Responses to Review 1

Title: Data assimilation of realistic boundary-layer flows for wind-turbine applications - An LES study

General Response:

We thank the reviewers for their time and their insightful comments which has led to major changes in the latest version of the manuscript. In particular, the reviewer comments have led to the discovery of some core issues in the formulation of the previous simulations. One such issue, for example, was the inclusion of Coriolis forces in our setup which led to the evolution of the flow beyond the nudging zone. To this end, we have redone each experiment with an improved setup, which results in much cleaner idealized results. At the request of a reviewer we have also included a different formulation of the Newtonian method, and offer a detailed comparison between three different methods now.
With these new simulations and additional relaxation method, the manuscript text itself has undergone a major restructuring. We believe that this revised version is much-improved. We first list here some of the major changes made in the current version, and then below we respond to the individual comments.

Here is a list of the major changes:

- The title is changed.
- In addition to the local Newtonian relaxation (Eq. 4) a modified approach (Eq. 6) is included in the paper following the "direct profile assimilation" approach from Allaerts et al. (2020)
- The numerical setup is altered. In particular, the Coriolis force is excluded in the assimilation simulations as it was identified to change the flow downstream of the nudging zone. Boundary conditions were altered and damping zones are included at top and the outflow boundary.
- The sensitivity to the relaxation time and to the natural frequency (respectively for the methods) is excluded in order to improve the readability. Results are shown for the parameters leading to the best results from the previous version.
- The figures are changed and show the results for the tested assimilation methods. Spatial averaging in the x-direction is avoided and more downstream positions are evaluated in order to investigate spatial variability.
- The TKE is evaluated instead of the turbulence intensity in order to show a more comprehensive turbulence analysis.
- Spectral analyses are included.
- Instantaneous flow fields are included showing the impact of the assimilation methods on the turbulent structure.

In the following we respond in detail to each comment/question:

General Comment:

Thank you for your submission. Microscale data assimilation is an important tool to have in the simulation toolbox but can be challenging to apply in practice, especially for LES. The authors demonstrate a recently developed method for data assimilation that appears attractive because when applied to a precursor LES flowfield, it can preserve the preexisting resolved turbulence. Reasonable steps have been taken to demonstrate the approach given different starting precursor simulations and in the end, results are shown for a wind turbine immersed in a near-neutral flow.

I think an advantage of using this approach is that it does not assume horizontal homogeneity like the work of Allaerts et al 2020, which allows for more general data assimilation scenarios—for example, assimilating simultaneous measurements or applicability in complex terrain.

However, the effectiveness or applicability of this approach for nonstationary conditions is not clear to me. The vibration assimilation approach is essentially an integral controller, which has known limitations. My concern is about the time lag associated with this forcing strategy. Perhaps an assimilation strategy that replicates a proportional–integral controller would be more appropriate.

- **Response:** We thank the reviewer for their insightful comments. In regards to the suggestion that a proportional–integral controller would be more appropriate, Allaerts *et al.,* (2020) tested an indirect profile assimilation which is an alternative to simple Newtonian relaxation. They mentioned in the discussion that the application of a proportional-integral controller is not sufficient to prevent unphysically high turbulence intensity. Therefore, we did not choose to include this method in our assimilation strategy.

  In response to the time lag issue, it is perhaps not clear that we are assimilating to a stationary profile, which does not evolve in time.

It would be useful for the authors to show:

- how the turbulent flow statistics downstream of the nudging zone evolve in time and space to inform the application of this assimilation technique.
- **Response:** Velocities and TKE are now shown for specific downstream positions. In Sect. 3 and 4 the spatial variability is addressed and results are shown at the positions: x=0.4 km (upstream of the nudging zone), x=2 km (outflow of the the nudging zone), x=3 km and x=4 km (downstream of the nudging zone). Spatial variability is now better presented and extensively described. As synchronized yz-slices from the precursor simulation are read at the inflow (x=0 km) throughout the whole simulation time with an open boundary condition at the outflow, a time dependent evaluation has not led to varying results for neither velocities nor turbulence.
- Recommendations for choosing the vibration frequency would also be helpful, given the sensitivity of downstream turbulence to this parameter.
- **Response:** The amplitude of the vibration frequency is derived from the setup from Nakayama and Takemi (2020). They indicated that the frequency in the method needs to be smaller than the peak frequency in the energy spectrum. The sensitivity of the method on this parameter has been investigated but is not shown in the revised version

because we think it did not improve understanding of the method compared to Nakayama and Takemi (2020). Instead, for the simulations in this study we focused on the frequency $f_0 = 0.002\ s^{-1}$ as it led to the best balance between the assimilation of the velocities and small damping effects of the TKE. We give a recommendation for the choice of the vibration frequency in the paper: "**...**the frequency for the oscillating velocity in the vibration equation which has to be set smaller than the peak frequency in the energy spectrum of the precursor simulation."

- If you start from one LES and nudge toward another LES solution, do you recover the same turbulence as the target LES?
- **Response:** We completely agree with the reviewer on this point and see this as a worthy endeavor. However, since we received the reviews there has be a major restructuring and rewriting the paper including redoing all simulations. This has unfortunately taken the majority of the time. Performing another LES and subsequently investigating was not possible with the given deadline. In any case, we clearly see the utility of such an investigation and will proceed with this in due course.

My biggest concern about this work is how:
Newtonian relaxation has been written off because the assimilated flow has reduced turbulence. If I understand the implementation correctly, the instantaneous velocity at each point within the nudging zone is relaxed from the turbulent flow field towards a mean profile. Therefore it is not surprising to me that the precursor turbulence is reduced or eliminated.
A more reasonable approach and fair comparison would be to relax the horizontal mean within the nudging zone towards the target mean profile. This would constitute a localized version of the "direct" profile assimilation from Allaerts et al 2020.

- **Response:** Thank you for this important remark. We have included the "direct" profile assimilation from Allaerts et al. (2020) in this work an refer to it as Newtonian relaxation (Eq. 6), while the old method is now called the local Newtonian relaxation. The results for the idealized NBL investigations in Sect. 3 (coarse grid) and Sect. 4 (fine grid) are now shown for the local Newtonian relaxation (Eq. 4), the Newtonian relaxation (Eq. 6) and the vibration method (Eq. 7). In fact, the results from Nakayama and Takemi (2020) could be only reproduced with the local Newtonian relaxation, which is consistent with their Eq. 6. While this approach leads to a significant decrease of the TKE, the Newtonian relaxation and the vibration method led to an increase of the TKE.

Please see the attached annotated PDF for more specific comments.
I have elected not to review a revised manuscript not because I am not interested but because I will be on family leave in the near future.

Comments in the PDF:
1 Introduction:

Paper: Furthermore, site-specific measurements show in general similar flow characteristics for one stratification and a main wind direction and only small differences in the hub-height wind speed, the vertical gradient of the velocity and the atmospheric turbulence.

- **Comment:** This statement is unclear to me. Are you saying that for a given set of atmospheric stability conditions and a wind direction, the wind speed, shear, and TI are generally similar across sites? This seems to neglect a lot of factors: the relationship between surface heat flux and shear, boundary layer height, and large-scale forcings.

- **Response:** The statement was misleading and is not further used in the manuscript. Within one atmospheric stratification there is still a variation of wind speed which is important to know for the prediction of power gain and the load on wind turbines. E.g. a neutral boundary layer flow can have different hub-height wind speeds alternating with time.

Paper: Which of the considered assimilation method is able to preserve turbulence?

- **Comment:** I think a broader, more appropriate objective would be to "produce realistic turbulence." Measurement accuracy and precision affect the assimilated wind profile and can have a pronounced effect on the resolved turbulence in an LES.

- **Response:** The aim of the study was to assimilate the velocities and taking the turbulence of the precursor simulation as ground truth. We think that statement is suitable, as we don't verify that the turbulence in the simulations is realistic.

2.2 Assimilation Methods

Paper: Eq. 4

- **Comment:** For completeness, this should have the independent variables included as in Eq. 5.

- **Response:** The equations are now written in the same terminology.

Paper: The severe drawback of this method is the damping of small-scale turbulent structures in the atmosphere

- **Comment**: I think it's worth explicitly mentioning that nudging approaches introduce additional modeling parameters to describe the extent of the nudging region and the spatiotemporal weighting applied.

- **Response:** This is a very good point. We highlighted this property of the nudging methods in the introduction and in Sect 2.2.

Paper: Eq. 5:

- **Comment**: This looks like an integral controller to me. In which case, you'll run into the issue of your simulated velocity field always lagging behind your observed value. Does this assume that the assimilated conditions are stationary (i.e., U_{OBS} is not a function of t) or U_{OBS}changes very slowly (e.g., could you assimilate a wind ramp)? Please discuss.

- **Response:** In our study U_{OBS} (v_{OBS} in the revised version) is stationary, a varying target profile has not been tested. The nudging area and the frequency are set to allow an adequate forcing of the velocities towards the target profile.

- **Comment**: Does this approach require U_{OBS} to be specified through the entire height of the computational domain? In other words, will WRF be needed in practice?
- **Response:** The target profile does need to be specified throughout the height of the domain. Observational data comes with the limitations that there is often not data available throughout the heights required for the simulations we

perform. This can be especially obvious on days where there is low cloud and LIDAR data has large gaps. For example, in Fig. 1, the observations cover heights at this time between 57 m and ~450 m. While one can extrapolate the data to fill these gaps, this could lead to large differences/uncertainties from reality. Therefore, it would make sense to use high-resolution WRF data, if available. However, in theory the gaps in the observed profiles could be filled in with any operational weather model data, to avoid additional computational cost.

- **Comment**: Setting omega^2 should be analogous to setting your integral controller gain. Along the same lines, t*omega^2 should correspond to an integral time scale. Is this a reasonable way to think about the approach? If so, could you contextualize your discussion in this way?

- **Response:** We think this is correct, it is the integral time scale in the method. Nakayama and Takemi derived the forcing term based on the vibration equation for the velocity oscillating around a basic state with a certain frequency. This equation consists of a proportional damping term and an integral oscillating term.

Paper: Eq. 6

- **Comment:** In general, should this term be a function of only x or both x and y? It does not make sense to me to distribute the forcing term along only a single horizontal direction.

- **Response:** As far as the forcing is imposed over the whole lateral width of the simulation domain and the boundaries are periodic a gaussian distribution in the y-direction is not necessary.

2.4 Precursor Simulations

Paper: Power Law

- **Comment**: This does not appear to be correct. Fig 2a shows the precursor planar-averaged u to be > 8 m/s at 300; this equation gives 1.38 m/s.

- **Response**: This was a mistake. The correct logarithmic equation is now given in Section 2.4. Thank you for this comment!

Paper: The atmospheric condition in this simulation corresponds to a stable stratification.

- **Comment**: More detail is needed for completeness - how stable was the ABL and how was the lower boundary handled?

- **Response**: The SBL has been performed by Englberger & Dörnbrack (2018) for the investigation of wind-turbine wakes during the diurnal cycle. A negative sensible heat flux (-10 W/m^2) and a drag coefficient of 0.1 were imposed at the lower boundary. For detailed information we refer to the publication of Englberger & Dörnbrack (2018).

3.1 Results of the NR Method

Paper: [….] drives the velocity towards the desired wind profile

- **Comment**: Please clarify this. It seems like you're driving the _instantaneous_ velocity within the nudging zone towards a desired _mean_ wind profile. As your results in this section show, this clearly would remove resolved turbulence from the LES because you're nudging towards a smooth target profile. A more reasonable approach would be to take a planar average within the nudging zone and derive your forcing based on the error between that mean and the target.

- **Response**: In response to this comment we extended the manuscript by the integration of the "direct" data assimilation from Allaerts et al. (2020) (see Sect. 2.2, Eq. 6). The results from Nakayama & Takemi (2020) could be only reproduced with the local Newtonian relaxation (Eq. 4). The different impact of the methods on the TKE is presented in Sect. 3 for the coarse grid an in Sect. 4 for the refined grid.

Paper: […] the velocity tends back to the original state.

- **Comment**: This implies some physical restoring mechanism. Isn't the velocity drifting from the target profile as a result of acceleration from the added Coriolis term, in which case, it's actually tending towards a new equilibrium profile (and not the original state)?

  Response: This is a perceptive comment, which has ultimately led us to redo all simulations without Coriolis force. To explain, from Eq. 2, the Coriolis force acts exclusively on perturbations to the environment flow, which is defined as the initial profile. As the flow is nudged towards a target profile (and away from the environment flow), the "perturbations" can become locally quite large. Where the perturbations are large there is indeed a relatively large Coriolis force acting on the flow, which tends to change the flow away from the target the further it moves downstream. When the simulations were performed again with the Coriolis term turned off, the flow remained much closer to the target flow at all distances analyzed.

Paper: […] The results are comparable to Fig.4 in N&T(2020)

- **Comment**: I'm not familiar with the NT2020 work but from looking at their Fig 4, I would disagree with this. Seems like your results are better. Their tau=300 result shows the LES being completely unresponsive to the forcing and their tau=30 case never reaches the target.

- **Response**: The Sect. 3. has been altered in order to show the performance and differences of the three tested methods. The results of the local Newtonian relaxation and the vibration method from Nakayama & Takemi (2020) could be reproduced in general. However, an entire reproduction of all of their results was not possible due to different numerical models. Furthermore, we altered their numerical approach and excluded the Coriolis forcing in order to avoid the evolution of the flow behind the nudging zone.

3.2 Results of the Assimilation Method using the Vibration Equation

Paper: […] a small tendency towards the original wind profile can be found for all three cases

- **Comment**: Same comment as with Newtonian relaxation result — is it actually tending toward the original profile or a new equilibrium?

- **Response**: See replies above to a similar comment for 3.1.

Paper: Fig 3: Reynolds stress in e) f)

- **Comment:** I think this is missing a negative sign, <u'w'> should be negative.

- **Response:** This is right! The plot was correct but, in the axis label the negative sign was missing. However, the whole presentation of turbulence was modified and TKE is now the only metric showing the impact of the methods on atmospheric turbulence.

5.1 NBL as Precursor Simulation
Paper: […] space averaged mean […]

- **Comment**: For clarity, consider describing these as "planar averages" vs "volume averages" in the text and figure captions.

- **Response**: Averages are now clarified throughout the paper. Temporal averages are indicated with an overbar, spatial averages are indicated with <>. In regard to comments of Reviewer 2 planar averages are replaced in Sect. 3, 4 and 5. Instead, single downstream positions are evaluated and the velocities and the TKE are only averaged in the y-direction.

Paper: The target velocity values are reduced

- **Comment**: From the WRF values by how much?
  What is fundamentally unclear to me is if you didn't shift your precursor or target at all, but ran your simulation long enough, your assimilation technique should drive the error between the precursor and target to 0. Can you please clarify?

- **Response**: The mass continuity in the numerical model inhibits the change of the mean flow of the precursor simulation averaged over the whole simulation domain. This means that the assimilation methods are only suitable if there is not much difference between the domain averaged mean flow of the precursor simulation and the domain averaged target value (to discover exactly how much difference is allowed requires further testing).

- **Comment**: In practice, your target isn't going to be adjustable and you'd also set up your precursor to be as close to the target conditions as possible — so it seems to me that neither correction makes sense. Can you please explain the motivation for this part of your study?

- **Response**: The ideal case would be one precursor simulation where the velocities could be assimilated towards arbitrary target profiles. If a new precursor simulation is needed for each considered velocity profile, the time saving aspect of the data assimilation method would be consumed. We wanted to test under which conditions it is appropriate to modify the precursor simulation in advance. Sect. 5 showed that the precursor simulation P2 is not suitable for the assimilation especially towards high meridional velocities. However, the precursor simulation P3 with larger wind shear and veer leads to promising results.

Paper: it was not possible to nudge towards the strong negative values because the Courant-Friedrich-Lewy-criterion was violated during computation

- **Comment**: I don't understand why your technique shouldn't still work. Why not reduce the time-step size if you're running into a CFL limit?

- **Response**: This argument has been removed from the publication as it is not the CFL criterion which limits the applicability of the assimilation method. In fact, the mass continuity equation in the Navier-Stokes equations inhibit an assimilation towards target profiles deviating from the domain averaged microscale mean of the precursor simulation.

5.2 SBL as Precursor Simulation

Paper: DWL-measurements and the reference data from WRF (resolved TI)

- **Comment**: Can you comment on how reasonable it is to use DWL or WRF (40-m LES) as ground truth for TI? There is measurement and discretization error, respectively.

- **Response**: This comment has led us to remove the comparison of turbulence characteristics of the LES with DWL or WRF data. The goal of the vibration method is to adjust the velocities with a reduced impact on the TKE compared to the initial flow of the precursor simulation. This has been achieved in Sect. 5.

Paper: However, there might be mesoscale effects which are not taken into account by the assimilation method and the precursor simulation.

- **Comment**: This is a vague conclusion, please be more specific. The precursor simulation certainly has no mesoscale effects but the assimilation should implicitly capture the mesoscale tendencies associated with momentum. What would be missing are temperature or moisture tendencies.

- **Response:** This conclusion has been removed from the paper. As the setup of the simulation and the turbulence analysis differ from the submitted version, also the results changed. Sect. 5 shows the efficient assimilation towards the target velocity profiles while the magnitude of the TKE is preserved. Potential temperature and moisture are not included in this work, as it originated from the work of Nakayama & Takemi 2020, but they are a logical next step for future work.

Paper: Figure 9: SBL as prec. sim.

- **Comment**: Why do these precursor u and v profiles differ from Fig 8?

- **Response**: The SBL precursor simulation was also modified according to Eq. 8-9 (revised paper) which is now indicated in Sect. 5.

6. Analysis of the Wind-Turbine Wake for an assimilated Atmospheric Inflow

Paper: First, we conducted one simulation with the wind turbine and the original SBL as a reference case. In a second simulation the inflow of the SBL is assimilated by the vibration assimilation method.

- **Comment**: How long was the turbine simulation and how long is the averaging period for the results shown?

- **Response**: The time for the wind-turbine simulation was 60 min. The velocities were averaged over the last 20 min.

Paper: the TI at the position *x/D* = -1 is subtracted

- **Comment**: It sounds like you subtracted the TI profile at x/D=-1 from all downstream locations to get the WT influence. Why not subtract the local TI sampled from the case without turbines from the local TI of the case with the turbine?

- **Response**: In the first version of the manuscript the wind turbine has been rotated in order to have a perpendicular flow at hub height. We decided in the revised version to show the interaction of the wake for a non-rotated wind turbine as the impact of the assimilation method can be seen more clearly. However, a comprehensive analysis of the TKE is difficult for a deflected wake and is therefore not shown in the revised version. A detailed analysis of the properties in the wake will be pursued when measurement data for the wind farm WiValdi is available.

Comment: Also, there's something that hasn't been covered yet in this paper that I would like to see. At what distance downstream of the nudging zone does the turbulent flow become fully developed (homogeneous)? I.e., how much "fetch" is there?

Response: The flow from the beginning in the nudging experiments is already fully turbulent as turbulence has spun up in the precursor simulation. It can be seen in the new vertical cross sections shown in Figs. 5 and 7 that no fetch exists.

We have attempted to clarify the methodology in Section 2 to avoid confusion.

References:

Allaerts, D., Quon, E., Draxl, C., and Churchfield, M.: Development of a time–height profile assimilation technique for large-eddy simulation, Boundary-Layer Meteorology, 176, 329–348, 2020.

Nakayama, H. and Takemi, T.: Development of a Data Assimilation Method Using Vibration Equation for Large-Eddy Simulations of Turbulent Boundary Layer Flows, Journal of Advances in Modeling Earth Systems, 12, e2019MS001 872, 2020

Englberger, A. and Dörnbrack, A.: Impact of the Diurnal Cycle of the Atmospheric Boundary Layer on Wind-Turbine Wakes: A Numerical Modelling Study, Boundary Layer Meteorology, https://doi.org/https://doi.org/10.1007/s10546-017-0309-3, 2018.