TESTING THE COUPLED WAKE BOUNDARY LAYER MODEL WITH LES OF TURBULENT FLOW IN WIDELY SPACED WIND FARMS

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Abstract The Coupled Wake Boundary Layer (CWBL) model combines a classical wake model with a "top-down" boundary layer model through two-way coupling to combine the strengths of these two analytical modeling approaches. The wake model part of the CWBL model captures the effects of the relative turbine positioning and the growth of wakes due to turbulence while the "top-down" part describes the interactions between the wind-farm and the turbulent atmospheric boundary layer. Previously, the CWBL model has been shown to provide improved predictions compared to the results obtained from classical wake and "top-down" models for the power production of aligned and staggered wind-farm configurations with turbine spacing of up to 8 turbine diameters. In addition the CWBL model has been validated against detailed LES results and field measurements for the Horns Rev and Nysted wind-farms. Here we will compare the CWBL model predictions for wind-farms with very large inter-turbine spacings with results from new large eddy simulations to verify the validity of the CWBL model in that regime.

INTRODUCTION

It has been shown that large eddy simulations (LES) can generate accurate predictions for wind-farm performance [5, 10, 12]. Therefore LES have been used to study the effect of wind-farm design parameters (such as turbine positioning, spacing, and height) on the average wind-farm power output [1, 15, 19]. However, due to the large computational cost of LES this method is not practical to design and optimize individual wind-farms. Instead industry uses wind-farm design tools, which are based on less computationally expensive methods such as RANS and input from analytical models, to evaluate the performance of different design choices under varying conditions.

LES are very useful for the further development, validation, and improvement of analytical models and wind-farm design tools. Two analytical approaches are commonly used. The first approach uses classical wake models [3, **?**, 8, 9, 11] to estimate the power output of wind-farms. Wake models describe the power output in the entrance region of a wind-farm well, but have difficulty in predicting the performance further downstream where many wakes interact [2]. In this fully developed wind-farm regime additional complexities arise due to the vertical structure of the atmospheric boundary layer and the associated wake-atmosphere interactions, which are described better by "top-down" models [4, 6]. However, these "top-down" models do not capture the effect of the relative turbine positioning [15].

COUPLED WAKE BOUNDARY LAYER MODEL

The Coupled Wake Boundary Layer (CWBL) model, which includes two-way coupling between the two analytical approaches described above, provides improved predictions for the power production of aligned and staggered wind-farms compared to the results from classical wake and "top-down" models. The wake model part of the CWBL model namely ensures that the effect of the relative positioning of the turbines is captured, while the interaction with the atmospheric boundary layer in the fully developed regime of the wind-farm is captured by the "top-down" portion of the model. Figure 1 compares the turbine performance in the fully developed regime of aligned and staggered wind-farms predicted by the wake, "top-down", and CWBL models with corresponding LES results [13–15]. This figure confirms that the CWBL model gives improved predictions over both the wake and "top-down" approaches. Only the CWBL model captures the main trends as function of the geometric mean turbine spacing $s = \sqrt{s_x s_y}$, where s_x and s_y indicate the non-dimensional (in terms of the turbine diameter D) streamwise and spanwise distance between the turbines, respectively.

LARGE EDDY SIMULATIONS

We model turbulent flow in wind-farms that consist of a regular array of wind-turbines, each having a diameter of $D = 100$ m and a hub-height of $z_H = 100$ m. We consider wind-farms with ten (or more) rows in the streamwise direction in order to study the fully developed state. This number of turbine rows ensures that the power output of the later rows is approximately constant in both aligned and staggered wind-farm configurations. The distances between wind-turbines are $s_x D$ and $s_y D$ in the streamwise and spanwise directions, respectively. We vary the streamwise spacing s_x in the range $\sim [3.5, 36]$ and the spanwise spacing in the range $\sim [3.5, 12]$ and consider different combinations of streamwise and spanwise spacings in this parameter range. Several of the planned cases will require computational domain discretizations

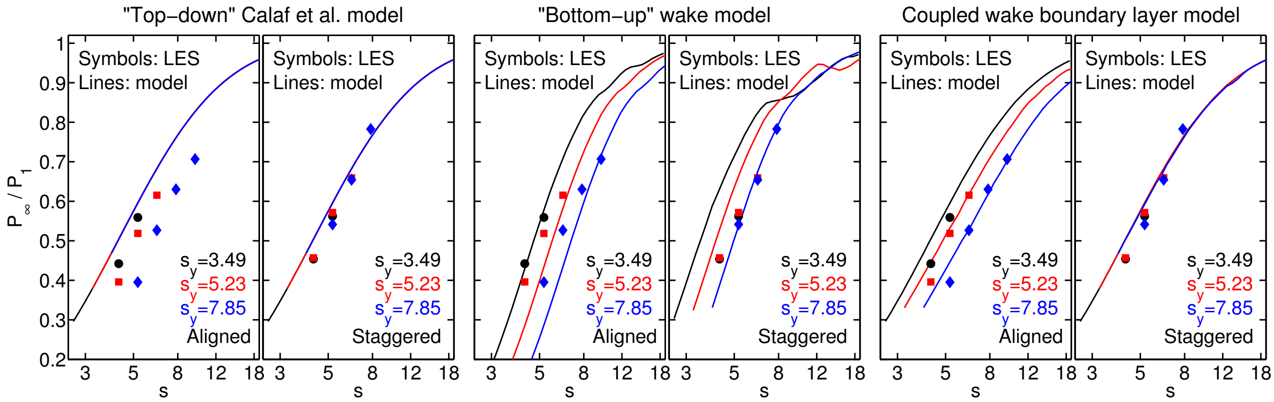

Figure 1. Predictions of the normalized turbine power output P_∞/P_1 in the fully developed regime for aligned and staggered wind-farms obtained from the "top-down" model [4], the wake model [**?**, 8], and the CWBL model [13, 14] compared to LES results [13–15]. Results are plotted as function of the geometric mean turbine spacing $s = \sqrt{s_x s_y}$, where s_x and s_y indicate the non-dimensional (in terms of the turbine diameter D) streamwise and spanwise distance between the turbines. Note that only the CWBL model captures the trend observed in LES data for both aligned and staggered wind-farms. Figure taken from Ref. [13]. Data point for which $s_x > 8$ is preliminary unpublished data.

with more than 10^8 grid points. The inflow in our simulations is obtained using a concurrent-precursor method [16] and the turbines are represented by an area averaged actuator disk model using a constant thrust coefficient C_T, which is representative of turbines operating in region II. Further details about the simulations can be found in Ref. [15]. Here we mention that this LES approach has been validated against similar LES codes, which show that good agreement among these codes is obtained [4, 18]. In addition, Yang et al. [18] and Wu and Porté-Agel [17] showed that the wake profiles obtained from such simulations agrees well with wind tunnel experiments after a distance of $3D$ into the wake. In addition it was found that such LES provide improved predictions for the deep wake effects in large wind-farms such as Horns Rev than some engineering wake models [10].

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