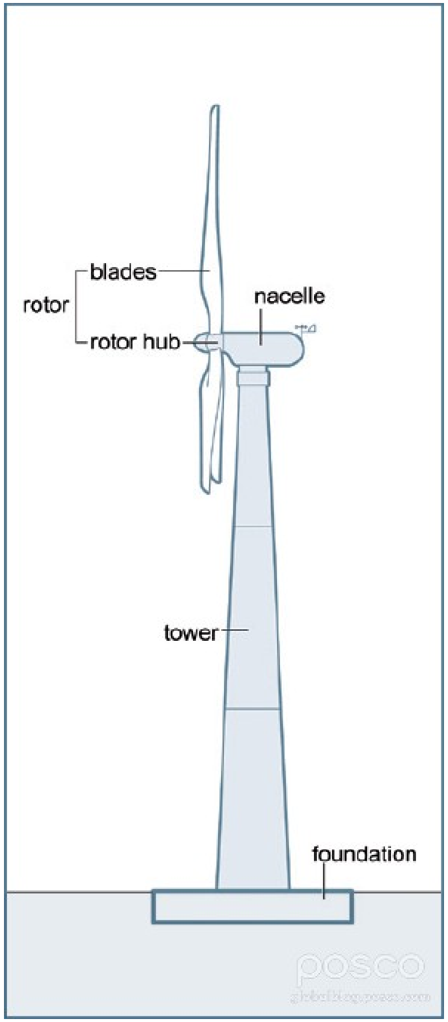
Wind Turbine Model

palm group

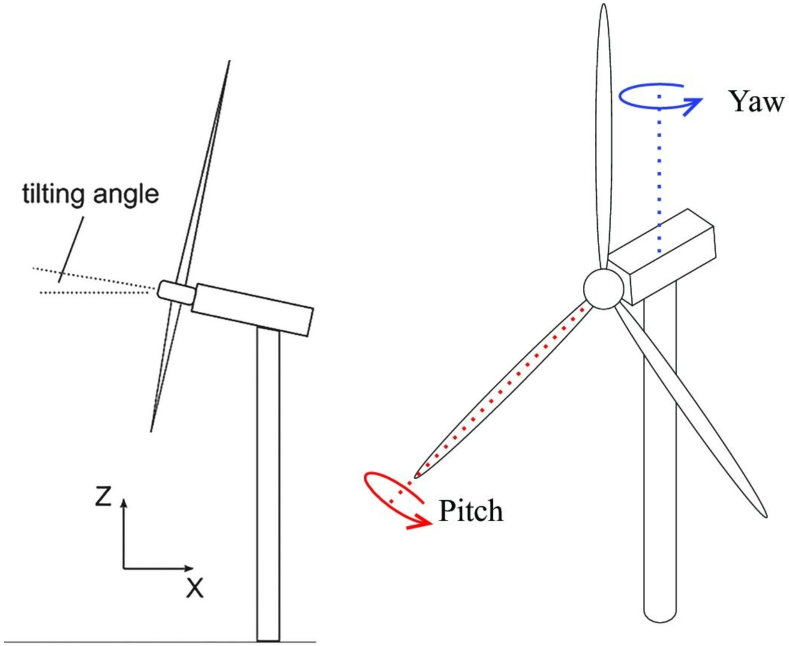
Institute of Meteorology and Climatology, Leibniz Universität Hannover

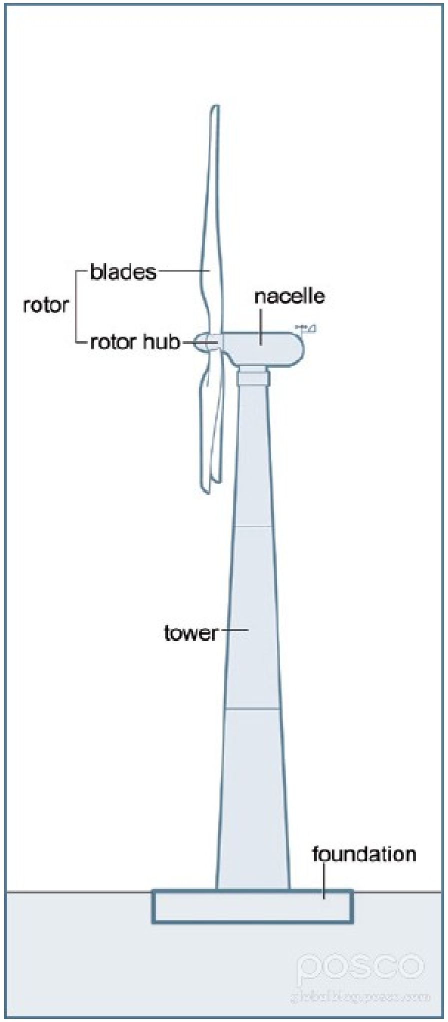


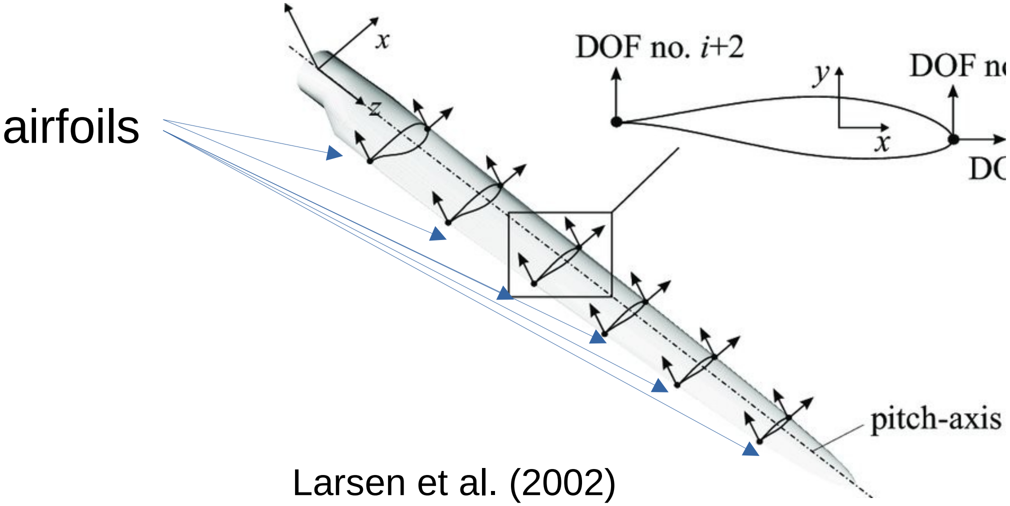
Degrees of freedom

- Yaw angle (horizontal angle of attack to rotor axis)
- Blade Pitch (Rotation of blades to adjust rotation)
- Tilt angle (vertical angle of attach to rotor axis)

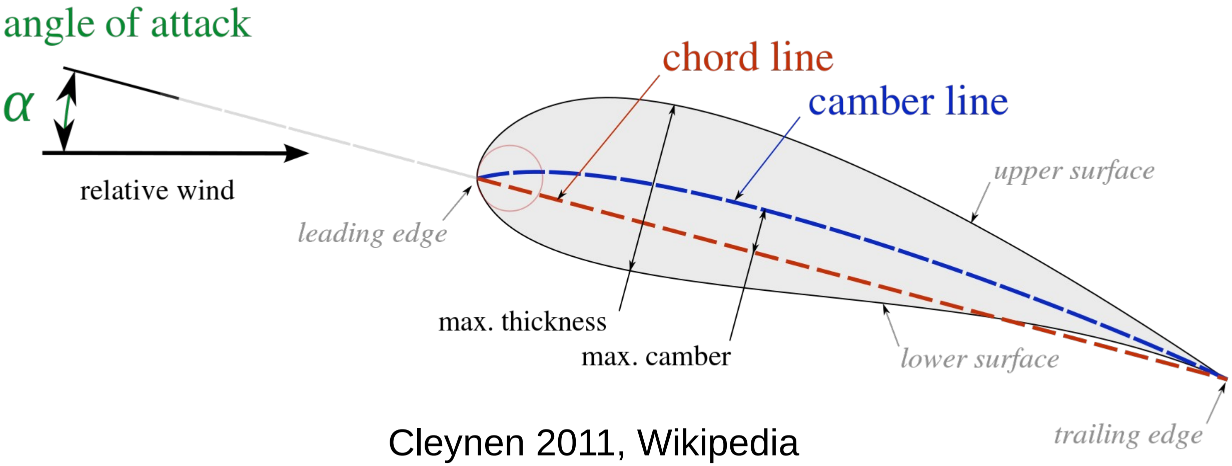
(+ pitch and roll for tower with offshore floating foundations)





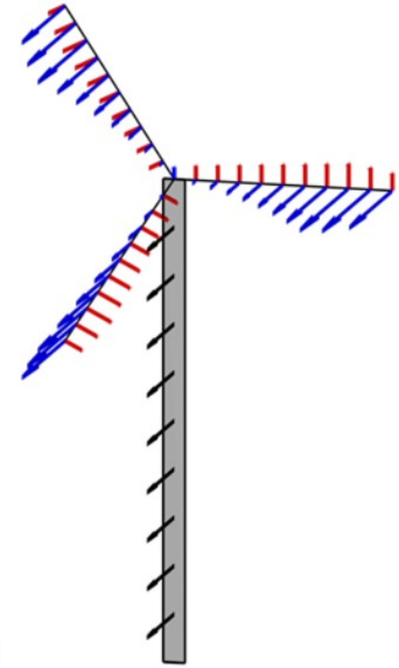


Larsen et al. (2002)



Cleynen 2011, Wikipedia

Actuator Line Model (ALM)



- Based on blade element momentum (BEM) method
- Rotors treated as lines, divided into segments
- Lift and drag force are calculated for each segment *Δr*:

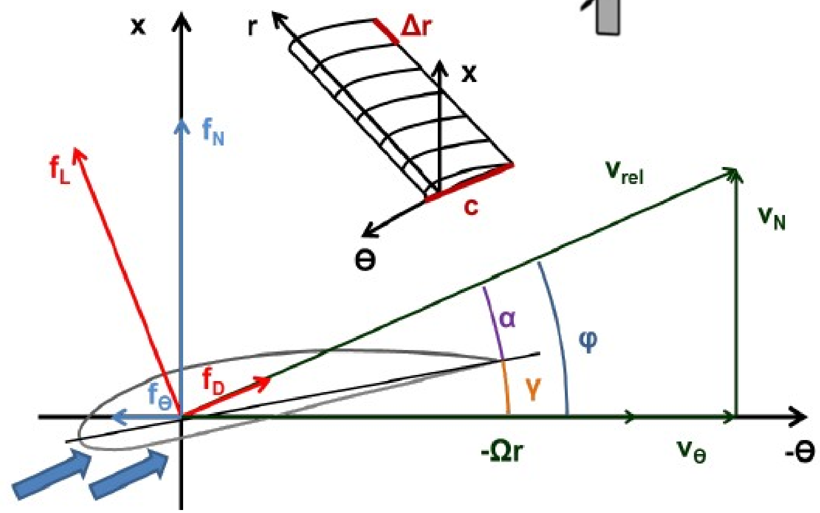
$$F_{L_{b,r}} = \frac{1}{2} \rho \, C_L \, V_{rel}^2 \, c \, \Delta r \qquad F_{D_{b,r}} = \frac{1}{2} \rho \, C_D \, V_{rel}^2 \, c \, \Delta r$$

- Lift C_L and drag C_D coefficients from look-up tables
- Projection on axial (F_N - Torque) and tangential (F - Thrust) directions:

$$F_{\theta_{b,r}} = F_{L_{b,r}} \sin\varphi + F_{D_{b,r}} \cos\varphi$$

$$F_{N_{b,r}} = F_{L_{b,r}} \cos\varphi + F_{D_{b,r}} \sin\varphi$$

$$\varphi = \arctan\left(\frac{V_N}{\Omega r - V_\theta}\right)$$

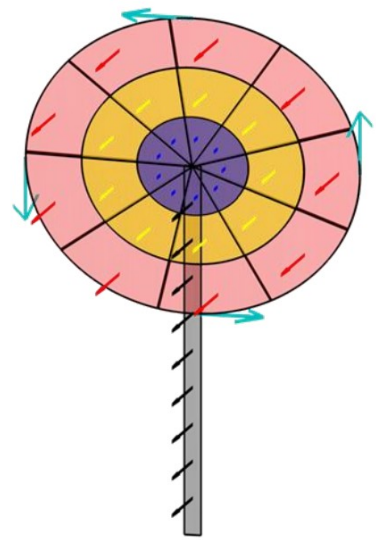


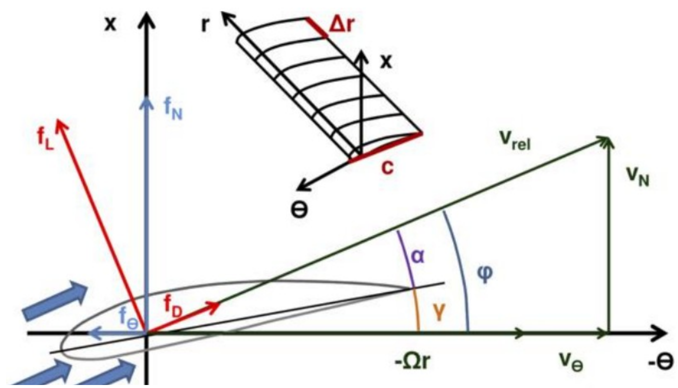
Rotating Actuator Disk Model (ADM-R)

- Rotor disk instead of lines (→ time step issue solved)
- Rotor plane is permeable disk
- Forces are not uniformly distributed (BEM forces)
- (similar to Wu & Porte-Agel, 2011)
- Rotor plane divided into rings and segments
- Lift and drag forces are calculated for each segment:

$$f_l = \frac{1}{2}\rho U_{rel}^2 c_l(\alpha)\frac{N_b c}{2\,\pi r_{seg}}$$ perpendicular to inflow

$$f_d = \frac{1}{2}\rho U_{rel}^2 c_d(\alpha)\frac{N_b c}{2\,\pi r_{seg}}$$ parallel to inflow





ρ	air density
U_{rel}	relative velocity
c_l	lift coefficient
c_d	drag coefficient
α	angle of attack
N_b	number of blades
c	chord length
r_{seg}	radial position of the segment
$\frac{N_b c}{2\,\pi r_{seg}}$	solidity factor

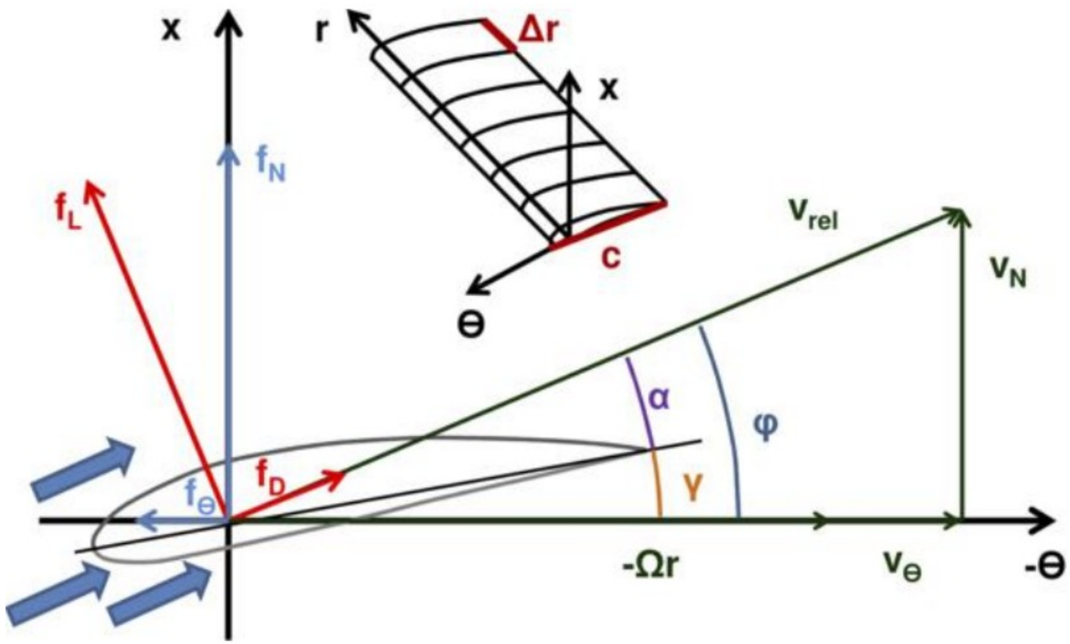
(percentage of circumference that is covered with blades)

Rotating Actuator Disk Model (ADM-R)

- Projection on axial (f_N) and tangential (f_θ) directions as for ALM:

$$f_N = f_l \cos\phi + f_d \sin\phi \qquad f_\theta = f_l \sin\phi - f_d \cos\phi$$

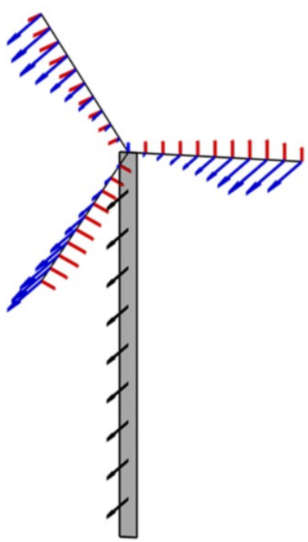
- Smearing to a Gaussian kernel to avoid numerical instabilities

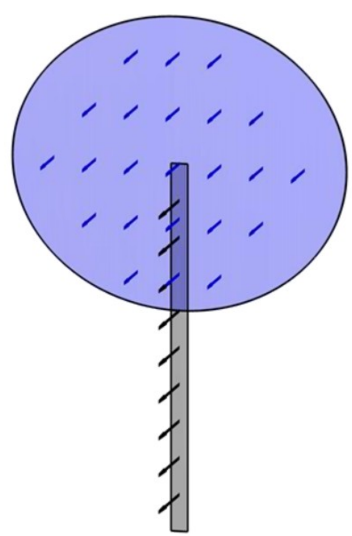


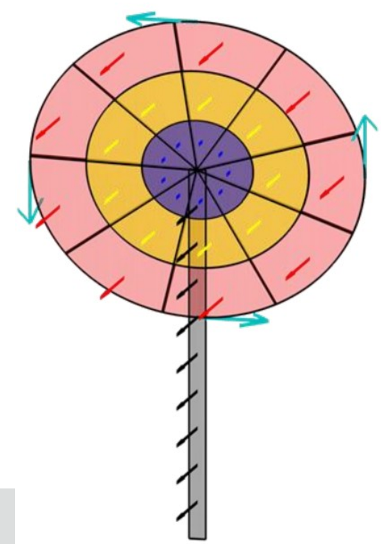
Wind Turbine Model

Overview of typical parameterizations

ALM	ADM	ADM-R
Actuator Line Model (Calaf et al. 2010)	Actuator Disk Model (Troldborg 2008)	Actuator Disk Model with Rotation
Local forces (lines) (BEM equations)	Spatially constant loads	Local forces (segments) (BEM equations)
Rotation (resolved blades)	No rotation	Rotation (blades not resolved)
Very slow (small time step)	Very fast	Fast (significantly faster than ALM)







- Drag force approach:

$$F_{tower} = -\frac{1}{2}\rho\, C_{D_{tower}}\, V_{ref}^2 \qquad V_{ref} = V_{local} \qquad C_{D_{tower}} = 1.2$$

$$F_{nacelle} = -\frac{1}{2}\rho\, C_{D_{nacelle}}\, V_{ref}^2 \qquad V_{ref} = V_{rotor} \qquad C_{D_{nacelle}} = 0.85$$

- Forces are added to the axial component of the forces generated by the rotor

Wind Turbine Model

How to use the WTM

- Add NAMELIST **&wind_turbine_parameters**

```
&wind_turbine_parameters
     ...
     n_turbines = 2,
     hub_x = 400.0,   400.0,
     hub_y = 500.0, 1500.0,
     ...
/
```

  - For all available parameters refer to:

https://docs.palm-model.org/23.04/Reference/LES_Model/Namelists/#wind-turbine-parameters

- Add file **<job_identifier>_wtm**, that contains rotor blade data:
  - airfoil, chord and twist distribution along the blade
  - lift and drag coefficients for used airfoils
  - File with data for the NREL 5MW turbine is available at:

/palm_model_system/packages/palm/model/tests/cases/wind_turbine_model/INPUT/wind_turbine_model_wtm

NREL 5 MW Reference Turbine

- Detailed data about the rotor blades is needed for ADM-R (and ALM), but usually confidential
- PALM-WTM is this shipped with the NREL 5-MW reference offshore turbine (Jonkman et al. 2009)
- Representative characteristics for current multi-MW turbines
  - Hub height: 90 m
  - Rotor diameter: 126 m
  - Nacelle diameter: 3 m
  - Tower diameter: 4 m
  - Ω = 12.1 rpm
  - C_L and C_D from look-up tables (depend on angle of attack and distance to hub)
  - Chord and pitch angles from look-up tables

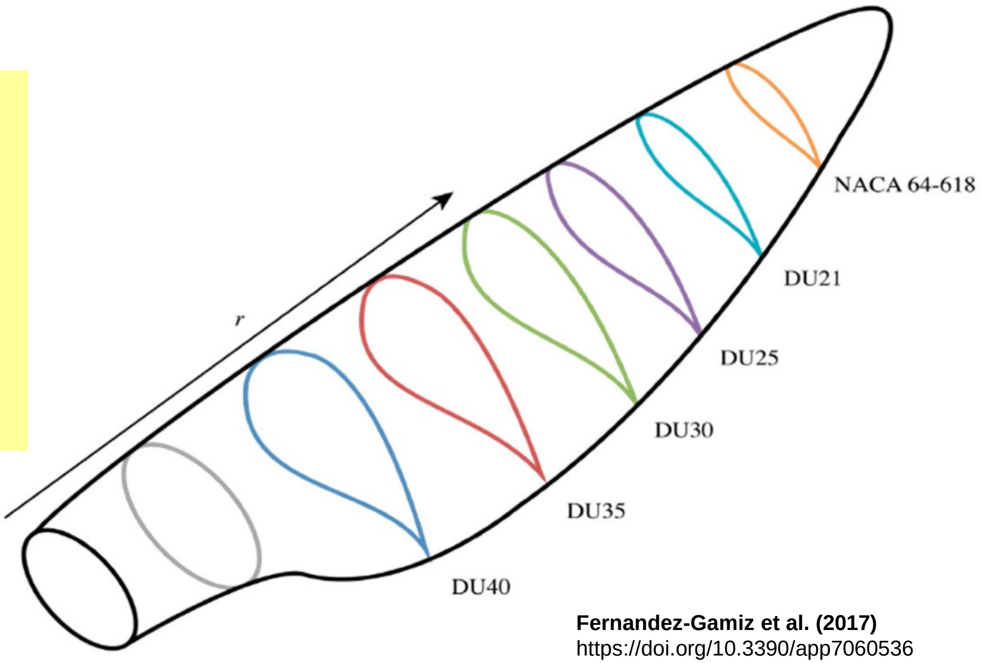
Rotor blade data in _wtm-file (1/2)

- Assign airfoils to radial positions along the blade:

```
# Tablefiles for nrel5MW
# Table 1: Distribution table
# Assigns the airfoils 1-8 to positions along the blade
0.0       1.5      0         0
1.5       5.6      1         1
5.6       8.3      1         2
...       ...
```

- Define twist angle and chord length:

```
# Table 2: Layout file
# Physical layout of the blade
# Pos[m] twist[deg] chord[m]
...       ...         ...
15.9     11.480     4.652
20.0     10.162     4.458
24.1      9.011     4.249
...       ...         ...
```



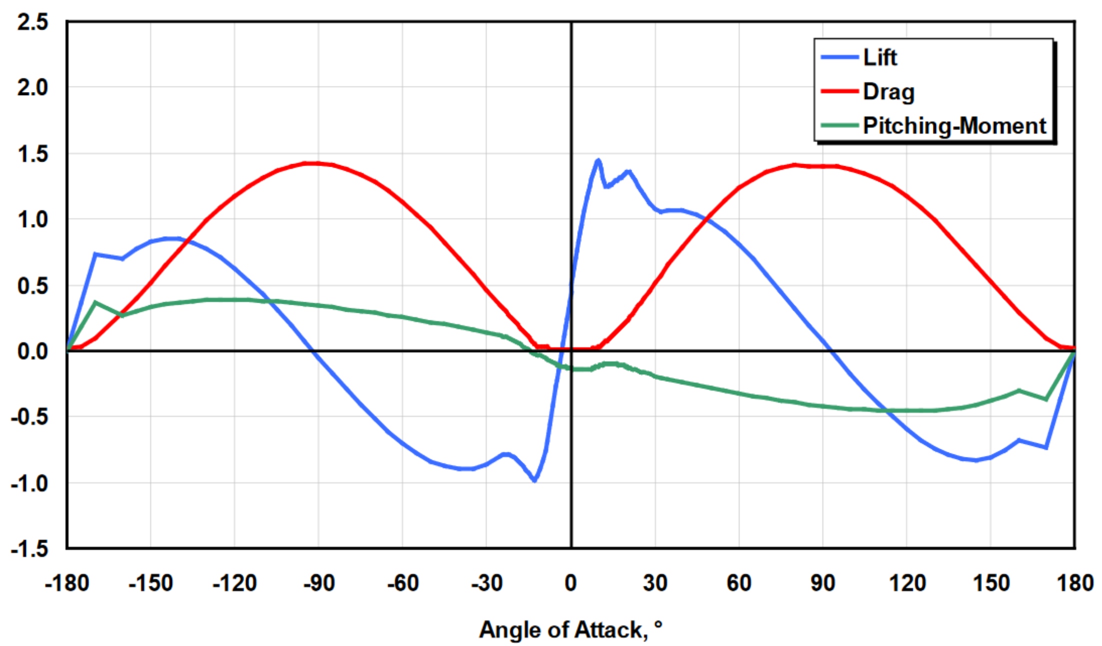
Fernandez-Gamiz et al. (2017)
https://doi.org/10.3390/app7060536

Wind Turbine Model

Rotor blade data in _wtm-file (2/2)

- Define lift and drag coefficients for each airfoil and angle of attack:

```
# Table 3: Lift and drag coefficients for airfoils 1-8
# alpha    ... C_l_3   C_d_3   C_l_4   C_d_4  ...
#
-180.00     ... 0.000  0.0602   0.000  0.0407 ...
-175.00     ... 0.218  0.0699   0.223  0.0507 ...
-170.00     ... 0.397  0.1107   0.405  0.1055 ...
...
```



Corrected coefficients of the DU25 airfoil

Jonkmann et al. (2009) DOI: [10.2172/947422](10.2172/947422)

Wind turbine controler

- Generator torque **speed controller (Jonkman et al. 2009)**
  - Must be adjusted for other turbines
  - Most properties can be adjusted via Fortran NAMELIST
- **Pitch controller**
- Active and automatic **yaw controller**
- All controllers can be switched on/off:
  - *speed_control = .F./.T.*
  - *pitch_control = .F./.T.*
  - *yaw_control = .F./.T.*

- single parameters, that are valid for all turbines:
  - n_turbines = 2 number of wind turbines
  - pitch_control = .TRUE. activate pitch control
  - yaw_control = .TRUE. activate yaw control

- list parameters, individual for each turbine:
  - hub_x = 400.0, 400.0, x-coordinate of the hub
  - hub_y = 500.0, 1500.0, y-coordinate of the hub
  - hub_z = 90.0, 90.0, z-coordinate of the hub (hub height)
  - rotor_radius = 63.0, 63.0, rotor radius

Wind Turbine Model

Output files

- One output file with time series of operational data of all turbines is saved in /<job_identifier>/OUTPUT/<job_identifier>_wtm.nc
- operational data are e.g.:
  - rotational speed
  - torque
  - power
  - blade pitch angle
  - yaw angle
  - …

Wind Turbine Model

Suitable setup for wind turbine simulations

- Use non-cyclic boundary conditions and the turbulence recycling method:
  - Be aware of the blockage effect:
    - Ensure that the wind turbines have enough distance to the recycling plane
    - 1 – 10 km required, depending on wind farm size and meteorological setup

```
&initialization_parameters
    bc_lr             = ‘dirichlet/radiation‘,
    initializing_actions  = ‘cyclic_fill‘,

    turbulent_inflow      = .TRUE.,
    recycling_width       = 4000.0,
    inflow_damping_height     = 700.0,
/
```

- Use non-cyclic boundary conditions and the synthetic turbulence generator:
  - no experience so far

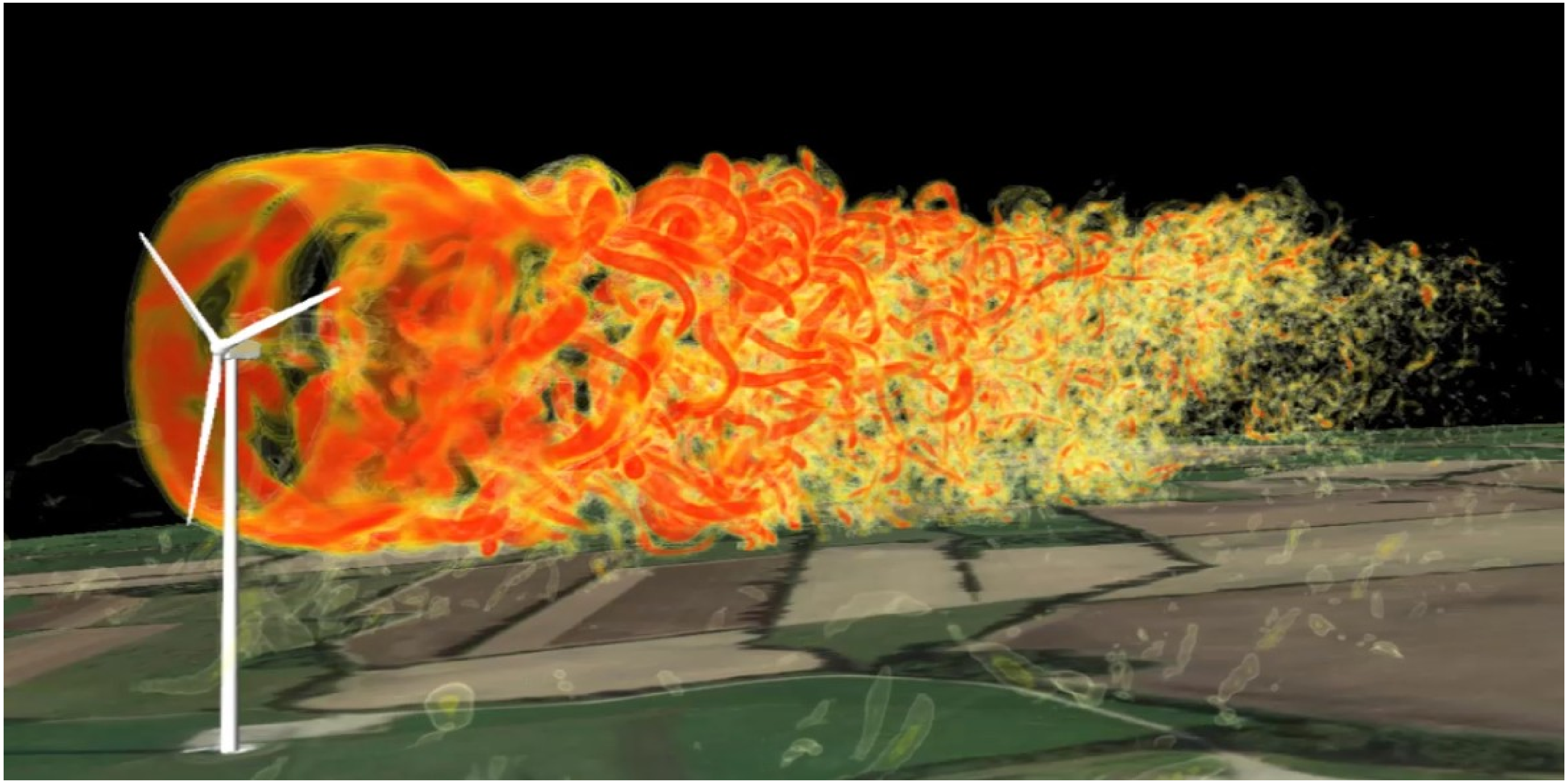
Wind Turbine Model

Additional notes

PALM has two wind turbines included

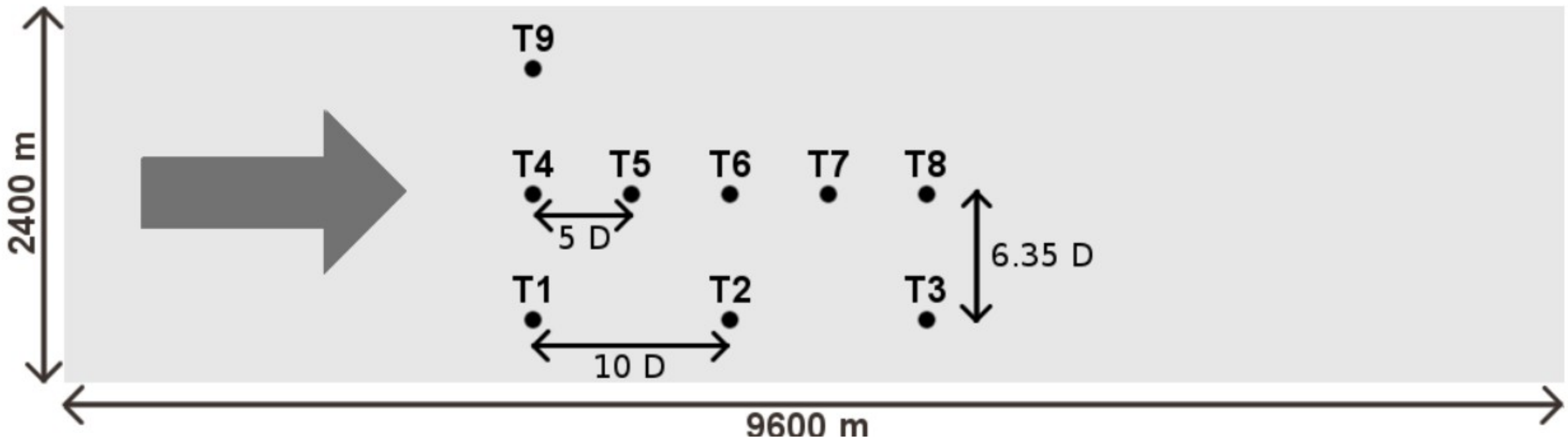
- 5 MW onshore NREL Reference turbine (available in the palm tests, see previous slides)
- 15 MW offshore IEA Reference turbine (will be used in the wind turbine exercise, currently not available in the PALM respository!)

ADM-R in PALM: Visualization



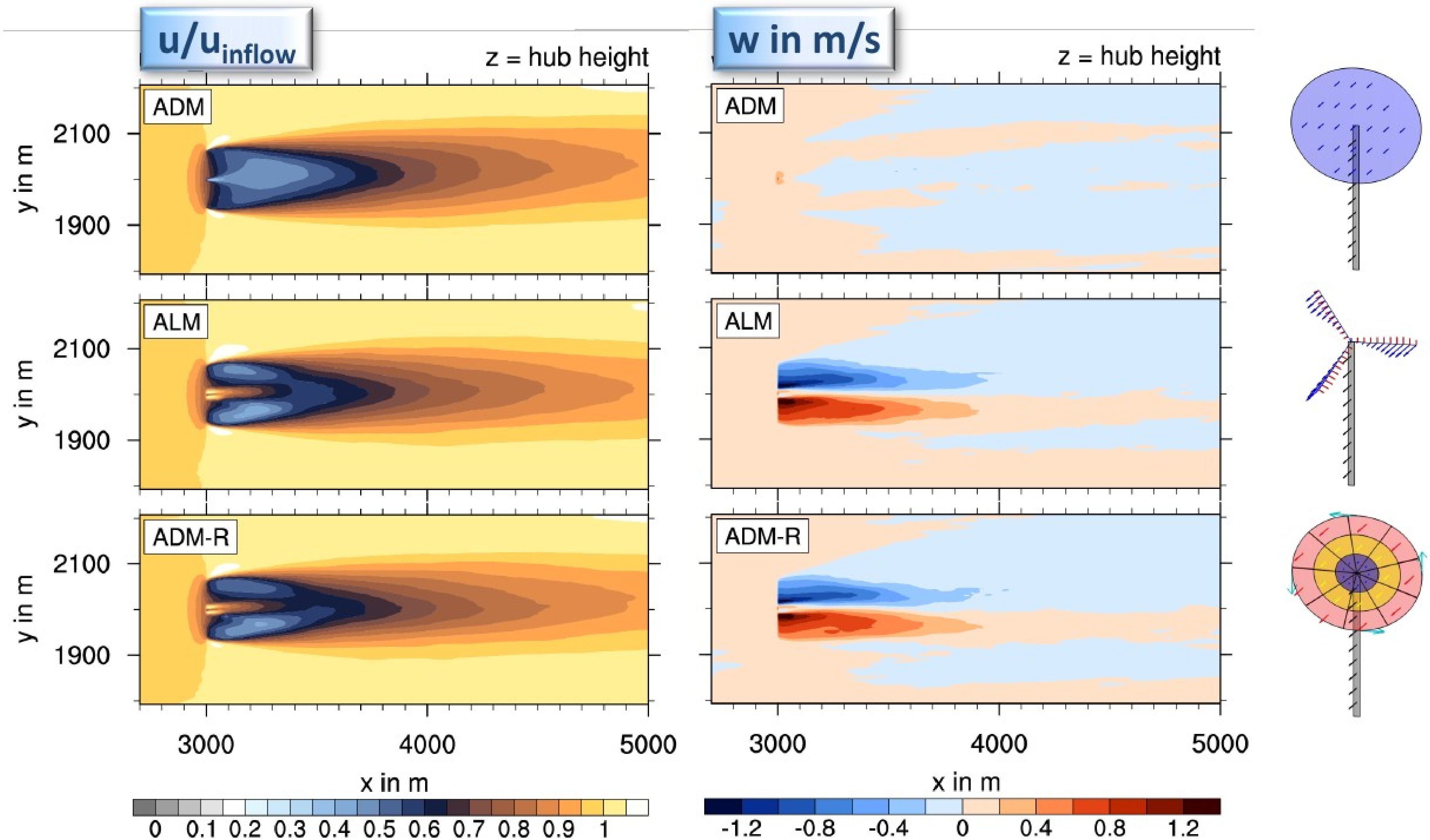
PALM-WTM validation/comparison

- PALM simulation of an idealized wind farm

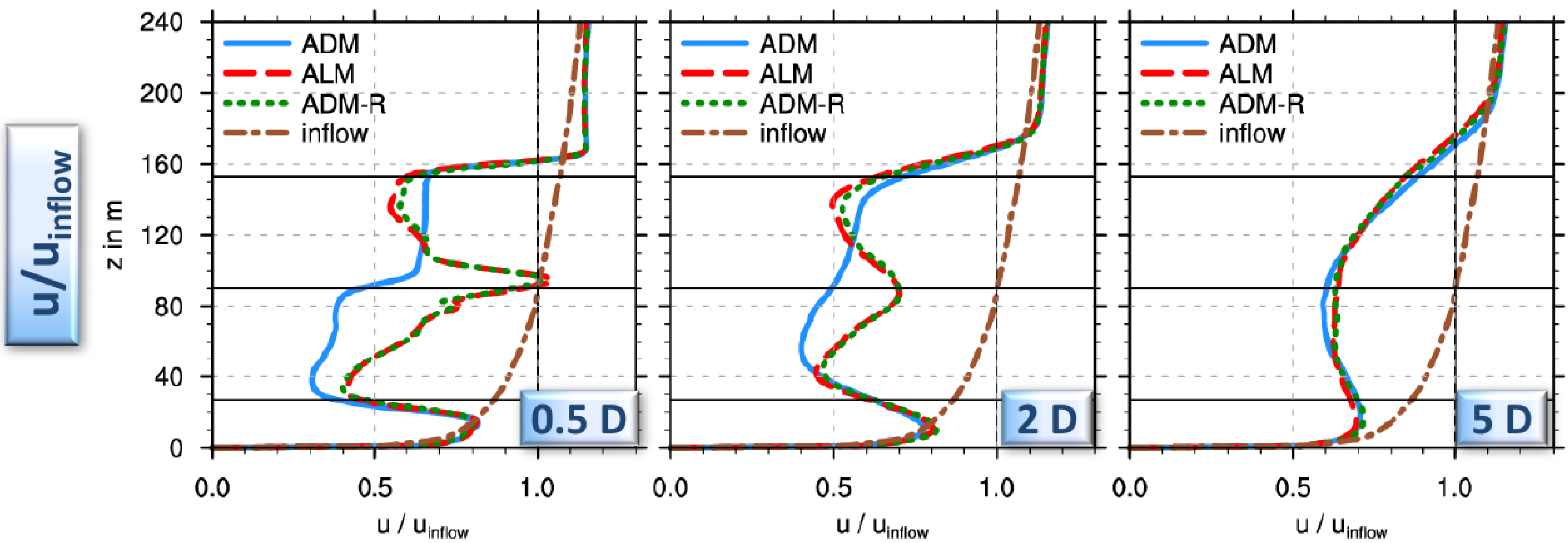


- Offshore conditions
  - $z0 = 0.0002$ m, $\langle u \rangle_{hub} = 8$ m/s
  - Neutral statification
- Non-cyclic horizontal boundary conditions with turbulent inflow
- Grid sensitivity test: 16 m, 12 m, 8 m, 4 m, 2 m

Validation: single wake (T9)



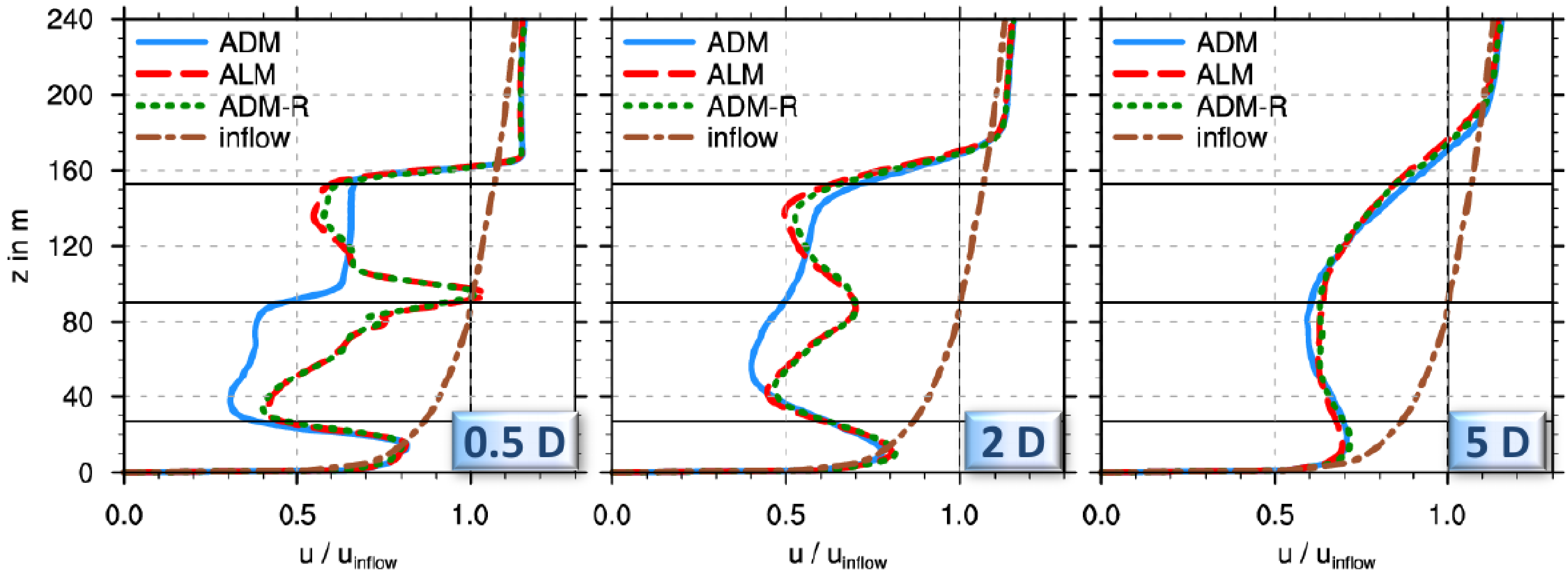
Validation: single wake (T9)



- ALM and ADM-R give almost identical results!
- Near wake is only reproduced ALM and ADM-R
- Far wake is also reproduced by all methods

Validation: single wake (T9)

u/u_{inflow}



- ALM and ADM-R give almost identical results!
- Near wake is only reproduced ALM and ADM-R
- Far wake is also reproduced by all methods

- Computational costs:

	ADM	ALM	ADM-R
Δ = 8 m	1	12.8	1.5
Δ = 4 m	1	8.1	2.0
Δ = 2 m	1	4.1	2.7

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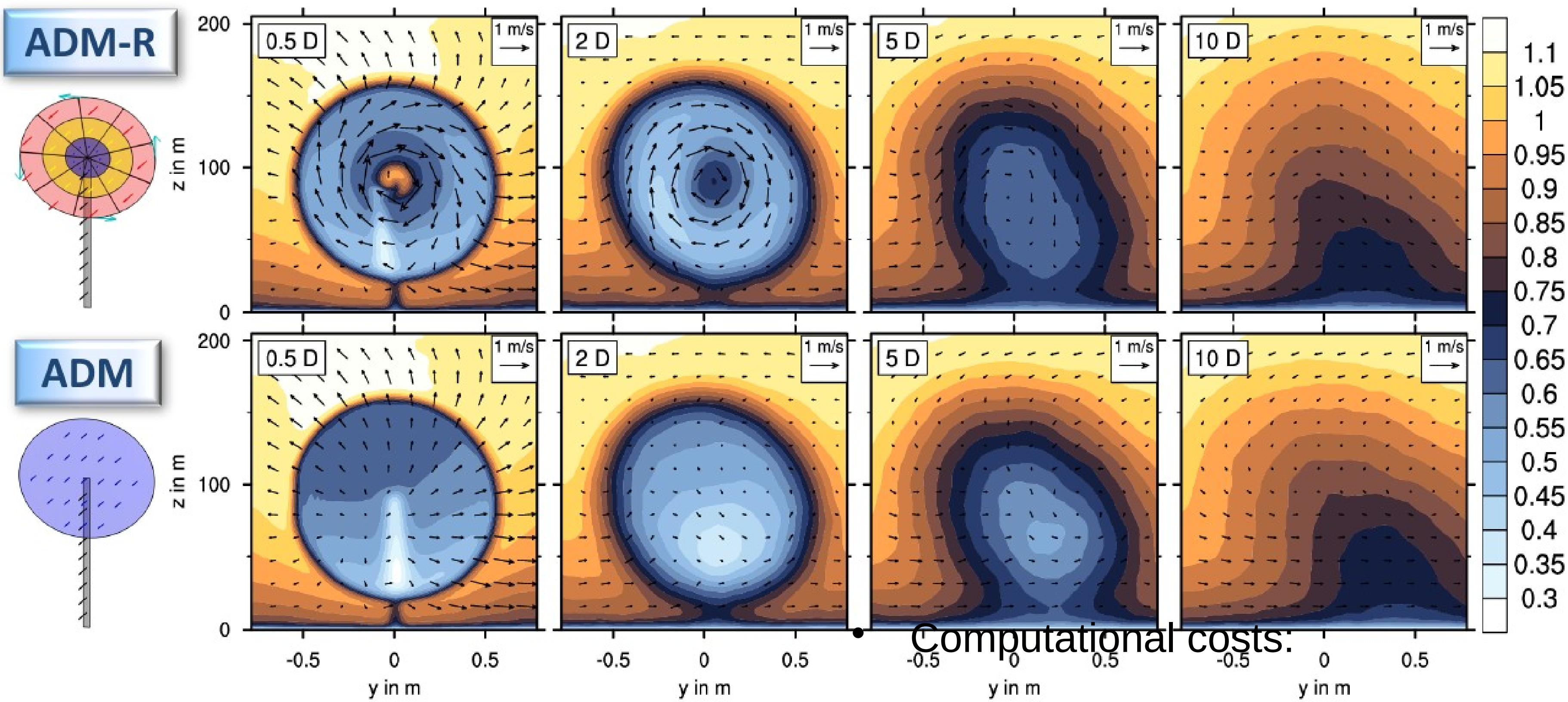
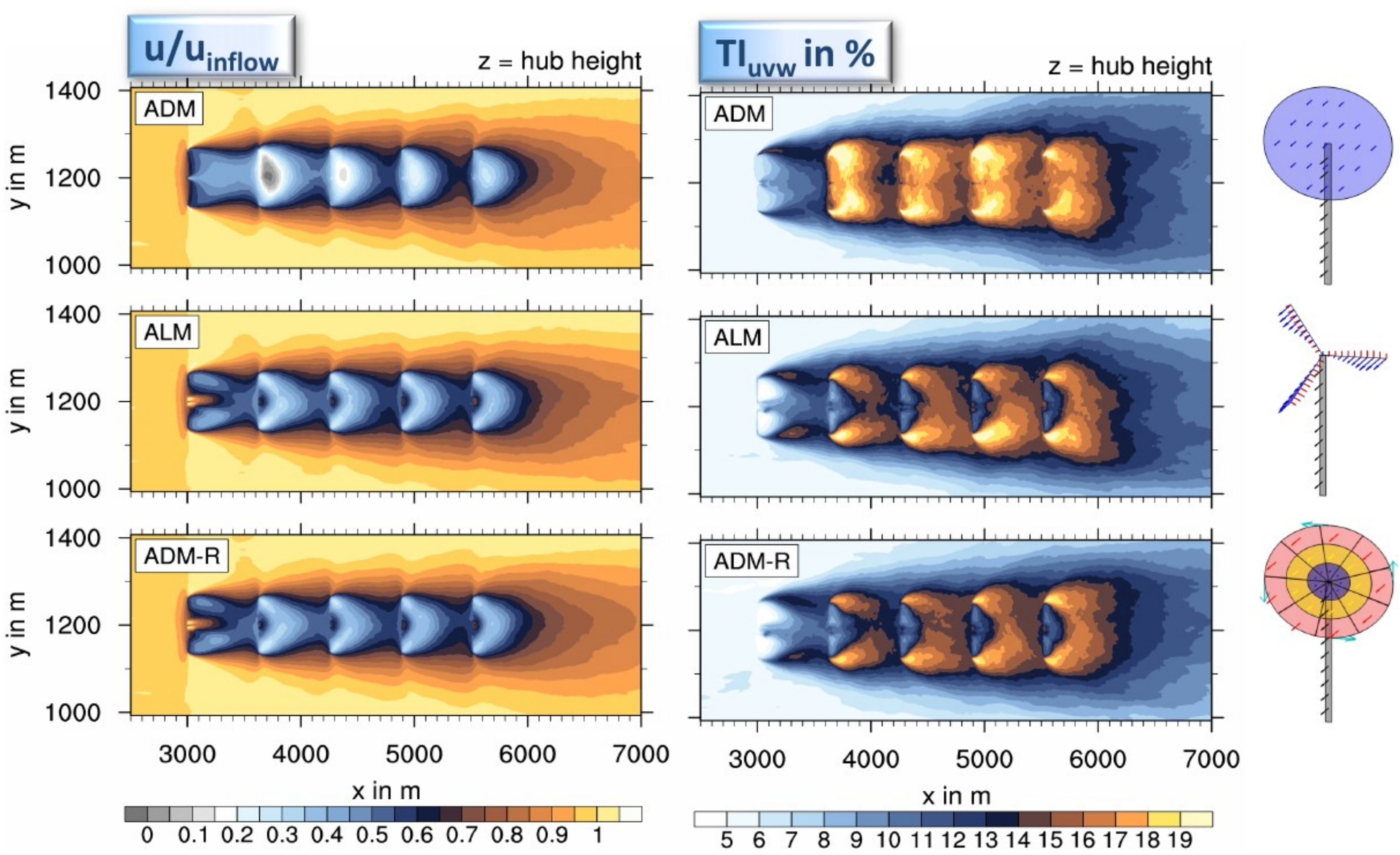
Validation: single wake (T9)



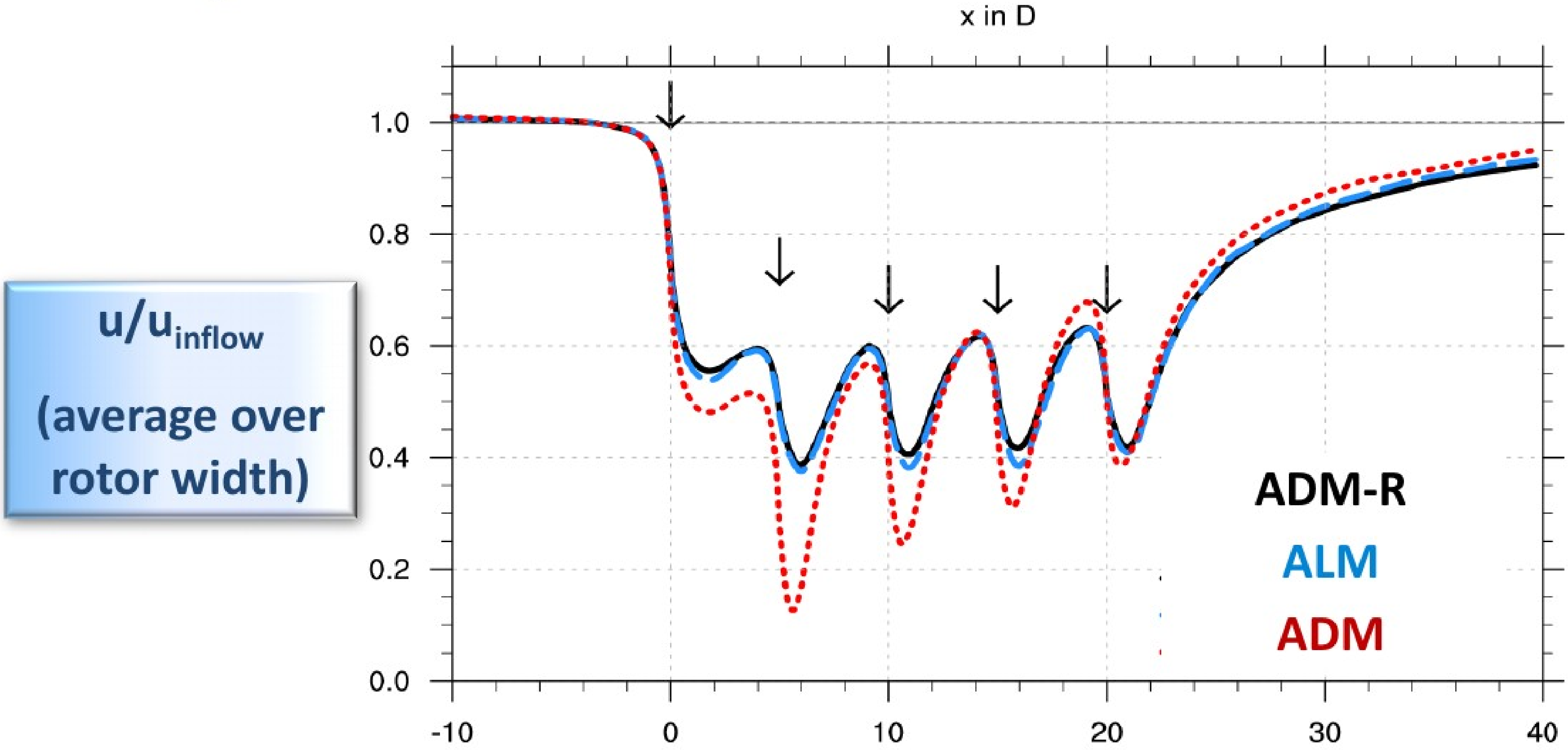
- Computational costs:

- ADM does not capture near wake and wake rotation
- Differences become small in the far wake

Validation: multiple wakes (T4-T8)

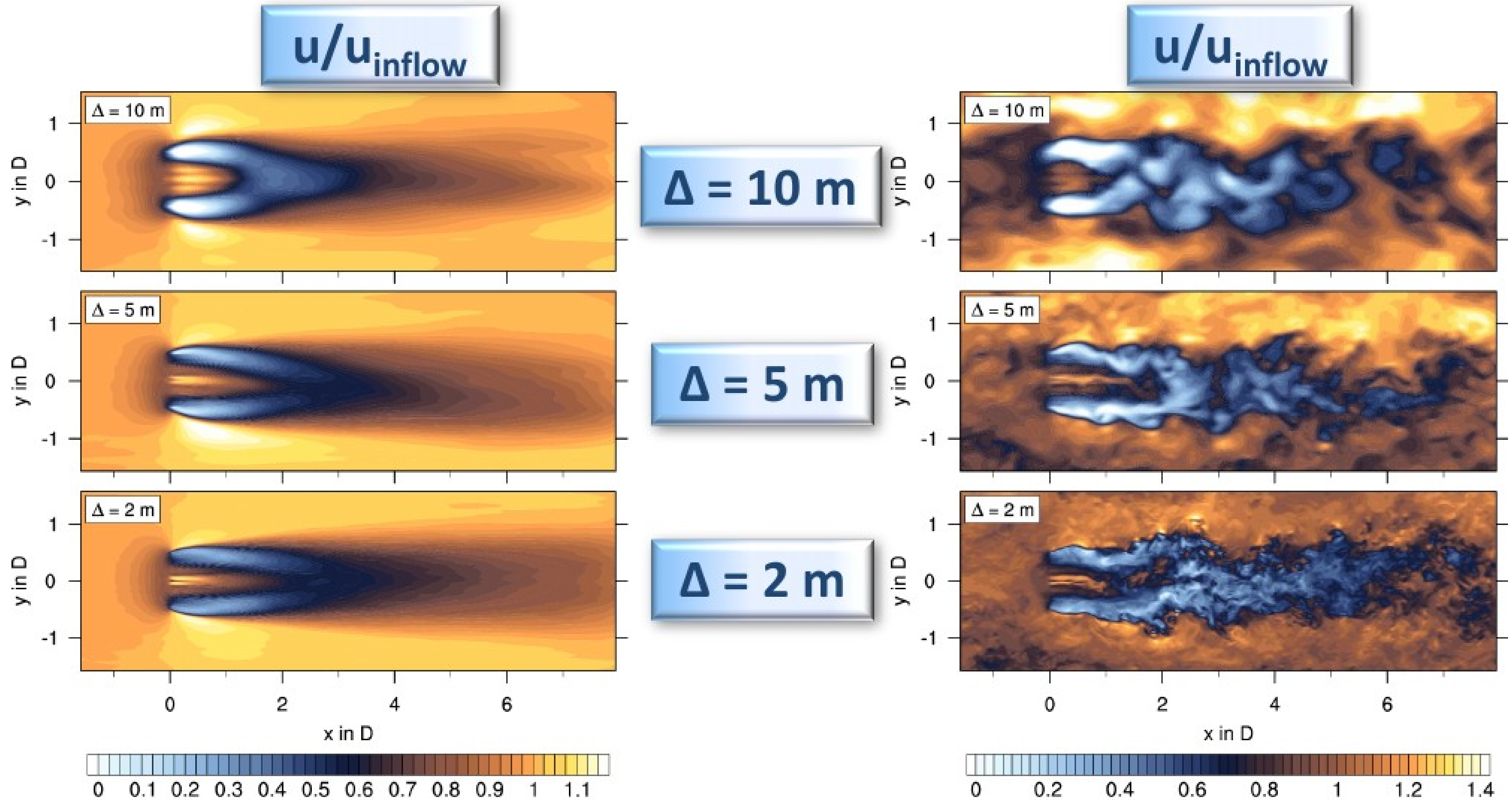


Validation: multiple wakes (T4-T8)



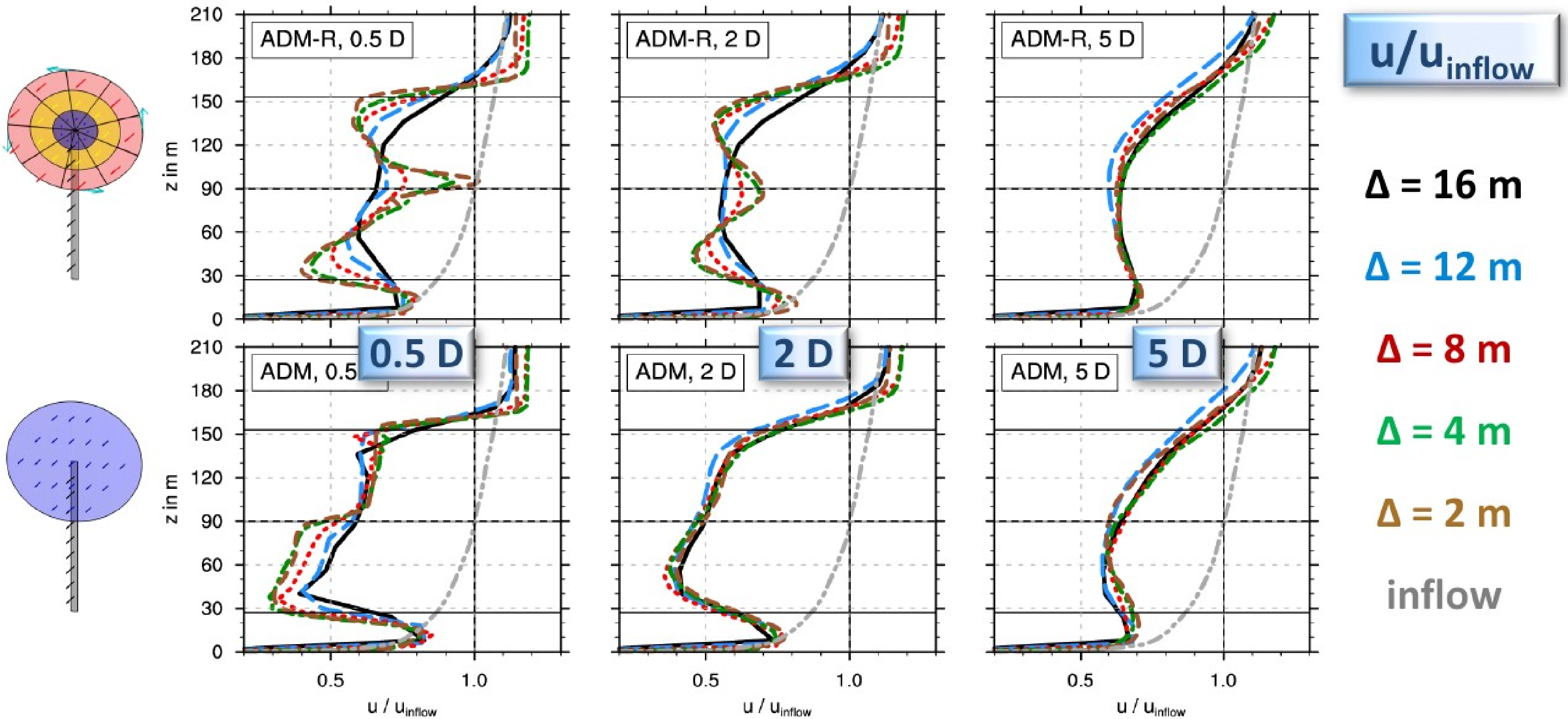
- u-deficit, maximum behind 2nd turbine
- Recovery area due to increased turbulence
- ADM displays strongest deficit and strongest recovery

Validation: grid sensitivity (ADM-R, T9)



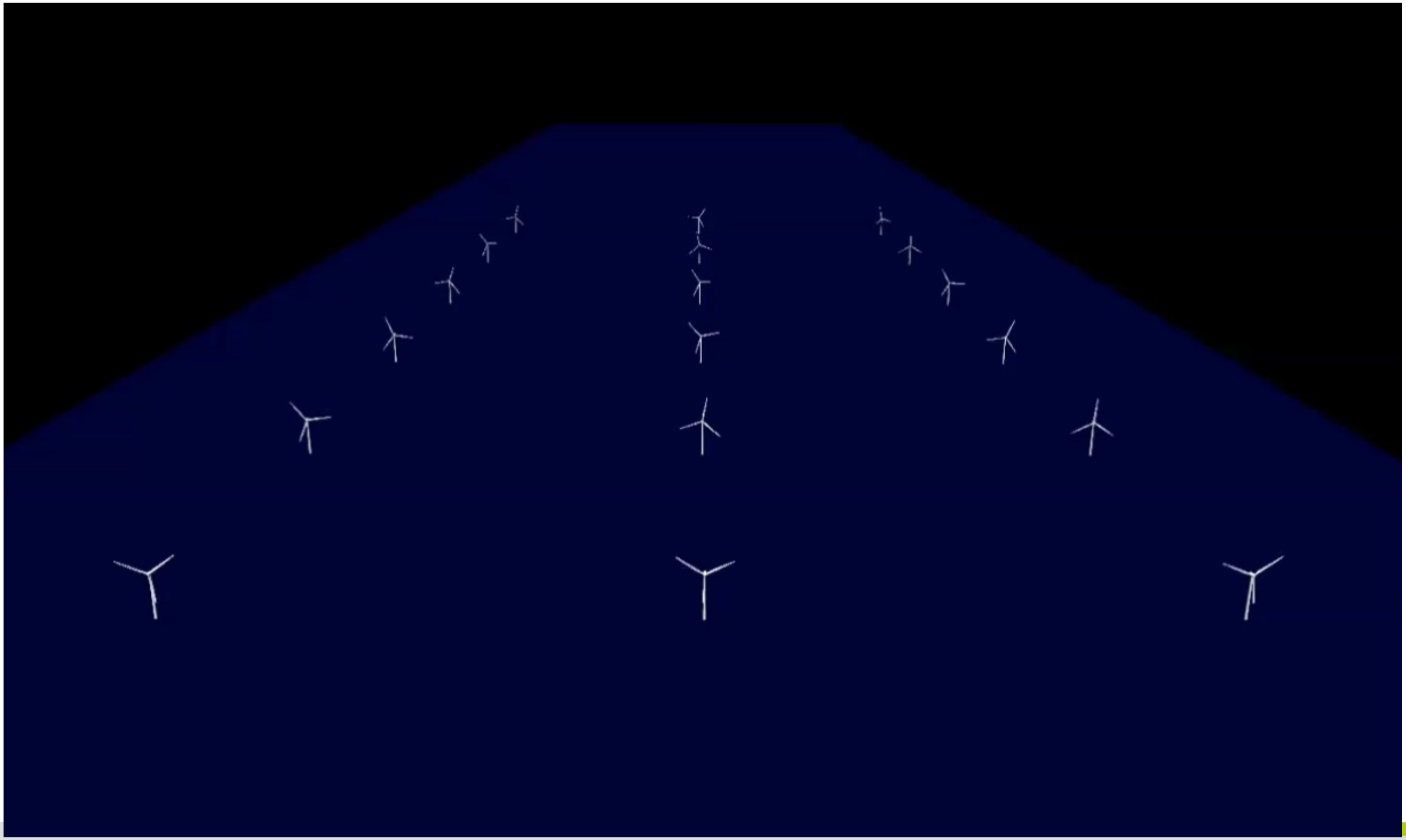
- Large-scale wake structure is well-reproduced at coarse grid
- Finer structures at finer grid spacings
- Longer wake for finer grid spacings

Validation: grid sensitivity (T9)



- Near wake: ADM-R: 30 grid points per rotor required
  - ADM: no sensitivity
- Far wake: no sensitivity

Example Application



- technical documentation:

https://palm.muk.uni-hannover.de/trac/wiki/doc/tec/wtm

- description of namelist parameters:

https://docs.palm-model.org/23.04/Reference/LES_Model/Namelists/#wind-turbine-parameters

- example test case:

palm_model_system/packages/palm/model/tests/cases/wind_turbine_model/INPUT/