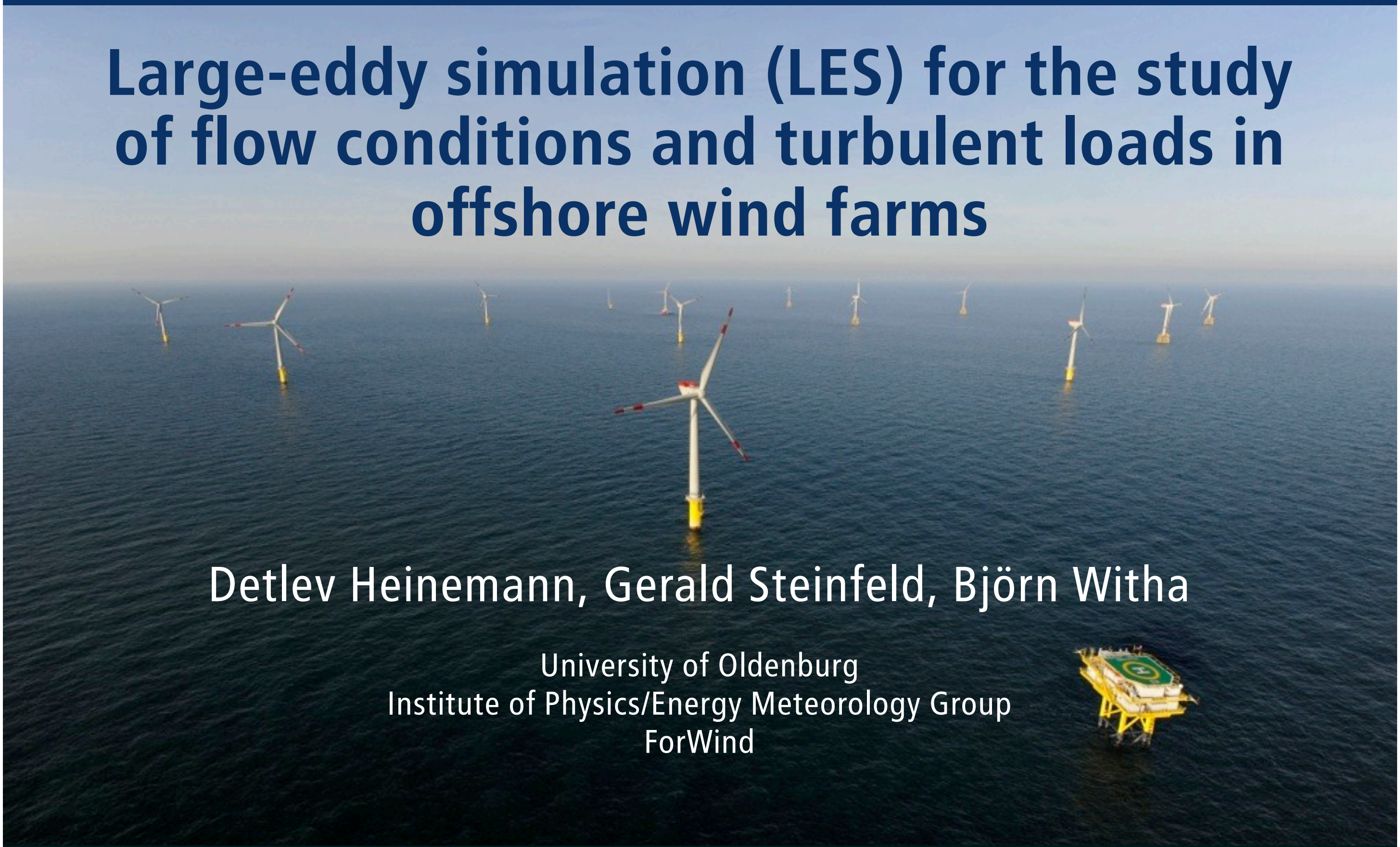

# Large-eddy simulation (LES) for the study of flow conditions and turbulent loads in offshore wind farms

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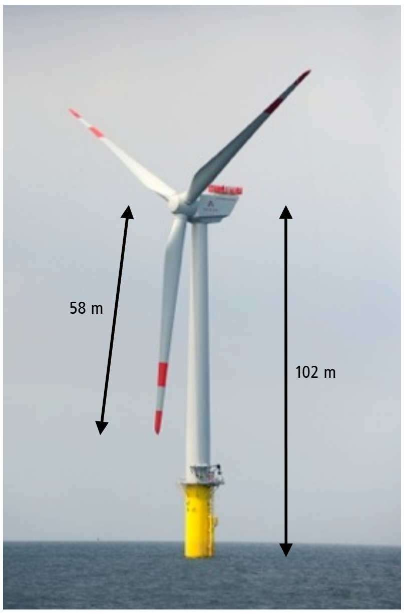
## MOTIVATION



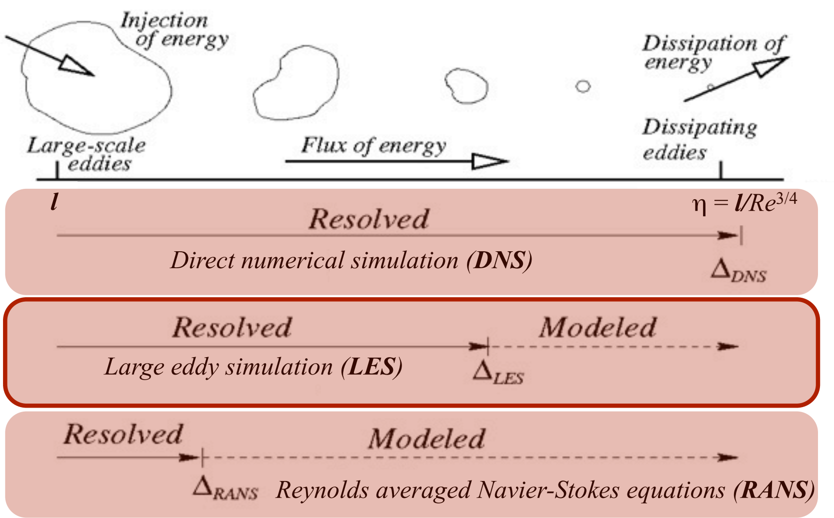

The exploitation of offshore wind resources is challenging!

Compared to onshore e.g.

- the wind turbines are larger,
- the bottom boundary condition is modified,
- the wind farms have a larger extent and consist of a larger number of wind turbines,
- the atmospheric stability is modified.

➡ Study impact on **mean flow** <u>and</u> **turbulence** in the atmospheric boundary layer with an **LES model**

# LARGE EDDY SIMULATION (LES)




Bakker, 2002



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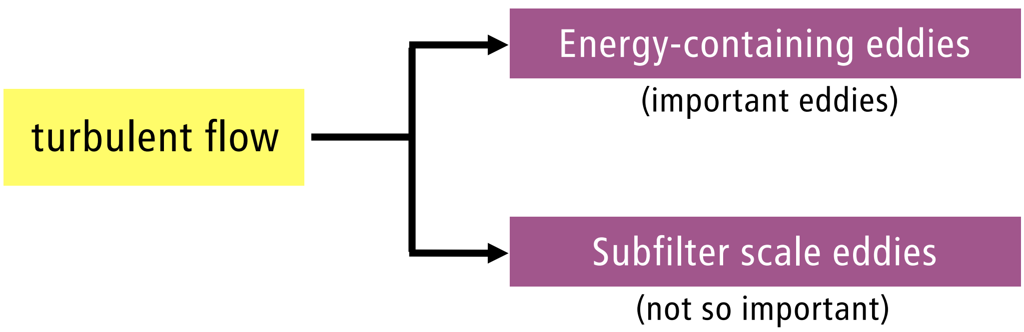
# LARGE EDDY SIMULATION (LES)

**Separation of scales:**

**Large scales:** contain most of the energy and fluxes, significantly affected by the flow configuration, are explicitly calculated

**Smaller scales:** more universal in nature & with little energy are pameterized (SFS model)

LES solution supposed to be insensitive to SFS model

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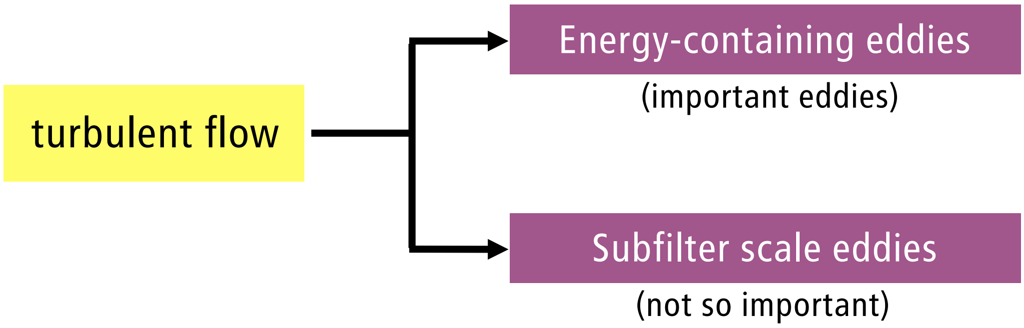
# LARGE EDDY SIMULATION (LES)

LES code:
PArallelised Large-eddy simulation Model (PALM)
(Raasch and Schröter, Meteorol. Z., 2001)



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# PARAMETERIZATION OF WIND TURBINES IN PALM (I)

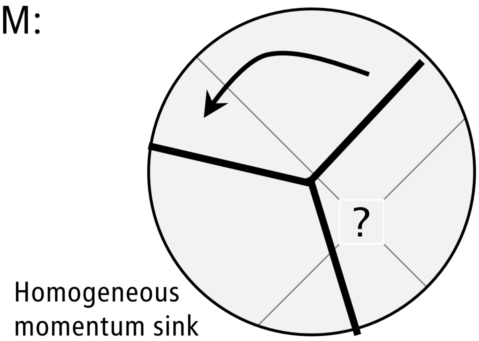
Simultaneous resolution of far wake flow and flow around the rotor not possible
→ Parameterization of wind turbine effects required

(I) Parameterization tested in PALM: Uniformly loaded actuator disc, i.e. a homogeneous momentum sink in the rotor-swept area realized by an additional force in the momentum equations, the thrust force

Different approaches have been implemented in PALM:

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

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

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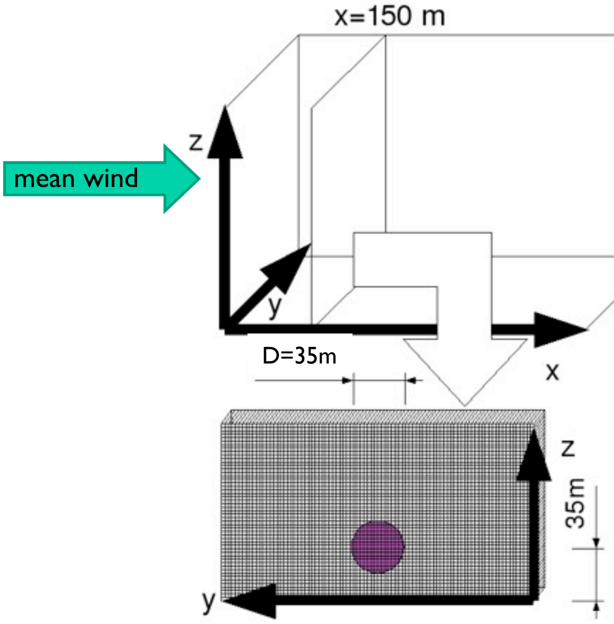
# VERIFICATION OF PALM WITH ACTUATOR DISC

Comparison with Jimenez et al. (2007)
Onshore-conditions: fixed roughness length 0.05 m, single wind turbine




$L_x$ = 6144 m, $\Delta x$ = 4 m
$L_y$ = 896 m, $\Delta y$ = 1.75 m
$L_z$ = 224 m, $\Delta z$ = 1.75 m

1536x512x128 grid points

Rotor area: 1413,7 $m^2$

cyclic horizontal boundary conditions

no Coriolis force

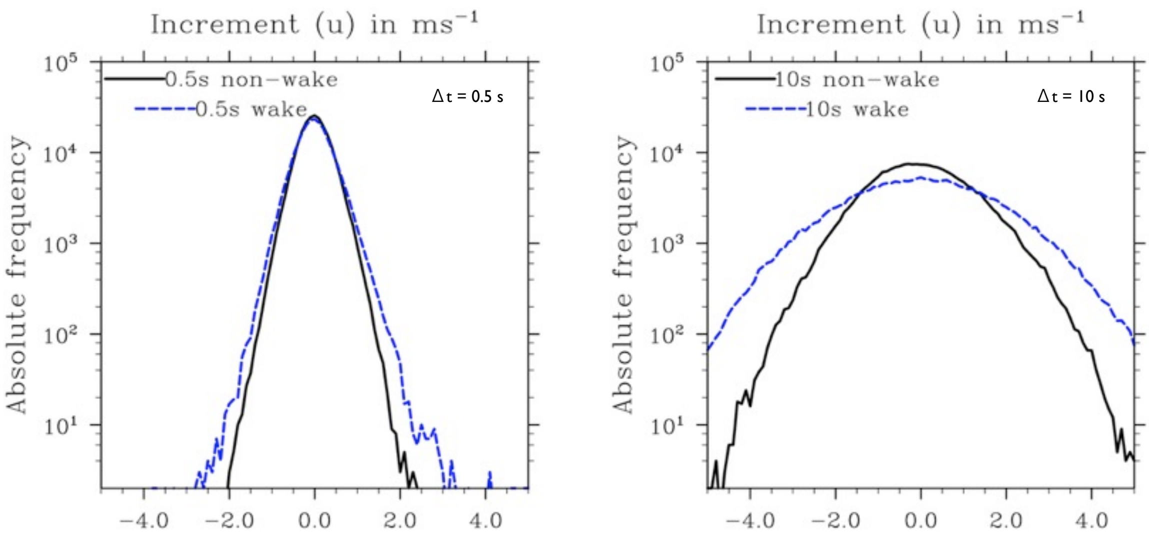
constant volume flow (=► dp/dx)

neutral stratification



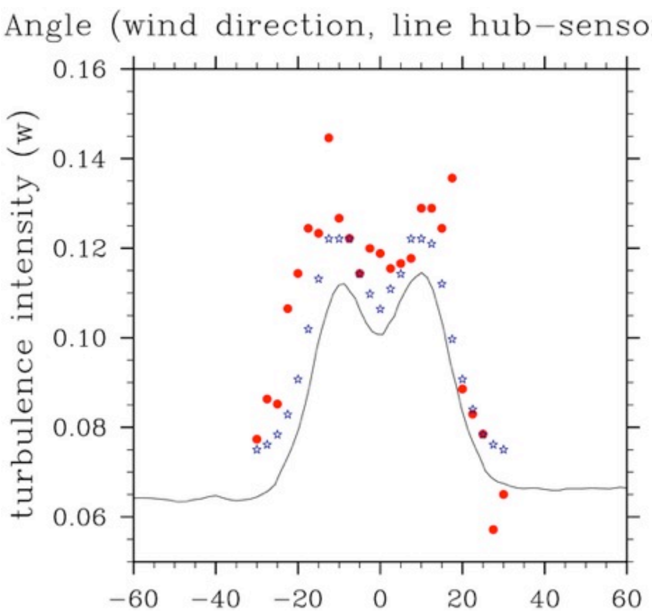


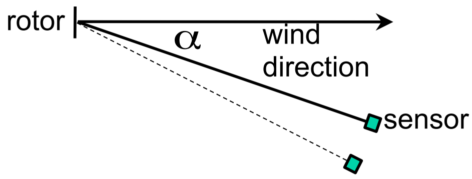
# RESULTS: INCREMENT ANALYSIS FOR U




Results reveal the increased risk of large velocity fluctuations in the wake

# RESULTS: $W_I$ AT HUB HEIGHT




black: PALM
red: measurements
blue: LES Jimenez et al. (2007)

Turbulence intensity at a distance of 75 m behind the rotor layer:

$$w_i(z) = \frac{\sigma_w(z)}{\bar{u}(z)}$$



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# ADVANTAGES AND DISADVANTAGES OF THE ACTUATOR DISC METHOD

**+**

- Computationally fast
- Requires only the thrust curve

**-**

- Difficult to determine the free stream velocity
- Accounts only for the removal of momentum in mean flow direction, not the transfer of momentum from horizontal into the vertical direction
- No tip vortices are generated

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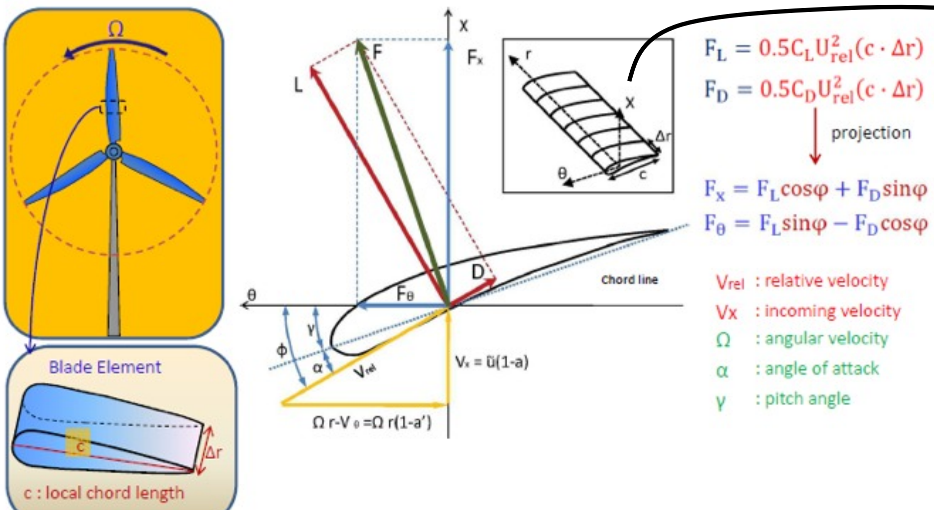
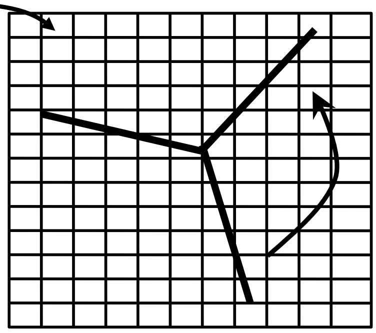
# PARAMETERIZATION OF WIND TURBINES IN PALM (II)

(II) Actuator line approach, i.e. 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: $F_\varepsilon = F \otimes \eta_\varepsilon$



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# SIMULATION OF WIND TURBINE WAKES WITH PALM

## Study: Impact of the sea surface on the wake flow

- Two simulations with comparable wind speed at hub height (9 m/s)
- 1536 x 256 x 64 grid points
- grid size: 4 m in all three directions in space
- Actuator line: Tjaereborg WT: hub height = 61m, radius = 31m
- ambient flow along x-direction (no Coriolis force)
- neutral stratification

Land surface:

- constant roughness length $z_0 = 0.05$ m
- flow driving pressure gradient dp/dx = -0.0008 Pa/m
- wind turbine starting after 4 h

Sea surface:

- variable roughness length, initially 0.5mm, later on calculated by $z_0 = (0.0185/9.81) * u_*^2$ (Charnock, finally 0.00012 m)
- flow driving pressure gradient dp/dx=-0.00025 Pa/m
- wind turbine starting after 5 h

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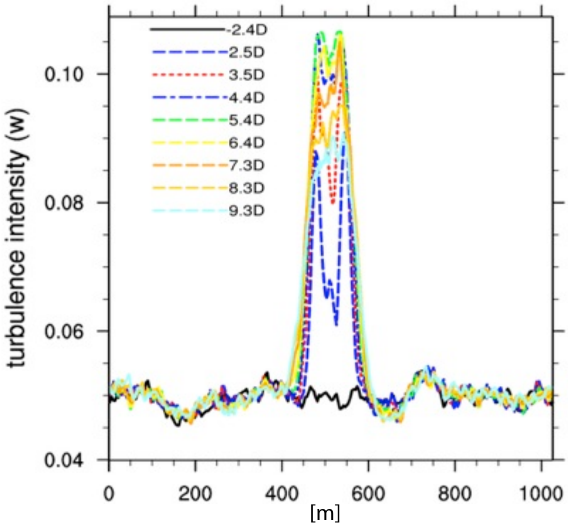
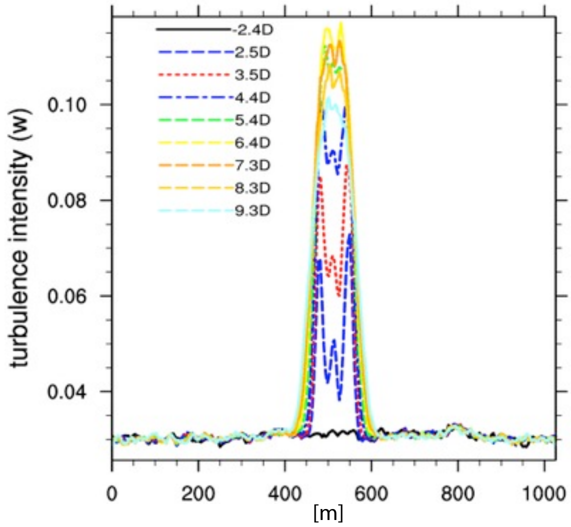
# SIMULATION OF WIND TURBINE WAKES WITH PALM

## Example: Lateral profiles of turbulence intensity (TI) downstream of the WT




land surface



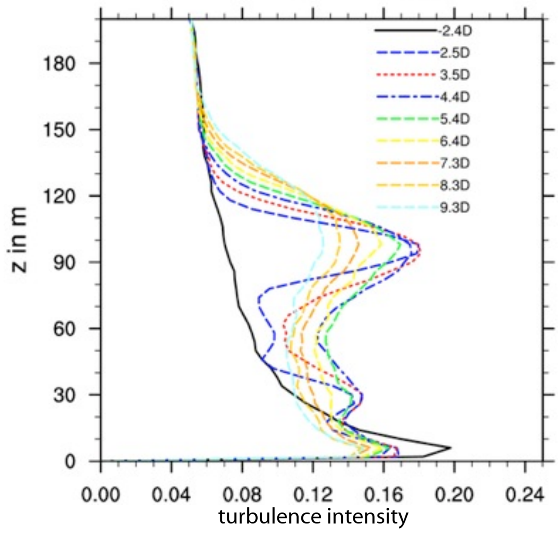

sea surface



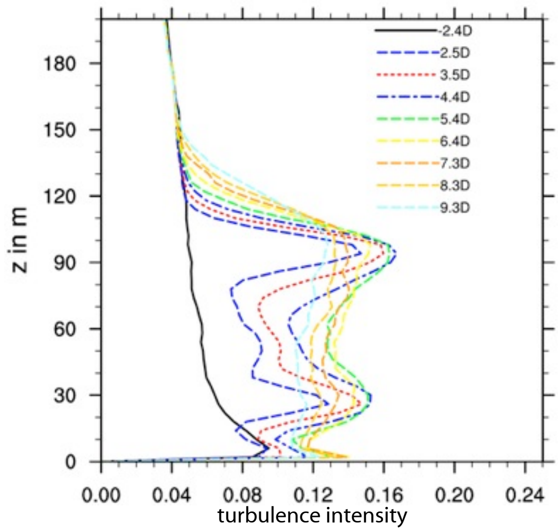


# SIMULATION OF WIND TURBINE WAKES WITH PALM

## Example: Vertical profiles of turbulence intensity (TI) downstream of the WT




land surface




sea surface

# ADVANTAGES AND DISADVANTAGES OF THE „ACTUATOR LINE“ METHOD

**+**

- It allows the resolution of such details as the tip vortices; therefore, this method might not be applicable to the study of the far wake region only, but also to processes in the near wake region

**-**

- Computationally expensive, as very small time steps are required (CFL criteria determined by rotor rotation)
- Requires much more information on the wind turbine, e.g. lift and drag coefficients, angular velocity of the rotor, pitch angle etc.





# OUTLOOK

- More realistic setup of simulations: Coriolis force switched on, stability effects (incl. humidity) considered
- Implementation of a non-uniformly loaded actuator method (that showed promising results in studies by other researchers)
- Application of non-cyclic boundary conditions: prevent that incoming flow is disturbed by the wake of a wind turbine
- Simulation of the flow in the complete full-scale wind farm “alpha ventus“
- Verification against results from measurements at the test site, e.g. LiDAR measurements of the wake flow

# Thank you for your attention!