Wake Conference 2017 IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **854** (2017) 012012 doi:10.1088/1742-6596/854/1/012012

The Long distance wake behind Horns Rev I studied using large eddy simulations and a wind turbine parameterization in WRF

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Abstract.

The aim of the present paper is to obtain a better understanding of long distance wakes generated by wind farms as a first step towards a better understanding of farm to farm interaction. The Horns Rev I (HR) wind farm is considered for this purpose, where comparisons are performed between microscale Large Eddy Simulations (LES) using an Actuator Disc model (ACD), mesoscale simulations in the Weather Research and Forecasting Model (WRF) using a wind turbine parameterization, production data as well as wind measurements in the wind farm wake. The LES is manually set up according to the wind conditions obtained from the mesoscale simulation as a first step towards a meso/microscale coupling.

The LES using an ACD are performed in the EllipSys3D code. A forced boundary layer (FBL) approach is used to introduce the desired wind shear and the atmospheric turbulence field from the Mann model. The WRF uses a wind turbine parameterization based on momentum sink. To make comparisons with the LESs and the site data possible an idealized setup of WRF is used in this study.

The case studied here considers a westerly wind direction sector (at hub height) of 270 ± 2.5 degrees and a wind speed of 8 ± 0.5 m/s. For both the simulations and the site data a neutral atmosphere is considered. The simulation results for the relative production as well as the wind speed 2 km and 6 km downstream from the wind farm are compared to site data. Further comparisons between LES and WRF are also performed regarding the wake recovery and expansion.

The results are also compared to an earlier study of HR using LES as well as an earlier comparison of LES and WRF. Overall the results in this study show a better agreement between LES and WRF as well as better agreement between simulations and site data.

The procedure of using the profile from WRF as inlet to LES can be seen as a simplified coupling of the models that could be developed further to combine the methods for cases of farm to farm interaction.

1. Introduction

As the number of wind farms offshore increases there will be more occasions where offshore wind farms will be situated relatively closely to each other due to the limited number of suitable sites and the desire to use the best sites first. Since the flow behind a wind farm is disturbed the question of how this might impact other wind farms, so-called farm to farm interaction, is

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therefore becoming more central. It is also worth noting that compared to onshore wakes the long distance wakes offshore are more persistent since the lower roughness and turbulence levels mean a slower recovery of the velocity behind the wind farm. An understanding of not only the wake inside wind farms but also the impact of farm to farm interaction due to the long distance wakes behind wind farms is needed to be able to perform accurate estimations of production for offshore wind farms in wind farm clusters.

The long distance wakes behind offshore wind farms can be in the order of 10 km [1] and can be studied with different wake and mesoscale models [2][3][4]. Large Eddy Simulations (LES) have been used in many studies of the near and far wake behind turbines and the wake interaction inside wind farms [5][6][7][8]. Compared to the mentioned models LES is much more computationally demanding but as computational power increases LES gradually becomes an alternative also for farm to farm interaction studies. The author has earlier performed studies of the long distance wakes behind a row of turbines and wind farms [9].

Mesoscale models are used for atmospheric simulations and generally include more atmospheric physics. Compared to LES the resolution in the grids used by mesoscale models are lower which allows for less demanding simulations. Wind turbines can be included using a parameterization [10] but the wake flow will include fewer details compared to LES. To combine LES and mesoscale models can be of interest and allows for the advantages of both models to be used. A first alternative in combining the two is to use a mesoscale simulation as an input to an LES (1-way nesting). A second alternative is to also feed back the LES into the mesoscale domain (2-way nesting) [11].

The aim of the current study is to obtain a better understanding of wakes generated by entire wind farms in order to improve the understanding of farm to farm interactions. In the study both the mesoscale model Weather Research and Forecasting Model (WRF) and LES using an actuator disc model (ACD) are used to study the same case.

The LES are set up to have a wind shear and turbulence level similar to those used in the simulation in WRF. The results are compared between the models and site data for the Horns Rev I wind farm (HR) for both energy production and recovery of the velocity behind the wind farm. For the simulations the wake expansion and the development of the atmospheric boundary layer (ABL) are further compared.

The current study is a continuation from earlier studies of the long distance wakes behind the wind farms of Horns Rev I [12] and Lillgrund [13]. The main novelties are that a) the whole wind farm is included in the LES (compared to the previous study of HR where only two rows were included with periodic boundary conditions at the lateral boundaries creating an infinitely wide wind farm) b) the wind veer is included in the LES (compared to a wind shear only in the streamwise direction in the earlier studies) c) compared to the former Lillgrund study the WRF simulations are performed with a higher resolution and an updated parameterization as in [14].

2. Study of wakes in and behind Horns Rev I wind farm

The simulations are performed for Horns Rev I, a wind farm situated in the North Sea west of Denmark. The 80 Vestas V80 wind turbines with a hub height of 70 m, a radius (R) of 40 m and a rated power of 2 MW are laid out in 8 rows and 10 columns (turned 7 degrees (deg) from North (N)-South (S)) with an internal spacing of 14 R, see Figure 1. In the figure the placement of the two met towers at 2 km respectively 6 km east of the wind farm can also be seen and the profiles along which the simulation results will be compared are marked with lines or an x. North (N) is marked with an arrow in the figure. A flow from the north corresponds to a 0 deg inflow angle.

The studied case considers a (at hub height) westerly wind direction sector of 270 ± 2.5 degrees (deg) with flow along the rows and a wind speed (U_0) of 8 ± 0.5 m/s. For the simulations and the site data a neutral atmosphere is considered. The vertical profile of the wind velocities (w) for streamwise direction (z) and (u) for the spanwise direction (x) can be seen in Figure 2

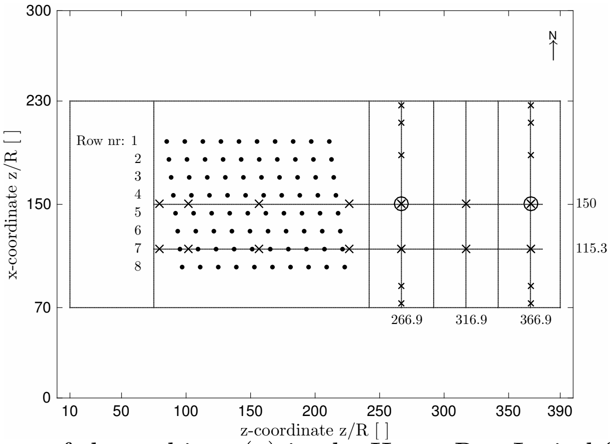

Figure 1. The placement of the turbines (•) in the Horns Rev I wind farm and the met towers (○) in the LES domain covering 300 R ∗ 400 R with an equidistant region (marked with the rectangle) of 160 R ∗ 380 R. The flow is studied along the marked lines and for vertical profiles at the x's.

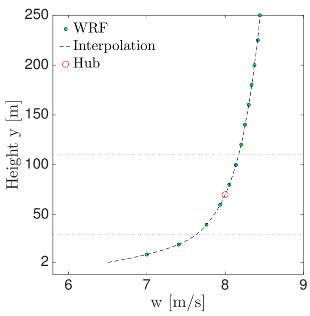

Figure 2. Wind shear with streamwise velocity (w) interpolated to fit the WRF-levels.

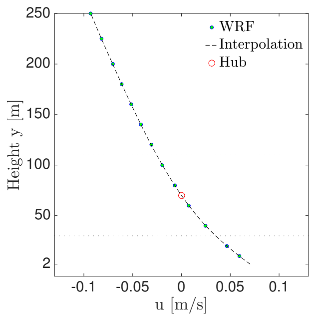

Figure 3. Wind shear with spanwise velocity (u) interpolated to fit the WRF-levels.

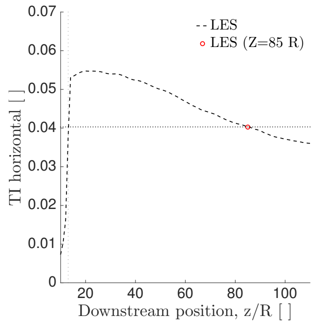

Figure 4. Downstream development of horizontal turbulence intensity (TI) at hub height in LES.

respectively in Figure 3. The vertical profile is based on the WRF simulation and is interpolated to be used in LES. From the two wind components the directional change with height can be calculated and over the rotor the wind veer in this case is 0.4 deg. At hub height the total turbulence intensity from WRF is 4.5 % and the horizontal turbulence for the LES is 4 % at the placement of the first turbine, see Figure 4. The simulation in LES using an actuator disc method uses the wind profile upstream of the wind farm from WRF as input. This is performed manually but has similarities to a 1-way nesting as information is transferred in one direction from WRF to LES (and no information is transferred back from LES to WRF).

The LES is further described in Section 3. The idealized WRF simulations using a wind farm parameterization are performed according to Section 4. Production data and met tower data are filtered to be comparable to the simulated wind direction sector and wind speed interval, see Section 5. The comparison between the simulations and the site data is presented in Section 6.

3. LES

The EllipSys3D code is used for the LES. The numerical model and the specific setup for the studied case is described below.

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3.1. Numerical model LES
Large Eddy Simulations (LES) resolve the largest and most energetic eddies and only the smallest eddies are modelled, here using the subgrid-scale model from Ta-Phouc [15]. The turbines are introduced into the simulations using an actuator disc method based on airfoil data [16]. A generator-torque controller is used to adjust each turbine's rotational speed in the variable flow in a realistic way [17]. The incoming neutral atmospheric boundary layer is mimicked by using a forced boundary layer (FBL) that uses body forces [7] to introduce the wind shear as well as a realistic atmospheric turbulence from the Mann model [18][19].

3.2. Simulation setup LES
The simulations are performed in a domain of 637 M-cells with 300 R width and 400 R length with an inner equidistant region with the non dimensionalized (with R) resolution (Δx) of 0.1 (4 m) covering 160 R $*$ 380 R, see Figure 1. The height of the equidistant region is 8 R and the total boundary layer height is 25 R (1000 m). The turbulence that is introduced at 17 R is ideally allowed to develop with the flow in the LES domain until the turbulence levels out at a level dictated by the wind shear before the first turbine is introduced. Here the first turbine is at 85 R, see Figure 4, as a compromise considering the needed computational power. The domain has fixed values for the inlet according to the used wind shear, cyclic boundary conditions for the sides, convective for the outlet and farfield for the top. The ground uses farfield that is setup as a noslip condition. A non dimensionalized (with U_0 and R) timestep (Δt) of 0.05 is used to conservatively fullfill the Courant-Friedrichs-Lewy (CFL)-condition (Equation 1) based on the non dimensionalized (with U_0) wind speed at hubheight ($U0_{norm}$):

$$\frac{U0_{norm} * \Delta t}{\Delta x} = \frac{1 * 0.05}{0.1} = 0.5 < 1 \tag{1}$$

The simulations are first run for 12000 time steps (ts) to allow the turbine to adjust to the flow and the flow to pass the domain with some margin. After that the analysed averaged values are studied for 12000 ts which corresponds to 50 min in physical time.

The wind shear used is interpolated from the coarser vertical grid levels used in WRF, see Figures 2 and 3. The used Mann turbulence is created for the roughness length (z_0) of 0.0001 m (the same as the surface roughness in WRF) and a wind speed of 8 m/s at 70 m. The Mann box covers the equidistant region with a resolution of 1.56 Δx /1.56 Δx in width/height. The length is 10 min using the Taylor frozen hypothesis and the length resolution gives a non dimensionalized time step of 0.2344.

The airfoil data representing the turbine in the ACD is based on the NREL 5 MW turbine [20] and is downscaled to correspond to the Vestas 80 regarding power and thrust coefficient [8].

The simulations are performed for three inflow directions 270 deg, 267.5 deg and 272.5 deg. For the cases $\pm$ 2.5 deg the inlet wind shear and the fluctuations in the Mann box are turned (for the Taylor frozen hypothesis the flow along 270 deg is, however, still assumed). The turbines are also yawed to face the mean wind direction in each case.

4. Mesoscale simulations
The Weather Research and Forecasting Model (WRF) is used for the mesoscale simulations. The numerical model and the specific setup for the studied case is described below.

4.1. Numerical model WRF
WRF is an atmospheric model system developed by the National Center for Atmospheric Research (NCAR) and maintained as a community model by the Mesoscale and Microscale Meteorology Laboratory (MMM) of NCAR. A detailed description of WRF can be found in [21]. WRF v3.5.0, which was used here, includes a wind farm parameterization where wind turbines are represented as an elevated momentum sink and a source of turbulent kinetic energy (TKE) [10],[22]. The source of TKE compensates for any wind turbine induced turbulence that is not

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accounted for by the sharper shear in the wake. Here a slightly modified parameterization with no source of TKE was used. Let us note that the used parametrization was orginally developed to study the impact of wind farms on the flow. For this reason the interaction between individual turbines inside the farm is expected to be less accurate.

4.2. Simulation setup WRF

WRF was setup for idealized simulations with 2 one-way nested domains over a sea surface. The parent domain was set up with dx = dy = 333 m model grid resolution and periodic boundary conditions. In the nested domain with dx = dy = 111 m boundary information was fed from the parent domain. The simulations were initialized with a uniform wind profile of w = 8.427 m/s and u = -0.462 m/s and uniform potential temperature below 1200 meters, increasing by 3 K/km above. The initial profile was chosen so that the wind speed and wind direction at hub height should match observed conditions after model spin-up. The coriolis parameter was set according to the location of the wind farm. The sea surface has a roughness length of $z_0 = 0.0001$.

5. Site data

Site data for the production and wind measurements at 2 km respectively 6 km east of the wind farm are used, see Figure 1 for the met tower positions. The data is filtered according to Hansen [23] to correspond to the studied case. The filtering includes suitable 10 min averages with correct wind direction and wind speed. The filtered data includes only periods with neutral conditions. It also excludes non suitable periods, for example when the turbines were not operational and during large changes of the weather conditions. The turbulence level according to site data is around 7 % in HR [24] for the studied case. The same site data was also used in the earlier study of HR assuming an infinitely wide wind farm [12].

6. Results

A comparison is performed between WRF, LES and available site data with an emphasis on increasing understanding of the modelling of flows behind wind farms. To highlight the level of improvements some results from the earlier study [12] are also included. For LES the mean of the results for the three directions (270 ± 2.5 deg) is presented (if nothing else is specified) and for WRF the results of 270 deg are presented (with an included spread of around ± 2 deg for the different time periods included in the simulation result). The presented data is non dimensionalized (with U_0 = 8 m/s and R = 40m). The results for the long distance wake are however also presented for the distance behind the wind farm in km.

Firstly the relative production (Section 6.1) of the turbines in the wind farm is studied. Secondly the development is studied for the normalized horizontal wind speed (U_{hor}) and the standard deviation of all velocity components (σ_{tot}) which describe the turbulence level (and divided with the local mean velocity correspond to the turbulence intensity). As illustrated in Figure 1 the downstream development of the flow is studied along the met towers and row 7 at hub height (Section 6.2). The vertical profile of the downstream development of the flow is also examined (Section 6.3). The downstream spanwise expansion of the wake is studied at hub height and for vertical profiles in Section 6.4.

6.1. Production

The relative production is the production normalized with the production of the first turbine in the row. In Figure 5 the relative production based on the mean value of the production for the turbines in row 2-7 is seen. Compared to the farm data the LES results show a lower production in the first portion and in contrast to the site data the level is relatively constant throughout the farm and ends up at the same level in the end of the rows. WRF shows a more gradual decrease of relative production with down stream distance, especially for the first part of the wind farm, and goes towards a production lower than both LES and farm data.

The sensitivity to the correct inflow angle for LES is seen in Figure 6. A 2.5 deg change from the full wake direction (270 deg) gives a higher relative production. Due to the layout the direction of the change also has an impact.

Uncertainties in the actual direction of the site data gives a wider range of directions compared to the performed simulations and could explain the behaviour of the higher relative production of the site data compared to the simulations. The turbulence level in the simulations is also lower compared to the site data which has more impact on the mixing in the first part of the wind farm. The lower relative production in WRF could indicate that the recovery of the flow between the turbine is too slow which also is discussed further in next section.

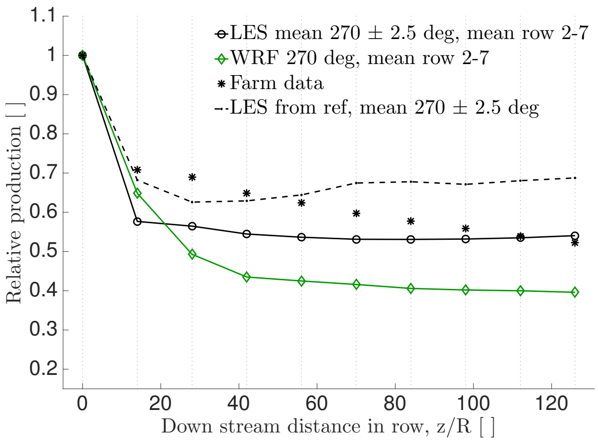

Figure 5. Mean of the relative production for the turbines in row 2-7 for LES, WRF and wind farm data. The older study [12] using LES with periodic boundary conditions is included for comparison.

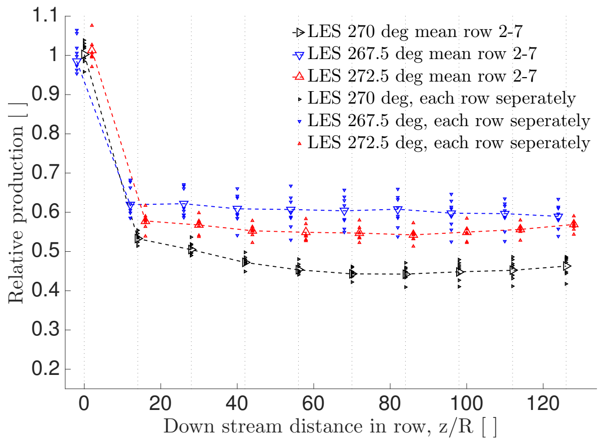

Figure 6. Dependency of inflow angle (270 ± 2.5 deg) on the relative production in LES. The relative production for each row shown separately as individual data points around each dotted line representing the average over the rows.

6.2. Flow recovery

The flow at hub height along the met towers respectively row 7 is here presented regarding horizontal velocity and turbulence level.

For the velocity in Figure 7 the general development down stream is similar in LES and WRF. As expected due to the more distinct wake in LES compared to WRF more fluctuations of the wind speed are seen for the LES along row 7 and a smaller decrease of velocity along the met tower inside the farm is seen.

The figure also shows the three different directions used in LES separately for the flow along the met towers. The velocity for the full wake direction (270 deg) in LES is relatively high at 2 km behind the wind farm possibly because the wakes of the rows have not expanded fully at the met tower position. Deviations from the full wake direction (270 deg) gives a decrease in the velocity along the met towers downstream in and behind the wind farm. The values for ± 2.5 deg have a trend closer to the met tower data.

In Table 1 the velocities at 2 km and 6 km behind the wind farm are seen. The WRF results show a faster recovery of the velocity compared to LES at 6 km. For the LES the results show an improvement when compared to the earlier study which had more than double as large overestimation of the velocities compare the new results.

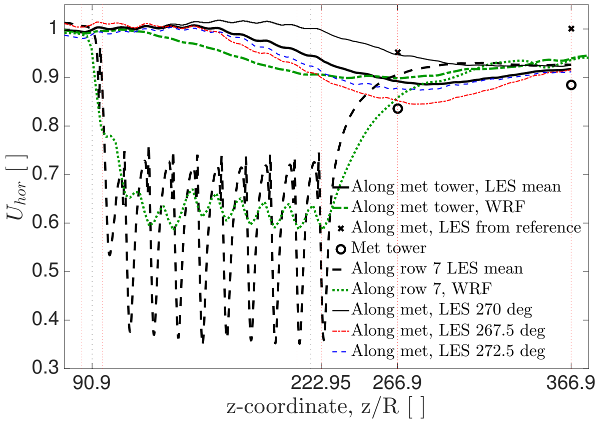

Figure 7. Normalized horizontal velocity (U_{hor}) in LES and WRF at hub height along the met towers and row 7. Site data and the older study [12] using LES with periodic boundary conditions are included for comparison.

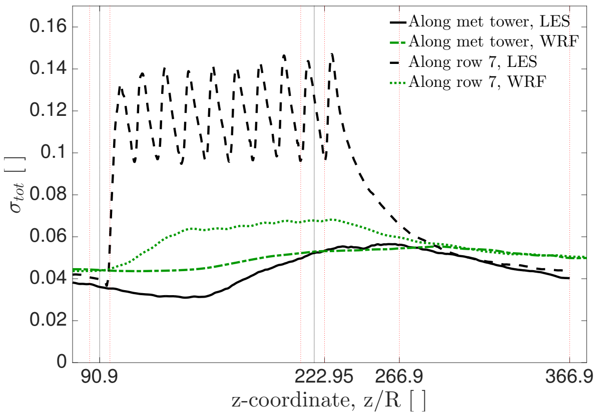

Figure 8. Total standard deviation of the velocity (σ_{tot}) in LES and WRF at hub height along the met towers and row 7.

Table 1. Normalized horizontal velocity (U_{hor}) at 2 km respectively 6 km behind the wind farm for LES, WRF, site data and results from the older study [12] using LES with periodic boundary conditions. In brackets the difference in percentage compared to the site data is shown.

Distance	**LES**	**WRF**	**Site data**	**LES ref [12]**
2 km	0.89 (+5.9%)	0.9 (+7.1%)	**0.84**	0.95 (+13.1%)
6 km	0.92 (+3.7%)	0.94 (+5.6%)	**0.89**	1.0 (+12.6%)

Along row 7 U_{hor} in LES the velocity is higher at 2 km behind the wind farm compared to the velocity along the met towers. This could be due to increased vertical mixing due to the higher turbulence level along this row which can be seen in Figure 8. The less distinct wake in WRF (due to the used resolution) can also be seen in the slightly higher levels of turbulence along the met towers. Along row 7 the turbulence level is lower in WRF compared to LES due to the used parameterization that does not add any extra turbine induced turbulence. The slightly slower recovery of the flow between the turbines can be a consequence of this.

6.3. Boundary layer

The development of the atmospheric boundary layer over and after the wind farm is studied along the met towers and row 7 for horizontal velocity and turbulence level. Profiles of horizontal velocity (Figure 9) and turbulence level (Figure 10) are studied for a vertical profile upstream from the farm, for three profiles in the wind farm as well as profiles at 2, 4 and 6 km behind it.

Looking first along the met towers it can be seen for the velocity before the wind farm that LES has higher velocities closest to the ground when compared to the inlet but at higher heights the profile is unchanged. Inside the wind farm a faster decrease can be seen using WRF compared to LES. However at heights above the farm the LES shows a larger reduction of the wind speed. WRF has higher turbulence level compared to LES with the exception of the last portion of the farm and WRF's vertical extension of increased turbulence is higher. After the wind farm in LES the velocity continues to decrease until 2 km before a recovery of the flow can be seen at the turbine height, however the impact above the turbine height in the first part of

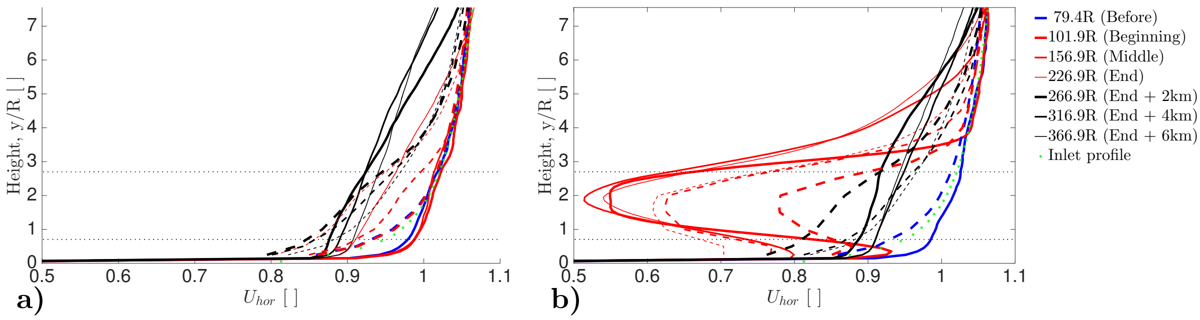

Figure 9. Normalized horizontal velocity (U_{hor}) in LES (solid lines) respectively WRF (dashed lines) for different downstream distances in the wind farm for: **a)** along the met towers **b)** along row 7.

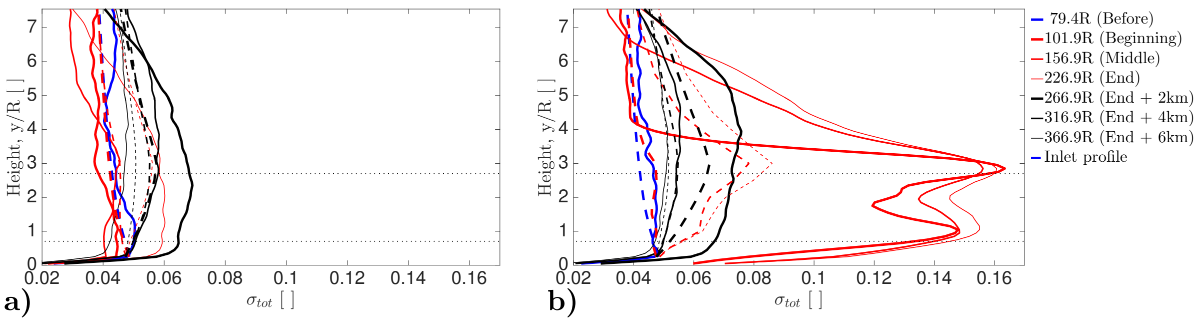

Figure 10. Total standard deviation of the velocity (σ_{tot}) in LES (solid lines) respectively WRF (dashed lines) for different downstream distances in the wind farm for: **a)** along the met towers **b)** along row 7.

the farm wake still increases. For WRF the velocity recovers slightly faster at the turbine height while at higher height no development is seen.

Along row 7 the more distinct wake in LES gives a larger reduction of the velocity inside the farm compared to WRF. At heights above the farm a larger reduction can be seen in LES as also was the case along the met towers. The level of turbulence is higher in LES inside the farm and in the first part of the wind farm wake while further down stream the level is similar in WRF. After the wind farm a recovery of the velocity in LES can be seen between 2 km and 4 km while the values at 6 km behind the wind farm are about the same level as at 4 km. A similar trend is seen for the turbulence but here the level decreases slightly after 4 km. For the turbulence it can also be seen that the level at higher heights decreases more slowly. For WRF the velocity reduction is higher at 2 km compared to LES. A faster recovery can be seen until 4 km after which a slower recovery can still be seen.

The vertical velocity profile has overall a sharper shear over the turbine height in the farm wake in the WRF results which could explain the slightly faster recovery of the velocity behind the wind farm.

6.4. Wake expansion

The expansion of the wake is studied for spanwise profiles at hub heigt for different downstream distances. The horizontal velocity is presented in Figure 11 and the turbulence level in Figure 12.

Looking 1 km behind the wind farm in LES the rows and the different distances from the last turbine in each row (due to the tilt of the layout) can be clearly seen. At 2 km the increased turbulence along the rows is still seen. For the velocities at 2km the reduction between the rows

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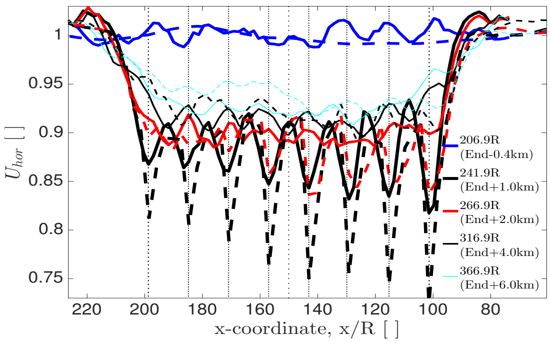

Figure 11. Normalized horizontal velocity (U_{hor}) in LES (solid lines) and WRF (dashed lines) along spanwise profiles at hub height for different downstream distances behind the wind farm.

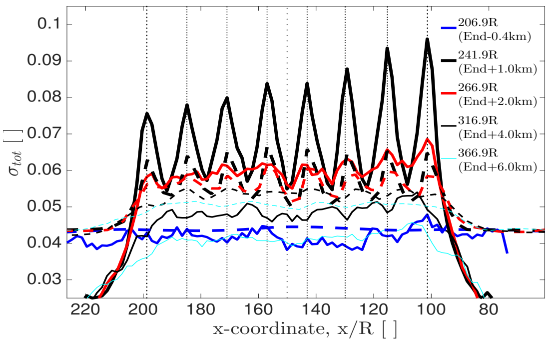

Figure 12. Total standard deviation of the velocity (σ_{tot}) in LES (solid lines) and WRF (dashed lines) along spanwise profiles at hub height for different downstream distances behind the wind farm.

is actually higher compared to along the rows, which could be due to the lower turbulence level. For 6 km the impact of the rows is hard to see. The expansion of the wake is about the same at 1 km and 2 km after which it increases downstream for 4 km and 6 km. Looking at the flow outside the farm wake an increase of the velocity can be seen in the first part of the farm wake. The turbulent fluctuations have at 6 km reached the same level as in front of the wind farm, however outside the farm the turbulence level is lower. The WRF results show that in comparison to LES along the rows of turbines there is a slower recovery for the first part of the farm wake while further down a slightly faster recovery can be seen in WRF compared to LES. The turbulence level starts at a lower level and decreases more slowly in the farm wake in WRF.

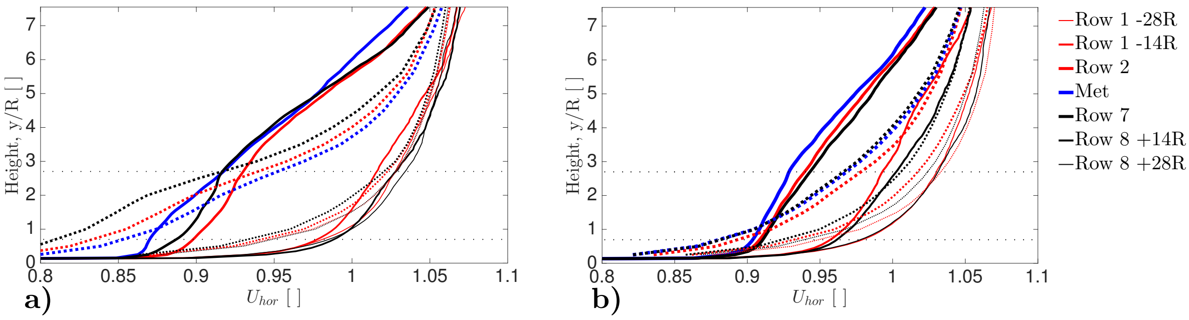

Figure 13. Normalized horizontal velocity (U_{hor}) in LES (solid lines) respectively WRF (dashed lines) for different spanwise positions in the wind farm for: **a)** 2 km behind the wind farm **b)** 6 km behind the wind farm.

The vertical profiles along a spanwise line at 2 km respectively 6 km behind the wind farm give further input to the wake expansion. In Figure 13 the horizontal velocity and in Figure 14 the vertical profiles of the turbulence level are seen. For LES 2 km behind the wind farm the wind speed is higher and the turbulence is lower along row 2 compared to row 7 as expected due to the distance to the last turbine. The velocity outside row 1 is slightly lower compared to outside row 8. The wake expansion seen at 6 km due to the differences between the profiles at 14 R respectively 28 R outside the outer rows should also be noted. The profile central along the met towers show at both 2 and 6 km a lower velocity compared to those along the rows also for higher heights above the wind farm. In comparison to LES the WRF results show at 2 km a higher velocity along the met towers in comparison to along the rows. It should be noted that

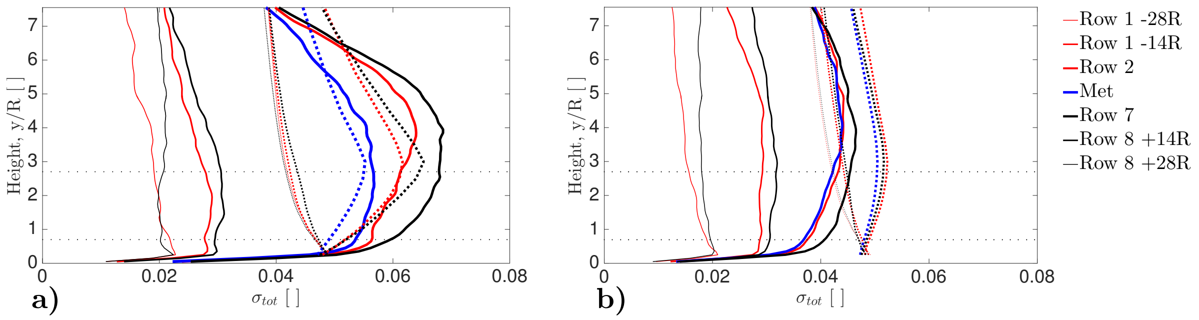

Figure 14. Total standard deviation of the velocity (σ_{tot}) in LES (solid lines)respectively WRF (dashed lines) for different spanwise positions in the wind farm for: **a)** 2 km behind the wind farm **b)** 6 km behind the wind farm.

there are also larger differences between the +14R and +28 R in LES compared to WRF.

7. Conclusion

To get an increased understanding of the modelling of long distance wakes behind whole wind farms the Horns Rev I (HR) wind farm has been considered for comparisons between microscale Large Eddy Simulations (LES) using an Actuator Disc model (ACD), mesoscale simulations (WRF) using a wind turbine parameterization, site data for production as well as wind measurements in the farm wake. The LES is manually set up according to the wind conditions obtained from the mesoscale simulation as a first step towards a meso/microscale coupling.

The relative production in LES is lower for the first portion of the farm compared to the wind farm data but by the end of the wind farm the level is about the same. The values for WRF show, like the site data, a more gradual decrease with down stream distance but the level of relative production is still underestimated. Inside the wind farm the horizontal velocity is in relatively close agreement between LES and WRF, but the more smoothed wake due to the lower resolution in WRF can still be noticed and WRF has a slightly lower velocity. The turbulence level is lower inside the wind farm in WRF with the used parameterization that adds no extra turbine induced turbulence. The lower turbulence could explain the slower recovery of velocity between the turbines and the resulting decreasing relative production. It should be noted that the turbulence level is distributed to greater heights in WRF and in LES a reduction in wind speed can be seen at greater heights. Behind the wind farm LES shows relatively good agreement with the met tower data for velocity, especially at 6 km. The long distance wake in WRF also shows relatively good agreement but a slightly faster recovery can be seen which could be related to a higher shear with resulting downward momentum transfer from higher heights.

The current study can be seen as a continuation from earlier studies of the long distance wakes behind wind farms of Horns Rev I [12] respectively Lillgrund [13].

In comparison to the earlier study of Horns Rev which assumed an infinitely wide farm [12] the down stream development of the relative production is closer to the site data. The velocity level in the farm wake is also closer to met data in the current study. The lower velocities in this study could partly be explained by the use of a less sharp shear which results in less turbulence downstream in the domain. The larger distance between the turbulence plane and the first turbine (letting the turbulence adjust to the LES) and lower blockage due to a larger domain cross section could also be part of the improvements. Given the other differences in the setup it is not possible to determine the relative impact of the increased realism in the simulation given by including the wind veer and the use of the real layout of the wind farm.

In comparison to the earlier study comparing LES and WRF [13] both the turbulence level and the velocity is here much closer between LES and WRF. The earlier study with WRF showed a much lower reduction of the velocity inside the wind farm and much higher added turbulence. The improved setup of WRF is the result of the increased resolution and the updated wind turbine parameterization which add less turbine induced turbulence that in the earlier study was found to be to large [14]. The turbulence is however lower than the LES in this study indicating that part of the turbine induced turbulence still needs to be added in the parameterization.

It can also be noted that there are a number of uncertainties in comparison between the site data and the simulations. Direction uncertainty is one of the difficulties in comparing measurements with simulations [25]. A change in the direction impacts not only the direction of the long distance wake but also the level and results of the relative production due to the resulting changes in wake interaction [24][26]. Another parameter of potential uncertainty is that the site data also might include data close to neutral on the unstable or stable side and this stability has an impact on the atmospheric boundary layer and the downstream development of the wake [27].

Overall an improvement could be seen comparing the LES results with the earlier LES results for the same case. The impact of the wind veer that was included in the LES to get as close as possible to the profile used in WRF (compared to a wind shear only in the streamwise direction in the earlier studies) and the change from an infinitely wide wind farm to the full layout could not be quantified. It would be of interest in a future study to more systematically quantify the relative importance of these parameters. Overall the results show a better agreement between LES and WRF compared to the earlier study. The results are a step towards bettering the study of long distance wakes by combining LES and WRF.

Acknowledgments
The simulations (LES) were performed on resources provided by the Swedish National Infrastructure for Computing (SNIC) at the National Supercomputer Centre in Sweden (NSC).

References

[1] Eriksson O and Ivanell S 2012 *A survey of available data and studies of farm-farm interaction.* (EAWE PhD Seminar on Wind Energy in Europe, 2012)

[2] Frandsen S, Barthelmie R, Rathmann O, Jørgensen H, Badger J, Hansen K, Ott S, Rethore P E, Larsen S and Jensen L 2007 *Summary report: The shadow effect of large wind farms: measurements,data analysis and modelling.* (Risø-R-1615(EN), Denmark)

[3] Brand A 2009 *Wind Power Plant North Sea – Wind farm interaction, The effect of wind farming on mesoscale flow.* (ECN, the Neatherlands)

[4] Hansen K S, Réthoré P E, Palma J, Hevia B G, Prospathopoulos J, Peña A, Ott S, Schepers G, Palomares A, van der Laan M P and Volker P 2015 *Simulation of wake effects between two wind farms* (Journal of Physics: Conference Series 625 012008)

[5] Ivanell S 2009 *Numerical Computations of Wind Turbine Wakes.* (PhD thesis, ISBN 978-91-7415-216, KTH Engineering Sciences, Sweden)

[6] Wu Y T and Porté-Agel F 2012 *Atmospheric turbulence effects on wind-turbine wakes: An LES study.* (Energies 2012, 5, 5340-5362)

[7] Troldborg N, Sørensen J N, Mikkelsen R and Sørensen N N 2014 *A simple atmospheric boundary layer model applied to large eddy simulations of wind turbine wakes.* (Wind Energy 2014; 17: 657-669.)

[8] Nilsson K, Ivanell S, Hansen K S, Mikkelsen R, Breton S P and Henningson D 2015 *Large-eddy simulations of the Lillgrund wind farm.* (Wind Energy 18, 449–467)

[9] Eriksson O 2015 *Numerical computations of wakes behind wind farms.* (Department of Earth Science Licentiate Thesis 2015, Uppsala University)

[10] Fitch A C, Olson J B, Lundquist J K, Dudhia J, Gupta A K, Michalakes J and Barstad I 2012 *Local and Mesoscale Impacts of Wind Farms as Parameterized in a Mesoscale NWP Model.* (Monthly Weather Review, Volume 140, Issue 9 .)

IOP Conf. Series: Journal of Physics: Conf. Series **854** (2017) 012012 doi:10.1088/1742-6596/854/1/012012

[11] Lundquist J K, Mirocha J D and Kosovic B 2010 *Nesting large-eddy simulations within mesoscale simulations in WRF for wind energy applications.* (Proceedings of the Fifth International Symposium on Computational Wind Engineering, Chapel Hill, NC)
[12] Eriksson O, Mikkelsen R, Nilsson K and Ivanell S 2012 *Analysis of long distance wakes of Horns rev 1 using actuator disc approach.* (J. Phys.: Conf. Ser. 555 012032)
[13] Eriksson O, Lindvall J, Breton S P and Ivanell S 2015 *Wake downstream of the Lillgrund wind farm - A Comparison between LES using the actuator disc method and a Wind farm Parametrization in WRF.* (J. Phys.: Conf. Ser. 625 012028)
[14] Baltscheffsky M, Söderberg S, Bergström H and Svensson N 2013 *Using a mesoscale atmospheric model to study wind turbine wakes and farm-farm interaction.* (EAWE Offshore 2013)
[15] TaPhuoc L 1994 *Modéles de sous maille appliqués aux écoulmements instationnaires décollés.* (Tech. rep. LIMSI 93074 LIMSI France.)
[16] Mikkelsen R 2003 *Actuator Disc Methods Applied to Wind Turbines.* (DTU, Denmark)
[17] Breton S P, Nilsson K, Ivanell S, Olivares-Espinosa H, Masson C and Dufresne L 2012 *Study of the effect of the presence of downstream turbines on upstream ones and use of a controller in CFD wind turbine simulation models.* (J. Phys.: Conf. Ser. 555 012014)
[18] Mann J 1998 *Wind field simulation.* (Risø, Denmark)
[19] Jakob M, Ott S, Jørgensen B H and Frank H P 2013 *WAsP Engineering 2000.* (Risø–R–1356(EN))
[20] Jonkman J, Butterfield S, Musial W and Scott G 2009 *Wind Turbine for Offshore System Development.* (NREL, the United states of America)
[21] Skamarock W C, Klemp J B, Dudhia J, Gill D O, Barker D M, Duda M G, Huang X, W W and Powers J G 2008 *A Description of the Advanced Research WRF Version 3.* (Technical Note NCAR/TN-475+STR)
[22] Fitch A C, Olson J B, Lundquist J K, Dudhia J, Gupta A K, Michalakes J, Barstad I and Archer C L 2013 *Corrigendum.* (Monthly Weather Review, 141, 1395–1395.)
[23] Hansen K S 2011 *Guideline to wind farm wake analysis, Guideline to wind farm wake analysis.* (Department of Mechanical Engineering, DTU, Denmark.)
[24] Hansen K S, Barthelmie R, Cabezon D and Politis E 2008 *Wp8: Flow Deliverable D8.1 Data Wake measurements used in the model evaluation .* (DTU.)
[25] Gaumond M, Réthoré P E, Ott S, Peña A, Bechmann A and Hansen K S 2013 *Evaluation of the wind direction uncertainty and its impact on wake modeling at the Horns Rev offshore wind farm.* (Wind Energy doi: 10.1002/we.1625)
[26] Ivanell S, Mikkelsen R, Sorensen J N, Hansen K S and Henningson D 2009 *The impact of wind direction in atmospheric BL on interacting wakes at Horns Rev wind farm.* (PhD thesis, ISBN 978-91-7415-216, KTH Engineering Sciences, Sweden)
[27] Hansen K S, Barthelmie R J, Jensen L E and Sommer A 2012 *The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev wind farm.* (Wind Energ., 15: 183–196.)