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Published in:
Proceedings of the 2013 International Conference on aerodynamics of Offshore Wind Energy Systems and wakes (ICOWES2013)

Publication date:
2013

Wake modelling combining mesoscale and microscale models

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ABSTRACT

In this paper the basis for introducing thrust information from microscale wake models into mesocale model wake parameterizations will be described. A classification system for the different types of mesoscale wake parameterizations is suggested and outlined.
Four different mesoscale wake parameterizations are demonstrated in the Weather Research and Forecasting mesoscale model (WRF) in an idealized atmospheric flow. The model framework is the Horns Rev I wind farm experiencing an 7.97 m/s wind from 269.4^o. Three of the four parameterizations use thrust output from the CRESflow-NS microscale model.
The characteristics of the mesoscale wake that developed from the four parameterizations are examined. In addition the mesoscale model wakes are compared to measurement data from Horns Rev I. Overall it is seen as an advantage to incorporate microscale model data in mesocale model wake parameterizations.

INTRODUCTION

Presently there are two main types of turbine wake model. There are models which resolve individual wakes from a number of individual turbines, such as the wake model Fuga [1] and the CRESflow-NS model [2]. These models operate at rather fine resolution, on the order of metres, and thus are called microscale models. There are also models which model the collective impact of multiple wakes from several wind turbines. These are used in mesoscale models, and thus are called mesocale wake models, for example [3], and have resolution on the order of thousands of metres. Mesoscale models are used to calculate atmospheric flow and meteorological processes, they are routinely used in national and commerical weather centres for weather forecasting, and for wind resource assessment. Initially the two modelling approaches had little cross-over. In this paper however the cross-cover of information provided by the microscale to the mesoscale models is developed, demonstrated and evaluated.

The main objective of wake modelling in this paper is to capture correctly both the interaction of wakes on neighbouring downwind turbines, and the total wake effect of a wind farm, including the wake at long distances from the wind farm (the so-called mesoscale far wake).
For such a range of scales microscale and mesoscale models must be used together. The mesoscale model cannot explicitly model the individual turbines wakes, yet the microscale model alone cannot model influences of mesoscale circulations (at scales of several kilometres), such as coastal winds, convective systems, and orographic forced flow which may have a strong influence on the wake behaviour. The basic idea is that information from microscale wake models is passed in some form to the mesoscale models. Several strategies for how this can be done are set out in this paper.
The Weather and Forecast Research [4], WRF, a very widely used community mesoscale model, already has an implementation of a parameterization of wind turbine wakes [3]. This model applies a thrust, via the prognostic velocity tendency equation. The thrust is vertically distributed across model vertical levels proportional to the turbine rotor swept area over the model levels. In addition, turbines are parameterized as a turbulent kinetic energy source. The presence of wind turbines is expressed as a turbine number density per grid cell and rated power is prescribed. Exact turbine position is not needed and there is no interaction of one turbine wake on another turbine, within a grid cell, i.e. all turbines experience the same hub height wind speed. This parameterization will be denoted by WRF-WF.
A new wind turbine wake parameterization, called WRF-EWP [5], imposes a wind turbine wake velocity deficit which is vertically distributed according to a diffusion based model for wake expansion. The presence of wind turbines is determined by a turbine number per grid cell and power and thrust curves (i.e. power and thrust as funtion of hub-height wind speed) are employed. As in WRF-WF, exact turbine position is not needed and there is no interaction between turbines insider the same grid cell.
On the microscale side, for turbine wake modelling there are models such as CRESflow-NS [6][2], the amended GCL model [7], and FUGA [1]. These models work on actual wind turbine positions and account for wake impacts on downwind turbines. On the other hand, a spatially homogeneous and steady large scale wind forcing is assumed, i.e. the undistrubed flow surrounding the wind farm is uniform and constant.
By combining microscale wake models and mesocale models, the strengths of each can be complementing and the weaknesses of each mitigrating. In the next section, methods for combining microscale wake and mesoscale models will be described. This is followed by a section giving some results. The penultimate section discusses the results, future work and implications. The final section gives short conclusions.

METHOD

In this section four mesoscale model wake parameterizations will be compared. Three of the parameterizations use results from the microscale model CRESflow-NS [6][2]. The basis for including the microscale model results in the mesoscale parameterization is universal and thus can be used with any other microscale model.

The model simulations' set-up is designed to provide a simple way of comparing the behaviour of the different parameterizations. The WRF (v3.4) mesoscale simulations for all parameterizations are run using an idealized model set-up with wind speed of 7.97 m/s and direction 269.4^o at hub height (70 m above surface level). The details of this idealized WRF set-up can be found in [5]. The model horizontal grid spacing is 2240 m. The domain covers 180 x 65 km in the horizontal, from surface to 10 km in the vertical, using 40 model levels in the vertical. Near the surface the vertical spacing between levels is of order 10s of meters. The wind farm set-up that generates the wakes is that of Horns Rev I, off the west coast of Denmark. The wind farm contains 80 Vestas V80 wind turbines each with a rated capacity of 2 MW. The farm configuration is a slightly rhomboidal array with 10 rows from west to east and 8 rows from south to north. The turbine spacing is 560 m.

In general it is possible to classify the wake parameterization in two types according to where the thrust information, creating the wakes, comes from. For type I, the turbine thrusts come from the mesocale parameterization itself, i.e. from turbine thrust curves. For type II, the turbine thrusts come from a microscale model, precalculated and passed to the mesoscale parameterization in some way.

Within type II there are two ways the turbine thrusts can be expressed. For type IIA the thrust is given as a single turbine thrust value with no information about its distribution in space. For type IIB, the whole flow field is available and via momentum theory the effective distribution of thrust for a given volume can be obtained. Type IIB has some special issues which will be discussed in a later part of the paper.

Within Type IIA and IIB there are different ways to aggregate the turbine thrusts. It can be done either by summing up the thrusts on the basis of the mesoscale grid cells, type IIA/Bi, or by summing up thrusts on the basis of the whole wind farm, type IIA/Bii. The type IIA/Bii was used in Prospathopoulos and Chaviaropoulos [2].

Next, it is possible to consider how the sub-mesoscale-grid scale vertical wake expansion is handled. The horizontal resolution of the mesoscale model is 2240 m in this study. The wake will develop within this distance, however, there is no means within the mesoscale model, that this can be modelled, due to lack of resolution. Therefore, this sub-grid scale process needs to be parameterized or addressed in some way. In this paper, only two methods are examined. The first uses a diffusion based vertical wake expansion. It is written up in detail in [5]. The second method actually neglects sub-mesoscale-grid vertical expansion. In this case the turbine thrusts are distributed across mesoscale model levels according to the swept area of the turbine rotor on each model level, as in [2].

Table 1 describes the four wake parameterization compared in this paper. The first WRF-EWP has been described in full in [5]. It serves as a reference parameterization here. The other parameterizations feature the inclusion of the microscale model CRESflow-NS results. For WRF-CRES-EWP the turbine thrusts are aggregated on the basis of the mesoscale grid. It features the sub-mesoscale-grid vertical wake expansion used within WRF-EWP. For WRF-CRES-ROTOR the aggregation basis is the same as WRF-CRES-EWP, but no sub-mesoscale-grid wake expansion is included. For WRF-CRES-ROTOR-FA, there is no sub-mesoscale-grid wake expansion and the aggregation basis is the whole wind farm (along the wind direction axis).

In practice, all the parameterizations, except WRF-CRES-ROTOR-FA, impose a thrust on 6

Parameterization	thrust calculation	vertical thrust distribution	aggregation
WRF-EWP	turbine thrust curve	diffusive wake expansion	meso grid aggr.
WRF-CRES-EWP	CRES	diffusive wake expansion	meso grid aggr.
WRF-CRES-ROTOR	CRES	proportional to rotor swept area per level	meso grid aggr.
WRF-CRES-ROTOR-FA	CRES	proportional to rotor swept area per level	wind farm aggr.

Table 1: Table summarizing the different wake parameters tested in this paper.

mesoscale grid points (3 along wind direction x 2 normal to wind direction), covering the horizontal extent of the farm. Whereas for the WRF-CRES-ROTOR-FA parameterization thrust is imposed on 2 grid points (1 along wind direction x 2 normal to wind direction).

Figure 1a provides a schematic view of the how the parameterizations are constructed. The rectangular boxes represent a vertical slice of a mesoscale grid cell containing three wind turbines. The vertical extent of the rectangular box contains a number of vertical model levels. The microscale model explicitly models the wake from each turbine and the interaction of wakes on downstream turbines. Thus the turbine thrusts will not necessarily be the same. This is a departure from the wake parameterizations of type I, where the turbine thrusts within a single mesoscale grid cell will be the same.

Next, Fig. 1 shows that for the mesoscale parameterization each turbine is treated separately, the turbine is placed in the centre of the grid cell, and the thrust distribution across vertical model levels is calculated. The grid point total thrust is the sum of the individual vertically distributed thrusts.

Figures 1b and 1c shows the difference in the vertical distribution of the thrust using the rotor distribution and the diffusion based vertical wake expansion. Note that for the wake expansion, the wake length is always half the grid point spacing. In the wake expansion case, it can be seen that the thrust also determines the degree of vertical wake expansion. This is because the scale parameter for the vertical wake expansion is determined by a sub-grid scale wind velocity, as well as the horizontal grid size and the rotor diameter.

In Fig. 2 plan view of the same turbines as in Fig. 1 is shown. The square box represents a mesoscale grid cell. The microscale model explicitly models the horizontal expansion of the wake from the same three turbines. However, the evolution of the horizontal characteristics of the wake cannot be retained in the mesoscale model. A single value of thrust for each model level for each grid point must be reached in the parameterization.

RESULTS

In Figure 3 the wake characteristics in the horizontal and vertical can be seen for the different parameterizations. The two parameterizations using the diffusive vertical wake expansion, WRF-EWP and WRF-CRES-EWP (Figs. 3a and 3b) are rather similar. The minimum wind speed obtained is approximately 6.8 m/s in the downwind portion of the wind farm. The horizontal extent of the wake is slightly longer for WRF-EWP. The vertical profile of velocity deficit is also similar between WRF-EWP and WRF-CRES-EWP, with the 0.8 m/s deficit reaching

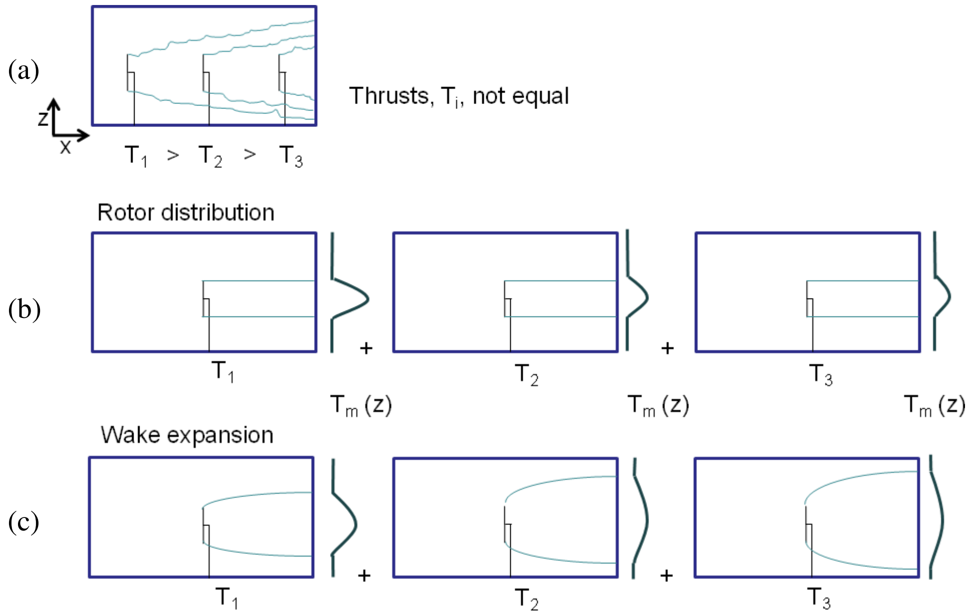

Figure 1: Schematic diagrams showing (a) the vertical expansion wake from three wind turbines of the same type calculated by a microscale model where the wind is blowing from the west (left) to east (right). Thrusts are calculated, and due to wakes effects on the downwind wind turbines, the thrust decreases as one moves eastwards. Schematic diagrams in (b) and (c) show how the microscale model calculated thrust can be used inside a mesoscale model. In (b) the thrust is distributed proportional to the swept area of the rotor on the mesoscale model vertical level. In (c) the thrust is distributed according to a vertical wake expansion contained in the wake parameterization scheme. In both cases there is no interaction between the turbines. It is as if the turbines were each in their own seperate mesoscale grid cell. The total thrust is the addition of the three separate vertical distributions of thrust.

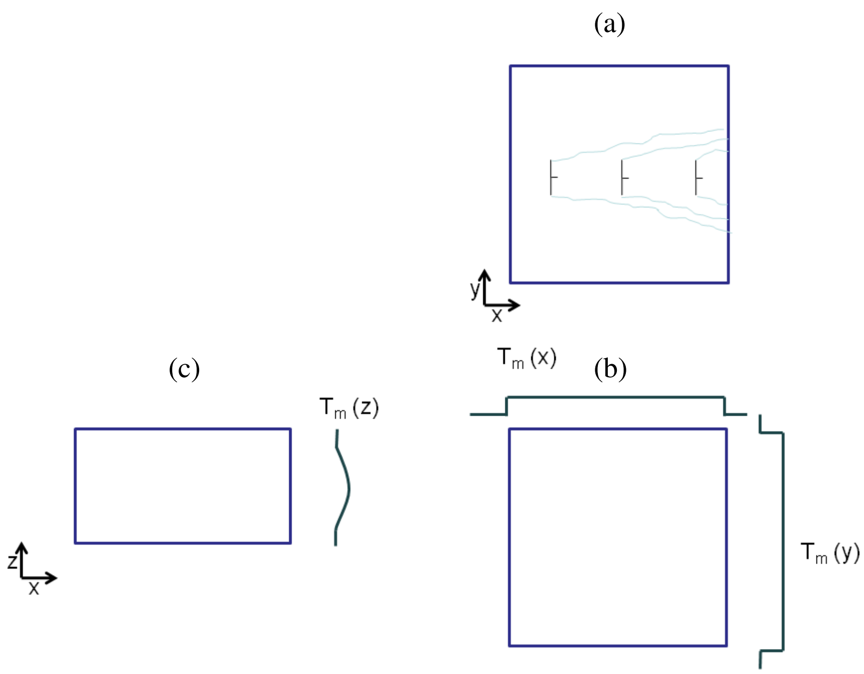

Figure 2: Schematic diagram showing (a) the horizontal expansion of wakes from the same 3 wind turbines shown in Fig. 1, calculated by a microscale model where the wind is blowing from the west (left) to east (right). The schematic diagrams in (b) and (c) illustrate that within the mesoscale grid cell the vertical distribution can be resolved (b), however the horizontal distibution cannot (c). Note: For mesoscale models, typical horizontal grid spacing is 1000s of metres, and vertical level spacing is 10s of metres near the surface.

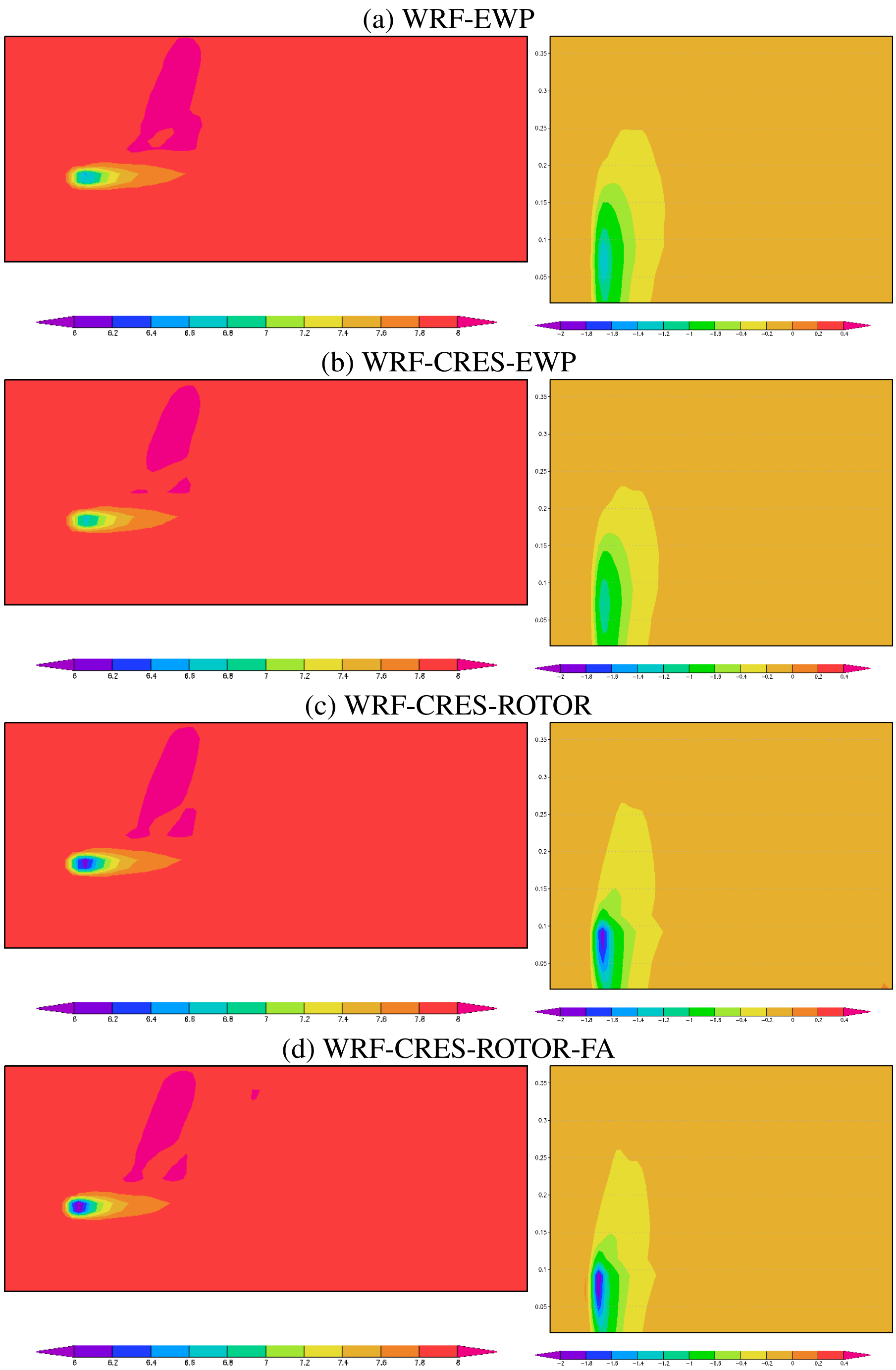

Figure 3: Plots giving maps of wake (left) and vertical sections of wake velocity deficit (right) for simulations having an inflow westerly surface wind of 8 m/s using different wake parameterizations, (a) WRF-EWP, (b) WRF-CRES-EWP, (c) WRF-CRES-ROTOR (d) WRF-CRES-ROTOR-FA. The wake maps (left) show the westerly component of wind speed at 70 m above surface level. The x-axis has 180 km extent and the y-axis has 65 km extent. The vertical sections of wake velocity deficit (right) are a slice through the wind farm. The x-axis extent is 180 km, the vertical extent is from 0 – 350 m above surface level.

approximately 150 m above surface level. However the WRF-EWP wake has a slightly large vertical extent.
For the two parameterizations using the vertical thrust distribution proportional to rotor swept area per level (i.e. no vertical wake expansion), WRF-CRES-ROTOR and WRF-CRES-ROTOR-FA, the minimum wind speed obtained is approximately 6.2 m/s and 6.0 m/s respectively. However the horizontal wake extent is shorter than for the diffusive vertical expansion parameterization. The shortest wake is for the WRF-CRES-ROTOR-FA parameterization. The vertical profile of velocity deficits are markedly different compared to WRF-EWP and WRF-CRES-EWP. The deficit exceeds 1.8 m/s in both cases, a little higher in the WRF-CRES-ROTOR-FA parameterization. However, the 0.8 m/s deficit reaches only 120 m above surface level. Consistent with the neglect of a sub-grid scale vertical wake expansion, it can be seen the deficit is more concentrated in the vertical in the WRF-CRES-ROTOR and WRF-CRES-ROTOR-FA parameterizations.
The difference between the mesoscale grid aggregation and wind farm aggregations parameterizations can be assessed by comparison of the WRF-CRES-ROTOR and WRF-CRES-ROTOR-FA results. The main differences are seen in the proximity of the wind farm, but further downwind the differences are reduced.
In Figure 4 the results from the mesoscale model parameterizations are compared with the measurements from the wind farm. The measurements are for wind speed within the range 7.5 – 8.5 m/s and wind direction within the range 255–285^o. The measurements are described in more depth in [8][5]. In Fig. 4 the wake wind speed deficit can be seen inside the farm at each turbine row and downstream of the wind farm at anemometers M6 and M7.
Considering WRF-EWP (Fig. 4a) as the reference [5], we can see that WRF-CRES-EWP (Fig. 4b) gives a slighly smaller wake deficit. Both parameterizations show good agreement with the measurement data, and lie well within the error bars. Considering next WRF-CRES-ROTOR (Fig. 4c), it can be seen that the wake deficit is large inside the wind farm, on the lower bounds of the error bars of the measurement data. Downwind of the wind farm, the difference compared to WRF-EWP is less pronounced, however the velocity deficits are still larger. Considering WRF-CRES-ROTOR-FA (Fig. 4d), it can be seen that inside the wind farm the deficit is very strong, below the lower bounds of the error bar. Downwind of the wind farm the difference is much reduced and agreement with measurement at masts M6 and M7 is good.

DISCUSSION

The differences in the wake simulations for the Horns Rev wind farm in this idealized set-up can be used to examine the characteristics of the various parameterizations.
The advantage of using turbine thrust information based on microscale modelling is that complex aspects of turbine interactions can be captured. For example, the difference in the behaviour between WRF-EWP and WRF-CRES-EWP is mainly due to the reduced turbine thrusts in the WRF-CRES-EWP parameterization.
The sub-mesoscale-grid vertical wake expansion is a necessary feature to capture the wake behaviour inside the wind farm and the near wind farm wake (c.f. WRF-CRES-EWP and WRF-

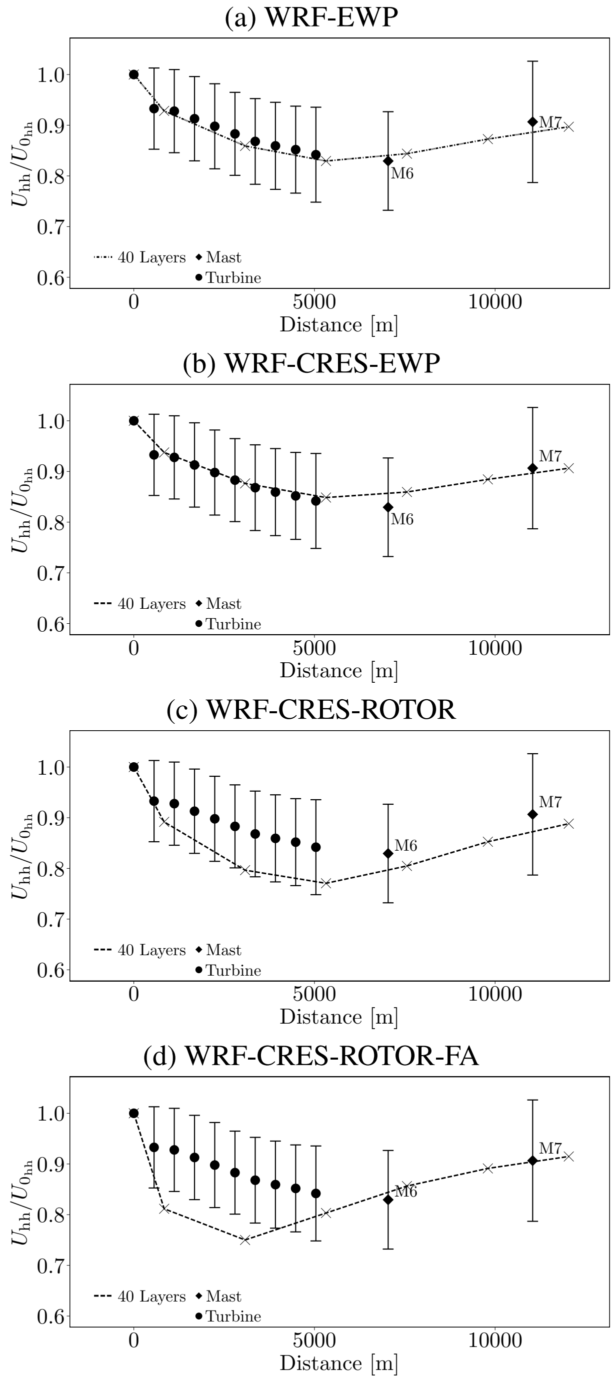

Figure 4: Recovery validation plots for different parameterizations used, (a) WRF-EWP, (b) WRF-CRES-EWP, (c) WRF-CRES and (d) WRF-CRES-FA. The x-axis is the distance in metres from the first turbine row, the y-axis is the wake horizontal wind speed expressed as a fraction of the inflow wind speed, both at 70 m above surface level, i.e. for first row turbines the value is 1. The black dots are measurements based on wind turbine power or from anemometers at mast 6 (M6) and mast (M7) downwind of the wind farm.

CRES-ROTOR). Without the vertical wake expansion the wake deficit tends to be too concentrated in the vertical, and associated with that, have too strong a deficit.
However, moving downwind of the wind farm into the far wake, the difference caused by including sub-mesoscale-grid vertical wake expansion, or not, becomes much less pronounced. In the far wake it is the mesoscale model that determines the wake and the initial vertical distribution of the wake becomes of less importance.
Aggregating the turbine thrusts according to the mesoscale grid or wind farm extent, has a large impact on the mesocale modelled wake within the wind farm. When imposing the thrust of the wind farm at 2 grid points rather than 6 grid points, the maximum wake deficit is too large compared to measurements. However, moving downwind of the wind farm, the model wake agrees well with measurement. It remains a question to what extent it is neccessary or beneficial to impose the wind farm thrust at few grid points.
Earlier in the paper it was stated that momentum theory can be used to determine the distribution of thrust associated with vertical wake expansion. This has the advantage that a model for the vertical wake expansion would no longer be required. However, there is a complication, if the wind farm covers several mesoscale grid cells. In that case, the inflow and outflow velocities of the grid cells, could be used to determine wake related thrust, but would include the effects of the continued expansion of wakes caused by turbines upwind of the grid cell in question. This is a problem, because the mesoscale wake parameterization should only address the representation of wakes caused by turbines in a single grid cell. The mesoscale model should thereafter alone deal with the developement of the wake downwind of the grid cell where the wakes originated.
It is for these reasons that a whole wind farm aggregation has some benefits, because in that case the application of momentum theory would be for a volume which envelops all turbines, and there would be no risk of double counting wakes by the microscale and mesoscale models.
A promising future development along these lines is the application of the FUGA microscale model [1]. In this model the application of momentum theory to determine wake thrust aggregated over mesoscale grid cells is possible because it is a linearized model, and a velocity deficit can be directly attributable to turbines in a single grid cell, even though there are developing wakes present from turbines in upwind grid cells.
In this paper only a single wind speed and wind direction is used, however the approach is readily extendable to any wind speed and direction by precalculating tables of turbine thrusts, for a number of wind speeds and directions. This data can be stored in a look-up table. Then within the parameterization the correct thrust data is retrieved depending on the mesoscale grid point wind speed and direction. However, a complication arises here. For unsteady mesoscale situations, the parameterization will be drawing from microscale model results, which assumed steady and unform flow situations. The impact of this mismatch needs to be addressed.
In the future, the mesoscale model also can provide upstream information such as wind speed (sheer), direction (veer or backing) and Richardson number for the microscale models. An extension of the cross-over between the two modelling scales is the application mesocale variability of conditions in the microscale models. For example, within a very large wind farm there may be significant variation of mesoscale wind conditions (speed and direction). This information, which can be provided by mesocale models, could be used in the microscale modelling of wakes, which at present assume a homogeneous mean wind speed and direction.

CONCLUSIONS

In this paper the basis for introducting thrust information from microscale wake models into mesocale model wake parameterizations was described. Different types of mesoscale wake parameterizations were outlined.
Four different mesoscale wake parameterizations were used in the mesoscale model WRF in an idealized atmospheric flow configutation. Three of the four parameterization used thrust output from the CRESflow-NS microscale model. The characteristics of the mesoscale wake that developed from the four parameterization was examined. In addition the mesoscale model wakes were compared to measurement data from Horns Rev. Overall it is seen as an advantage to incorporate microscale model data in mesocale model wake parameterizations.

ACKNOWLEDGMENTS

The authors wish to thank funding from the project EERA DTOC FP7-ENERGY-2011-1/ Number 282797, and from the WAUDIT programme (financed by Marie Curie ESR-FP7), which made this study and article possible. DONG Energy is thanked for providing the data for Horns Rev I. Kurt Hansen, DTU Wind Energy, is thanked for discussion and provision of analysed measurement data.

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