Impact of turbulence on wind turbine wakes

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DLR

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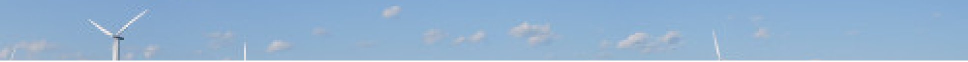


WIND TURBINE LESS WITH REALISTIC ATMOSPHERIC TURBULENCE CONDITIONS

Wind turbine simulations: open horizontal boundary conditions

⇒ **1. Real-time input of atmospheric turbulence**
→ One precursor simulation of the complete diurnal cycle
→ Computationally very expensive

⇒ **2. Parameterization of atmospheric turbulence**
→ Parameterisation of the background atmospheric state, valid for different regimes of atmospheric turbulence with one end state of a precursor simulation
→ Effective and computationally efficient

1. Real-time input of atmospheric turbulence

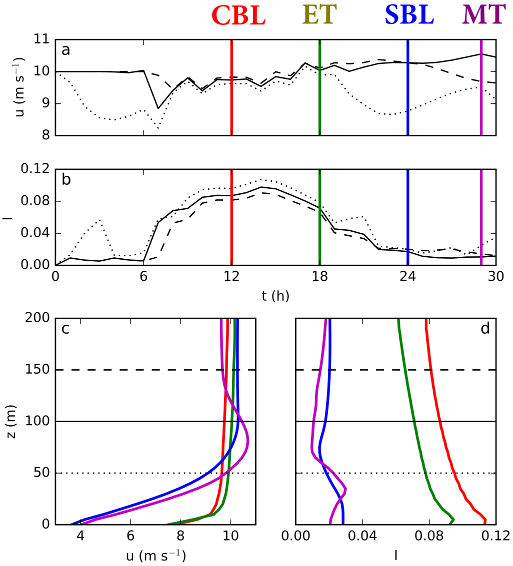
Idealised atmospheric boundary layer (ABL) simulation

- geophysical flow solver EULAG
- Δ_x=Δ_y=5 m (512 x 512 grid points)
- L_z=2 km; $\Delta_z = \begin{cases} 5\ m & z \leq 200\ m \\ 10\ m & 200\ m < z \leq 800\ m \\ 20\ m & z > 800\ m \end{cases}$
- periodic horizontal boundary conditions
- Coriolis force
- initial wind: u_0=10 m s^{-1}; v_0=0 m s^{-1}; w_0=0 m s^{-1}
- initial potential temperature: $\Theta_0 = \begin{cases} 300\ K & z\ \leq\ 1\ km \\ 300\ K + z \cdot 10\ K\ km^{-1} & z\ >\ 1\ km \end{cases}$
- sensible heat flux:

  $$\text{SHF} = \begin{cases} -10\ W\ m^{-2} + 150\ W\ m^{-2}\ sin^2\left(\frac{\pi(t - t_{trans})}{2 \cdot \tau_{trans}}\right) & 4\ h \leq t < 20\ h \\ -10\ W\ m^{-2} & t < 4\ h\ ||\ t \geq 20\ h \end{cases}$$

  t_{trans}=4 h: time of transition since start of simulation; τ_{trans}=8 h: transition time scale
- 30 h of simulation (one full diurnal cycle)

1. Real-time input of atmospheric turbulence



Top tip = 150 m - - - - -

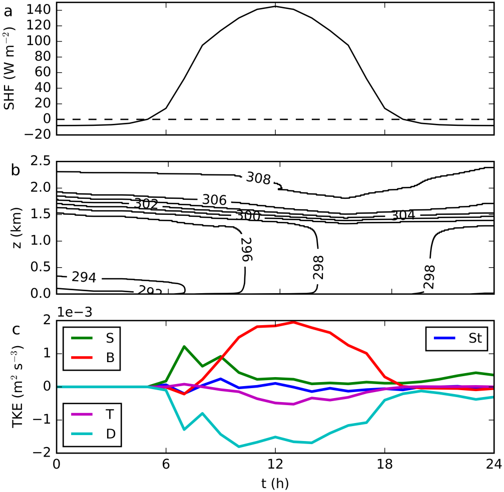
Hub Height = 100 m ———

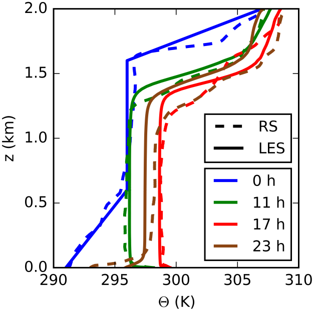
Bottom tip = 50 m ·········

$$I_{i,j,k} = \frac{\sigma_{u_{i,j,k}}}{<u_{i,j,z_h}>_t},$$

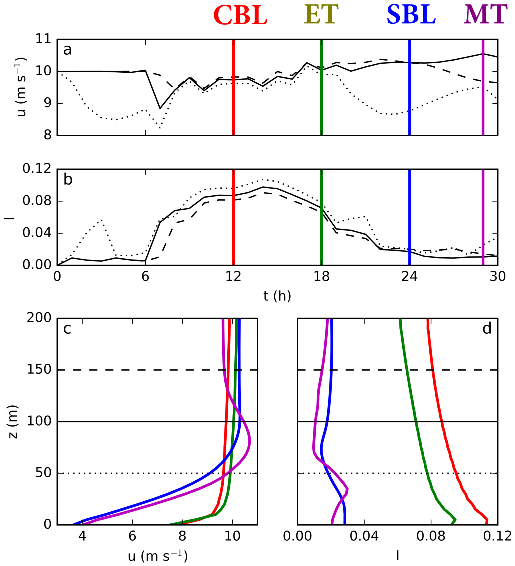
with $\sigma_{u_{i,j,k}} = \sqrt{< u'^2_{i,j,k} >_t}$

and $u'_{i,j,k} = u_{i,j,k} - < u_{i,j,k} >_t$


a
SHF (W m^{-2})
140
120
100
80
60
40
20
0
−20
b
z (km)
2.5
2.0
1.5
1.0
0.5
0.0
308
306
302
300
304
296
298
298
294
292
c
TKE (m^2 s^{-3})
1e−3
2
1
0
−1
−2
S
B
St
T
D
0
6
12
18
24
t (h)


z (km)
2.0
1.5
1.0
0.5
0.0
290
295
300
305
310
Θ (K)
RS
LES
0 h
11 h
17 h
23 h

1. Real-time input of atmospheric turbulence



Top tip = 150 m - - - - -

Hub Height = 100 m ———

Bottom tip = 50 m ………

$$I_{i,j,k} = \frac{\sigma_{u_{i,j,k}}}{<u_{i,j,z_h}>_t},$$

$$\text{with } \sigma_{u_{i,j,k}} = \sqrt{< u'^2_{i,j,k} >_t}$$

$$\text{and } u'_{i,j,k} = u_{i,j,k} - < u_{i,j,k} >_t$$

1. Real-time input of atmospheric turbulence

Wind turbine (WT) simulation

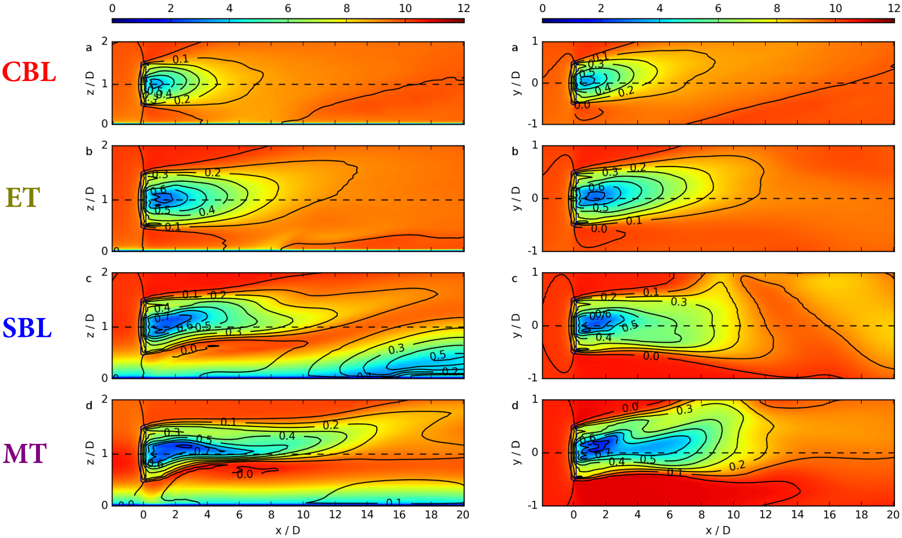
- geophysical flow solver EULAG
- $\Delta_x = \Delta_y = 5$ m (512 x 64 grid points)
- L_z=420 m; $\Delta_z = \begin{cases} 5\ m & z \leq 200\ m \\ 10\ m & z > 200\ m \end{cases}$
- open horizontal boundary conditions
- rotor diameter $D = 100$ m; hub height $z_h = 100$ m; nacelle
- $\frac{d\mathbf{v}}{dt} = -G\boldsymbol{\nabla}\left(\frac{p'}{\rho_0}\right) + \mathbf{g}\frac{\Theta'}{\Theta_0} + \boldsymbol{\mathcal{V}} + \mathbf{M} + \frac{\mathbf{F}_{WT}}{\rho_0}$
- $\mathbf{F}_{WT}\Big|_{x_0,y,z} = \mathbf{F}_x\Big|_{x_0,y,z} + \mathbf{F}_\Theta\Big|_{x_0,y,z}$
- $|F_x|\Big|_{x_0,y,z} = \frac{1}{2}\rho_0 \frac{Bc}{2\pi r_{x_0,y,z}}(c_L \cos\Phi + c_D \sin\Phi)A_{x_0,y,z}\frac{u^2_{x_\infty,y,z}(1-a)^2}{\sin^2\Phi}$
- $|F_\Theta|\Big|_{x_0,y,z} = \frac{1}{2}\rho_0 \frac{Bc}{2\pi r_{x_0,y,z}}(c_L \sin\Phi - c_D \cos\Phi)A_{x_0,y,z}\frac{u_{x_\infty,y,z}(1-a)\Omega r_{x_0,y,z}(1+a')}{\sin\Phi\cos\Phi}$
- 1 h of simulation for different phases of the diurnal cycle (CBL, ET, SBL, MT)

1. Real-time input of atmospheric turbulence

Interface between ABL simulation and WT simulation

- initial conditions in WT simulation ($u_{i,j,k}$, $v_{i,j,k}$, $w_{i,j,k}$, $\Theta_{i,j,k}$) are set to the corresponding atmospheric state of the idealised ABL simulation
- horizontal averages of initial conditions (u_0, v_0, w_0, Θ_0) are used as background condition in WT simulation
- two dimensional y-z slices of u, v, w, Θ of the ABL simulation contribute as real-time inflow at each timestep to $u_{1,j,k}$, $v_{1,j,k}$, $w_{1,j,k}$, $\Theta_{1,j,k}$ at $i = 1$

1. Real-time input of atmospheric turbulence



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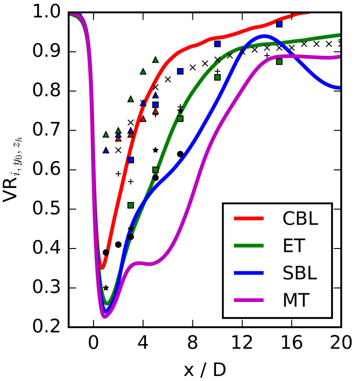

marker	ABL	data
+	NBL	LES (Wu and Porté-Agel (2011))
🟩	NBL	LES (Wu and Porté-Agel (2012))
🟦	NBL	LES (Wu and Porté-Agel (2012))
×	NBL	RANS (Gomes et al. (2014))
●	SBL	lidar (Aitken et al. (2014))
★	SBL	WRF-LES (Aitken et al. (2014))
▲	CBL	lidar (Mirocha et al. (2014))
▲	CBL	WRF-LES (Mirocha et al. (2014))
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🟩 $z_0 = 1 \cdot 10^{-5}$ m; 🟦 $z_0 = 1 \cdot 10^{-1}$ m
▲ SHF = 20 W m^{-2}; ▲ SHF = 100 W m^{-2}

$$VR_{i,j,k} = \frac{<u_{i,j,k}>_t}{<u_{1,j,k}>_t}$$

2. Parameterization of atmospheric turbulence

Computational costs of 30 h of idealised ABL precursor simulation:
13 days (performed on 256 Intel Xeon E5-2697 v3 threads at 2.6 GHz)
(one output of full.nc tape: 4 GB)

↓

Methodology to **maintain the turbulence of the background flow** for WT simulations with open horizontal boundary conditions without the permanent import of turbulence data from a precursor simulation by applying the **spectral energy distribution** of an NBL on WT simulations

↓

Empirical factor α in new method controls the energy content of the background turbulence and makes it appropriate for different regimes (CBL, ET, SBL, MT)

2. Parameterization of atmospheric turbulence

Precursor NBL simulation

- Forcing $-u_*^2/H$ with the friction velocity $\mathrm{u}_* = 0.4$ m s^{-1} and the height of the computational domain H applied on the u component of
  $$\frac{d\mathbf{v}}{dt} = -G\boldsymbol{\nabla}\left(\frac{p'}{\rho_0}\right) + \mathbf{g}\frac{\Theta'}{\Theta_0} + \boldsymbol{\mathcal{V}} + \mathbf{M}$$
- same number of grid points as in the WT simulation
- periodic horizontal boundary conditions
- no Coriolis force
- u_0=0 m s^{-1}; v_0=0 m s^{-1}; w_0=0 m s^{-1}
- cdrag = 0.1 m
- obstacle for a few timesteps
  → additional velocity gradients in neutral flow provide seed for turbulence to develop
  → equilibrium state of NBL precursor simulation is attained more rapidly

2. Parameterization of atmospheric turbulence

Methodology

Perturbation velocities $\mathbf{u}_p^*|_{i,j,k}^{\xi}$, which are extracted from a precursor NBL simulation via

$$\mathbf{u}_p^*|_{i,j,k}^{\xi} = \alpha \cdot \beta \cdot \left(\underbrace{\mathbf{u}_p|_{i*,j,k}}_{II} - \underbrace{\frac{1}{n \cdot m} \sum_{i=1}^{n} \sum_{j=1}^{m} \mathbf{u}_p|_{i,j,k}}_{I} \right),$$

I: height-averaged mean value of u, v and w

II: streamwise direction shift by one grid point every timestep

β: random number $\beta \in [-0.5, 0.5]$

α: perturbation amplitude

contribute at every timestep to the velocity field of the WT simulation $\mathbf{u}|_{i,j,k}^{\xi}$

2. Parameterization of atmospheric turbulence

This methodology offers several possibilities for the numerical scheme:

1. Open inflow and outflow Neumann boundary conditions.
2. The perturbation data from the precursor simulation are imported only once and are stored in three 3 D fields (u, v, w) during the WT simulation.
3. The method is computationally very efficient, as it allows to reapply the background turbulence of one precursor simulation to a variety of WT simulations.
4. The response of a wind turbine to different intensities of the background turbulence can be easily investigated by changing the parameter α.

2. Parameterization of atmospheric turbulence

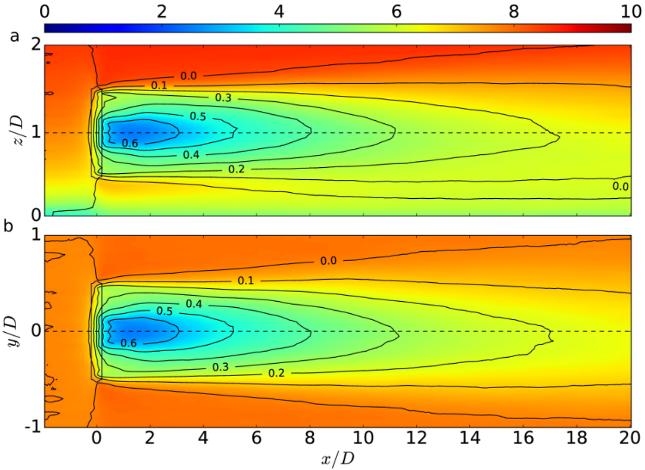
Wind turbine simulation

⇒ Same WT setup as in previous simulations with one difference.

Difference:

No real-time inflow at each timestep. Instead, in the new methodology, the logarithmic wind profile $u_{x_\infty,y,z} = \frac{u_*}{\kappa}\ln(\frac{z}{z_0})$ with $u_* = 0.45$ m s^{-1} and $z_0 = 0.1$ m is superimposed by the velocity fluctuations of u, v and w resulting from the precursor NBL simulation.

2. Parameterization of atmospheric turbulence



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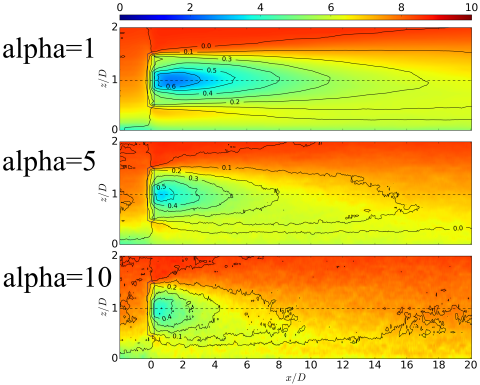
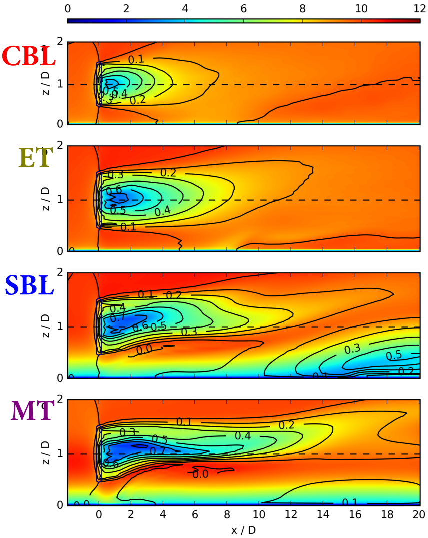
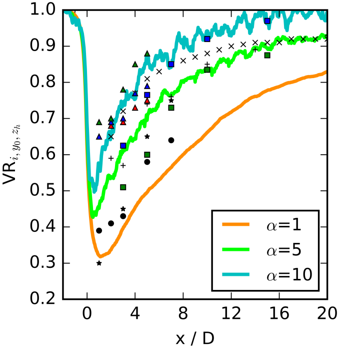




2. Parameterization of atmospheric turbulence



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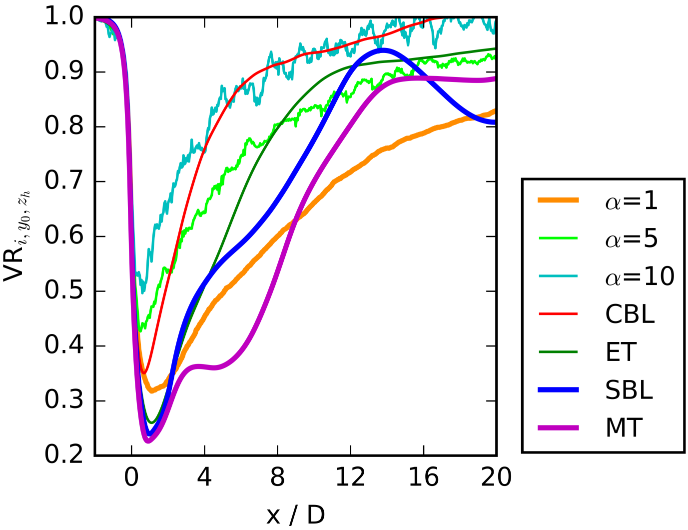
2. Parameterization of atmospheric turbulence



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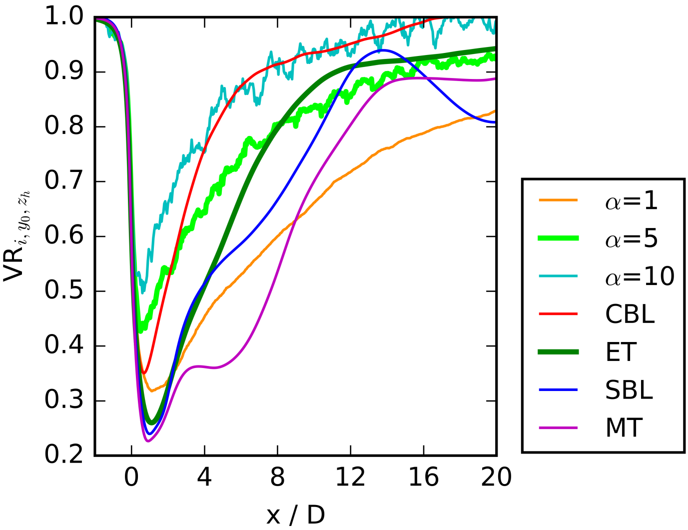

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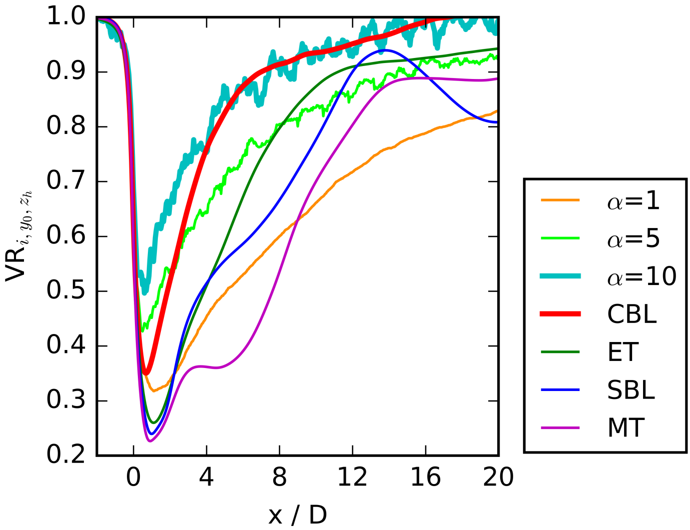

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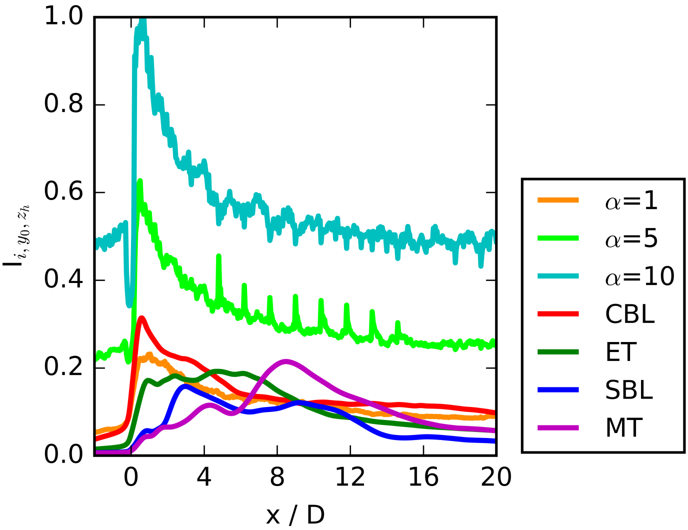

2. Parameterization of atmospheric turbulence

⇒ Streamwise profiles of the velocity ratio are in rather good agreement with other measurements and numerical simulation results and also with the results of the diurnal cycle WT simulations for α=1, α=5 and α=10.

⇒ Streamwise profiles of the turbulent intensity are only comparable for α=1. Simulations with α=5 and α=10 result in too large I values.

Possible improvements:

- $\alpha_{i,j,k}$ instead of one α value
- $\alpha_{i,j,k}$ could dependent on:

$$\Theta, \frac{\partial u}{\partial z}, \mathrm{TKE}_{i,j,k} \ldots$$

Impact of turbulence on wind turbine wakes

Thank you for your attention!

Englberger A. and Dörnbrack A.: Impact of atmospheric boundary-layer turbulence on wind-turbine wakes: A numerical modelling study, Boundary-Layer Meteorology, in press, 2016

Englberger A. and Dörnbrack A.: Impact of the diurnal cycle of the atmospheric boundary layer on wind turbine wakes: A numerical modelling study, Atmospheric Chemistry and Physics Discussions, published online, 2016