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# Comments of Anonymous Referee 2 on 'The impact of the diurnal cycle of the atmospheric boundary layer on physical variables relevant for wind energy applications' by A. Englberger and A. Dörnbrack

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First of all, we would like to acknowledge the comments. They were very helpful for improving the manuscript. Below the general comments and the specific comments made by referee 2 are discussed in detail.

Additionally, we changed the title from 'The impact of the diurnal cycle of the atmospheric boundary layer on physical variables relevant for wind energy applications' to 'Impact of the diurnal cycle of the atmospheric boundary layer on wind turbine wakes: A numerical modelling study'.

## General comments

Referee The paper discusses an LES study of a full diurnal cycle of the ABL that is validated with data from the BLLAST Field program. The study is an intermediate step toward a full LES model that incorporates wind turbine modeling. I have three general concerns regarding the manuscript. The first concern is that the paper does not appear to be sufficiently novel to stand as an independent publication. The contributions of the paper, in their current state, seem more appropriate as a chapter of a larger study.[1.1] This is due to much of the introduction discussing turbine modeling, something that is not actually modeled in the paper. The introduction should put less emphasis on turbine modeling and more emphasis on literature relevant to modeling the full diurnal cycle with realistic boundary conditions. A quick Google search reveals that a number of previous LES publications have studied the full diurnal cycle. What is unique and novel about your approach?[1.2]

Author [1.1] Considering your comment, we decided to incorporate wind turbine (WT) modelling for an independent publication. Therefore, we performed an additional idealised atmospheric boundary layer (ABL) simulation over homogeneous surface with a geostrophic wind of $u = 10$ m s$^{-1}$ and $v = 0$ m s$^{-1}$. This precursor simulation is used as background, initial and inflow condition of $u$, $v$, $w$, and $\Theta$ in the WT simulations for different regimes (convective boundary layer (CBL), evening transition (ET), stable boundary layer (SBL), morning transition (MT)). We expand the idealised ABL simulation to 54 h to also include the second diurnal cycle, investigating the difference of the WT wakes between the diurnal cycle of day 1 and day 2. The ABL BLLAST simulation is now a chapter (chapter 3) of the new version of the manuscript. Chapter 4 is updated with the new idealised ABL simulation. The WT study follows in chapter 5.

[1.2] As described in [1.1], WT modelling is included in the manuscript, leading to a unique and novel approach in the new version of the manuscript. This is stated in the following paragraph of the new version of the manuscript: 'Further, we perform a simulation of an idealised ABL throughout two full diurnal cycles with periodic horizontal boundary conditions. This is for two reasons. First, to investigate the diurnal variation of different atmospheric variables relevant in wind energy research. Second, as real-time atmospheric inflow condition in simulations of a single WT with open horizontal boundary conditions for the investigation of the impact of the CBL, the ET, the SBL and the MT in the course of a day on the wake structure. To our knowledge, this is the first study which investigates the influence of a full diurnal cycle, including the ET and the MT, on the wake of a single WT.'

Referee Second, the validation with the BLLAST dataset is unconvincing for two reasons. First, the model was run with winds at 10 m s-1 while the observations showed that the wind speed was closer to 3 m s-1. A convincing validation should match wind speeds.[2.1] Second, the model is only validated with three potential temperature profiles and the comparison is largely qualitative. I'd like to see a quantification of the errors as well as validation with additional observations from the BLLAST campaign.[2.2] The discussion of the results then shows that the LES model is able to capture the expected structure of the ABL. The discussion fails to highlight what is novel about these results compared with previous LES studies of the ABL[2.3]

Author [2.1] We rerun the BLLAST ABL simulation initialised with the measured wind profile from the 0000 UTC radiosonde launch for u and v in addition to Θ instead of a geostrophic wind of $u = 10$ m s$^{-1}$ and $v = 0$ m s$^{-1}$ and updated the results in chapter 3. In the new version of chapter 3 we investigate the time and space variation of the potential temperature, the individual turbulent kinetic energy (TKE) budget terms integrated over the height of the ABL and as vertical evolution and the temporal evolution of the potential temperature (old Fig. 1). (See Fig. 1 below.)

[2.2] We tried to compare the temporal and spatial evolution of $u$ and $v$ with sodar measurement for $z \leq$800 m and with UHF wind profiler data for $z >$800 m. This comparison does not lead to a satisfying agreement after a few hours of simulation. In our opinion, it is very difficult to fit the observed values of the wind speed and the wind direction with the LES. This is for two reasons. First, our numerical simulation strategy. We initialise with the 0000 UTC radiosonde data, however, we do not nudge during the simulation to measured wind profiles. Second, mesoscale processes. The dynamics of the atmosphere might be dominated by mesoscales processes like mountain-valley flows, which are not considered in the LES. We considered this in the new manuscript as: 'Considering 23 h of simulation with the limited prescribed external forcings, the colder temperature in the lowest levels can be caused by additional large-scale effects, which are not included in our simulation, e.g. colder air close to the surface advecting from the mountains as part of the mountain-plain circulation. '

In addition, we tried to compare the temporal and spatial evolution of $\theta$ with radiometer measurements. Unfortunately, from the 01.07.11 to the 05.07.11 there are not data available.

In summary, we arrive at the conclusion that the validation with the BLLAST data of $\theta$ from the radiosonde launch gives confidence in the ability of the geophysical flow solver EULAG to simulate the diurnal cycle of idealised ABL simulations, which is an important step towards the investigation of the diurnal variation of different atmospheric variables relevant in wind energy research ($u$, $I$) and the investigation of the wake structure in WT simulations. We stated this in the new version of the manuscript as: Introduction: 'We simulate the complete diurnal cycle of one day by using observations from the BLLAST field campaign and the large-eddy simulation (LES) model EULAG. The chosen day was characterized by a surface driven weather situation with minimum larger scale disturbances. Therefore, it is well-suited to validate the geophysical flow solver EULAG.' Conclusion: 'The validation of a full diurnal cycle of the BLLAST field experiment with our LES model EULAG gives confidence in ABL simulations. ' For this purpose, we decide that we do not need a more detail investigation and quantification of the errors for the new main statement of this manuscript, the impact of the diurnal cycle of the atmospheric boundary layer on wind turbine wakes.

[2.3] See detailed answer in [1.2].

Referee Finally, the grammar, sentence structure and general readability of the manuscript need to be improved.[3.1] I encourage the authors to carefully edit the manuscript and highlight what is unique about their approach/results and resubmit.[3.2]

Author [3.1] We aim to improve the grammar, sentence structure and general readability of the paper.
[3.2] See detailed answer in [1.2].

**Specific Comments**

Referee: 5 "In this way, this contribution to the special issue of ACP 'The Boundary-Layer Late Afternoon and Sunset Turbulence project' satisfies the purpose of the BLLAST experiment: to provide a dataset for the validation of numerical simulations aiming to study transient BL processes" – This is not necessary to include in the abstract, include major conclusions instead.

Author: We skip this part. Further, we include the major conclusions e.g. in the abstract via: 'A diurnal cycle simulation with the unique dataset gathered during the BLLAST (Boundary Layer Late Afternoon and Sunset Turbulence) field experiment gives confidence in our idealised diurnal cycle simulation of the atmospheric boundary layer performed with the geophysical flow solver EULAG. The diurnal cycle significantly impacts on the wind shear and the atmospheric turbulence. Specifically, a strong vertical wind shear and a change of the wind direction with height occur in the stable boundary layer and during the morning transition, whereas the atmospheric turbulence is much larger in the convective boundary layer and during the evening transition. These different characteristics of the atmospheric boundary layer are well-suited for studying the interaction with a wind turbine wake, by applying real-time turbulent inflow data from the idealised atmospheric boundary layer simulation with periodic horizontal boundary conditions to the wind turbine simulation with open horizontal boundary conditions. The resulting wake is strongly influenced by the stability of the atmosphere and recovers more rapidly under convective conditions during the day, compared to the night. The wake characteristics of the transitional periods are influenced by the flow regime prior to the transition. Further, there is barely seen any difference between the corresponding wake structures throughout two full diurnal cycles.'

Referee: 15 It may not be necessary to include so much detail regarding the ABL in ACP. Is it possible to include the ABL schematic from Stull?

Author: We changed it. Now it is much more compact included in the following sentence: 'Based on thermal stratification and the dominant mechanism of turbulence production/destruction, the ABL is classified into stable, convective and neutral (Stull, 1988).' Further it says: 'These transition periods are referred to as MT and ET and are defined following Grimsdell and Angevine (2002) as the time period in which the sensible heat flux changes sign.'

Referee: 34 "initiated by a positive heat flux" – Use "upward" instead of "positive"

Author: We changed it.

Referee: 73 "the inflow wind field a wind turbine is exposed to strongly influences the wake structure and the turbine loading, both affecting the power production of a wind turbine" – Confusing sentence structure. Consider rewording

Author: We changed it to: 'Atmospheric turbulence has an impact on the power produced by a WT and on the turbine loading (Sathe et al., 2013) because it affects the streamwise extension of the wake, the magnitude of the velocity deficit and the turbulence in the wake. The influence of atmospheric turbulence on these wake characteristics has been investigated in experimental studies considering different atmospheric stratifications (Baker and Walker, 1984; Medici and

Alfredsson, 2006; Chamorro and Porté-Agel, 2010; Zhang et al., 2012, 2013; Tian et al., 2013; Hancock and Pascheke, 2014; Hancock and Zhang, 2015).'

Referee: 83 “Which impact have the individual phases of the diurnal cycle on the physical variables relevant for wind energy applications?” – Confusing, please reword

Author: We changed it to: 'Further, we perform a simulation of an idealised ABL throughout two full diurnal cycles with periodic horizontal boundary conditions. This is for two reasons. First, to investigate the diurnal variation of different atmospheric variables relevant in wind energy research. Second, ...'

Referee: 98 “Most of the performed LES simulations on the characteristics of the BL, mentioned above, prescribe homogeneous surface conditions. However, the Earth's surface is not homogeneous. It is strongly affected by different land use, buildings, and so on. Therefore, considering heterogeneous surface conditions will especially improve the turbulence structure close to the ground” – Without validation or a reference, this is a non-sequitur conclusion. Just because “realistic” surface conditions are implemented, it does not guarantee that the model will more accurately capture the near-surface turbulence structure. Please include a reference to where this has been validated or show this with your data.

Author: We agree with the reviewer, a much more detailed investigation of the simulations with heterogeneous surface would be necessary. We skip this investigation in this manuscript (old chapter 5), because a detailed investigation of the ABL simulation over heterogeneous surface together with the corresponding WT simulations over heterogeneous surface would result in a rather long manuscript. Further, we choose WT simulation throughout two full diurnal cycles as new mayor topic (new chapter 5) of the manuscript, as we thought it fits better to chapter 3 and chapter 4 of the old paper. ABL and WT simulations over heterogeneous surface are considered as a self-consistent topic and future research will include it.

Referee: 258 “validated against the other three measurements” – Name the other three measurements Figure 1 Caption – “The initial starting profile is also plotted for 0000 UTC” – That's the dotted line?

Author: We try to make it more clear by excluding the initial starting profile (dotted line). Fig. 1 (Fig. 3 in new manuscript) now includes the radiosonde measurements (dashed lines) and the LES results (solid lines) for 0 h, 11 h, 17 h and 23 h (other three measurements correspond to the dashed lines at 11 h, 17 h and 23 h). Further, we rename 'measurement' in 'RS' (radiosonde measurement) (definition in the legend of new Fig. 3). See Fig. 1 below.

Referee: 309 “At 2300 UTC, there is a difference prevalent between the measurement and the LES result in the lowest levels.” – It'd be nice to see a bit more discussion on this since it's the only simulated profile of the SBL

Author: A detailed discussion of the stable profiles is given in the additional idealised ABL simulation over homogeneous surface considering the SBL, the MT and the low-level jet (LLJ) in chapter 4 of the new manuscript: '... Specifically, in the CBL and during the ET the vertical wind shear is rather small, whereas in the SBL and during MT it is very pronounced. A supergeostrophic situation prevails during the MT near hub height corresponding to a LLJ with a change in wind shear from a positive value below to a negative value above. A supergeostrophic situation also exists in the SBL simulation of Aitken et al., 2014, Fig. 4, Bhaganagar and Debnath, 2014, Fig. 1$a$ and Bhaganagar and Debnath, 2015, Fig. 1. In our simulation, the LLJ is not yet prevalent in the SBL, only a positive wind shear exists between bottom tip and hub height, because the onset time as well as the height of the LLJ depend on the amount of infrared irradiation at night and on the atmospheric situation of the previous day (Bhaganagar and Debnath, 2014, 2015).'

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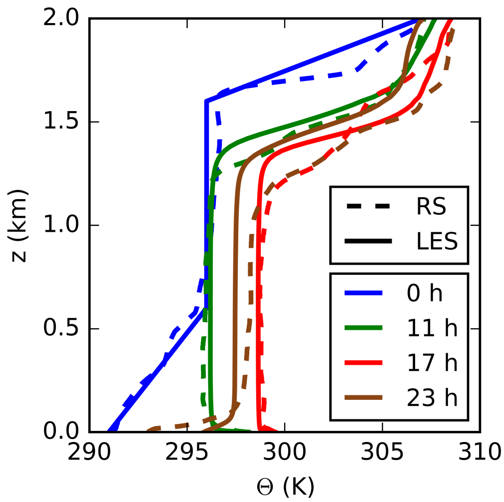


**Figure 1.** The temporal evolution of the horizontal average of $\Theta(z)$ (solid lines) and the corresponding radiosonde measurements (dashed lines) at 0 h, 11 h, 17 h and 23 h for the lowest 2 km.