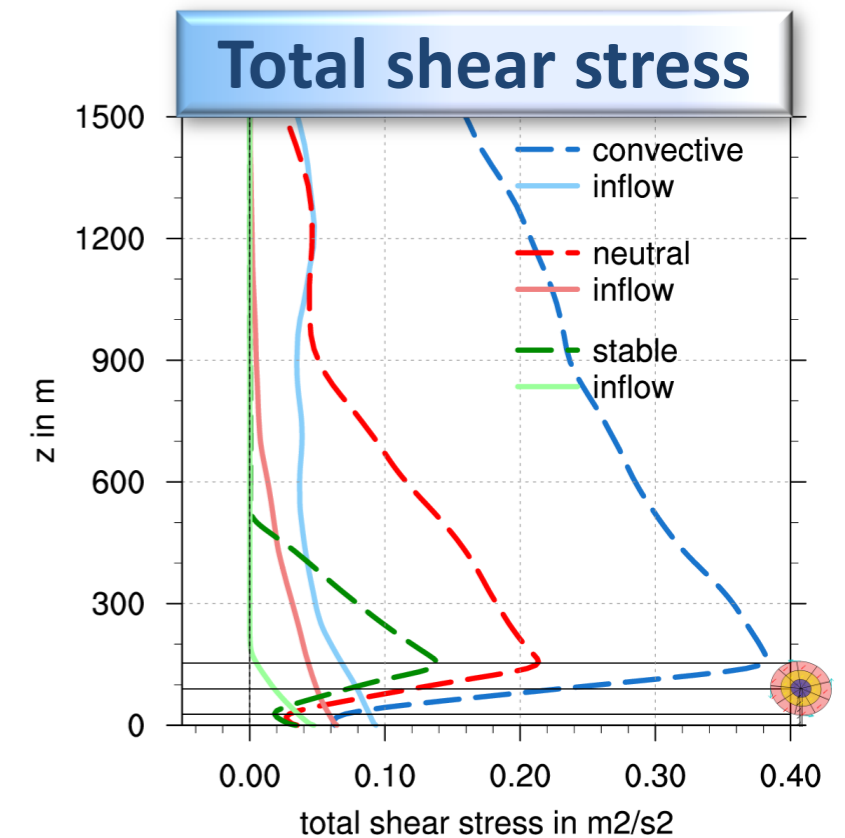
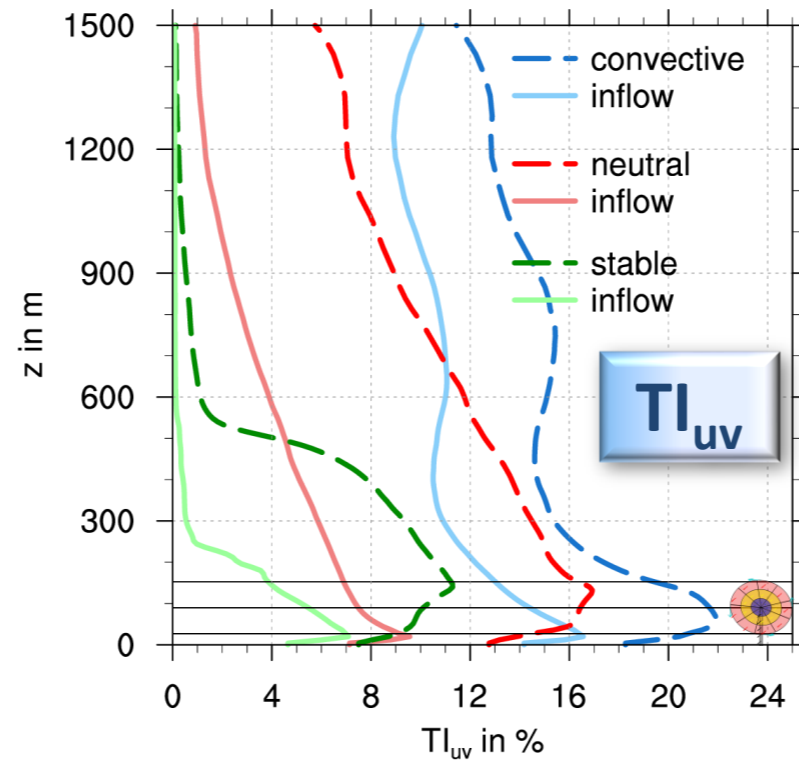
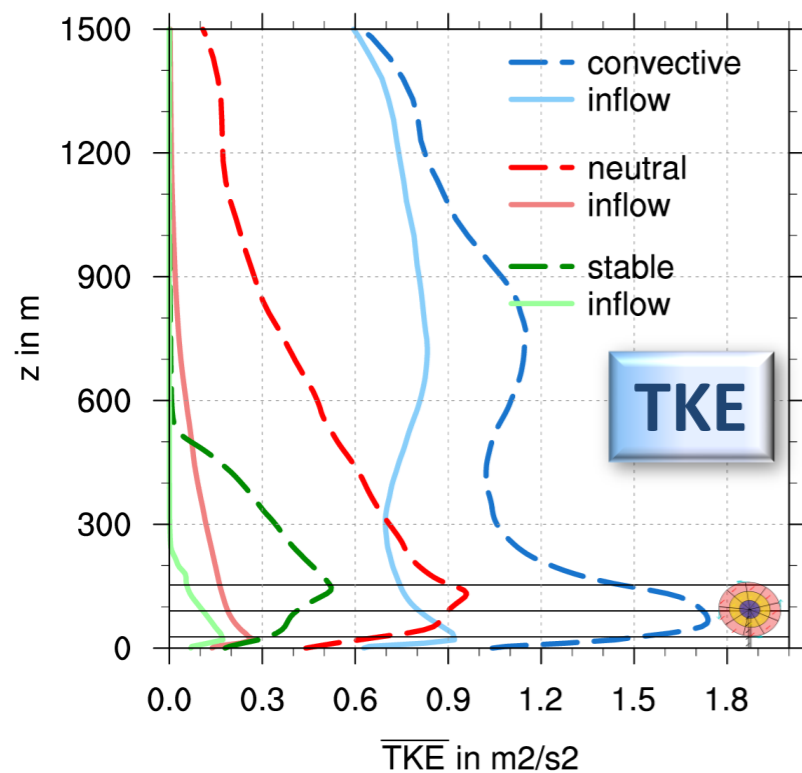
(1) Finite vs. infinite wind farms – power output



(2) Infinite wind farms – variation of stability



convective
neutral
stable



Conclusions

- An internal wind farm boundary layer is developing in large wind farms – growing up to several times the turbine height
- Both atmospheric stability and turbine spacing affect the internal wind farm boundary layer significantly (as do other parameters as wind speed and surface roughness)
- Infinite wind farms are easy to simulate but not representative of typical large wind farms – only of VERY large wind farms (e.g. 50 x 50 turbines)

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