Responses to Review 2

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:

Review 2:

This article investigates the use of data assimilation to provide forcing for LES modeling of ABLs with the intent of modeling wind-turbine impacts. The paper presents comparisons between Newtonian relaxation (nudging) and another, more sophisticated approach proposed by Nakayama and Takemi (2020) based on the vibration equation with an imposed frequency. The authors compare the two approaches and highly idealized conditions and then include an example where the approach is applied to a combination of vertical lidar profile blended with mesoscale WRF data. Generating turbulence consistent with a specified forcing conditions is a topic of relevance to wind energy studies. However, there are a number of critical fundamental issues that need to be addressed and that make the study in its current (and very preliminary state) non suitable for publication in Wind Energy Science. These major concerns are outlined here below.

Major Comments

- Reviewer 2: The manuscript (starting from the title) is full of quotes and claims of this data assimilation method to be able to generate "*realistic inflow fields*". There are a number of reasons because of which this is actually not the case, and it is in fact the opposite. Firstly, the method does not consider data assimilation for buoyancy and moisture effects, as only considers forcing terms for the momentum equations (Eq. 5). Secondly, it relies on a single vertical profile and evolves conditions from an idealized, flat, laterally periodic ABL, leading to homogeneous forcing. Even if the authors use a profile from observations to assimilate mean wind speed forcing, a single local observation is typically not in equilibrium neither represents spatially averaged conditions properly, which does not imply any realism as heterogeneous effects are not accounted for (both in space and time). These crucial aspects make the method exclusively suitable for highly idealized conditions. The tone of the paper comes across in the current form as excessively overselling of the approach, not outlining any of the limitations, and needs to be significantly altered to provide a fair view of what the method brings to the table and what the limitations are.

- **Response**: We agree that the way that the original text was formulated could have misled the reader in regard to the aims and abilities of the method. We have altered the paper and replaced the term 'realistic' and attempted to downplay any excessive overselling. We have now also implemented the Newtonian relaxation method using a horizontal average flow field, similar to Allaerts et al (2020, 2023), in order to provide a fair comparison with the vibration technique to existing methods.

  We agree, the vibration method in our work is limited as it accounts only for assimilation of velocities, and not buoyancy or moisture. Buoyancy effects and moisture would imply additional sources of variability. As the main point of our work is testing the vibration method for a wind-energy relevant resolution of 5 m, we choose a setup close to the original 40 m resolution work by Nakajama & Takemi, 2020.

  The observed profile that we implement in this work, taken from the LIDAR at WiValdi, is actually a 10-min time average (from 18:30-18:40 UTC, 19 Nov 2021), and also due to the conical scanning strategy of the LIDAR, contains also some spatial averaging at the site over this time period. While this profile does not represent the entire range of conditions that a wind turbine experiences over a longer time period, the profile is realistic and is a typical condition that a wind turbine encounters (as seen in our climatology at the wind park). For the current work, in testing assimilation methods, we feel that this is a reasonable first step towards more realistic scenarios.

In this work, our aim is to test the assimilation of an idealized profile towards a single observational profile. In general, the method is able to assimilate towards simultaneous (time varying) measurements, as it works with open horizontal boundary conditions. But it is beyond the scope of this work and has not been tested so far.

With the modifications made, we aimed to offer a fair comparison of all three methods without an overselling of the vibration method. We further highlight the main limitation, that none of the investigated methods is able to completely preserve the inflow TKE.

- Reviewer 2: A significant portion of the manuscript is devoted to repeat the results from Nakayama and Takemi (2020). All these results and discussion do not provide any new insights besides showing that the implementation is correct. Nakayama and Takemi (2020) already demonstrated that the "nudging" approach is not good in order to produce reasonable turbulence quantities, so all that part of the manuscript is redundant. I would recommend the authors to remove the majority of that content, and perhaps move a minimal part of these results to an appendix if at all.

- **Response:** This part of the study shows the correct implementation of the assimilation methods in the numerical code EULAG, which had not been previously done. As the numerical models (EULAG and LOHDIM-LES) are significantly different (e.g. surface parameterization) it is necessary to confirm that the methods produce similar results. With the restructuring of the paper to its current version, the addition of a more sophisticated Newtonian relaxation approach, gives new scientific insight in this chapter. Further, we changed our numerical setup in comparison to Nakayama & Takemi (2020), excluding the Coriolis force in response to comments from Reviewer 1 (see comments to other review) on the evolving flow in our original simulations. The results with coarse resolution are also necessary to enable a comparison with the results with a finer grid and they are a verification for our numerical setup without Coriolis force, which differs from Nakayama and Takemi (2020).

  However, we agree that a large amount of manuscript was used to describe these results, which was not necessary. We have restructured this section and made it much more concise.

- Reviewer 2: It is not surprising that assimilating a wind speed profile would lead to a matching velocity field within the area of the domain where the assimilation is applied, as the influence from the governing equations is being overpowered by that forcing term. The emphasis, which the authors attempt to provide in this study, is the quality of the resulting velocity fluctuations (i.e., turbulence). First, the authors should refrain from using turbulence intensity (TI) as a metric for comparison. TI is a very misleading derived quantity. I understand engineers like it, but you can have the right TI with properly offset wind speed and TKE. Please use TKE for the analyses instead (same for Reynolds stress). Secondly, to that end, run a precursor case with equivalent forcing so you can properly assess the skill of the approach, otherwise it is impossible to judge the adequacy of the results.

- **Response:** TI was used for in this paper to offer a comparison to Nakayama & Takemi (2020), because there, TI is shown only. In the revised manuscript we have changed all analyses to TKE. In regards to the comment running a precursor case with equivalent forcing we completely agree with the reviewer. However, since we received the reviews there has been a major restructuring and rewriting of the paper including a redoing of all simulations. This has unfortunately taken the majority of the time. Performing another precursor and subsequent investigation was not possible with the deadline. In any case, we clearly see the utility of such an investigation and will proceed with this in due course.

- Reviewer 2: Averaging over a spatial area is not a good idea. While that approach will inevitably lead to smoother results, it does implicitly hide any spatial variability. In the end, this method will be used in a limited area domain, as shown in Fig. 11. The authors need to quantify the spatial variability as the flow moves out of the nudging region. This evolution of the wind field is evident from Fig. 11 when examining x-direction evolution for abs(y/D) > 1.0. Please perform proper spatial analyses to understand this key practical aspect.

- **Response:** Thank you for your comment. It was very helpful, as it leads to the Coriolis force issue, which we have fixed. The evaluations and analysis are completely changed and show now the values for specific positions up- and downstream. Spatial variability is now better presented and explicitly described. In Sect. 4 we show also yz-slices of the fine grid simulations.

- Reviewer 2: The turbulence analyses need to be more rigorous and comprehensive. Again, the first-order mean may be captured somehow, but that does not guarantee proper balanced turbulence. The authors need to include energy spectra computed over time and show how the data assimilation approach alters the energy distribution across scales due to the oscillatory, single frequency nature of the assimilated forcing. Also, length scales are important. The authors need to show instantaneous flow fields to get started with, and then dig deeper into more careful and systematic comparisons of turbulence quantities.

- **Response:** We thank the reviewer for this helpful remark. This point has been realized throughout the whole paper. Turbulence analyses include now TKE to show turbulence development in space. Instantaneous flow fields are presented in Sect. 4, Fig. 5 and Sect. 5, Fig. 7. Energy spectra for varying positions in x-direction are presented to qualify the impact of the assimilation method on atmospheric turbulence. From the vertical cross sections in Fig. 5 and 7 there appears to be no zonal evolution of the flow. Also, the simulations are run for a relatively short time period. Therefore, the usefulness of spectral analysis in time is questionable.

  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.

- Reviewer 2: An aspect that appears to be essential to the method and that should be explored in the manuscript is how the disparity between the reference LES data and the forced profile influences the required area where the assimilation is applied, as well as how the amplitude of the forcing needs to be adjusted. Please explore different reference LES and target profiles to elucidate this aspect. Otherwise, practical applicability of the method cannot be guaranteed.

- **Response:** We performed already a sensitivity study of the length of the nudging area (400 m, 1000 m, 2000 m) but we didn't include this finding in the original submission as it was not a new finding. Our results agree with those of Nakayama and Takemi (2020) who stated that a length of 1 km is appropriate for the assimilation: "This fact ensures that the representative horizontal scale of TBL flows is 1 km." An in-depth investigation of the required nudging areas as well as the forcing amplitudes is beyond the scope of the current paper.

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.

Allaerts, D., Quon, E., and Churchfield, M.: Using observational mean-flow data to drive large-eddy simulations of a diurnal cycle at the SWiFT site, Wind Energy, 26, 469–492, 2023.

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.