Responses to the interactive comment on *"Measuring dynamic wake characteristics with nacelle mounted LiDAR systems" by Inga Reinwardt et al., manuscript number: wes-2019-89*

Responses to the referee: Helge Aagaard Madsen (hama@dtu.dk)
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We are delighted for your valuable comments on the paper. Considering your comments leads to a significant improvement of the paper. We thank you a lot for taking the time to review this paper.

Specific comments
Abstract

The sentence: "the formulation of the quasi-steady wake deficit in the DWM model has been adjusted" is not precise.
It´s proposed to describe that it´s the correlation of the impact of ambient turbulent to the eddy viscosity that has been investigated and that an improved correlation function (parameter) has been determined based on the present measurements.

Response: The sentence has been adjusted to: *"Based on the findings from the LiDAR measurements, the impact of the ambient turbulence intensity on the eddy viscosity definition in the quasi-steady deficit has been investigated and, subsequently, an improved correlation function has been determined, resulting in very good conformity between the new model and the measurements."*

2. Wind farm

Line 68:

- What is the instrumentation in the met mast ? Please describe in the paper.

Response: It is equipped with 11 anemometers, two of which are ultrasonic devices, three wind vanes, two temperature sensors, two hygrometers, and two barometers. The sensors are distributed along the whole metmast, but at least one of each is mounted in the upper eight meters. A Figure with the instrumentation and measurement heights was added.

Line 76:

- What type of load measurements and have they been used for DWM simulations on the turbines?

Response: Strain gauges are installed at the three turbines to measure tower bottom, tower top as well as blade edge- and flapwise moments. Unfortunately, the load measurements are not in the scope of this paper but will be introduced in future publications, i.a., to verify the recalibration. A hint that these load measurements are used for further investigations was added.

3. Data filtering and processing

Line 86:

- … "and sorted in accordance with ambient wind speed, ambient turbulence intensity, windshear, atmospheric stability, and wind direction".
    - is it 10 min, mean values that the data are sorted on basis of ?

Response: Yes, the data are filtered based on the 10-min time series statistics from the metmast. The information was added to the manuscript.

4. Wind speed deficit in MFR calculation

Line 119:

- … "In the analysis presented here only results from a horizontal line scan are analyzed, so that no vertical meandering is considered and the measurement results are fitted to a one-dimensional Gaussian curve defined as follows:"
    - In my view this is an important limitation of the experimental set-up. Overall the impact is that the depth or strength of the deficits are smaller than if the 3D location of the deficits was used. The impact can be investigated using a DWM model and simply set the vertical meandering to zero. Please discuss this limitation of the measurement set-up and what impact it has on the final result.

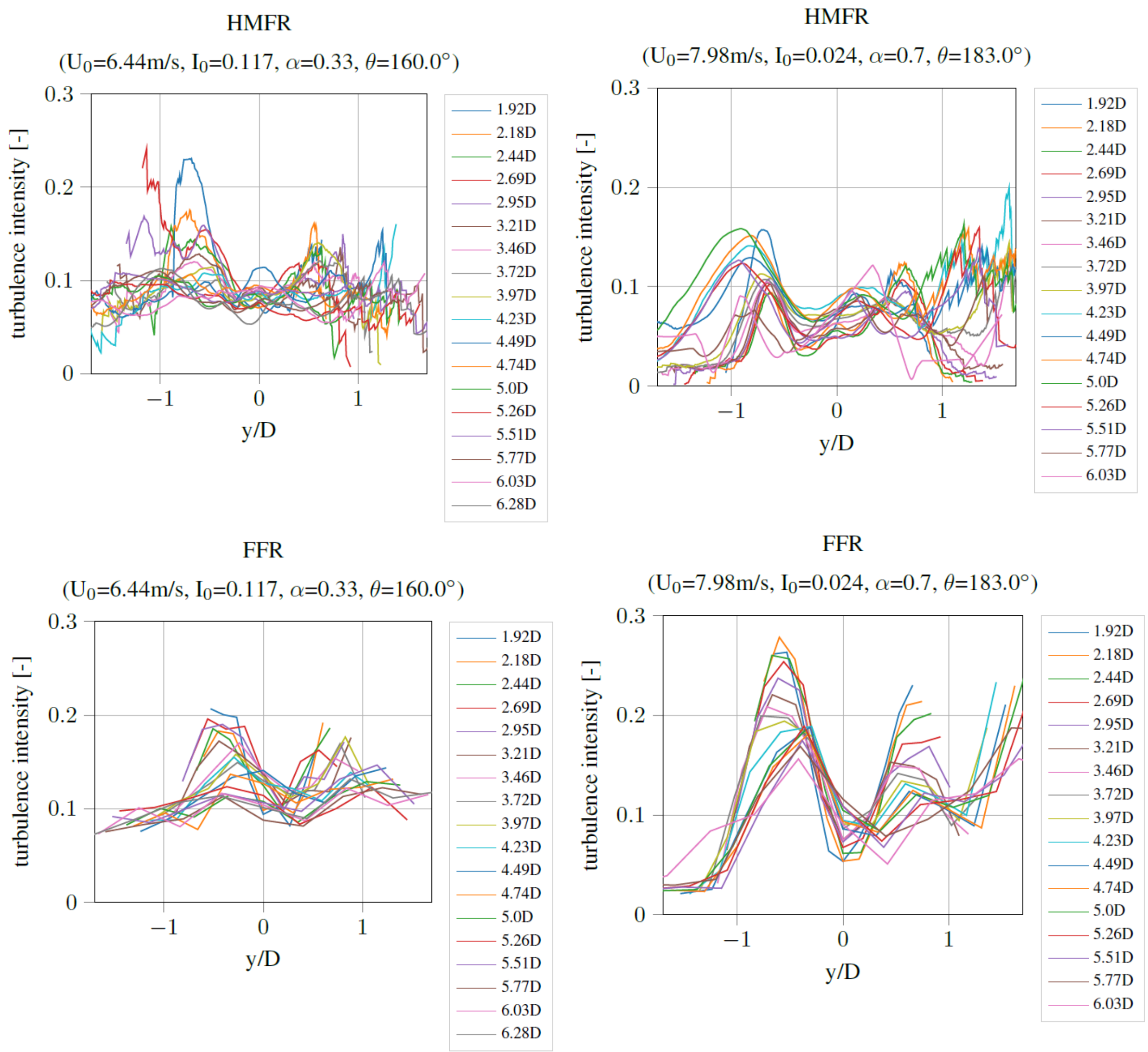
Response: A comparison of the simulated wind speed deficit with the DWM model in the complete MFR and without eliminating the vertical meandering in the wind speed deficit was added. There are only small discrepancies around the center of the wake. Nevertheless, in the comparison between the simulated wind speed deficit and the measured wind speed deficit the vertical meandering is not eliminated, so that in both cases the wind speed deficit is similarly reduced in depth. Naturally, the minimum wake wind speed deficit in the MFR without elimination of the vertical meandering is used for the recalibration, too. To clarify that the vertical meandering is not eliminated in any case, but included in the wind speed deficit, the abbreviation HMFR (horizontal meandering frame of reference) is introduced and used instead of MFR.

Line 137:

- … "After averaging, the plausibility of the results is inspected. If the calculated minimum mean wind speed in the MFR is higher than the minimum mean wind speed in the FFR, it is assumed that the Gauss fit failed and the results are no longer considered.
    - Besides this plausibility check I would propose to show the standard deviation of all the measurement points around the average MFR from the individual scans, just for a few cases. This will give information about how much averaging is behind the final MFR deficits.

Response: The plots for the corresponding turbulence intensities for Figure 6 (HMFR) and 7 (FFR) are given below. The comparison of the turbulence intensity in the HMFR and FFR show a decrease of the two maxima at the turbulence intensity in the HMFR, which is expected due to the transformation to the HMFR. The two maxima do not vanish completely in the HMFR graphs due to the small-scale turbulence, which is related to blade tip and root vortices as well as the wake shear itself. Additionally, the turbulence which is related to the vertical meandering is still included. Furthermore, the ambient turbulence intensity of

11.7% and 2.4% can be seen towards the edges of the curve, where the wake influence decreases.



Line 148:

- In figure 2 as I understand the procedure:
  - – shouldn´t the x axis after the interpolation be in y/d units and not in deg. ?. Likewise in Figure 3b.

Response: The label refers to the scan direction, because it is the interpolated scan direction. Nevertheless, it is clearer if the axis is in y/d to correspond to the Figures in section 7. Both graphs were adjusted.

5. LiDAR simulation

Line 159:

- Were the lidar simulations with the DWM model shown in Figure 3 carried out with ambient turbulence or only a meandering turbulence – please specify?

Response: It is the complete DWM model wind field with ambient turbulence. It is specified in the text.

Line 160:

- … "Whenever the wind speed deficit is mentioned in subsequent validations, it implies the neglection of the vertical meandering, which has only a marginal impact on the shape of the wind speed deficit in the FFR.".
  - As the meandering turbulence components scales with 0.8 and 0.5 in horizontal and vertical direction relatively to the streamwise turbulence component I am not convinced that this statement is correct. Please expand on this eventually based on simulations with the DWM model.

Response: A comparison of the simulated wind speed deficit with DWM model in the complete MFR and the HMFR was added (see also response to comment on Line 119).

6. Dynamic wake meandering model

Line 175:

- … "It compares directly to the LiDAR measurements after transforming the measurements into the MFR as explained in the last section".
  - As mentioned above the measured wake deficit might be less sharp (deep) due to neglecting the vertical meandering and due to the averaging of many individual deficits impacted by ambient turbulence.

Response: That is true, although, the DWM model simulations showed that the influence is small. In the comparison between the simulated and the measured wind speed deficit the vertical meandering is also neglected, hence in both cases the wind speed deficit is less deep. Since the sentence seems to be misleading, it was deleted.

Line 189:

- … "The error that inherently comes with this assumption is accommodated by using the wind speed deficit two rotor diameters downstream (beginning of the far-wake area) as a boundary condition for the solution of the thin shear-layer equations. "
  - It might be important to point out here that the eddy viscosity model in the DTU DWM implementation is run from the rotor plane and downstream with the fully expanded wake deficit (eq. 6 and 7) as boundary conditions but where a fit of the deficit at 2D downstream to Actuator Disc simulations determined eq. 8 and the filter function for non- turbulent flow.

Response: The equations are also directly solved from the rotor plane in the implementation here. It is rephrased to:

"The error that inherently comes with this assumption is accommodated by using the wind speed deficit two rotor diameters downstream (beginning of the far-wake area) as a boundary condition for the solution of the thin shear layer equations. The equations are solved directly from the rotor plane by a finite-differences method with a discretization in axial and radial direction of 0.2D and 0.0125D combined with an eddy viscosity (ν_T) closure approach."

In section 6.1.1 DWM-Egmond following sentence was added:

"The filter function as well as Equation 8 are calibrated against actuator disc simulations at a downstream distance of 2D, the beginning of the far-wake area, where the wake is fully expanded (Madsen et al., 2010)."

Line 272:

- … "It shows that for lower turbulence intensities and moderate to high turbine distances the wind speed deficit degradation is too low."
    - Maybe write "was too low in the model version from 2010 – ref J. Sol. Energy Eng., 132, 041 014, 2010." The deviations were the reason to recalibrate the model as presented in the 2013 paper.

Response: This sentence is rephrased to: "*It shows that the wind speed deficit degradation is too low for lower turbulence intensities and moderate to high turbine distances in the model version from Madsen et al. (2010). For this reason, the downstream distance dependent function F_{amb} was introduced into the eddy viscosity description in Larsen et al. (2013).*"

7. Measurement results

Line 289:

- … "The corresponding mean wind speed deficit is illustrated in Figure 6(b)."
    - In order to evaluate what this mean deficit it would be valuable if the standard deviation of the 11 raw measurement points for each scan are shown

Response: The plots of the corresponding turbulence intensities are given in the comment on Line 137.

Line 310:

- … "The reason is probably the wake of other turbines in the wind farm".
    - It could also be due to wake rotation as seen in 3D CFD rotor simulations in sheared inflow. It shows that high velocity flow at one side of the rotor is rotated down towards the ground and the opposite on the other side of the turbine.

Response: If it is due to wake rotation, shouldn't the wind speed on the right edge of the deficit be higher than the ambient wind speed from the metmast? Currently, the wind speed agrees with the ambient wind speed.

Line 323:

- … "In this range both turbines operate under optimal and most efficient conditions resulting in maximum energy output from the wind. The thrust coefficient is constant in this region. Therefore, the axial induction and the wind speed deficit normalized by the turbine's inflow wind speed are also expected to be constant for similar ambient conditions over this wind speed range."
    - Its mentioned ".. expected to be constant". What is actually used in the DWM simulations ?
    - Further down at line 368 is mentioned : ".. that the axial induction of both turbines is slightly different under partial load conditions." So is the detailed aero loading of each of the two turbines are simulated ?

Response: DWM model simulations for the single turbulence intensity bins and both turbine types are carried out and the same axial induction is applied over the whole wind speed range. That means, each turbine type is modelled separately and all turbulence intensity bins are simulated. The sentence is rephrased as follows: *"DWM model simulations were carried out for both turbine types, since the axial induction of both turbines is slightly different under partial load conditions. To calculate a mean value of the simulated minimum wind speed and thus allow a comparison with the results in Figure 12, simulations with both turbine types are carried out for each turbulence intensity bin and weighted in accordance with the number of measurement results per turbine listed in Table 2.".*

8. Comparison between measurements and DWM model simulation

Line 358:

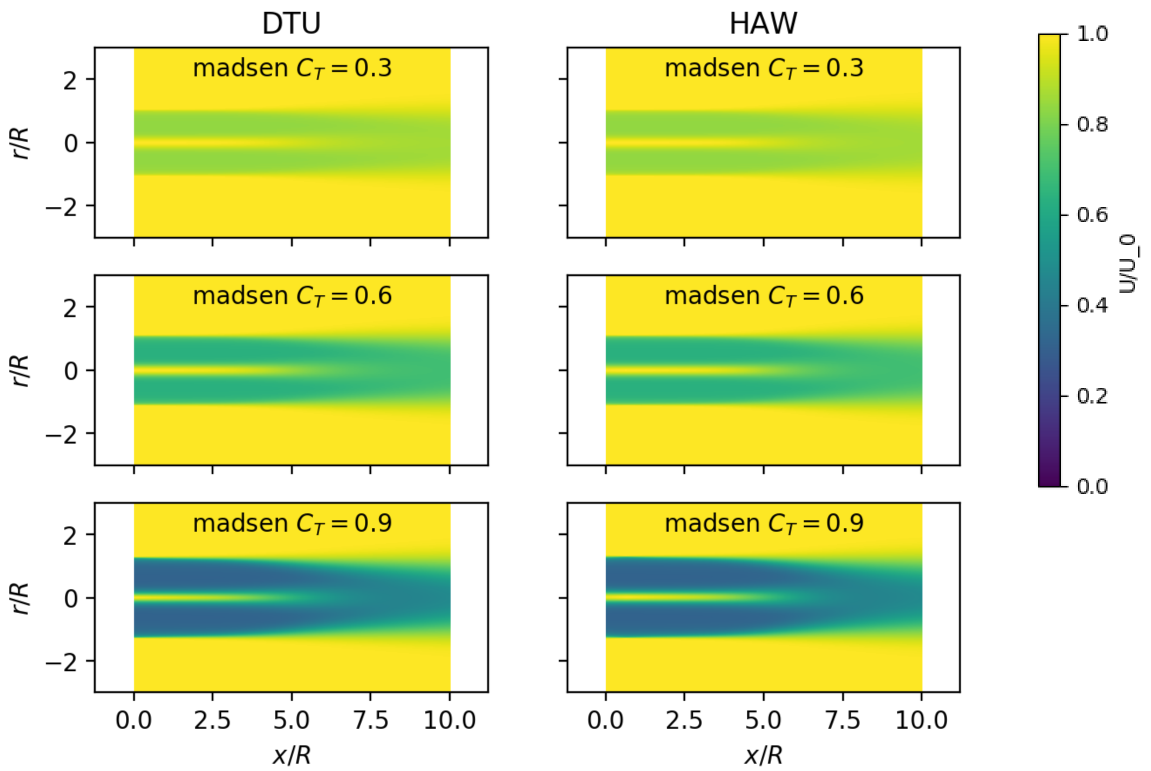
- "For lower turbulence intensities and higher distances (greater than 3D) there is a relatively large discrepancy between measurements and simulations. A similar observation was made in Larsen et al. (2013)."
  - This comment was on the model before the recalibration so it should be deleted if pointing to the "DWM-Egmond model"

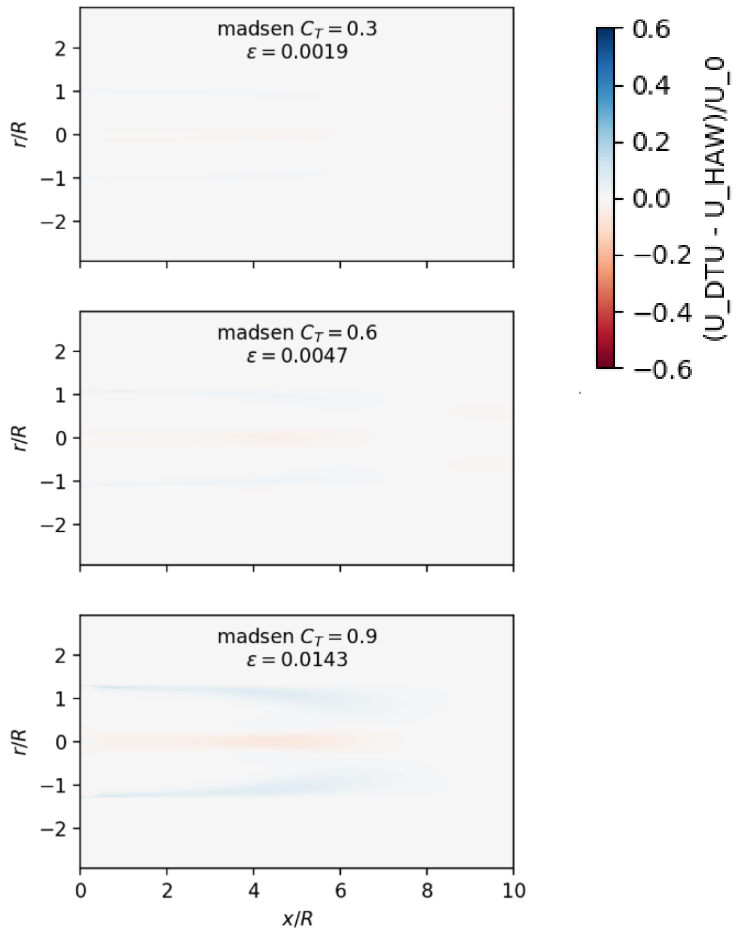
Response: It is rephrased to: *"A similar observation was made in Larsen et al. (2013) with the model version in Madsen et al. (2010). Aiming at the adjustment of the simulated degradation of the wind speed deficit in Larsen et al. (2013) for cases like the one presented here, the DWM model has been recalibrated…"*
The sentence is not deleted here, because it should be pointed out that the method of recalibration is similar to the one in Larsen et al. (2013).

Line 362

- As concerns the results in Figure 10 and Figure 11 for the DWM-Egmond model they seem not to agree with simulations with our DTU implementation of the DWM model, however with the uncertainty of just assuming a similar turbine operation but without knowing the details of the turbine
  - The authors are encouraged to share and upload more details of their simulations so that the results can be checked with an original implementation of the so-called DWM-Egmond model.
  - Further, it is proposed to show a figure with e.g. the mean velocity of the wake deficit or the mean velocity cubed (to show reduction in power of the downstream turbine) and otherwise in the same way as Figure 9. The mean velocity is a more robust characterization of the wake deficit than the minimum value velocity within the deficit. The minimum value can easily be influence by the details of the aerodynamic modelling of the turbine.

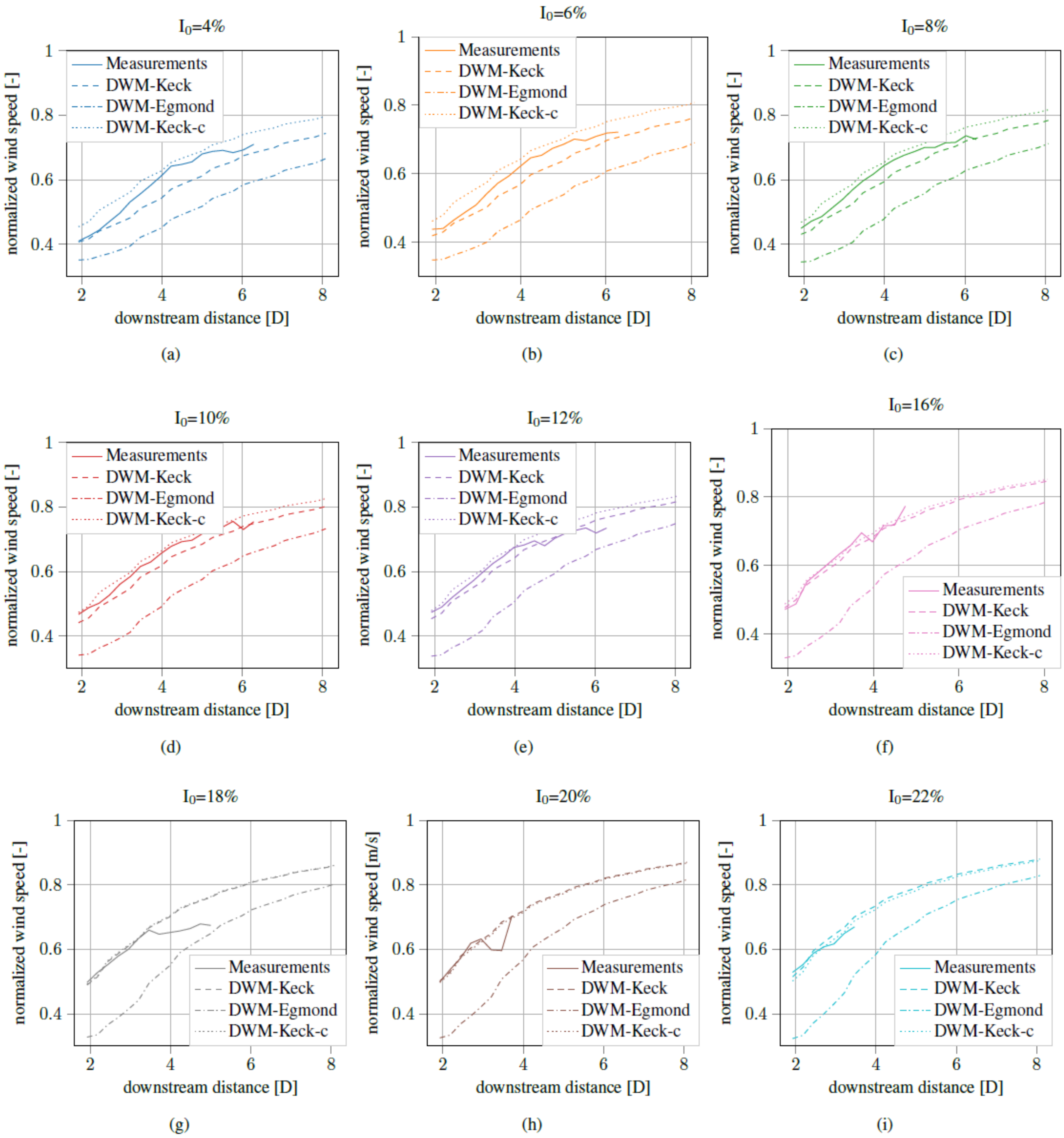
Response: A comparison between the static deficit, respectively the solution of the thin-shear layer equations with an implementation of the DTU has already been carried out. The model has been compared to the Python implementation of Jaime Yikon Liew. The two implementations match very well (see following figures). The figures show results from the so-called DWM-Egmond model of both model implementations and their difference (ε is the mean difference).



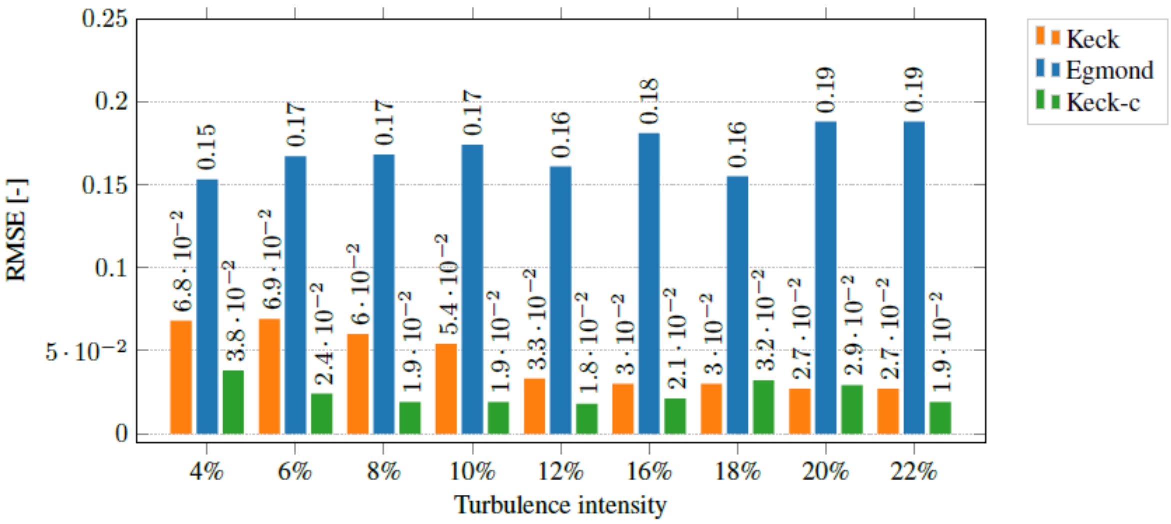


The comparison between the two implementations can be found here: https://github.com/jaimeliew1/dwm_benchmark

The normalized mean wind speed for all turbulence intensity bins are illustrated in the following:



The mean wind speed over a distance of +/- 60m from the wake center is illustrated. Furthermore, a graph from the RMSE between these curves and all model versions is illustrated.



The improvement of the mean wind speed is less clear in comparison to the normalized minimum wind speed. But nevertheless, there is an improvement in almost all turbulence intensity bins or similar good results could be achieved. In the smaller turbulence intensity bins and closer distances, the recalibrated DWM-Keck-c model agrees less well with the measurements. At closer distances the wind speed deficit gets coarse since less scan points are gathered and the influence of the turbulence at the tails is much higher. This leads to an error in the mean wake wind speed but not in the minimum wind speed, which explains these discrepancies. This is the reason why the minimum wake wind speed is illustrated in the paper and used for the recalibration of the DWM-model.

Some final conclusive remarks

- There is no discussing of the impact of the findings. Changing the wake recovery characteristics have obviously an impact on power production and loads.
  - For the Egmond aan Zee case the DWM model was as mentioned calibrated to the power reduction of the second turbine in a row relative to the first one for different spacings and turbulence intensities. Using this calibration an overall good correlation of simulated and measured loads was found.
  - Have the present recalibrated model been used for power and load simulations and compared with measurements in the present wind farm?
  - The reviewer finds that due to the above mentioned uncertainties/limitations related to the measurements of the deficits in the meandering frame of reference there will be a bias of the measured deficits being more smooth. Please comment on this view.

Response: The comparison of the recalibrated model with power productions and loads in the wind farm is currently analyzed and will be published soon.
Comments according to the bias in measuring the wind speed deficit in the meandering frame of reference were answered directly at the specific positions above. A graph with DWM model simulations with and without vertical meandering was added.