Interaction of wind turbine wakes and inter wind farm effects (RAVE-OWEA)

G. Steinfeld, B. Witha, E. Stütz and D. Heinemann
ForWind – Center for Wind Energy Research
Carl von Ossietzky Universität Oldenburg

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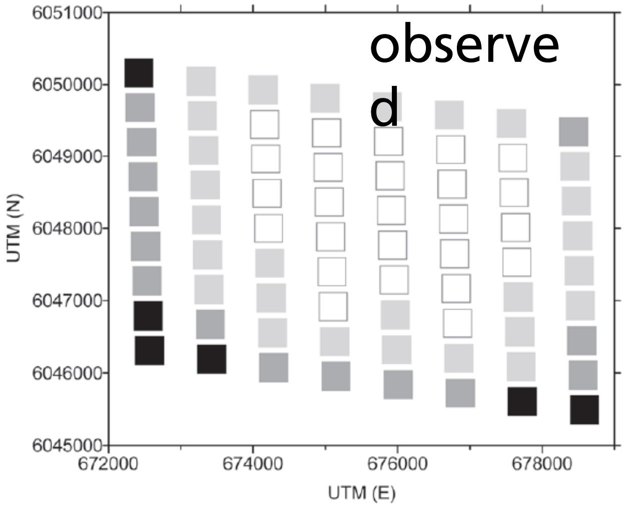
Supervisor

PtJ Projektträger Jülich Forschungszentrum Jülich

Coordination

Fraunhofer IWES

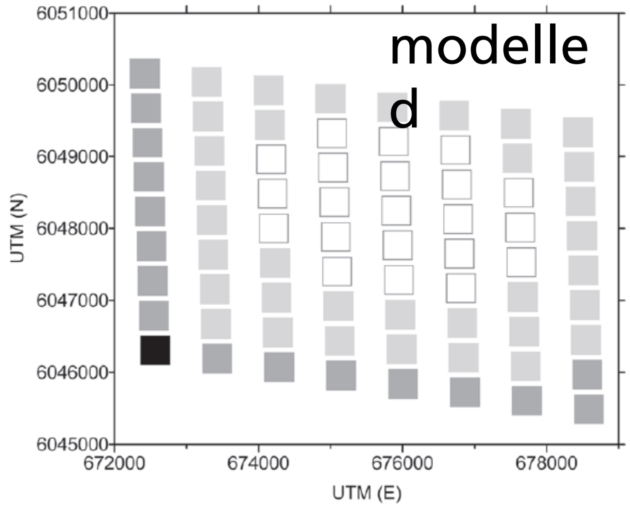
OWEA project: Intra wind farm flows – Simulation of wind farm flows with a large-eddy simulation model



-7.5 to -2.5
-2.5 to 2.5
2.5 to 7.5
7.5 to 12.5

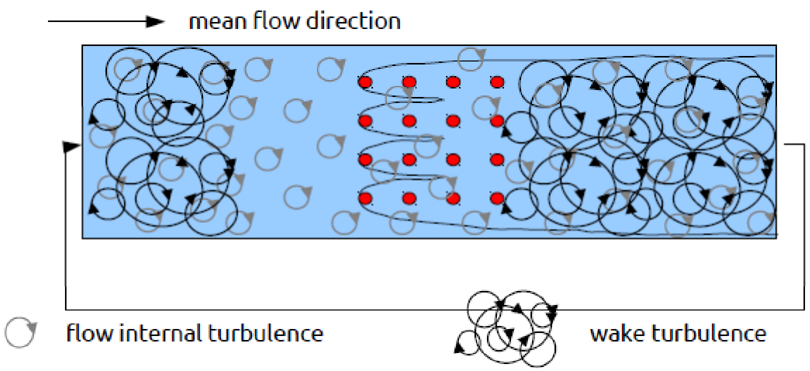
Deviation of mean efficiency

Barthelmie and Jensen, 2010, Wind Energy, 13, 573-586

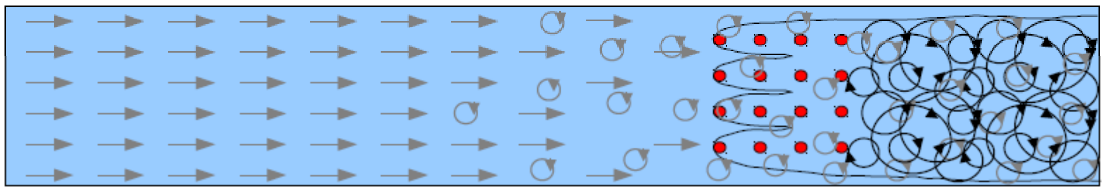


- Velocity deficit → Lower energy yields of wind turbines in the wake
- Increased TI → Larger loads at wind turbines in the wake
- So far, simple engineering wake models or Reynolds-averaged Navier-Stokes simulations used for wake calculation
- Now: HPC clusters allow for large-eddy simulations

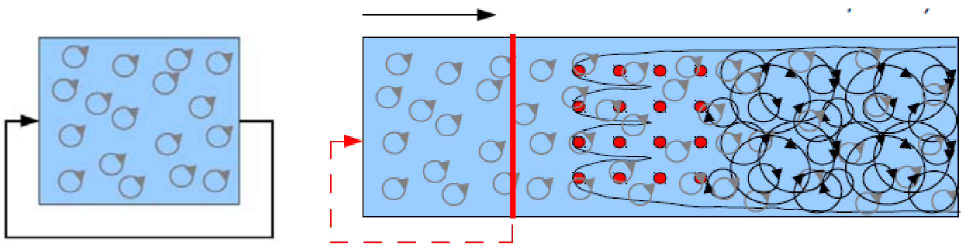
Challenges for LES of wake flows: boundary conditions I



As long as no infinitely large wind farm shall be simulated, **cyclic boundary conditions** might bias the results, as wake enters the model domain again and modifies the flow upstream of the wind farm

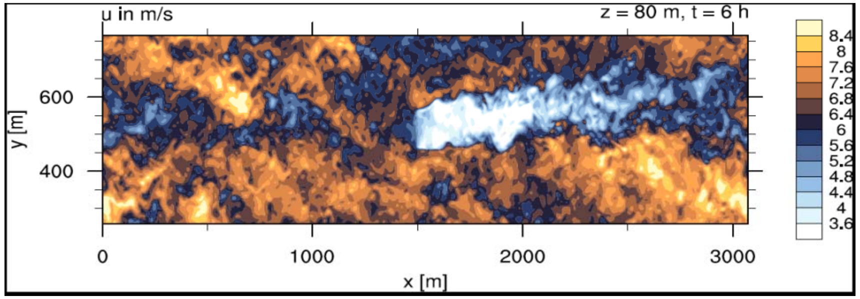


With **non-cyclic boundary conditions** the inflow is laminar → a very long model domain is required to generate flow-internal turbulence

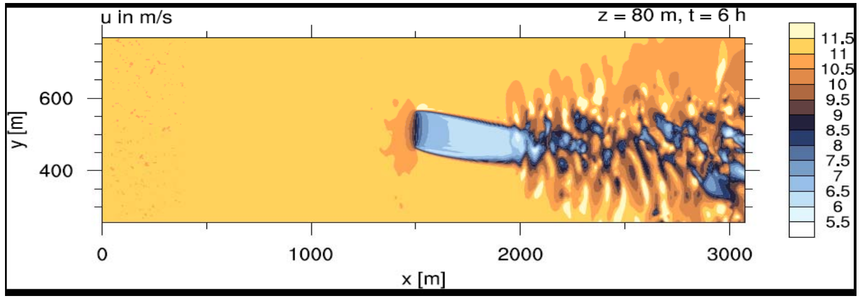


Non-cyclic boundary conditions with turbulent inflow: initial turbulence is created by a prerun, recycling of turbulence in the main run → turbulent inflow, small domain sufficient

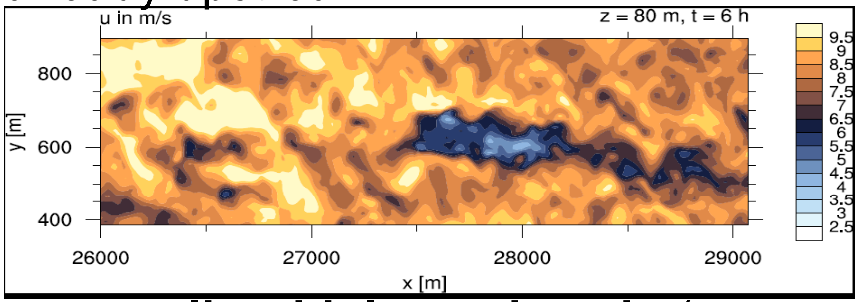
Challenges for LES of wake flows: boundary conditions II



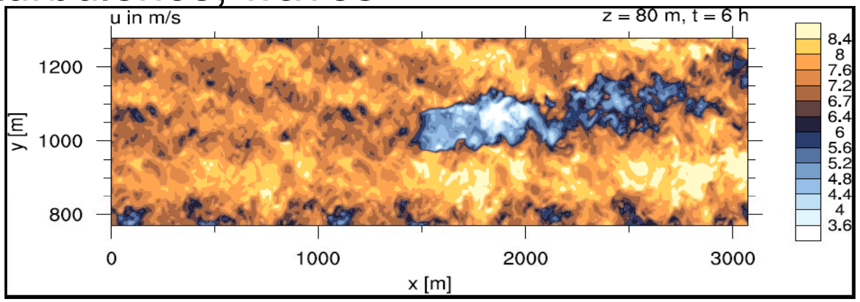
cyclic: highly turbulent due to re-entering wake, lower wind speed already upstream



non-cyclic: laminar inflow, no upstream turbulence → no realistic wake turbulence, waves



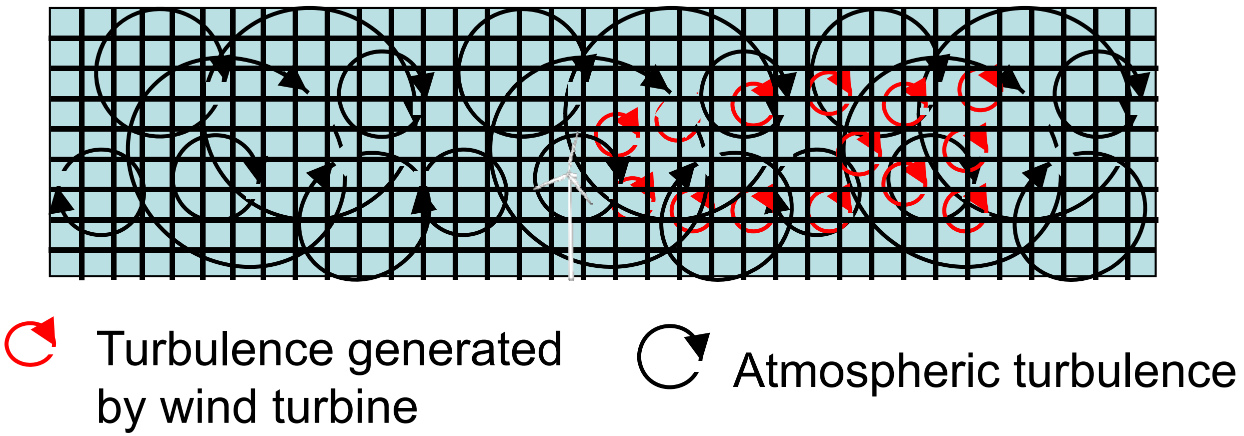
non-cyclic with large domain (coarser resolution**)**: upstream turbulence has developed



non-cyclic with turbulent inflow: upstream turbulence, realistic wake turbulence, higher (undisturbed) wind speed compared to cyclic run

Challenges for LES of wake flows: simultaneous resolution of the ABL flow and the wake flow

- Model domain has to be large enough to contain the largest turbulence elements of the ABL flow
- Model resolution has to be fine enough so that also the turbulence generated by the wind turbine can be resolved explicitly

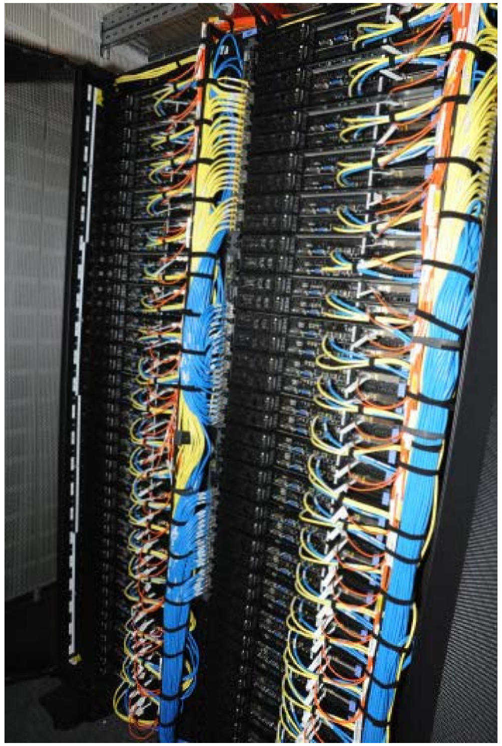


Both challenges can be addressed with the LES model PALM

Atmospheric (+oceanic) code: PArallelised Large-eddy simulation Model (PALM) (Raasch and Schröter, Meteorol. Z., 2001); allowing the prescription of a turbulent inflow using the recycling method of Lund et al., 1998

+

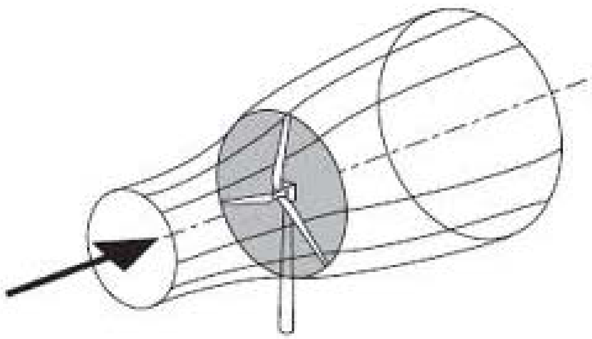
Access to powerful supercomputers:
HPC cluster FLOW with 2232 cores at the Carl von Ossietzky University of Oldenburg: Solely dedicated to wind energy research;
SGI Altix ICE at HLRN (Berlin/Hannover) with about 25000 cores;

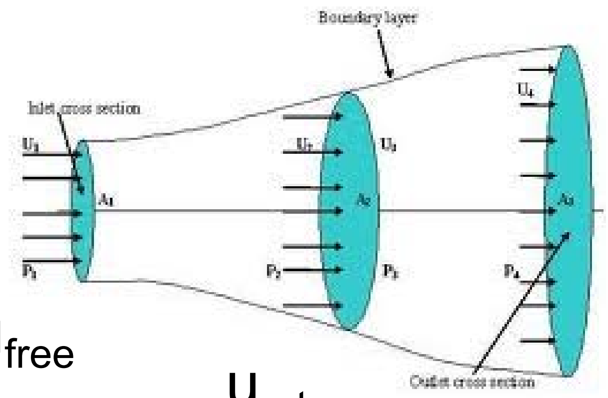


Simulations with up to 4096^3 grid points:
- model domains: several tens of km^2
- grid resolution of about 1 m

Wind turbine parameterisations in PALM:
1. Actuator disc model (uniformly loaded)

- No consideration of rotational effects
- Integration of thrust force over time





u_{free}

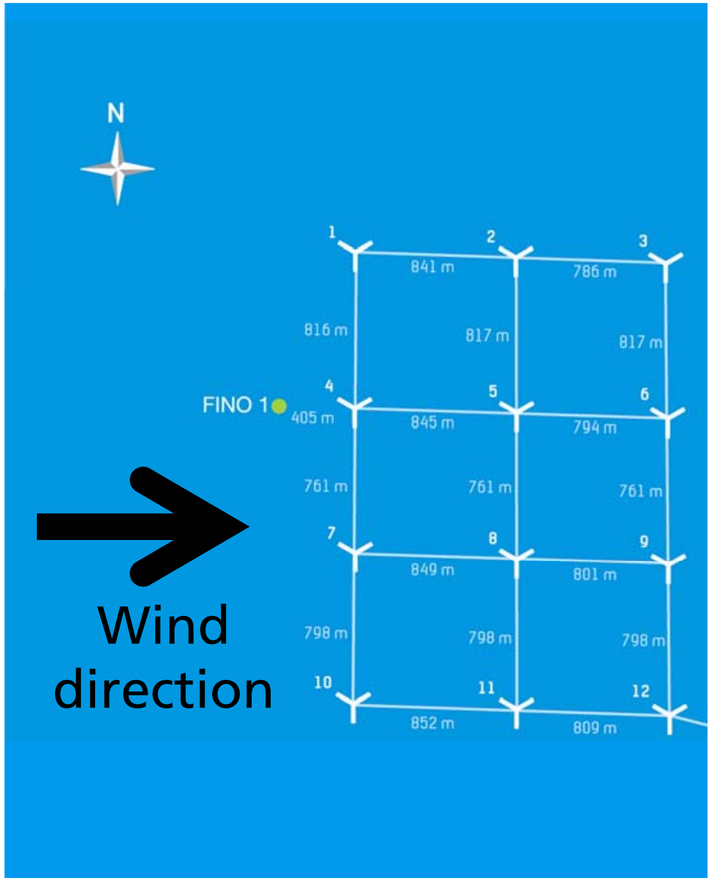
u_{rotor}

$$F = -\frac{1}{2} C_t A u_{free}^2$$ Jimenez et al. (2007)

$$F = -\frac{1}{2} C_t A \left(\frac{1}{1-a} u_{rotor}^2 \right)$$ Calaf et al. (2010)

Rotor swept area:
Homogeneous
momentum sink

Impact of atmospheric stability on wake effects in the wind farm alpha ventus: Setup of the simulations

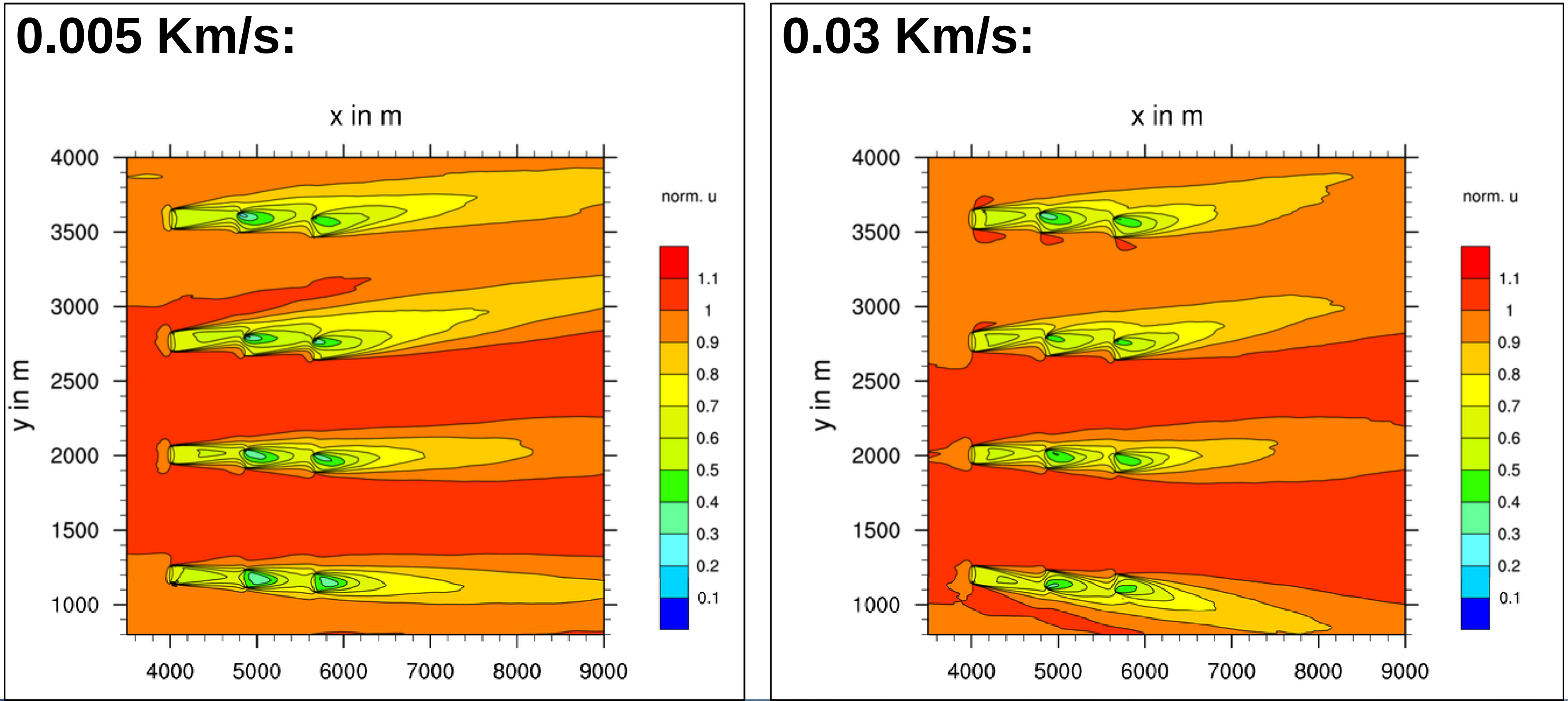


- 1586(3072)x768x288 GP
- resolution: 6 m
- cyclic prerun + main run with stationary model domain and turbulent inflow
- roughness length from Charnock relation
- Prescribed near-surface heat flux (0.005 or 0.03 Km/s)
- Actuator disc model: about 400 cells in rotor swept area
- CPU time: 41 h (288 PEs), for 1 h of simulated time

Impact of atmospheric stability on wake effects in the wind farm alpha ventus

u/u_inflow(x,y) averaged over 1800 s at hub height

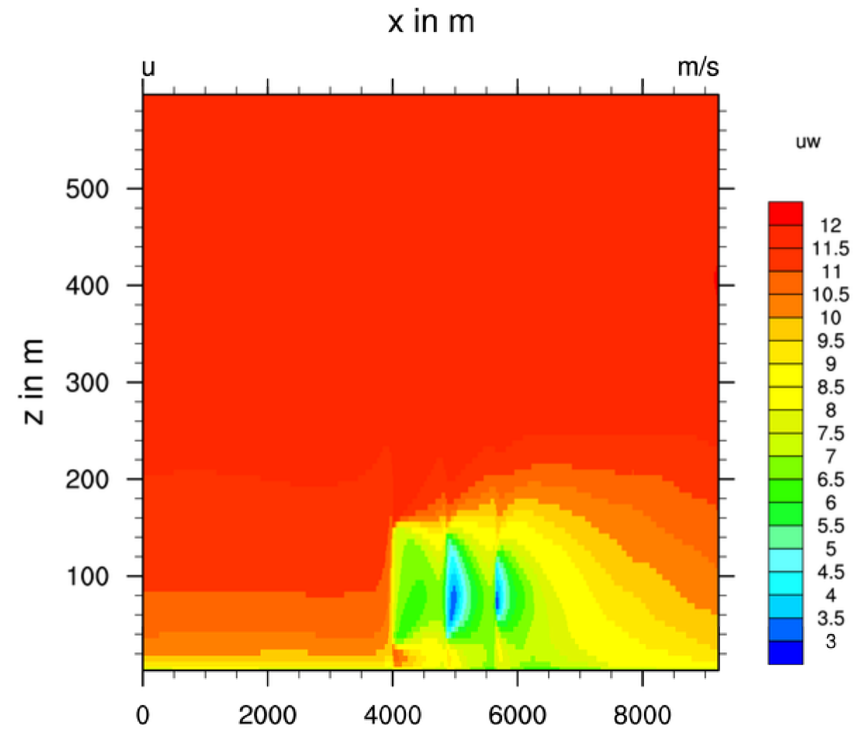
0.005 Km/s: **0.03 Km/s:**



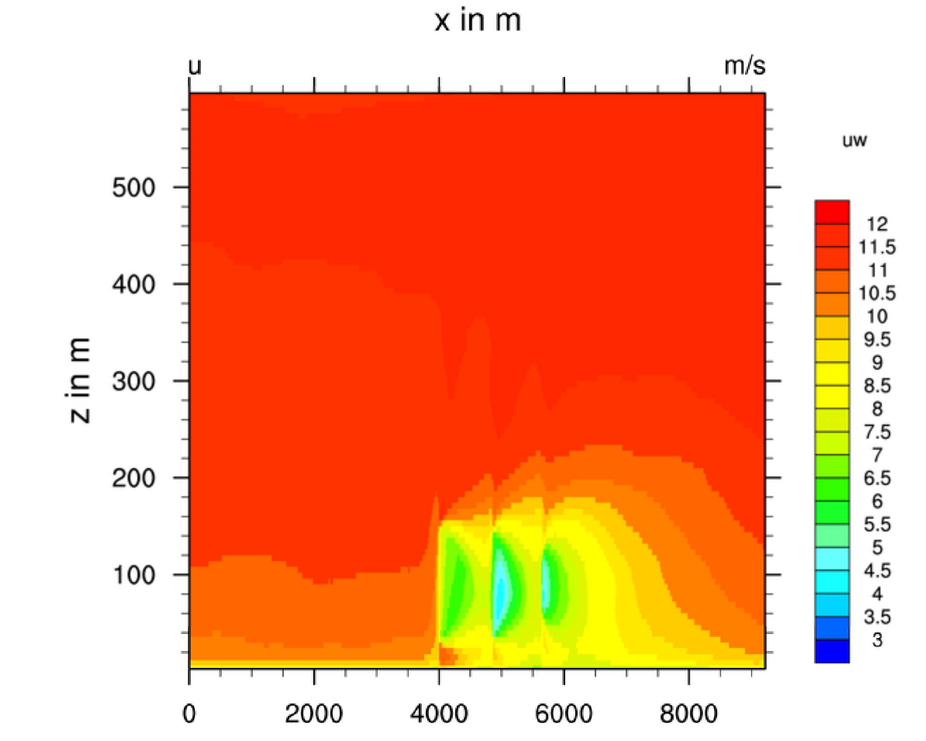
Impact of atmospheric stability on wake effects in the wind farm alpha ventus

u(x,z) averaged over 1800 s (row AV7 – AV9)

0.005 Km/s:

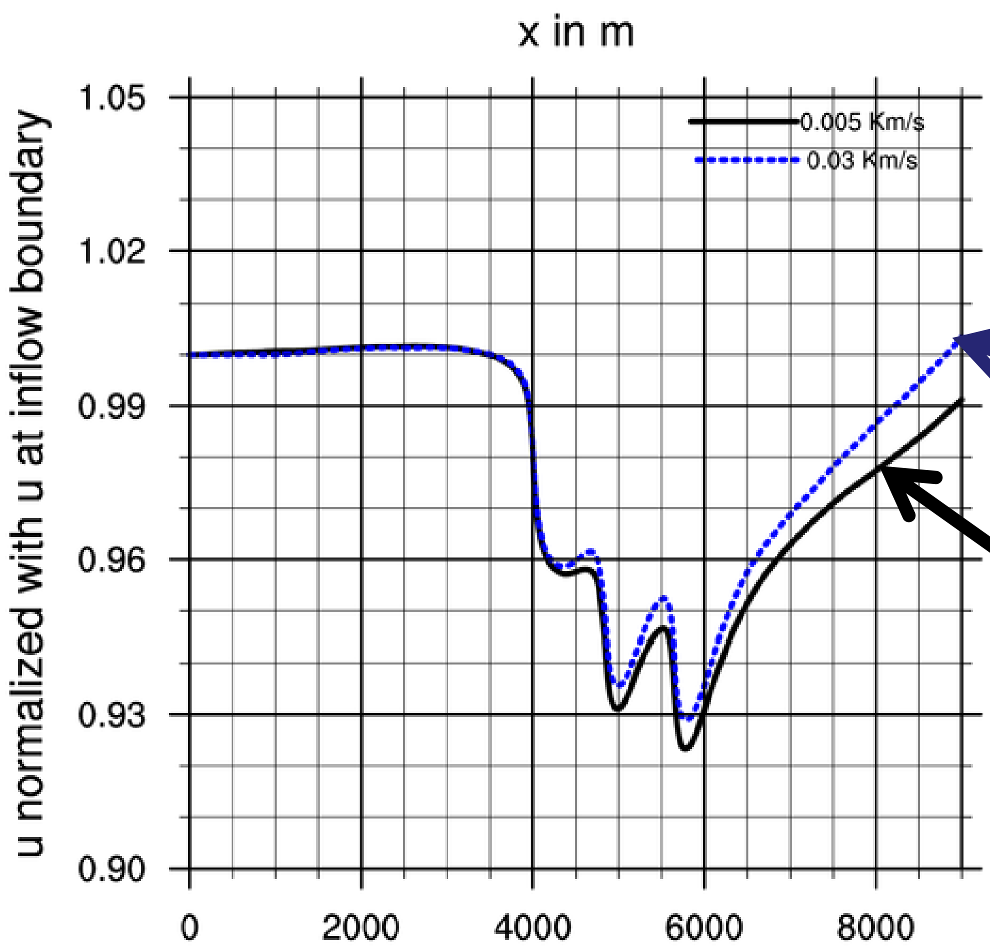


0.03 Km/s:



Impact of atmospheric stability on wake effects in the wind farm alpha ventus

u_avg_y / u_avg_y_inflow (x)



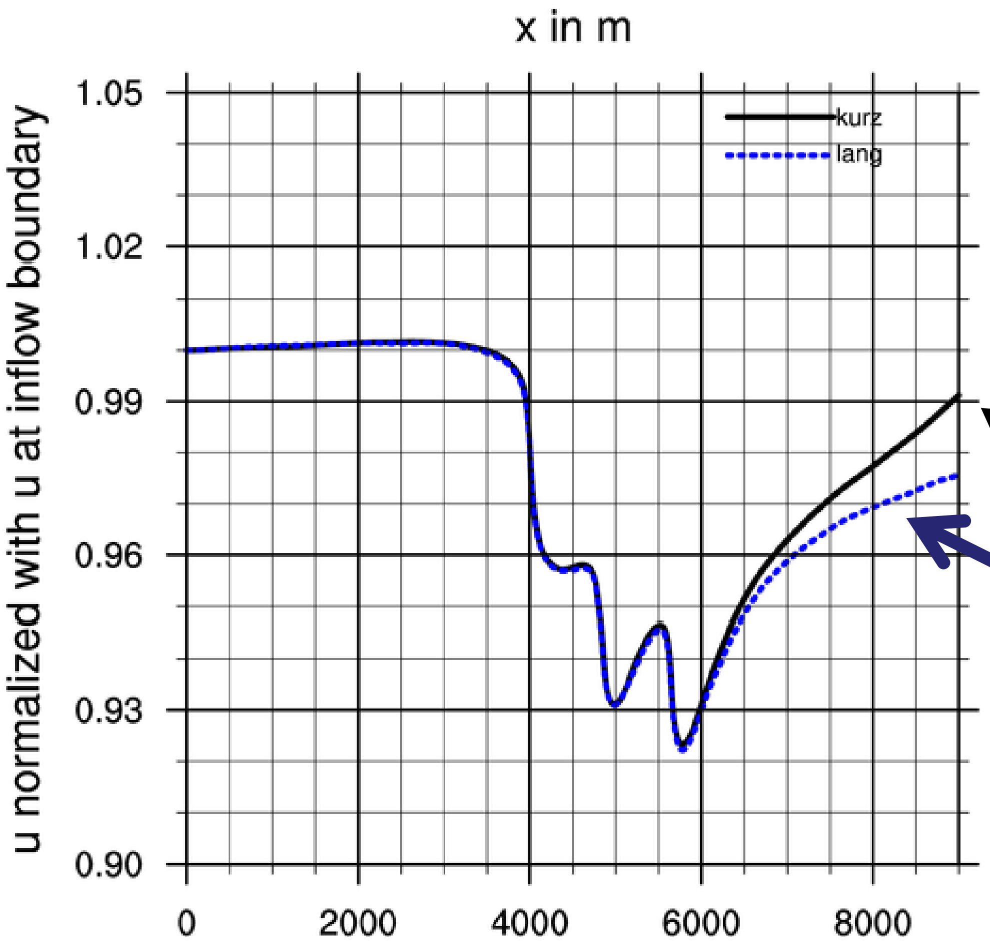
0.03 Km/s

0.005 Km/s

Faster decay of the velocity deficit with larger near-surface heat flux!

Impact of atmospheric stability on wake effects in the wind farm alpha ventus

u_avg_y / u_avg_y_inflow (x)

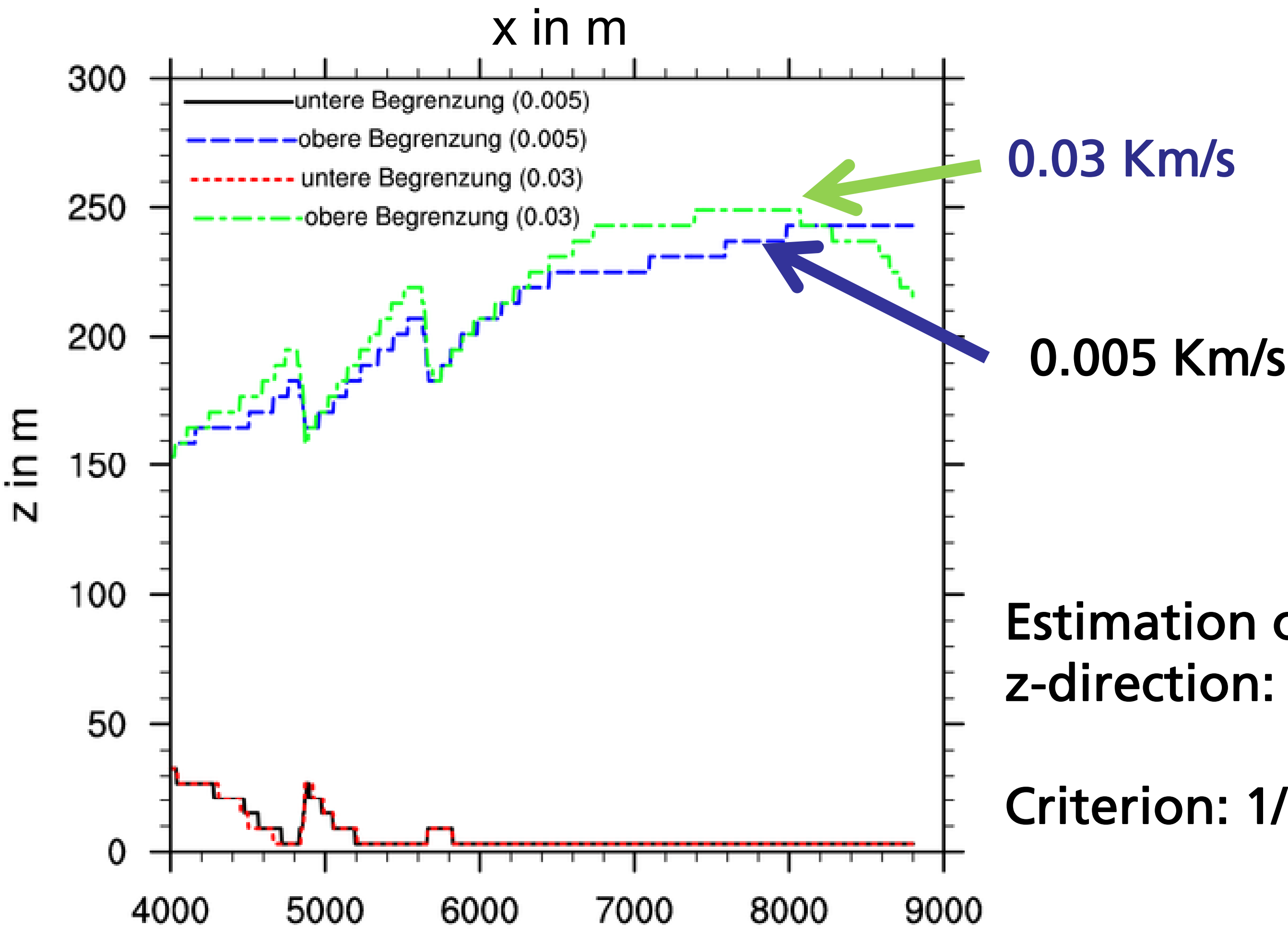


small model domain

large model domain

Size of the model domain has an impact on the flow, but only in the last third of the domain!

Impact of atmospheric stability on wake effects in the wind farm alpha ventus: wake extension

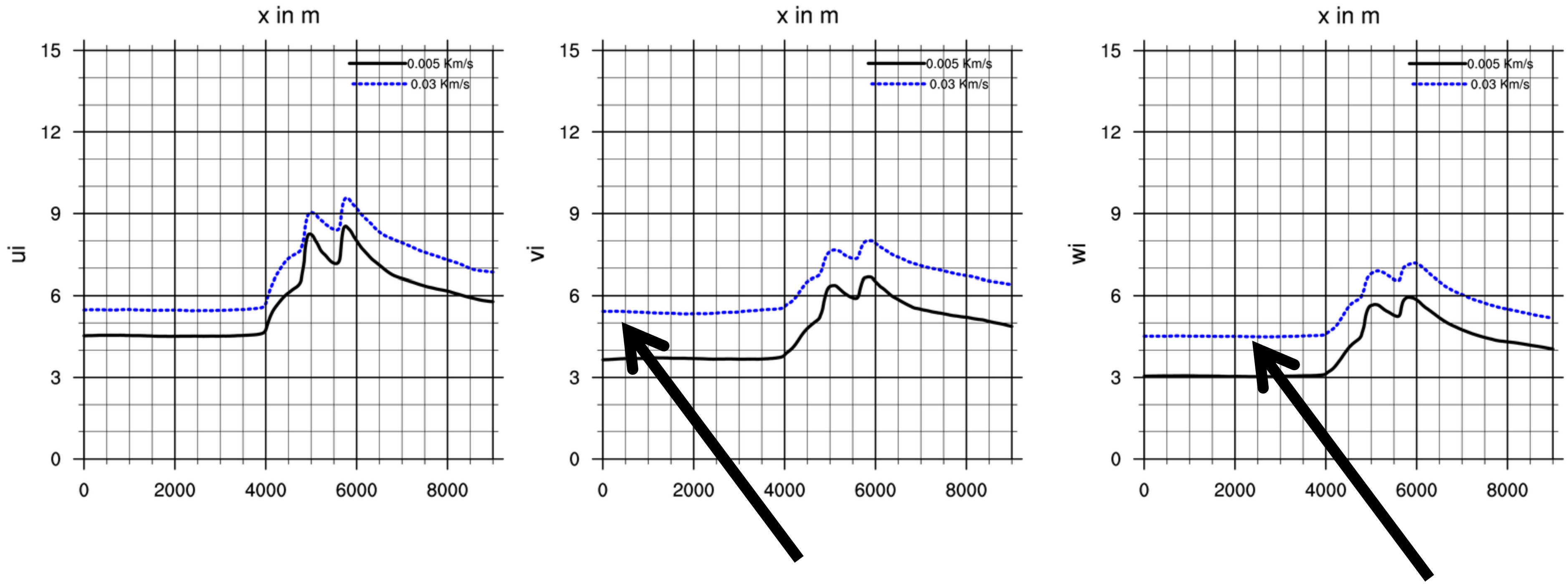


Estimation of wake depth in z-direction: row AV7-AV9

Criterion: $1/e^2$ * u_diff_max

Impact of atmospheric stability on wake effects in the wind farm alpha ventus: wake extension

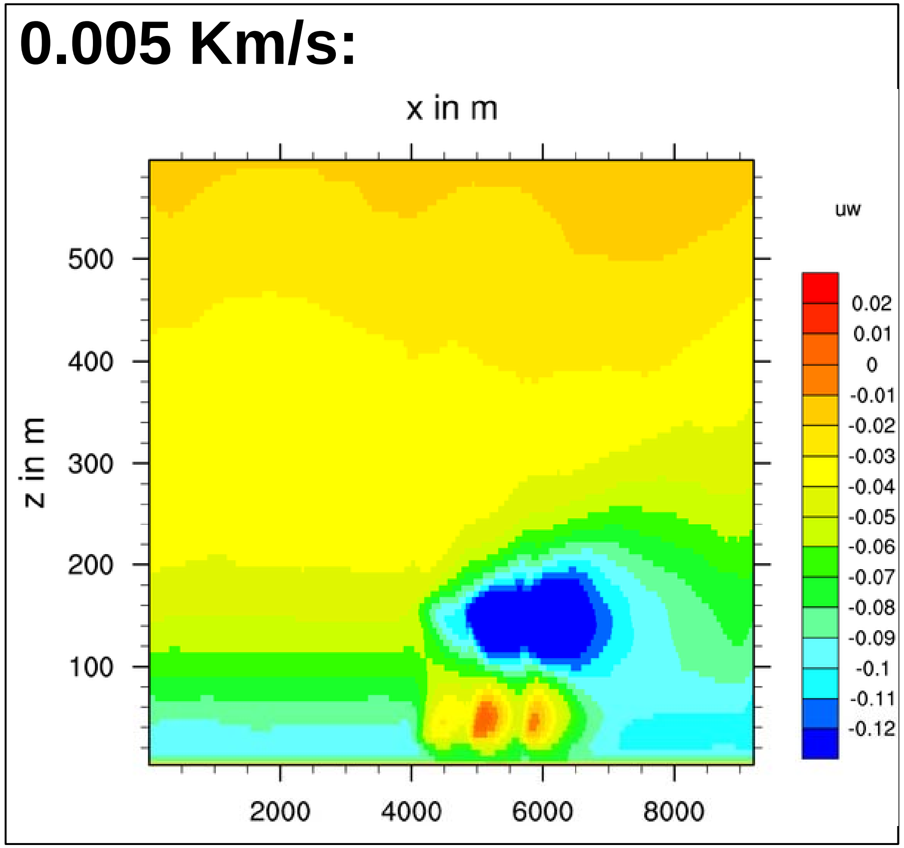
Turbulence intensities u_i, v_i and w_i (averaged along y)

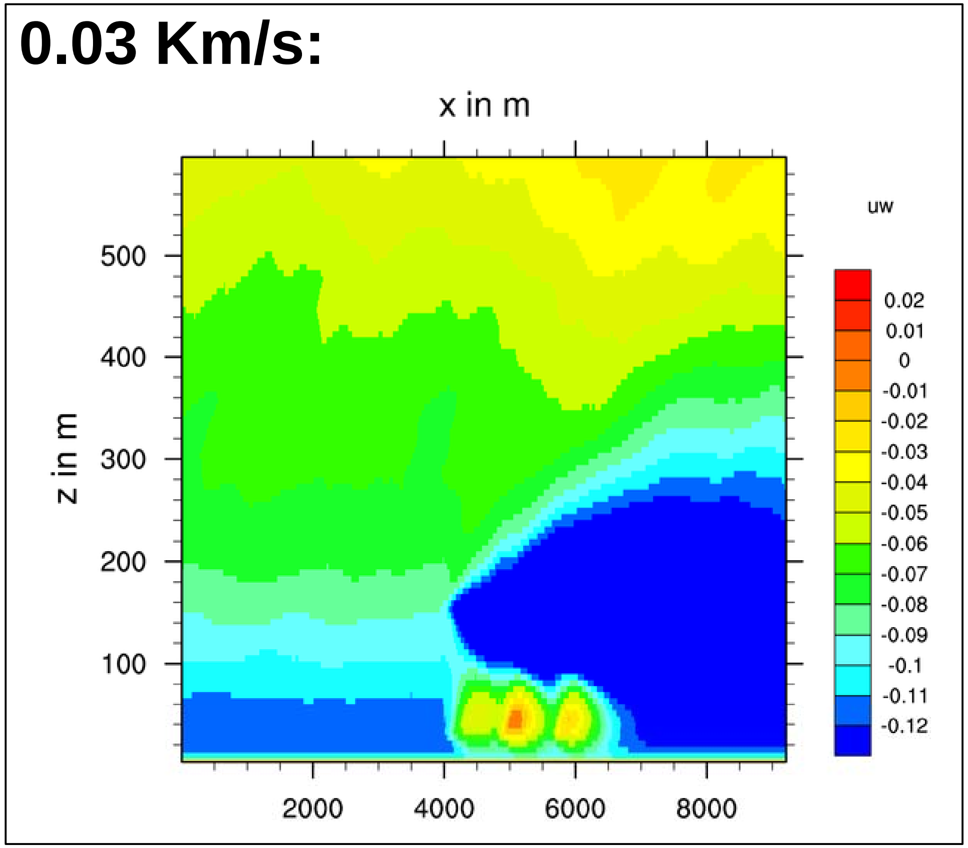


Larger v_i and w_i: More intense exchange with high momentum areas!

Impact of atmospheric stability on wake effects in the wind farm alpha ventus

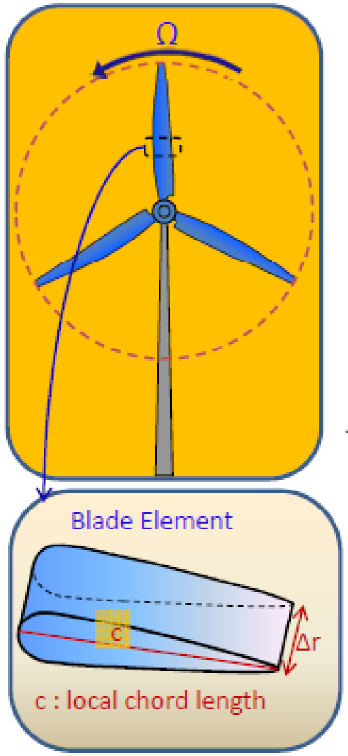
res. turbulent momentum flux uw averaged over 1800 s and along y

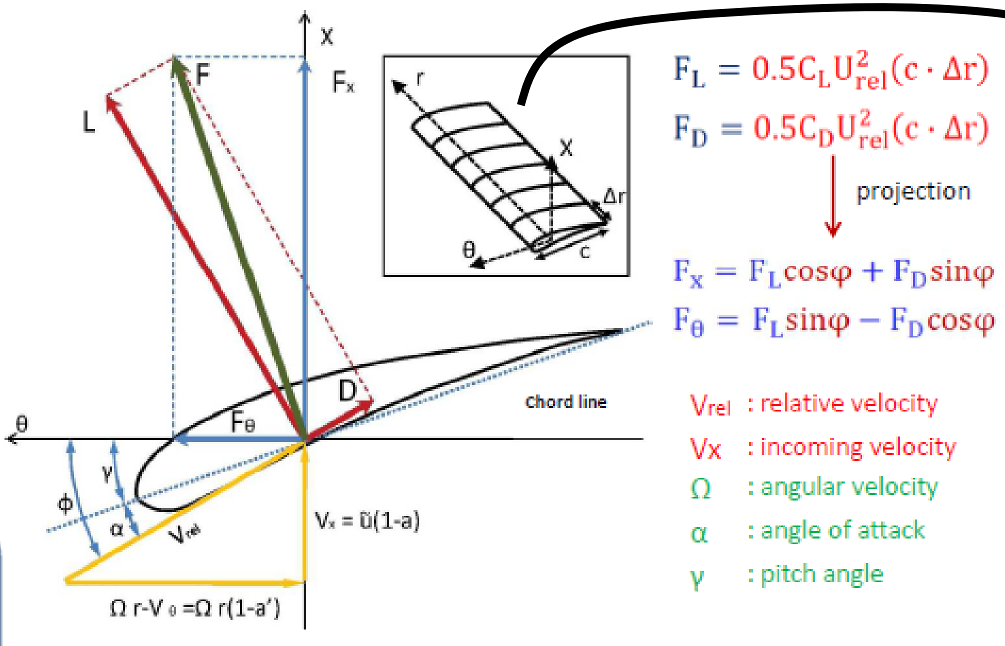




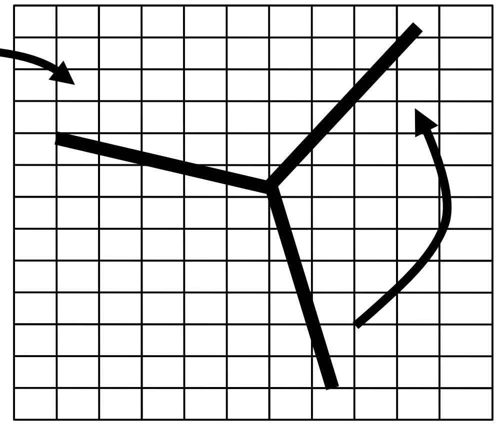
Wind turbine parameterizations in PALM:
2. Actuator line model

Additional lift and drag forces that attack along rotor lines are realized by additional body forces in the Navier-Stokes equations





from Wu and Porté-Agel, 2011

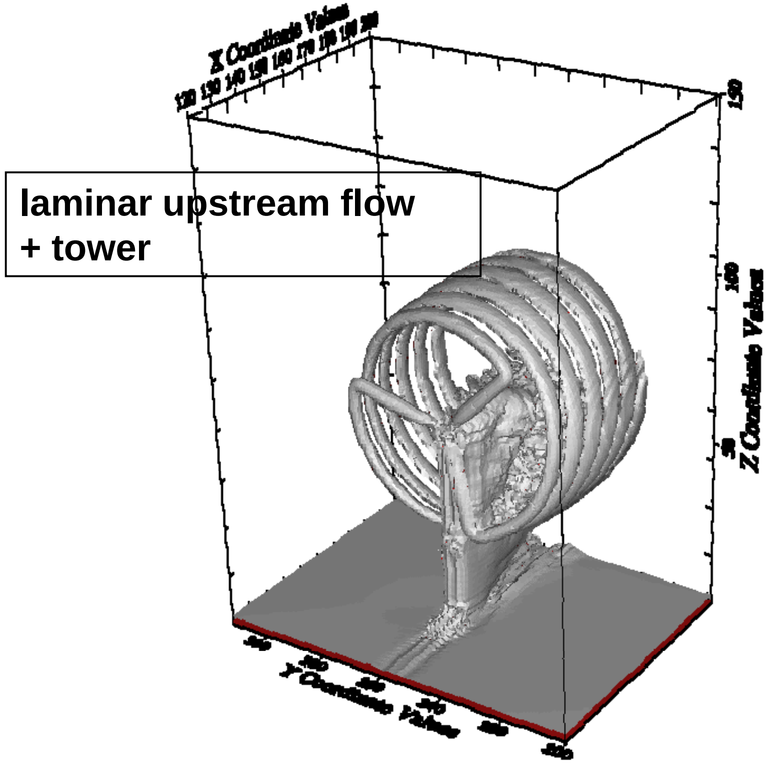


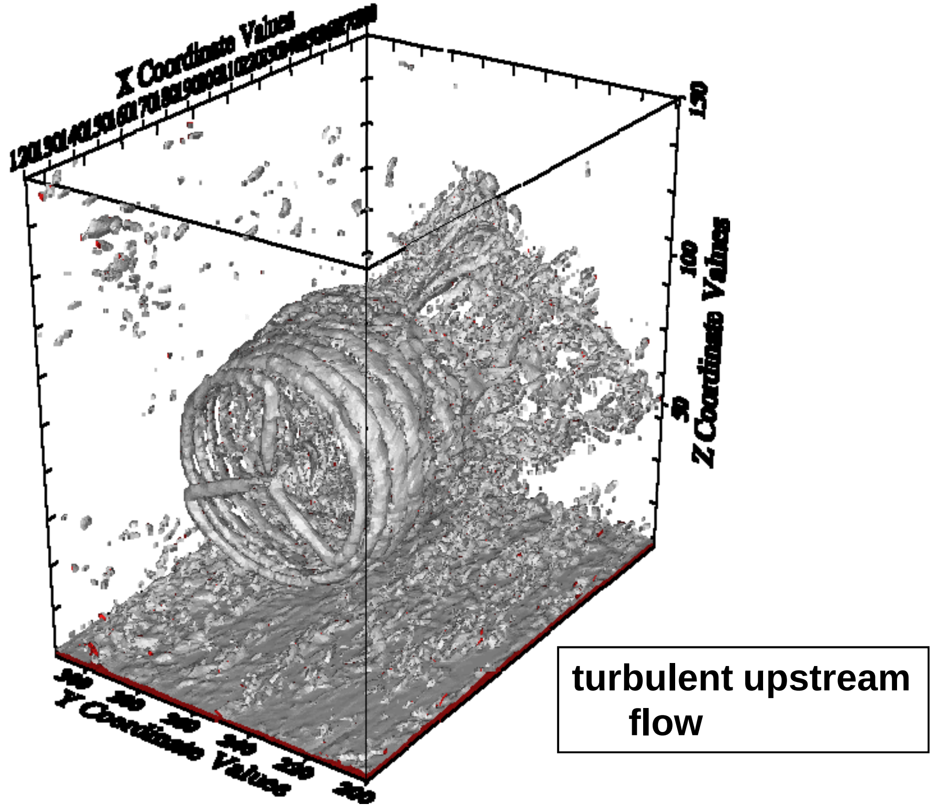
Regularization kernel for (Gaussian) smearing of wind turbine effects:

$$F_\varepsilon = F \otimes \eta_\varepsilon$$

Wake flows simulated with the actuator line model

- PALM simulations using actuator line method
- 1536*512*256 grid points, Δ = 1m, Δt = 0.01s
- CPU time (turbulent flow): 1 week on 1024 PEs of SGI-Altix-ICE

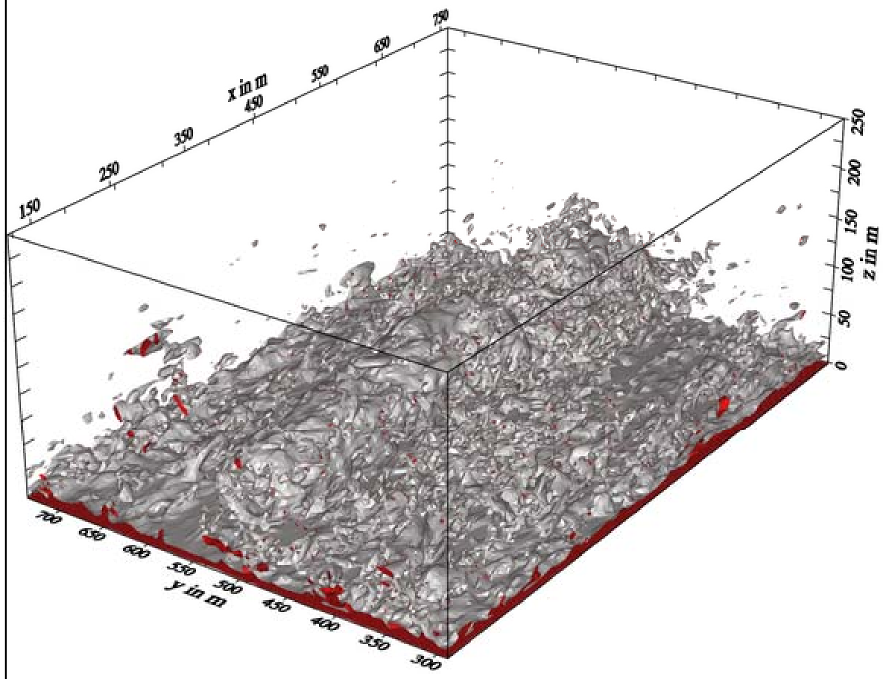




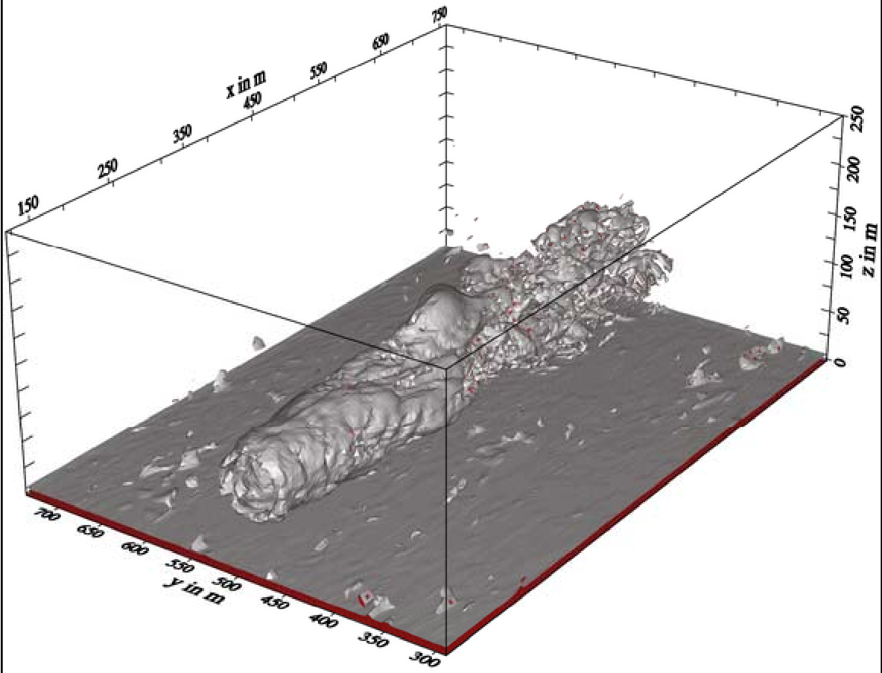
Study: impact of surface conditions on wake flows

Isosurfaces of vorticity (instantaneous)

land surface:



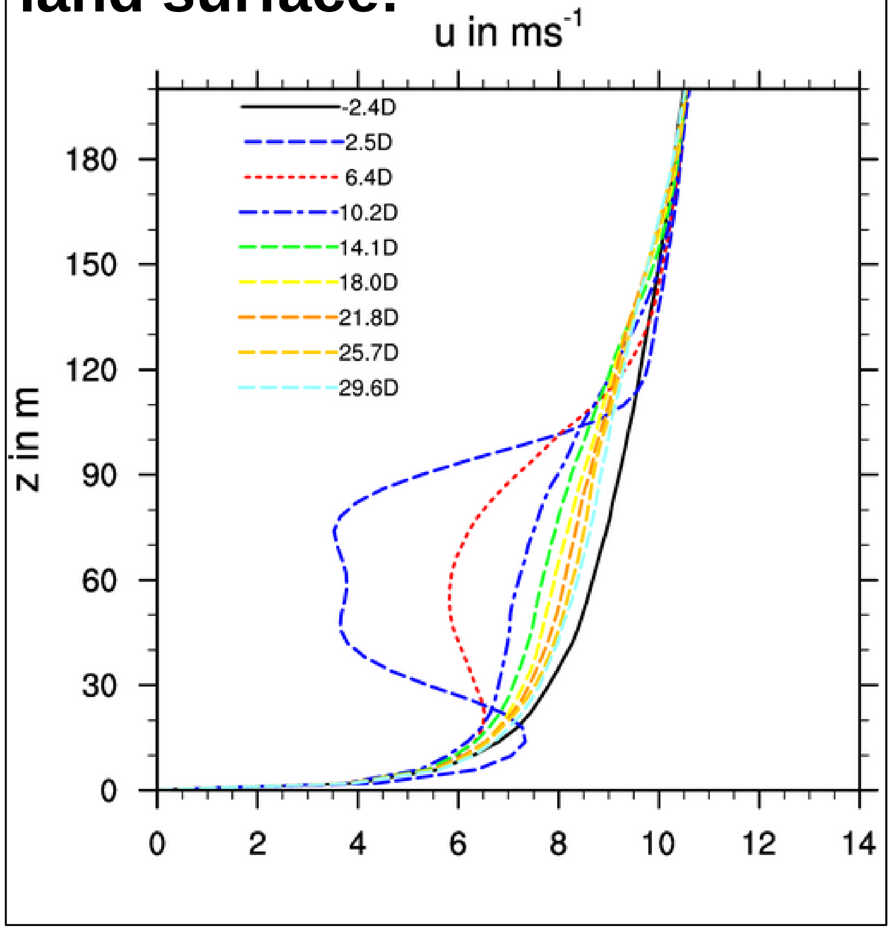
sea surface:



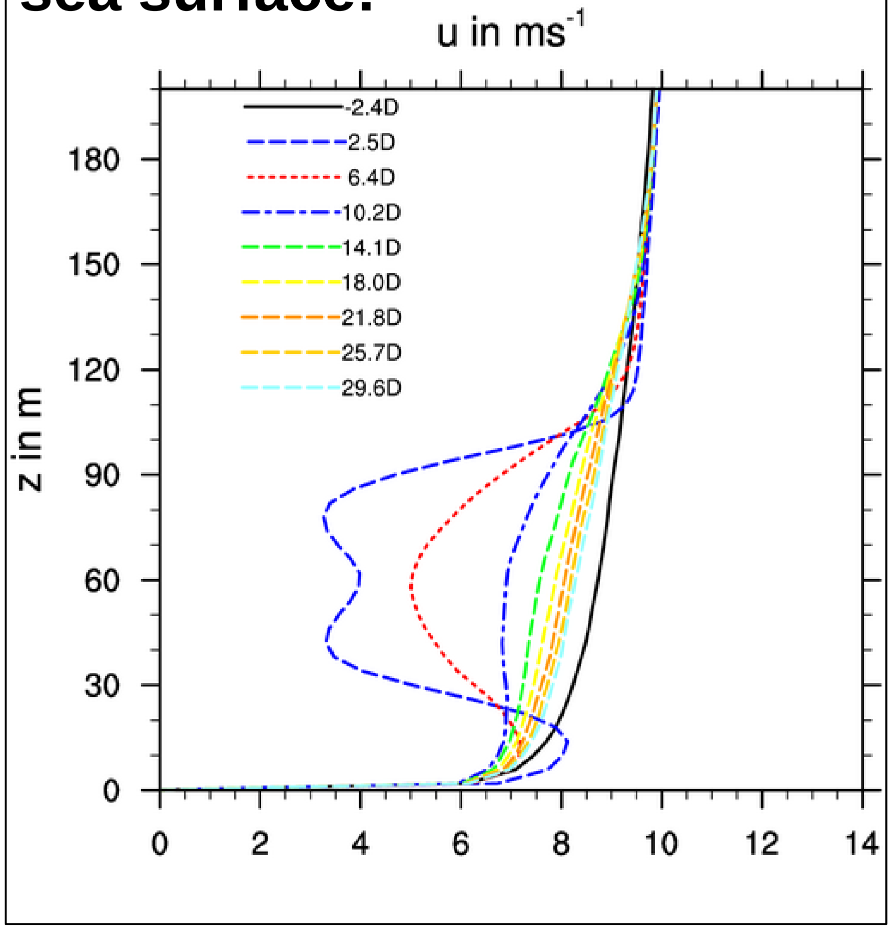
Study: impact of surface conditions on wake flows

Velocity profiles in dependency on the distance from the WT

land surface:

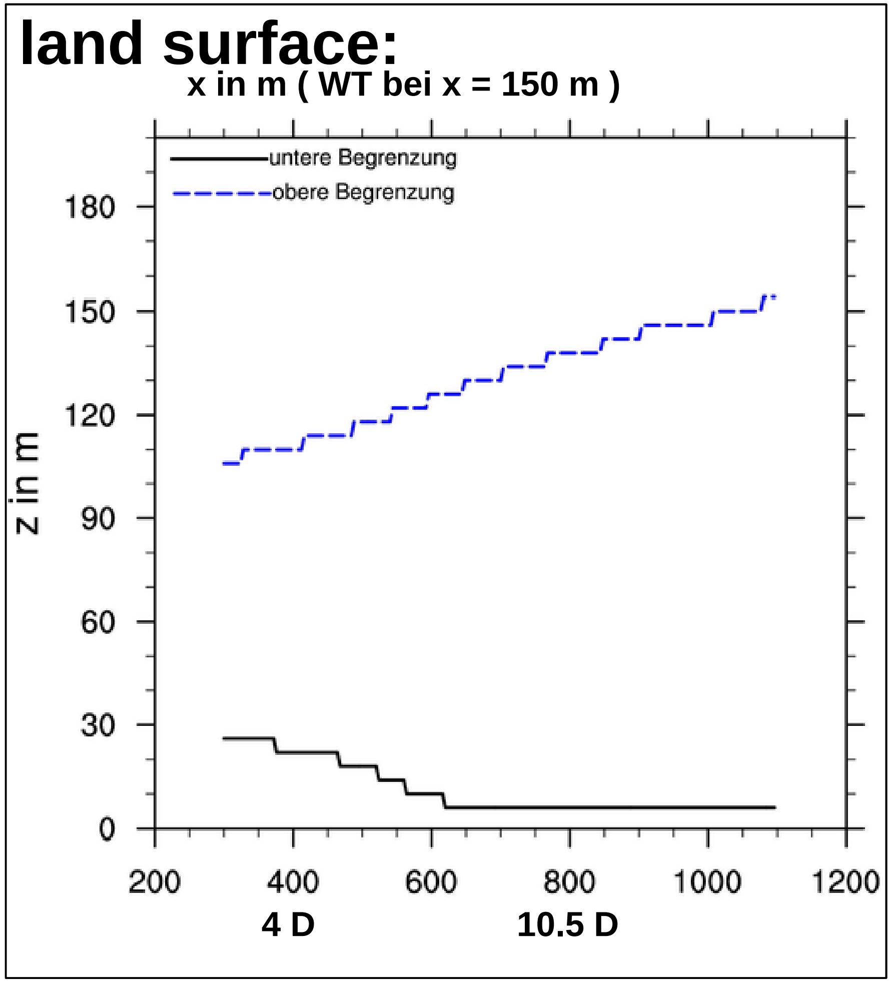


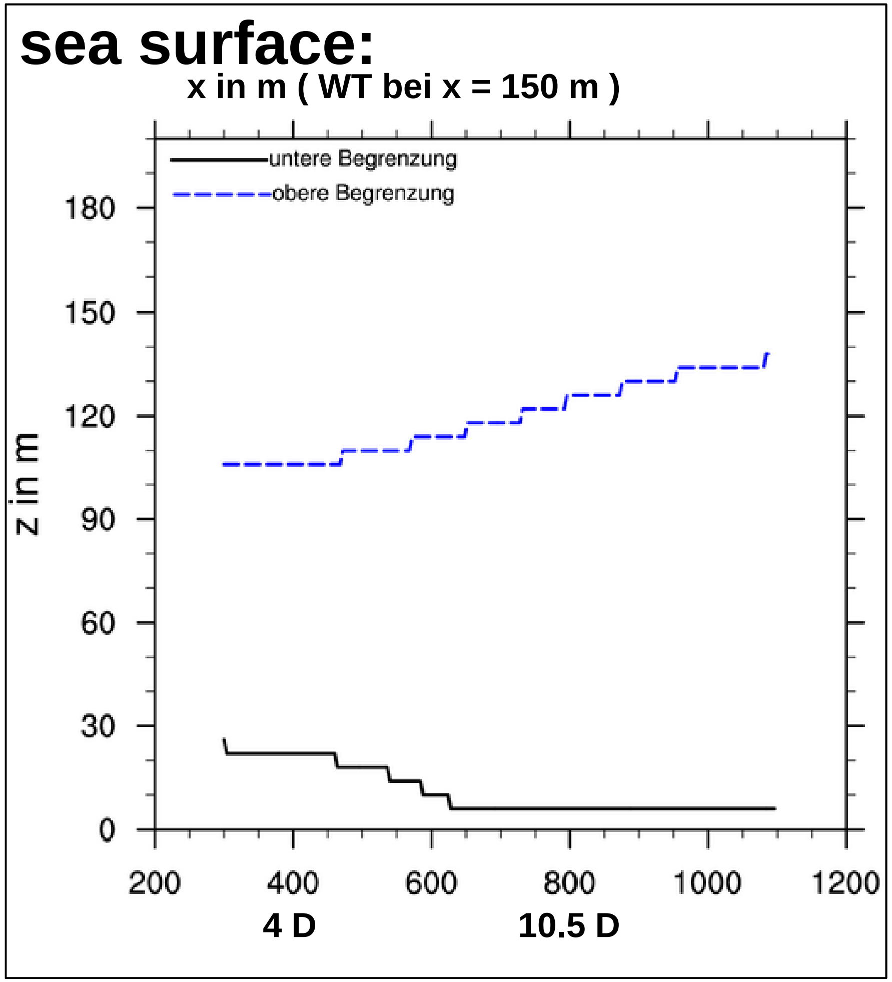
sea surface:



Study: impact of surface conditions on wake flows

Wake extension in vertical direction





Recovery of the wake deficit

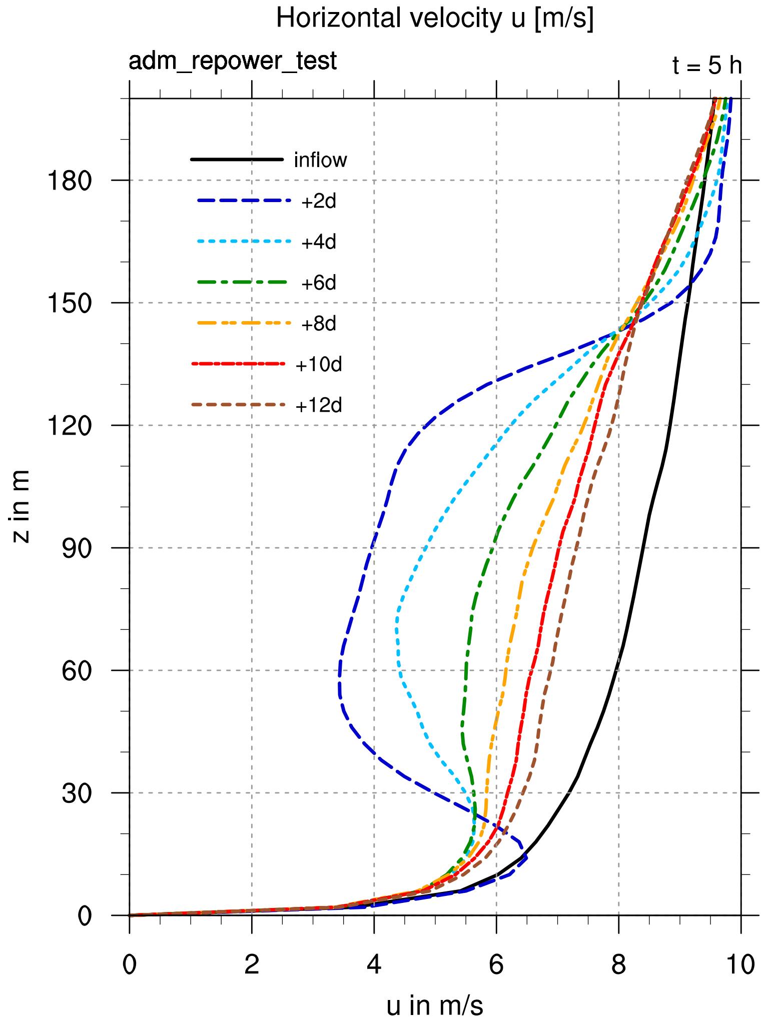
land surface:

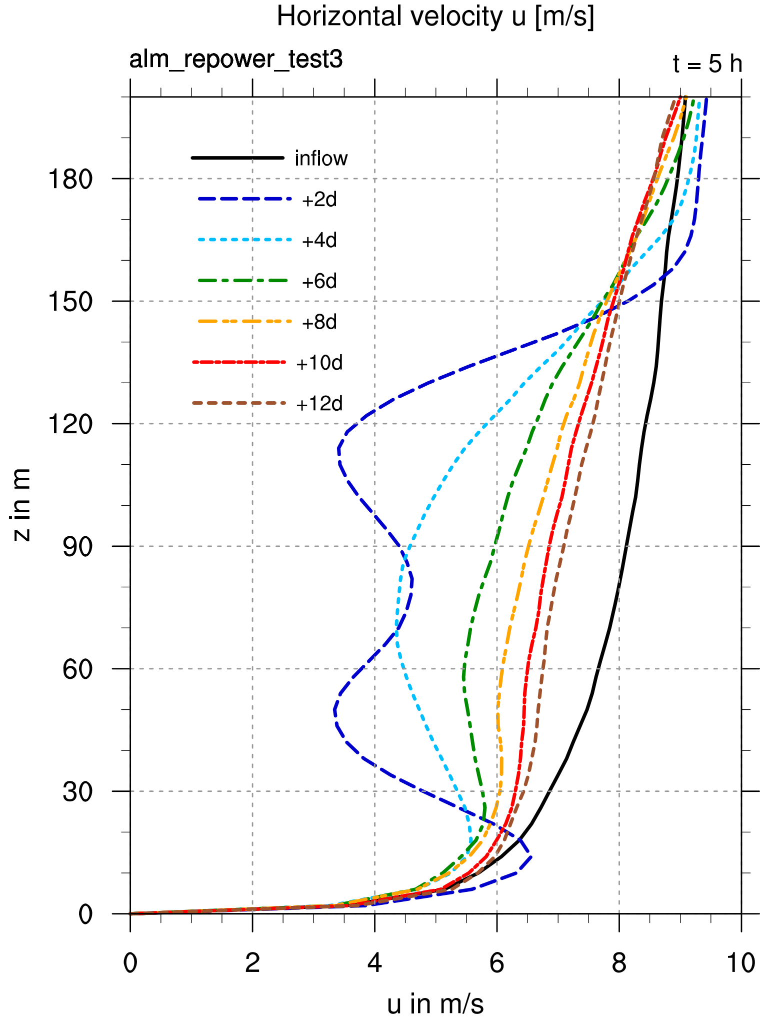
Recovery state	Distance in m	Distance in D
70 %	422	6.8
75 %	486	7.8
80 %	570	9.2
85 %	710	11.5
90 %	982	15.8
95 %	1554	25.1
98 %	2514	40.5

sea surface:

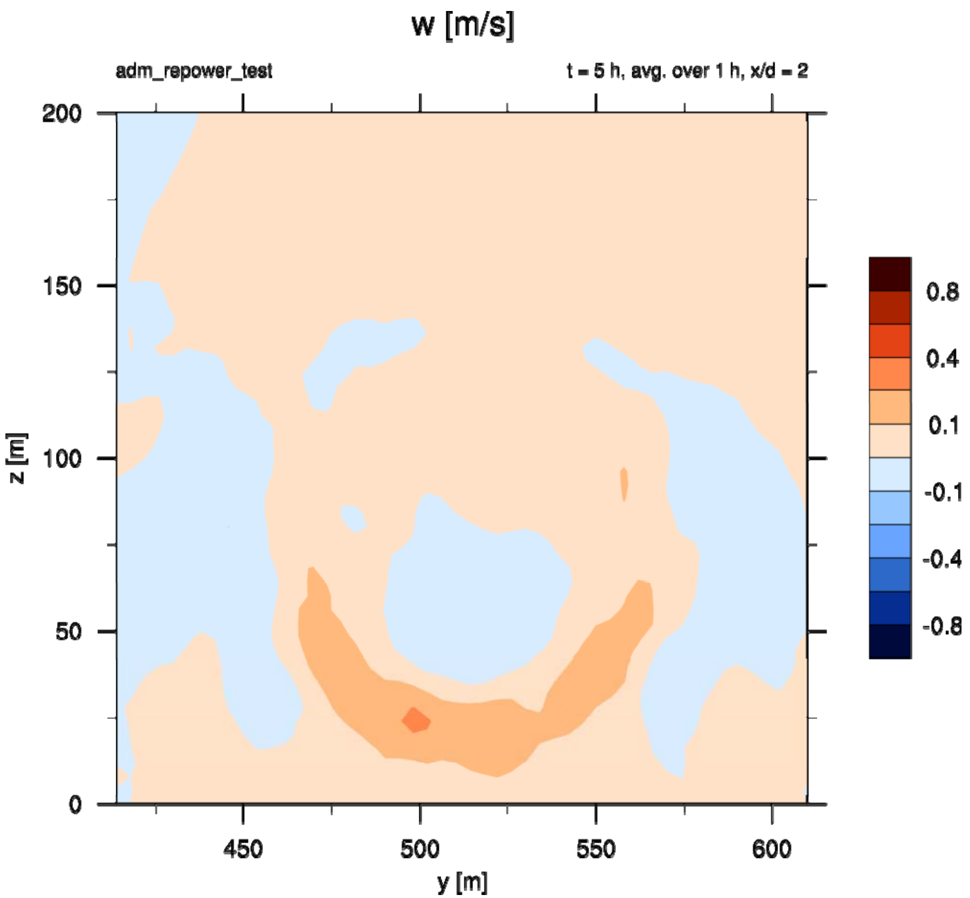
Recovery state	Distance in m	Distance in D
70 %	502	8.1
75 %	562	9.1
80 %	654	10.5
85 %	814	13.1
90 %	1094	17.6
95 %	1894	30.5
98 %	2770	44.7

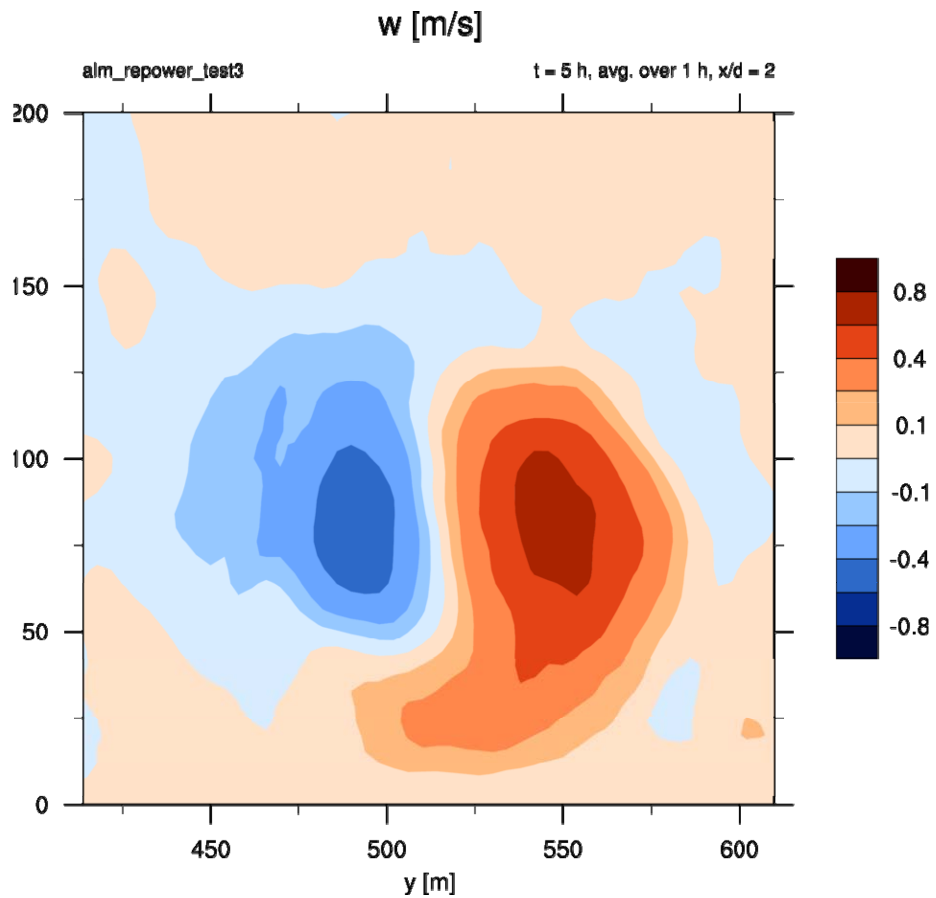
Comparison between actuator disc and actuator line model I



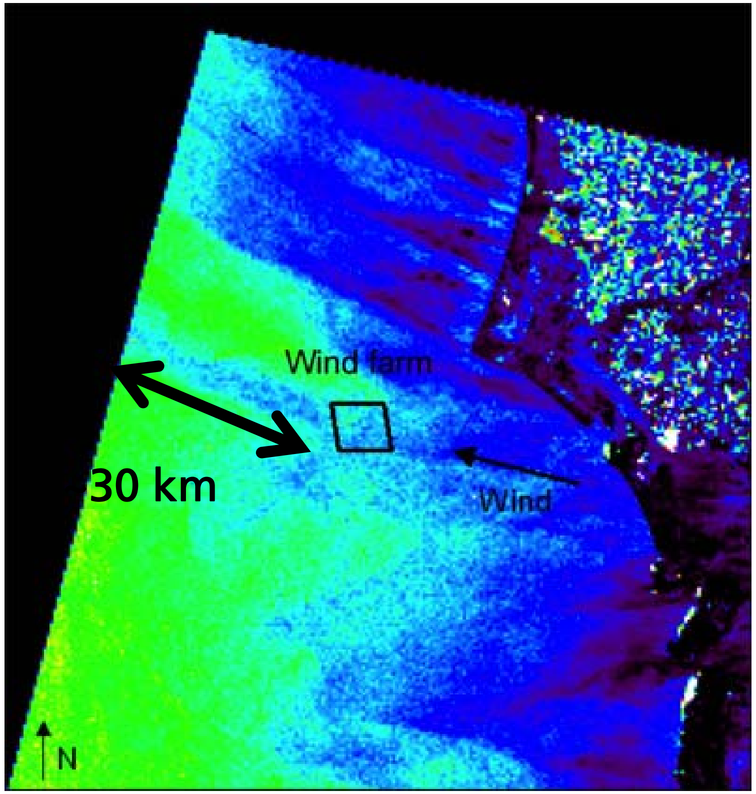


Comparison between actuator disc and actuator line model II

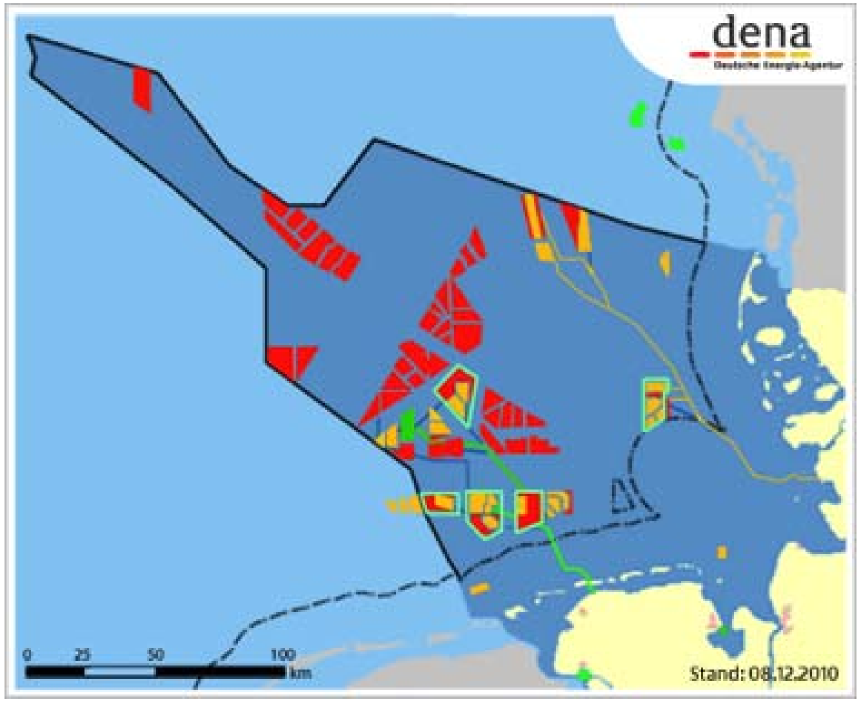




OWEA project: Inter wind farm flows – Parameterization of wind farm effects in the meso-scale model COSMO



http://galathea3.emu.dk/billeder/satelliteeye/projekter/wind/Wind_16_L.jpg



http://www.offshore-wind.de

Wind farm wakes might play an important role! Adjacent wind farms should be accounted for!

OWEA project: Inter wind farm wakes – Parameterization of wind farm effects in the meso-scale model COSMO

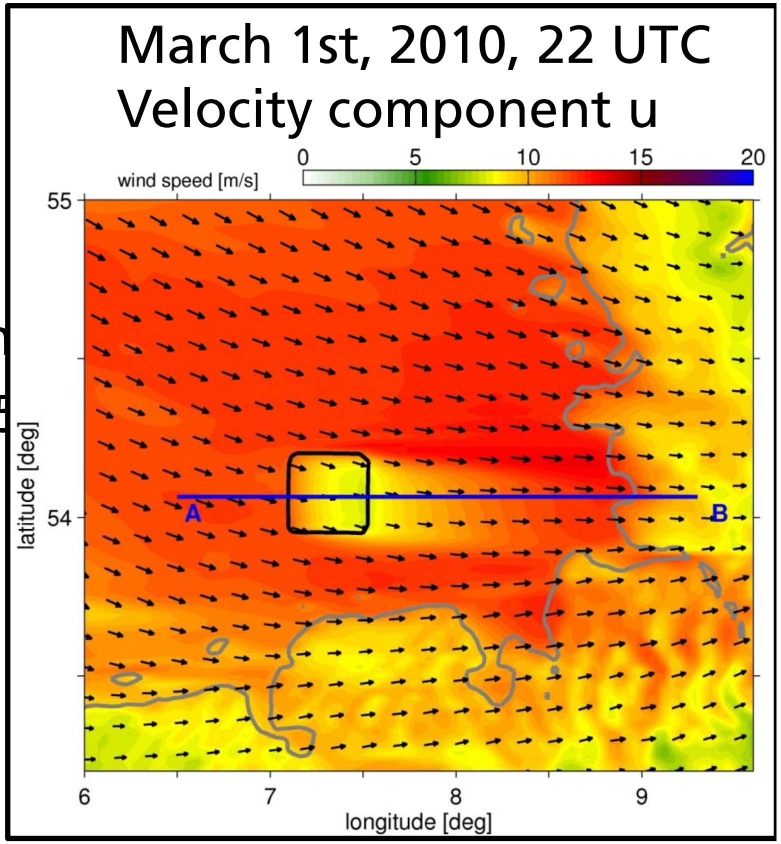
- Using LES for the study of inter wind farm effects is difficult, as LES is computationally too expensive
- Atmospheric flow field would have to be simulated over distances of several tens of kilometers
- Resolution of some meters would be required for an adequate representation of wind turbines in the LES

- Therefore, inter wind farm flows (i.e. wake effects of wind farms) are currently studied with the means of meso-scale simulations and especially developed wind farm parameterizations

Mesoscale model used here: COSMO LM

- The LM (Lokalmodell) is a non-hydrostatic, mesoscale, limited-area atmospheric prediction model. The LM has been developed at the DWD and is run operationally since 1999.
- Set up of simulation:

Resolution:	2.8 km (7 km)
Grid points:	200 x 200 (149 x129)
Vertical layers:	55 (near surface 15 m
PBL parameterization:	Mellor-Yamada 2.5
Forcing data:	ERA Interim
Simulated day:	March 1st, 2010
Wind farm:	27.8 x 28.1 km²
Wind turbines:	5 MW, h=92 m,
	r=58 m, d=800m



Lettau Wind Farm Parameterization (WFP)

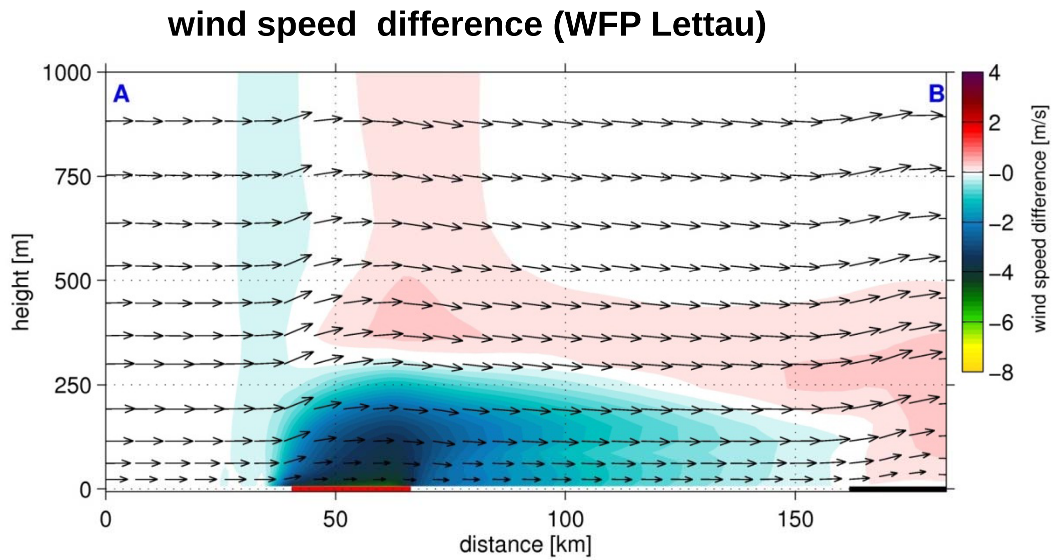
- WFP Type: modified (enhanced) surface roughness length
- based on Lettau 1969, applied by Rooijmans (2004) and Barrie and Kirk-Davidoff (2010).
- Modification: The surface roughness length (z0) only depends on geometrical measurements.

$$z_0 = 0.5h\frac{s_s}{S_L}$$

h ...vertical extent of roughness elements, (for wind farm = rotor diameter D)

s_s .. the vertical cross-section area presented to the wind ($\pi(D/2)^2$) by one wind turbine

S_L...the total wind farm area divided by the number of wind turbines

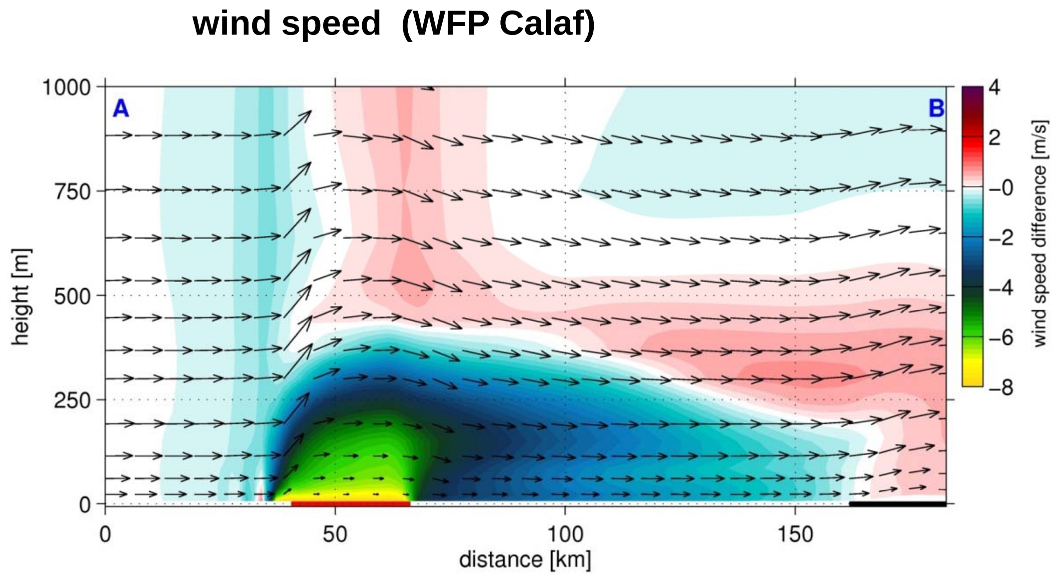


Calaf Wind Farm Parameterization

- WFP Type: modified (enhanced) surface roughness length
- based on Calaf et al. 2010
- Modification: The surface roughness length (z0) is a function of geometrical measurements and roughness characteristics

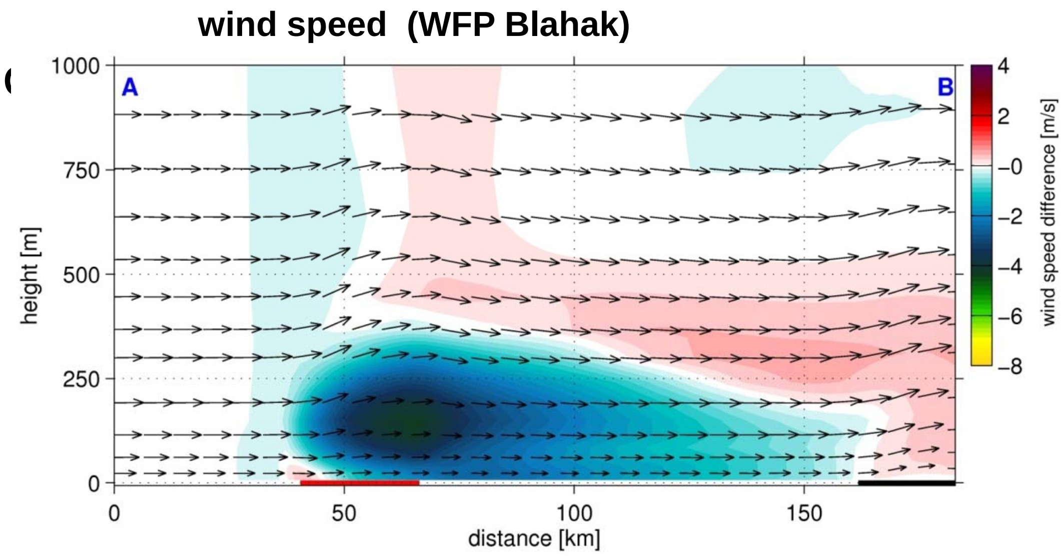
$$z_0 = funct(h, z_{0,lo}, D, c_{ft}, \kappa)$$

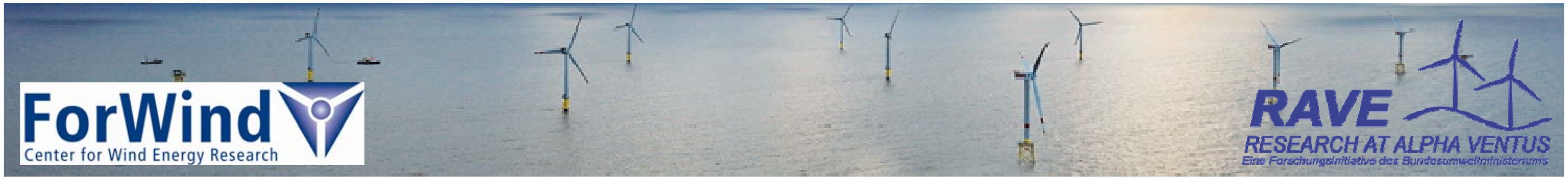
h …hub height
D .. rotor diameter
$z_{0,lo}$..unmodified surface roughness length
c_{ft}... friction coefficient based on horizontal surface
κ... von Karman constant



Blahak (WRF) Wind Farm Parameterization

- WFP Type: adding enhanced drag, that is generated by wind turbines
- based on Adams and Keith 2007, Blahak et al. 2010, the WFP is already implemented by Fitch in the Weather Research and Forecasting (WRF) model Version 3.3
- Modification: horizontal win speed deficit and an additional TKE term are calculated for all layers, that are intersected by the rotor area, and added to the tendencies of the horizontal wind speeds and TKE, respectively.





Parameterization of wind farm effects - future work

- Grid spacing of mesoscale simulations is of the order of several kilometers – wind farm alpha ventus cannot adequately be represented in a mesoscale simulation

- Verification of the implemented parameterizations should be done by comparison with LES data and with LiDAR measurements downwind of the wind farm Bard Offshore I in the GW Wakes project

- Parameterizations will certainly need to be improved: so far the topology of the wind farm layout is not taken into account, further investigation of the proportionality constant α is required

Summary

- On HPC clusters, it is possible to simulate wind turbine wakes and intra wind farm wakes and resolve the relevant scales of turbulence with the LES model PALM
- The interaction between ABL flow and wake flow and the dynamics of wakes can be studied
- An adequate setting of inflow boundary conditions is important
- Both a large model domain and a high resolution are required
- Different wind turbine parameterizations are applied in PALM: Actuator disk and actuator line approaches
- Mesoscale simulations of inter wind farm flows show that large wind farms have a considerable impact on regional flow conditions

Acknowledgements

The further development of PALM for its application to the simulation of wind turbine wakes has been funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear safety.

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für Umwelt, Naturschutz
und Reaktorsicherheit

aufgrund eines Beschlusses
des Deutschen Bundestages

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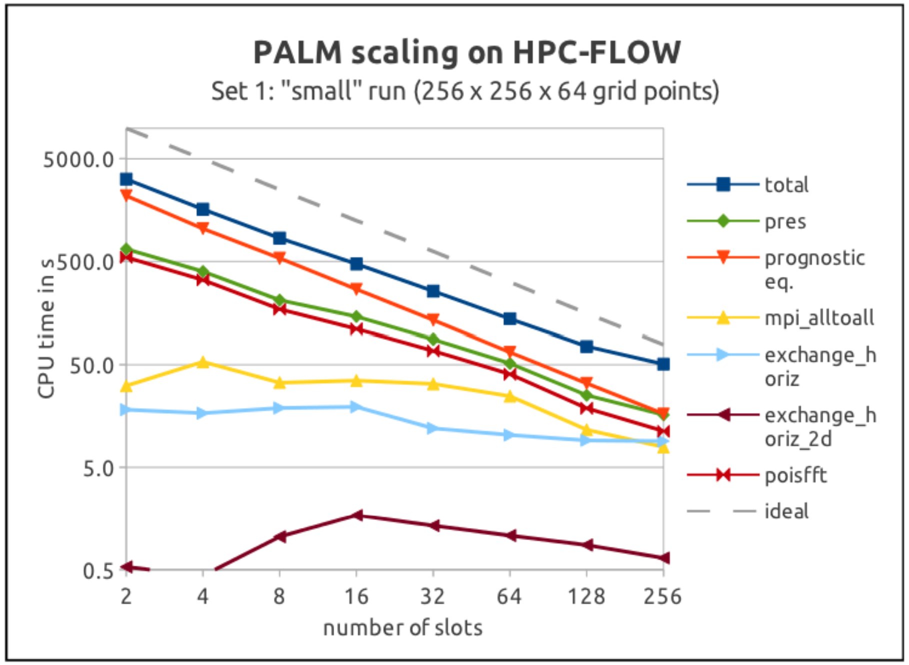
HLRN

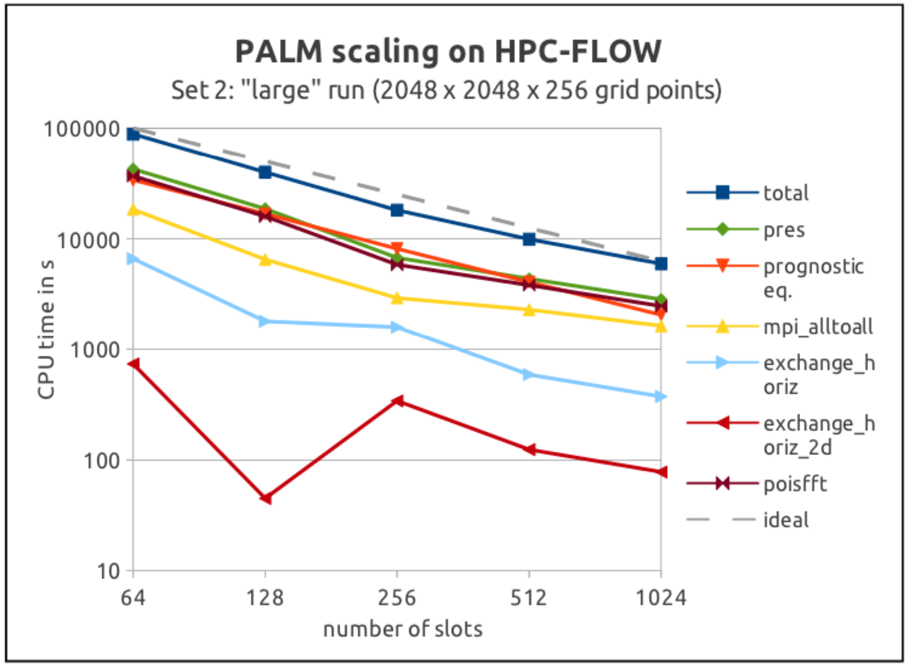
Thank you for your attention!

ForWind
Center for Wind Energy Research

RAVE
RESEARCH AT ALPHA VENTUS
Eine Forschungsinitiative des Bundesumweltministeriums

Performance of PALM on IBM-Cluster

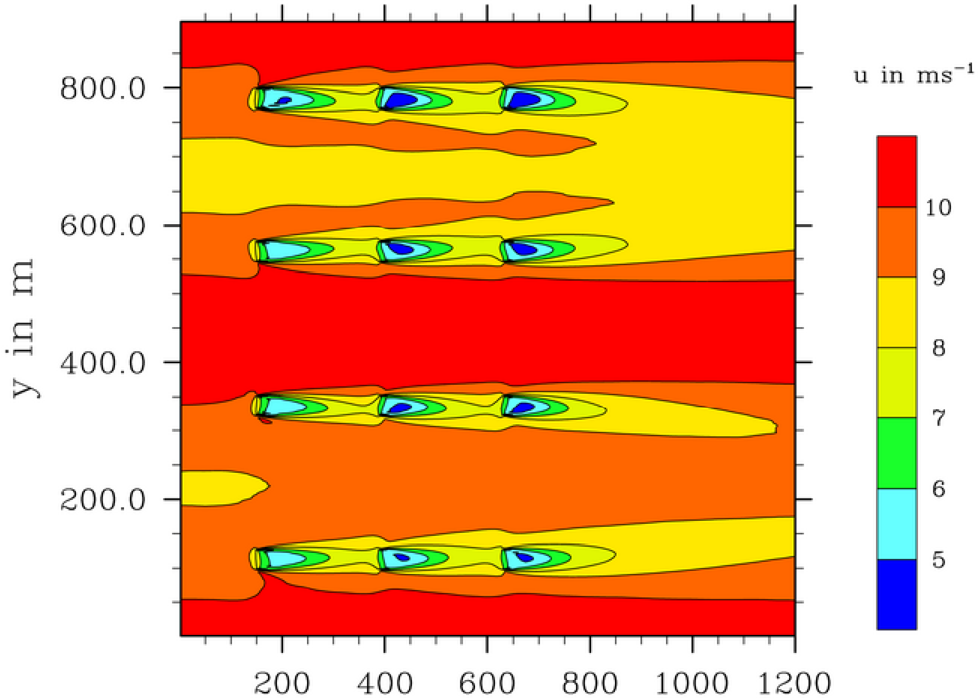




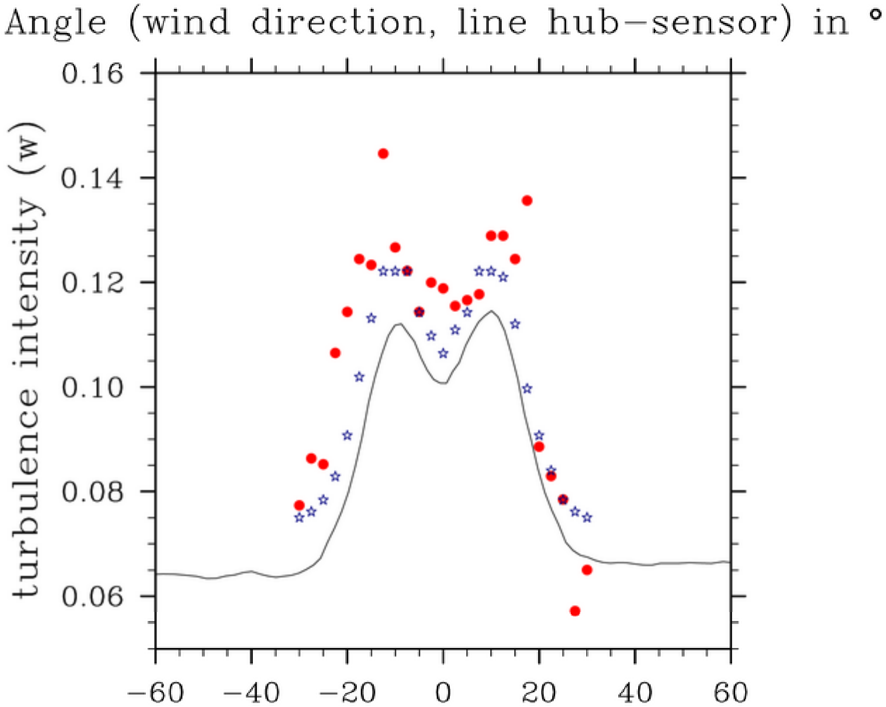
- The „small“ run scales almost linearly up to 128 CPUs
- The „large“ run scales even superlinearly for 64 to 256 CPUs → CPU time is reduced more than half when number of processors is doubled. For more than 256 CPUs, the performance is slightly reduced but still very good (ratio of CPU time needed for communication between CPUs to total CPU time is increasing)

Example: result for simulation with actuator disc model

Temporally averaged **u** at hub height

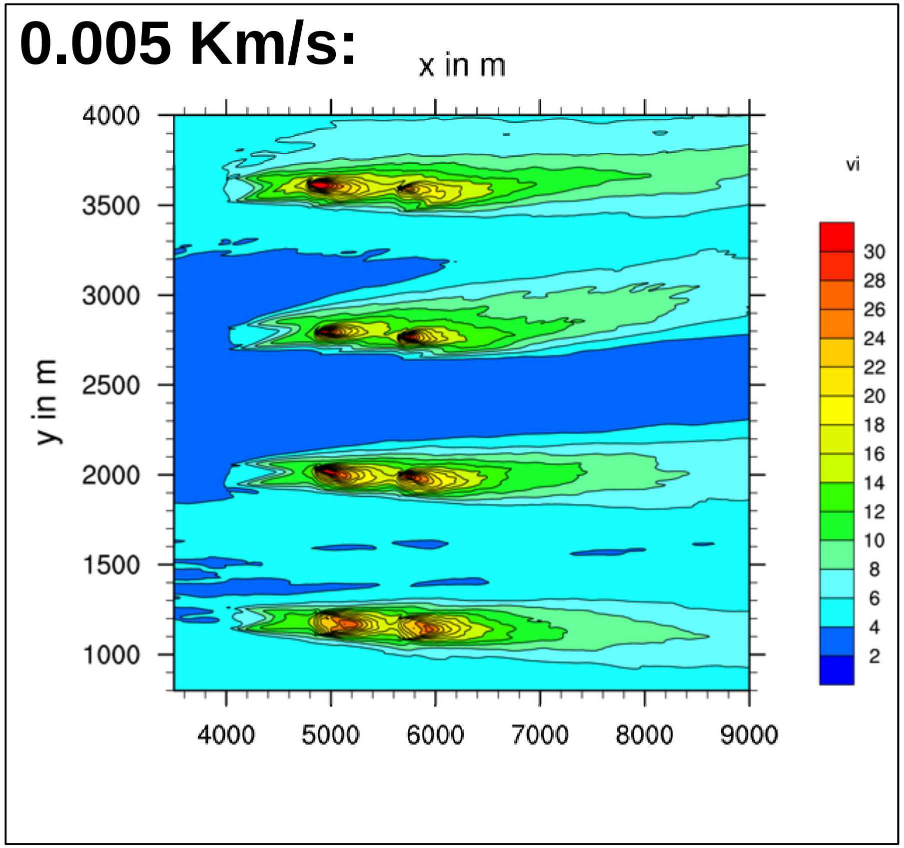


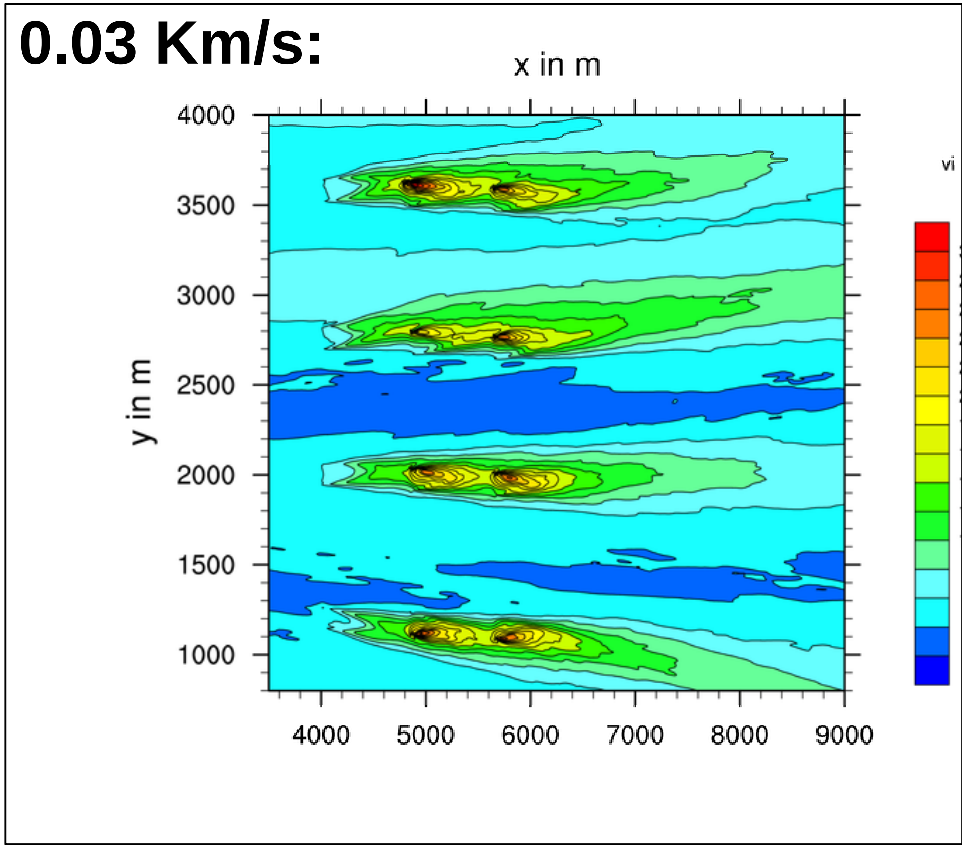
Turbulence intensity $w_i(z) = \frac{\sigma_w(z)}{\bar{u}(z)}$ at a distance of 75 m behind the rotor layer



Impact of near-surface heat flux on wake effects in the alpha ventus wind farm

vi (in %) averaged over 1800 s

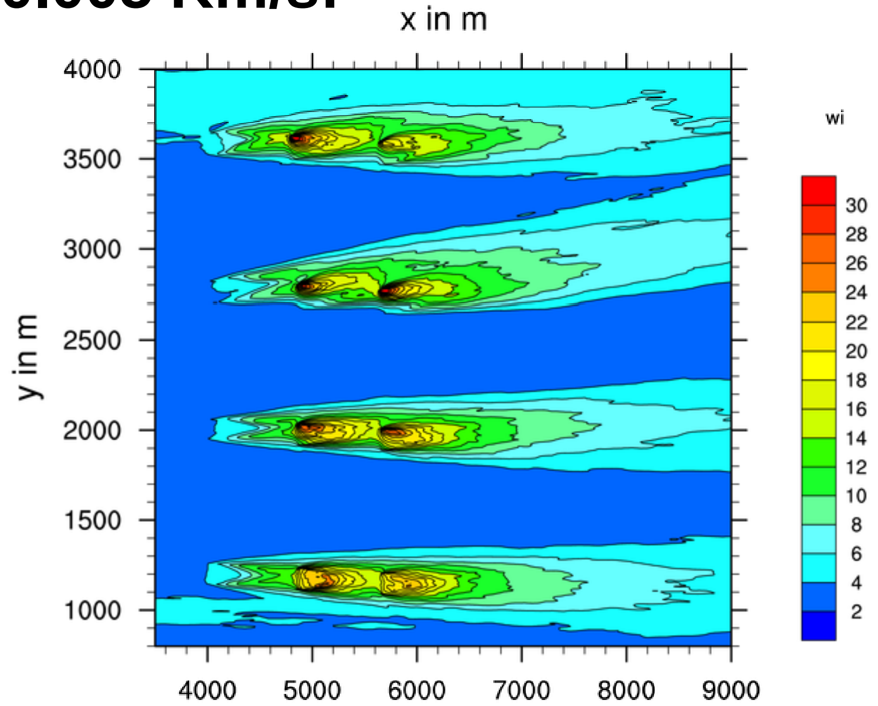




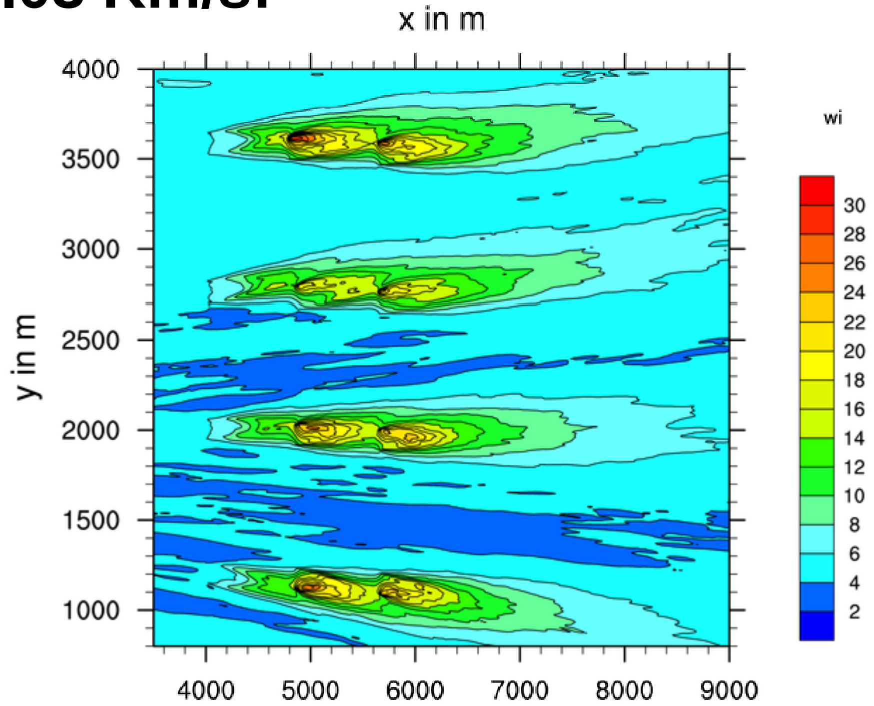
Impact of near-surface heat flux on wake effects in the alpha ventus wind farm

wi (in %) averaged over 1800 s

0.005 Km/s:

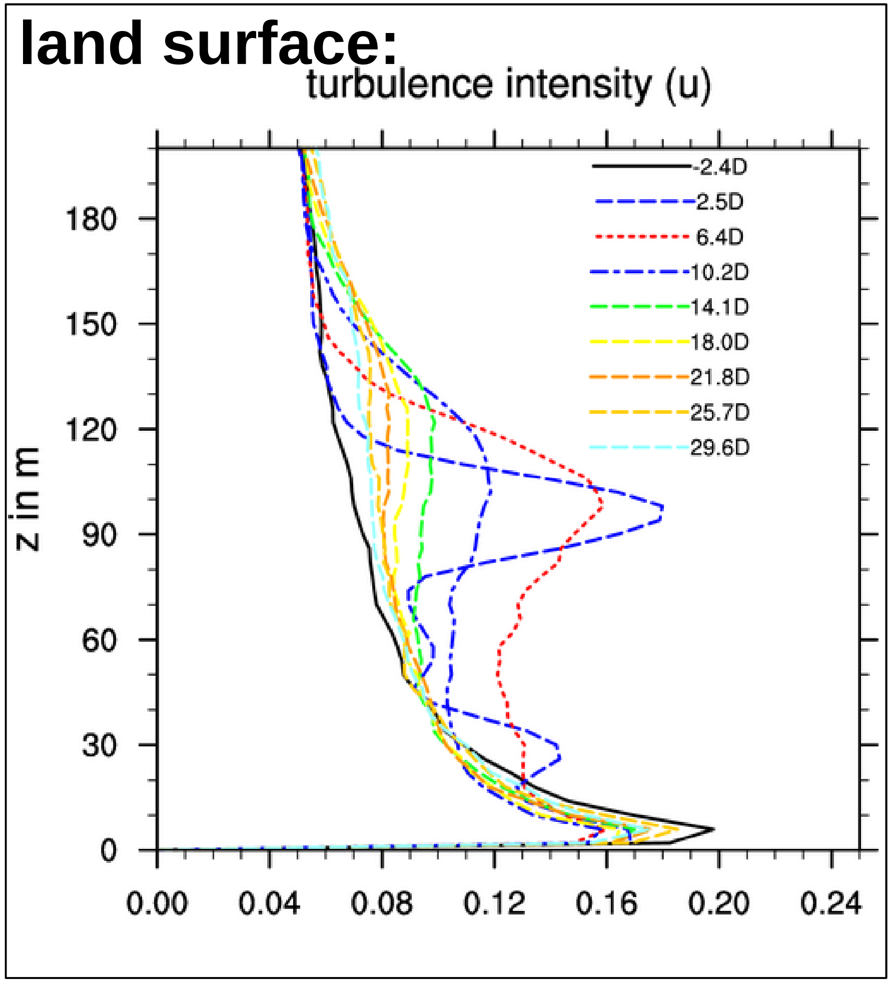


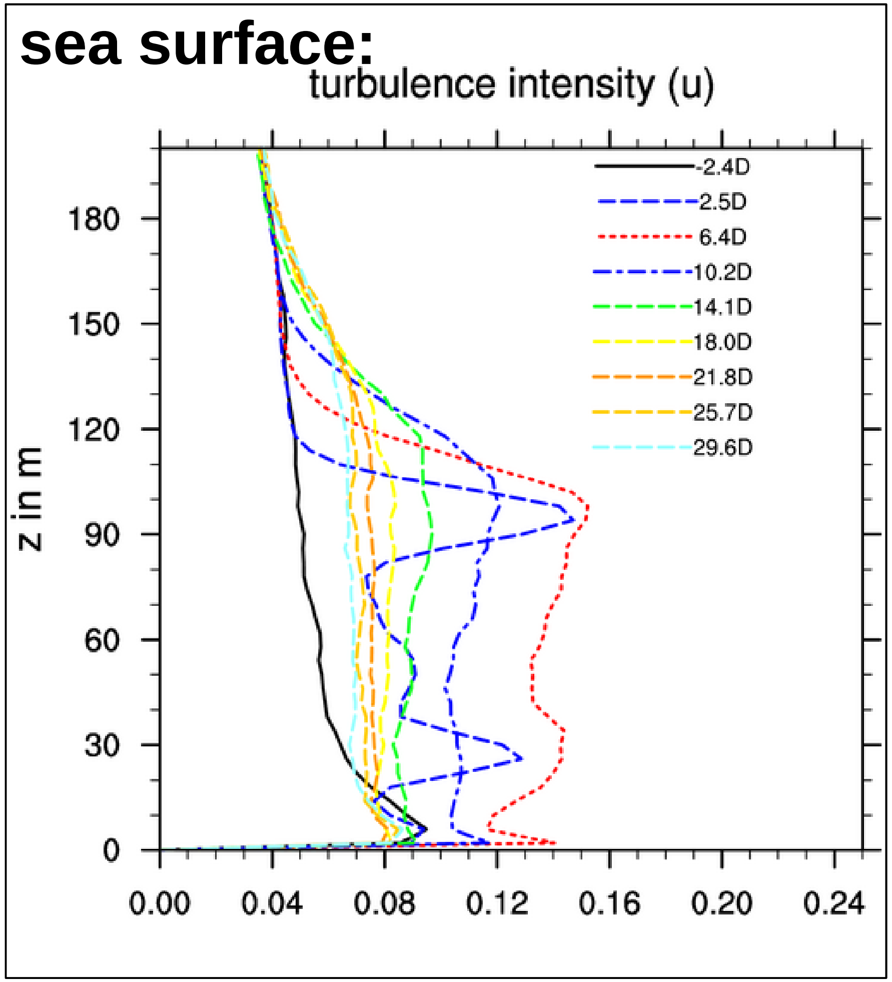
0.03 Km/s:



Impact of surface conditions on the wake development

Profiles of TI in dependency on the distance from the WT





Blahak (WRF) Wind Farm Parameterization II

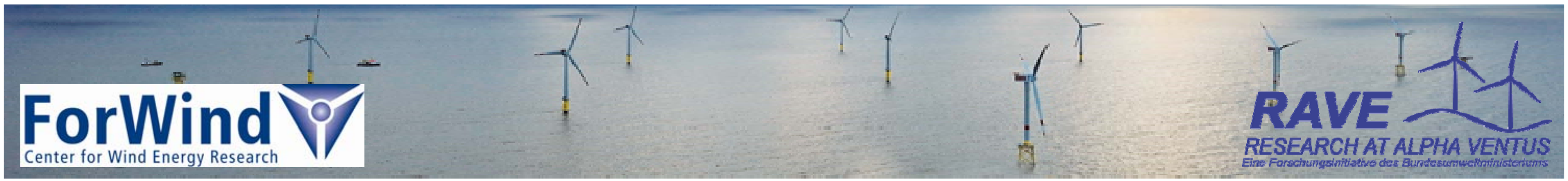
Major steps of the derivation of this parameterization (following Blahak (2010)):

- Power output of a wind turbine: $P(v_{rh}) = C_p \frac{\rho_{l0}}{2} v_{rh}^3 \frac{\pi}{4} d_r^2$

- Cp can be divided in an aerodynamic part and a loss factor: $C_p = C_a \eta_{elmech}$

- The aerodynamic part can thus be written as: $C_a(v_{rh}) = \frac{P(v_{rh})}{\eta_{elmech} \frac{\rho_{l0}}{2} v_{rh}^3 \frac{\pi}{4} d_r^2}$

- Instantaneous time rate of loss of kinetic energy due to wind power production in volume enclosing one wi $\dot{E}_{kin}\Big|_{wp} = -\frac{P(v_{rh})}{\eta_{elmech}} \approx -C_a(v_{rh}) \iint\limits_{A_r} \frac{\rho_l}{2} v_h^3 dA$



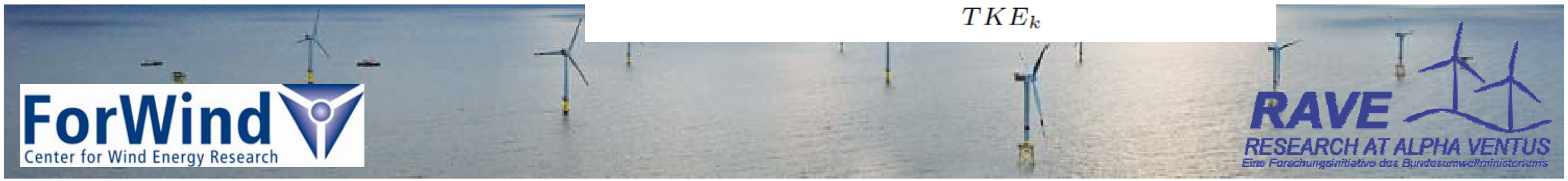
Blahak (WRF) Wind Farm Parameterization III

Major steps of the derivation of this parameterization (continued):

- Kinetic energy in the model consists of kinetic energy of the mean flow and the turbulent kinetic energy

$$E_{kin,k} = \int\limits_{\Delta x}\int\limits_{\Delta y}\int\limits_{z_k}^{z_{k+1}} \frac{\rho_l}{2}\left(u^2+v^2+w^2\right) dz\, dy\, dx \; = \left(\frac{\widehat{u}^2+\widehat{v}^2+\widehat{w}^2}{2}+\frac{\widehat{u''^2}+\widehat{v''^2}+\widehat{w''^2}}{2}\right)\overline{\rho_l}V_k \quad .$$

$$\frac{\partial}{\partial t}E_{kin,k} = \frac{\partial}{\partial t}\underbrace{\left(\frac{u_k^2+v_k^2+w_k^2}{2}\rho_{lk}V_k\right)}_{E_{kin,grid,k}} + \frac{\partial}{\partial t}\underbrace{\left(\frac{\widehat{u''^2}+\widehat{v''^2}+\widehat{w''^2}}{2}\rho_{lk}V_k\right)}_{TKE_k}$$



Blahak (WRF) Wind Farm Parameterization IV:

Major steps of the derivation of this parameterization (continued):

- Assumption: gain of turbulent kinetic energy is proportional to the loss of total kinetic energy

$$\rho_{lk} V_k \; T\dot{K}E_k \Big|_{wp} = -\alpha \;\; \dot{E}_{kin,k} \Big|_{wp}$$

- Therefore, the rate of change of kinetic energy of the grid volume averaged flow is

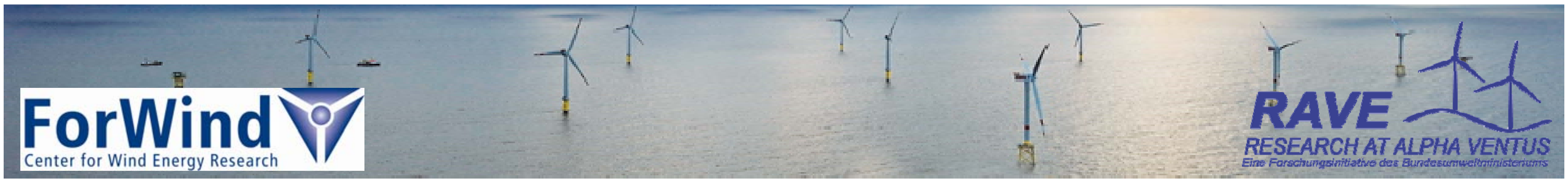
$$\dot{E}_{kin,grid,k} = (1+\alpha) \;\; \dot{E}_{kin,k} \Big|_{wp}$$

- which finally leads to

local number of wind turbines per area

$$\frac{\partial v_{hk}}{\partial t}\Big|_{\text{wtdrag,tke}} = -\,(1\,+\,\alpha)\;\frac{C_a(v_{rh}^{(ij)})\; f_{ij}\; v_{hk}^2\, I(z_k, z_{k+1})}{z_{k+1}\,-\,z_k} \longleftarrow$$

Rotor area within grid volume



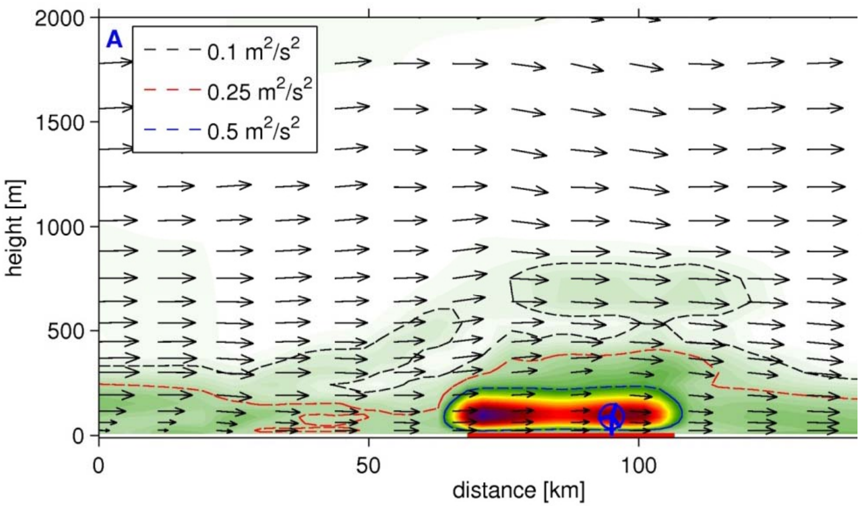
Blahak (WRF) Wind Farm Parameterization IV:

Major steps of the derivation of this parameterization (continued):

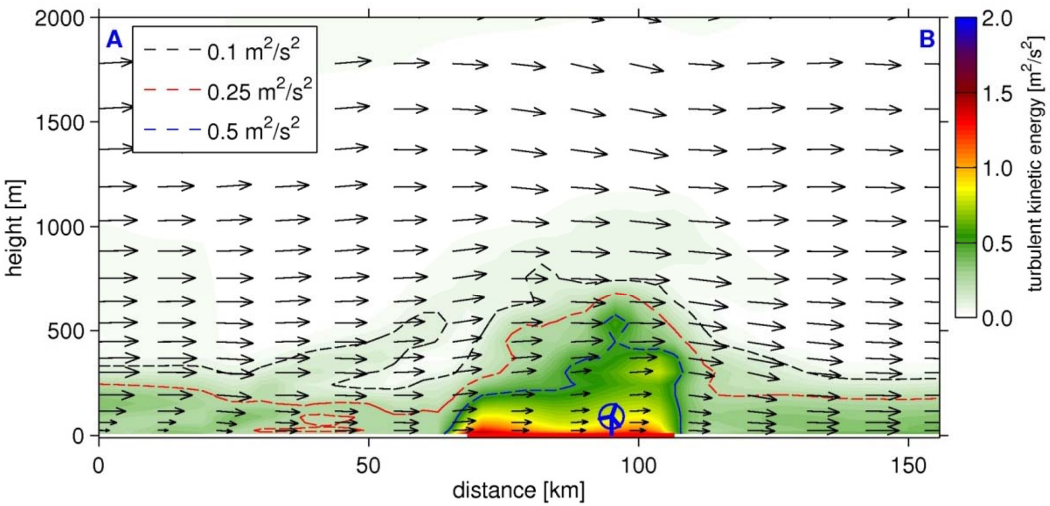
- and

$$T\dot{K}E_k\Big|_{wp} = \alpha \, \frac{C_a(v_{rh}^{(ij)})\, f_{ij}\, v_{hk}^3\, I(z_k, z_{k+1})}{z_{k+1} - z_k}$$

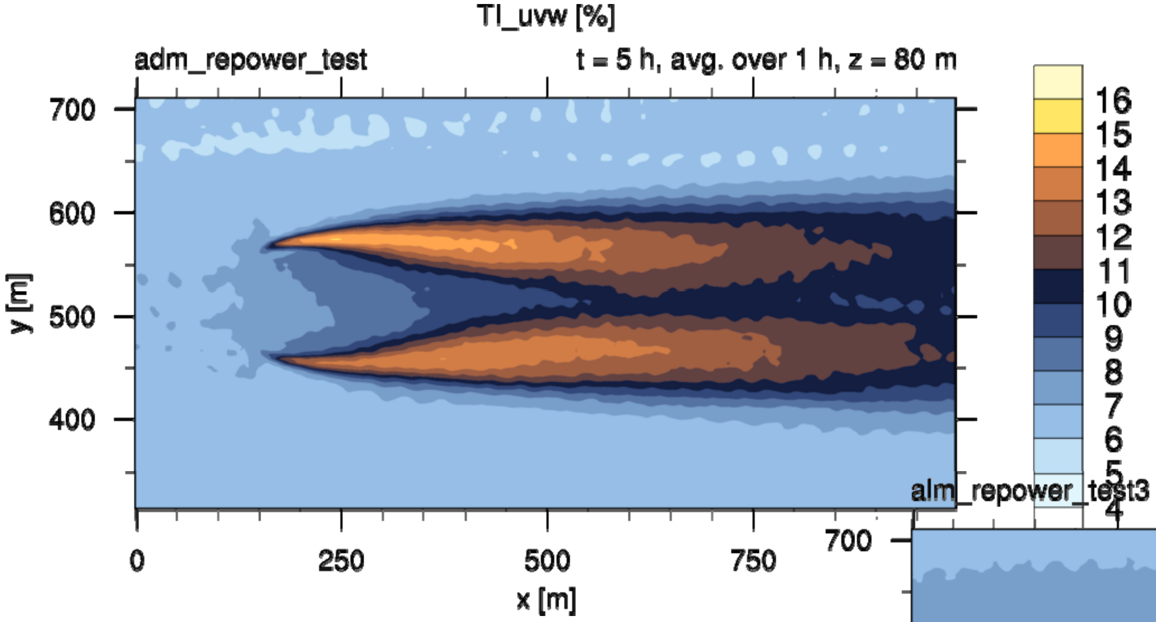
TKE with Blahak

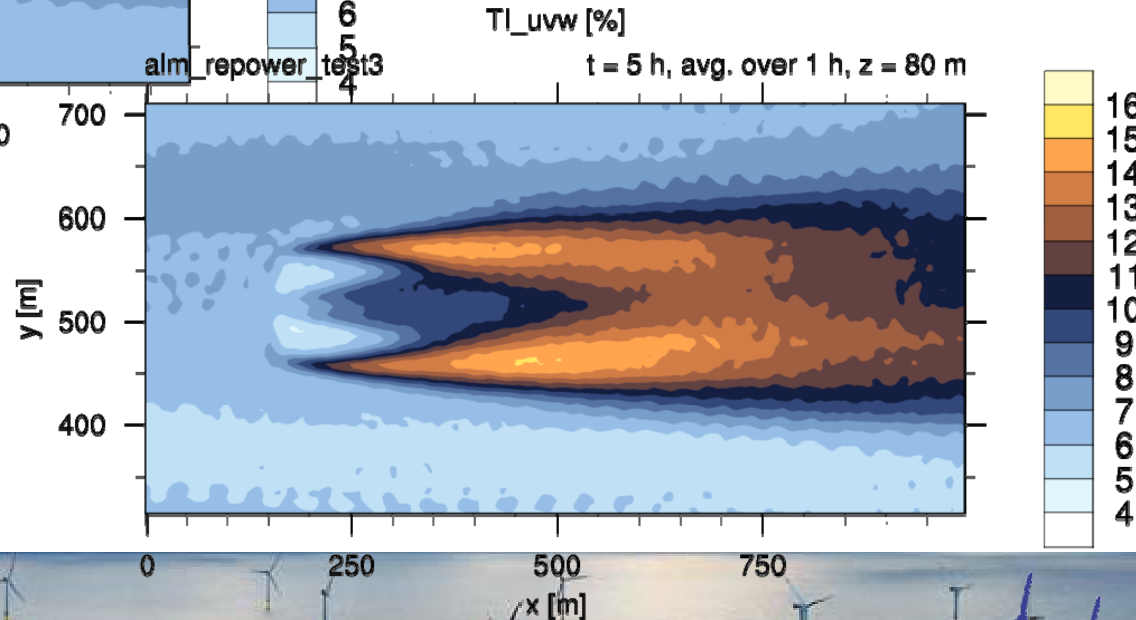


TKE with Calaf



Comparison between actuator disc and actuator line model III





Comparison between actuator disc and actuator line model IV