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Open Access WIND ENERGY SCIENCE DISCUSSIONS

From wake steering to flow control

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Abstract. In this paper, we investigate the role of flow structures generated in wind farm control through yaw misalignment. A pair of counter-rotating vortices are shown to be important in deforming the shape of the wake and in explaining the asymmetry of wake steering in oppositely signed yaw angles. We motivate the development of new physics for control-oriented engineering models of wind farm control, which include the effects of these large-scale flow structures. Such a new model would improve the predictability of control-oriented models. Results presented in this paper indicate that wind farm control strategies, based on new control-oriented models with new physics, that target total flow control over wake redirection may be different, and perhaps more effective, than current approaches. We propose that wind farm control and wake steering should be thought of as the generation of large-scale flow structures, which will aid in the improved performance of wind farms.

1 Introduction

Wake steering is a wind farm control concept where the upstream turbines are intentionally misaligned to deflect its wake away from a downstream turbine (Wagenaar et al. (2012).) Although the turbine upstream loses power because of this misalignment, the downstream turbine can be shown to yield a large gain to produce a net increase in power.

Early work in wake steering made assessments of the technique using computational fluid dynamic (CFD) simulations of small arrays of wind turbines. For example, Fleming et al. (2015) examined wake-steering performance for an offshore array of two turbines separated by 7 diameters, and observed an increase in total power.

In order to design controllers to implement wake-steering control strategies, it is necessary to build engineering models that contain the relevant physics but are described in a computationally efficient way such that the model can be used in large-scale optimizations or used as an internal model within a real-time controller. A first model of wake steering, based on CFD analysis, was provided by Jiménez et al. (2010). The model predicts wake deflection as a function of yaw angle and thrust coefficient.

In Gebraad et al. (2016), an engineering wake model, known as FLORIS (FLow Redirection and Induction in Steady-State) was introduced. The model combined the wake-steering model of Jiménez et al. (2010) with the wake recovery model of Jensen (1984). In addition, this model separates the wake into zones that recover at different rates. The model is shown to predict the behavior of wake steering and, given its execution speed, can be used to design controllers as well as look at coupled wind farm layout and controls optimizations (c.f. Gebraad et al. (2017)). In this model, the wake appears as a deficit of energy that flows downstream and is characterized as (i) an initial deficit determined by the turbine thrust, (ii) a rate of recovery determined by topology, i.e. FLORIS inherits wake-recovery parameters from the Jensen model whose values are set by rules of thumb for

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onshore/offshore, and (iii) a wake deflection caused by wake-steering. This version of FLORIS was used to design a strategy for wake steering that was tested at a commercial offshore wind farm in Fleming et al. (2017b) with an improved wind farm power performance under waked conditions.

More recently, the FLORIS model has been improved by incorporating the theoretical models of wake behavior and steering presented in Bastankhah and Porté-Agel (2014, 2016); Niayifar and Porté-Agel (2015). One of the improvements was the inclusion of turbulence to describe the wake recovery. Turbulence in turbine wakes is generated by ambient wind conditions as well as turbine operating conditions. These critical changes greatly improve the general applicability of models such as FLORIS. For example, wake expansion and the recovery are now dependent on ambient and induced turbulence intensity, which can resolve the modeling discrepancies observed in Annoni et al. (2016).

To date, engineering models are beginning to include modeling of the main atmospheric components (turbulence intensity, veer, and shear) needed to accurately predict and control wakes via wake steering. The basic conception of wake steering remains that a rotor operating in misaligned conditions creates a force perpendicular to the flow that generates the deflection in wake direction and decreases the thrust and overall velocity deficit in the wake. Further, based on Bastankhah and Porté-Agel (2014, 2016); Niayifar and Porté-Agel (2015), the change in thrust also impacts recovery rate. Wind tunnel tests in Schottler et al. (2017) and Bartl and Sætran (2017) show good agreement overall with these latest models.

However, recent research has shown that in addition to changing a the deficit and location of a wake, yaw misalignment changes other properties in the flow, which can be observed as impacting the shape of the wake. In Vollmer et al. (2016), large-eddy simulations (LES) are used to study the behavior of wake steering under varying atmospheric conditions. The authors note that the shape of the wake under yawed conditions is curled rather than circular. This curvature is shown to impact the estimate of the wake center. Further, the authors explain the change in shape by showing that the cross-flow wind of an aligned turbine is largely due to counter-rotating vortices that appear in the flow behind a yawed turbine and generate this distortion.

Howland et al. (2016) studies the curled wake phenomenon experimentally using a porous actuator disk and with LES using an actuator disk and an actuator line model. The curled wake is observed in experiments and simulations. The mechanism behind the curled wake is again explained as a pair of counter rotating vortices which are shed from the top and bottom of the rotor due to yaw misalignment. This mechanism was later confirmed by Bastankhah and Porté-Agel (2016).

In Fleming et al. (2017a), a rear-facing nacelle-mounted lidar is used to scan the wake of a turbine in aligned and yawed conditions at five locations downstream ranging from 1 diameter to approximately 3 diameters. The deflection predicted by earlier simulation models is clearly observed as well as the curling of the wake shape.

The current state of control-oriented models supposes that the change in wake "location" and strength can be well modeled as a deflection of a wake generated with a lower thrust. In other words, the effect of the counter-rotating vortices on the flow is assumed to be captured in the engineering models that modify only the deflection, deficit and recovery of the wake. A curled wake of some deflection amount might be well-enough described by a circular wake of larger deflection.

In this paper, a CFD-based analysis is used to examine how the consideration of the counter-rotating vortices can impact wind farm control analysis and design. This paper undertakes an investigation of the impact of these vortices on yaw-based wake control. The contributions of this paper are first a demonstration that a deflection-only control-oriented model of wind farm

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control can not reconcile all observed effects when considering multiple turbines directly downstream. A second contribution is the demonstration that the influence of the vortices is especially critical when arrays of multiple turbines are considered. A third contribution is a proposed new approach of wind farm control based on this analysis. Finally, the paper proposes recommendations for improvements to control-oriented modeling.

2 Models

This paper focuses on two specific models of wind farms. First, FLORIS, is a control-oriented model of wind farm control, which includes several possible wake models. In this work, we focus on the most-recent models proposed by Bastankhah and Porté-Agel (2014, 2016); Niayifar and Porté-Agel (2015). The FLORIS model is python-based, open source, and available for download on github (https://github.com/WISDEM/FLORIS). The overall approach of FLORIS is to provide an engineering model of wakes that predicts the important average behaviors of wakes in a computationally efficient way such that it can be used to derive control strategies through optimization or function as an internal controller model. A recent report compares predictions of the latest FLORIS model to lidar data from a utility-scale wind turbine operating in yaw and provides good agreement (Fleming et al. (2017a)).

Second, the Simulator fOr Wind Farm Applications (SOWFA), is a high-fidelity framework used to perform large-eddy simulations (LES) of wind farm flows. In LES, the filtered Navier-Stokes equations are solved numerically, providing a time-evolving three-dimensional flow field in the wind farm. Within SOWFA, wind turbines are modeled using an actuator disk/line model with torque, blade pitch, and yaw controllers. SOWFA is based on the OpenFoam libraries, and has been used in past research of wind farm controls for design and analysis.Churchfield et al. (2012)

3 Method

In past research, the two models have been used together. In a typical workflow, SOWFA simulations of a small farm are run to provide tuning inputs to FLORIS, which is then used to predict optimal controllers that are then tested in SOWFA. Successful iterations of this process yield controllers that can be used in field testing.

One constraint of this approach is that, given the computational requirements of running SOWFA, tuning cases are typically limited to approximately 10-20 runs, and these are focused on high-loss scenarios such as one turbine directly waking another. For example, simulations of two turbines aligned in the flow, with and without yaw, for different distances downstream are a typical focus.

In this approach, the SOWFA simulation includes one turbine modeled as an actuator disk (see Fig 1.) The simulation is run for 2,000 seconds, and the flow is averaged over the last 1600 seconds to allow for transients to dissipate. From the averaged flow, a power is computed, which would have been produced by an additional hypothetical at some point downstream. This approach was adapted from power calculations used in Vollmer et al. (2016) This power is computed by averaging the cubed

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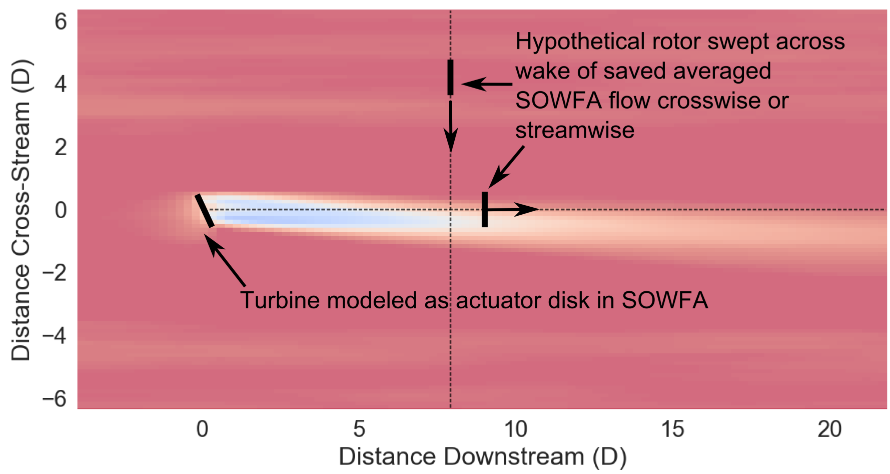

Figure 1. Diagram of the method used in the paper. In this example, a single turbine is included in a SOWFA simulation. A period of 1600 seconds of the flow is averaged and then the hypothetical turbine rotor is scanned across this averaged flow to compute the power that would have been produced by a turbine at a given location.

wind speed over a hypothetical rotor disk from the averaged flow. The cubed average is then converted to power through

$$P = 0.5\rho A C_p U^3 \tag{1}$$

where ρ is the density, A is the rotor area, C_p is the coefficient of power (which is derived from a look-up table based on wind speed precomputed from the aero-elastic turbine simulator FAST), and U is the rotor averaged wind speed. The hypothetical turbine can be swept across the area behind the turbine in the averaged flow to compute the effect on power for turbines across a wide range of locations. This method allows for inspection of change in power for a wide variety of turbine array configurations. For comparison, this process can be repeated directly in FLORIS to compute the power of a downstream turbine for a range of locations.

All simulations in this paper are of a neutral atmospheric boundary layer, with a mean-wind speed of 8 m/s, similar to what has been used in past studies (Fleming et al. (2015)). The domain size is 5 km x 1.8 km x 1 km. The simulations include National Renewable Energy Laboratory's (NREL's) 5-MW reference turbines from Jonkman et al. (2009), modeled as an actuator disk for computational efficiency. In our previous work, this method has shown to be comparable to an actuator line model in predicting power.

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4 One turbine case

The one turbine case shown in Fig. 1 is the first case to be analyzed where a single NREL 5-MW turbine is placed in the flow. In one case, it is has no yaw offset (denoted as "baseline"), and then +/- 25○ of yaw. In the first case, the hypothetical turbine is swept downstream (x is downstream, y cross-stream) with no lateral offset. The results are shown in Fig. 2.

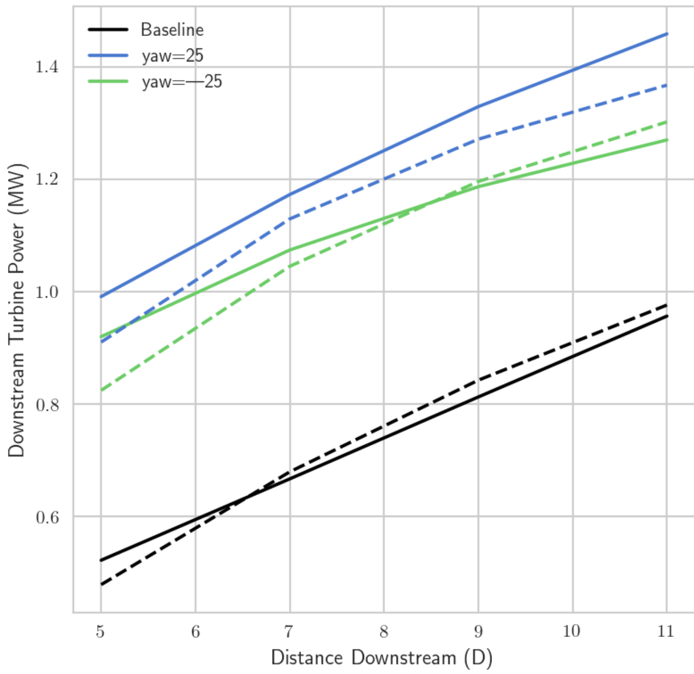

Figure 2. Power output in SOWFA (solid) and FLORIS (dashed) for a hypothetical turbine directly downstream of a baseline, or yawed turbine at different distances.

In both SOWFA and FLORIS, power is improved by misaligning the upstream turbine. In addition, more power is generated in the positive (CCW) yawed case than in the negative (CW) yawed case (see Fig. 2.) This asymmetry of wake steering, which has been documented previously, is an important result. For example, in Fleming et al. (2015), after deducting the power lost because of yaw on the first turbine, only positive yaw produces an overall gain in power for a case of two turbines separated by 7 diameters.

In the original FLORIS model (Gebraad et al. (2016),) this asymmetry is captured by assuming that a wake has a certain natural deflection, even when operating in non-yawed conditions. This offset was previously used to describe the asymmetry between positive and negative wake-steering angles. However, this natural deflection in non-yawed conditions is not observed

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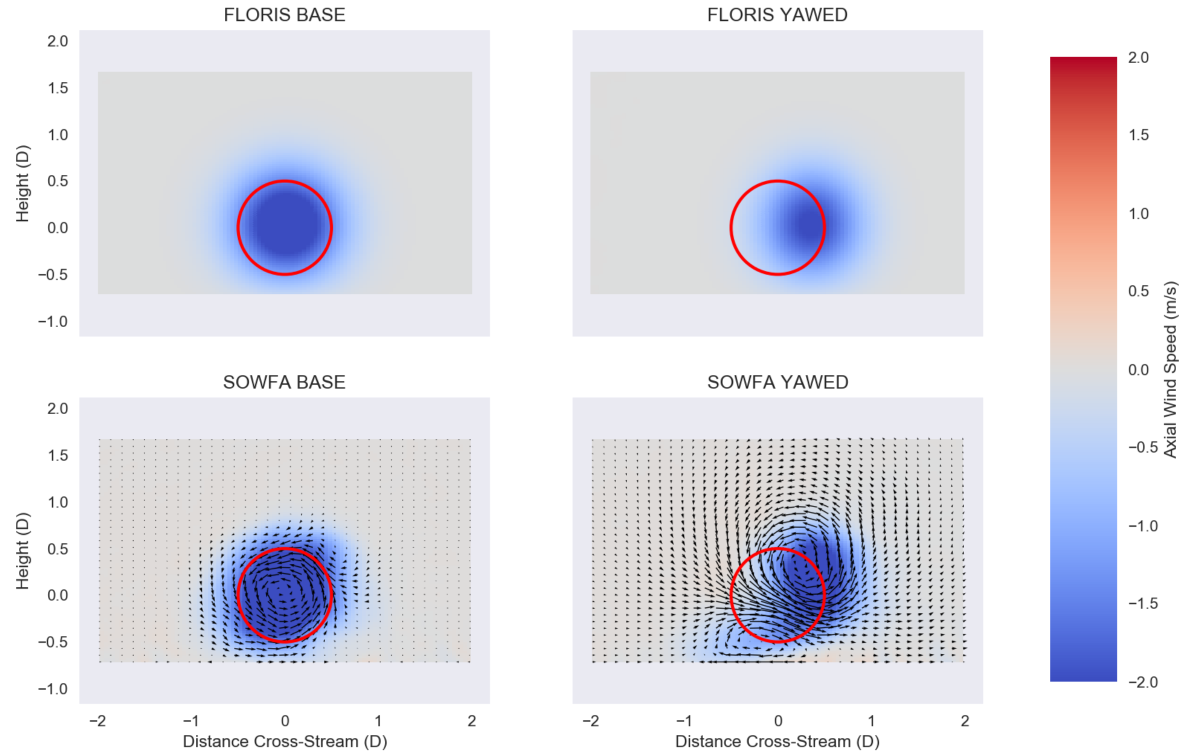

Figure 3. Cut-through of SOWFA flow, minus the background flow, at a distance of 7 diameters behind the turbine for baseline and yawed 25○. Deficit in axial flow is shown in blue, saturating at a deficit of 2 m/s to broadly show the wake area. For the SOWFA cases, the in-plane flow is visualized by arrows whose relative size indicates the strength of the flow. Red circles indicate a rotor located directly downstream of the turbine.

in simulations without the Coriolis effect or where the Coriolis effect is smaller, (i.e. simulations close to the equator.) This paper further reconsiders the source of this asymmetric behavior of the wake and its impact on the wind farm control strategy.

One way we can investigate the impact of the generated vortices on the wake is to look at cut-through slices of the flow at a distance downstream of the turbine. This is shown in Fig. 3 and Fig. 4. In these plots, the time-averaged flow with no turbines is first subtracted and so only the change from the background is plotted. These cut-throughs are plotted for both FLORIS and SOWFA.

Comparing the figures, we can note that FLORIS shows the impact of positive yaw as primarily impacting the location of the wake and the depth of the deficit. SOWFA, however, includes a large impact on wake shape, which is caused by the two

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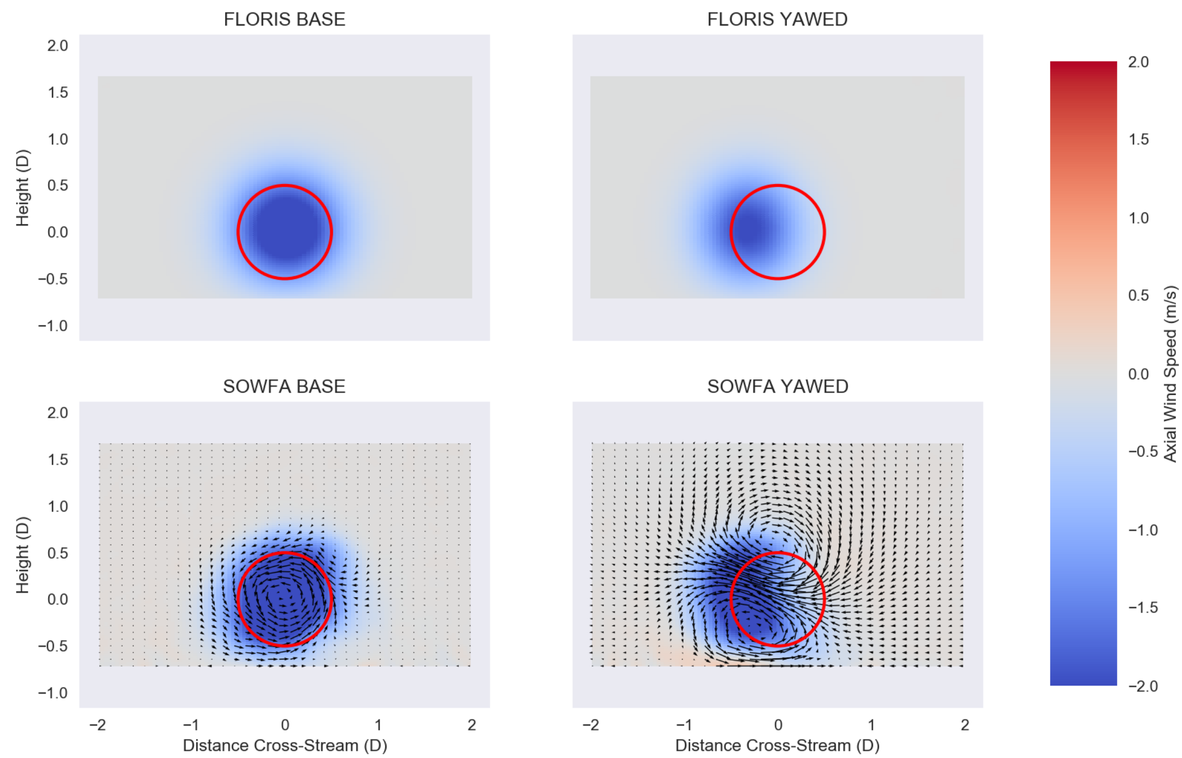

Figure 4. Cut-through as in Fig. 3 but for a yaw of $-25°$

counter-rotating vortices seen in Fig. 3 and Fig. 4. This is in line with the analysis of Vollmer et al. (2016); Howland et al. (2016); Fleming et al. (2017a). Visual inspection indicates some discrepancies between SOWFA and FLORIS.

As a first observation of the baseline cases, there does not appear to be any natural deflection. The natural deflection angle appears to be absent in this case and similar cases where the amount of veer in the simulation is kept to a minimum. Second, observing the in-plane flow, shown by arrows in the SOWFA plots (bottom row in Fig. 3 and Fig. 4), the asymmetry in wake behavior likely comes from the interaction of the counter-rotating vortices with the rotation caused by the rotation of the turbine rotor (as seen in the SOWFA baseline case of Fig. 3) and the wind shear. More specifically, in the positive yaw case, the top vortex rotates in the same direction as the underlying wake (generated by the rotation of the turbine), making the top vortex stronger. In the negative yaw case, the lower vortex interacts with the vortex generated by the rotation of the turbine. The top vortex is stronger because the wind speed is stronger at the top of the rotor as compared to the bottom of the rotor due to the shear layer and the interaction with the ground. This difference in vortex interaction may explain the asymmetry in the wake

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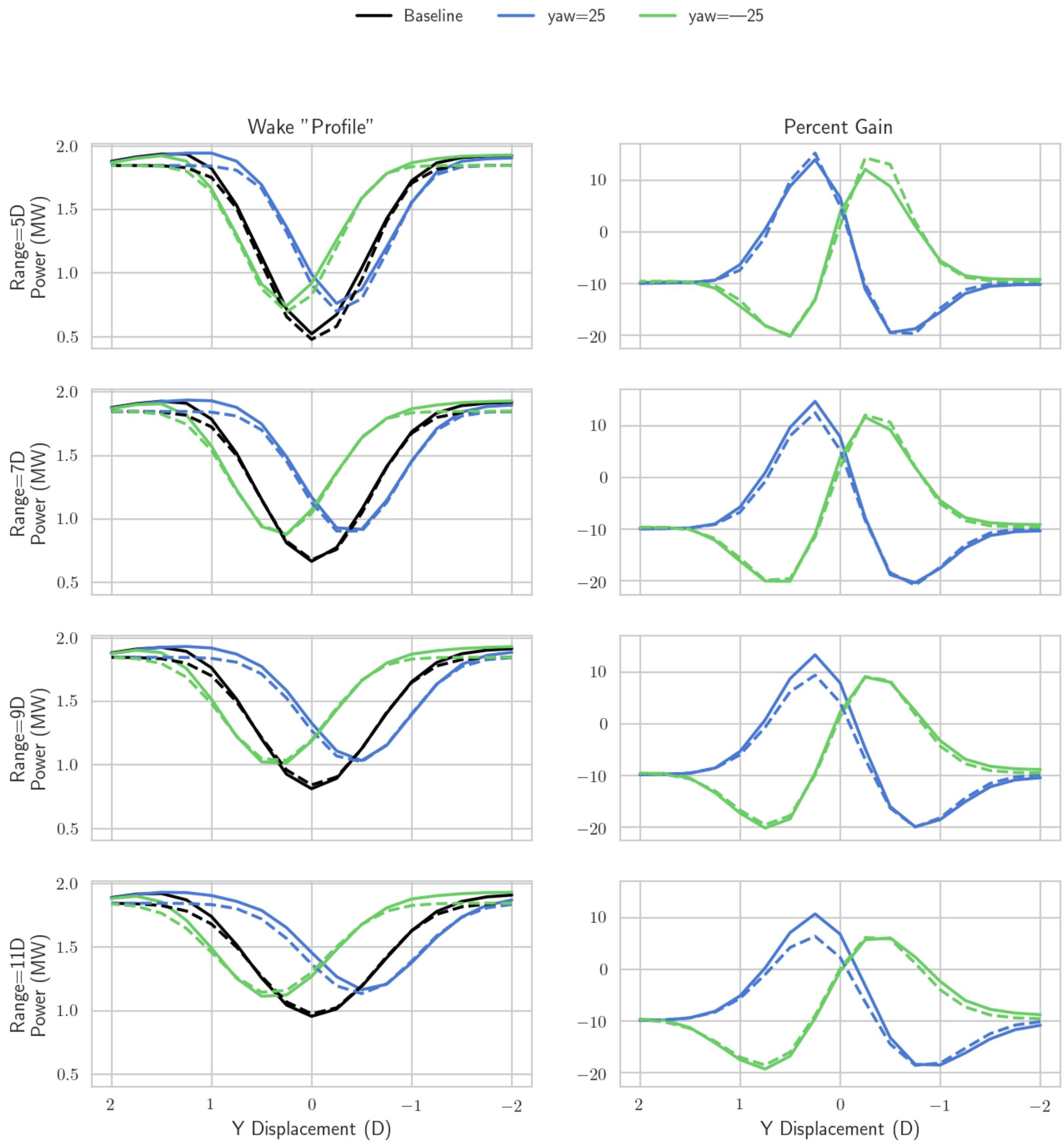

Figure 5. Power output of hypothetical downstream turbine for various downstream distances and lateral offsets (left). Solid lines are SOWFA results, and dashed are from FLORIS, showing good agreement in the depth of deficits and location of maximum deficit. On the right, the percent gain (of the total power of the actual and hypothetical turbine) is shown relative to the baseline of the two yaw angles.

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based on yaw misalignment. A third observation is that, in the positive yaw case (Fig. 3), the left side of the wake has been moved further to the right than FLORIS estimates, which computes deflection based on the center alone.

Figure 5 shows the power of the hypothetical turbine that is swept laterally across the wake at different distances downstream. The left column of figures show the wake "profile" (measured in MW), and we see very good agreement between SOWFA and FLORIS. Note that the largest impact in gain in power (right column) is offset from turbine directly downstream. This percent gain includes the loss of the upstream turbine.

Under positively yawed conditions, the power improvements for turbines negatively offset from the wake center line are greater than what FLORIS estimates for distances greater than 5 D. We note here that this effect cannot be modeled through a re-tuning of FLORIS. The main parameter available for implementing deflection asymmetry is a natural deflection angle, and increasing this raises the error observed in the baseline and negatively yawed case. Further, we cannot simply assume the wake recovers more quickly in positively yawed cases, because we note that in all cases, the trough of the deficit is predicted accurately by FLORIS. Therefore, the shape of the wake is a factor in being able to more accurately predict the power gain due to yaw misalignment, especially in cases of turbines offset from exactly downstream.

A first result of the paper is the suggestion that the asymmetry in wake steering, where positive yaw is superior to negative yaw, is better explained by vortex-wake interactions than a natural deflection angle. This is most important for a two-turbine interaction when the downstream turbine is not directly downstream.

5 Three-turbine arrays

The impact of the counter-rotating vortices becomes even more clear when the simulation includes multiple turbines. In a second simulation, a case is considered where two turbines are in the flow 7 diameters (D) apart. The first turbine is either operating with no yaw misalignment or operating with 25° yaw misalignment while the second turbine is always aligned. The layout is shown in Fig. 6

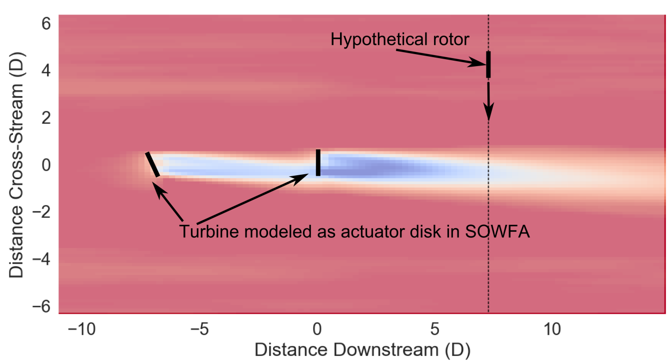

Figure 6. Layout of SOWFA simulation as in Fig. 1, now with two turbines. Note that only the first turbine is yawed in controlled cases.

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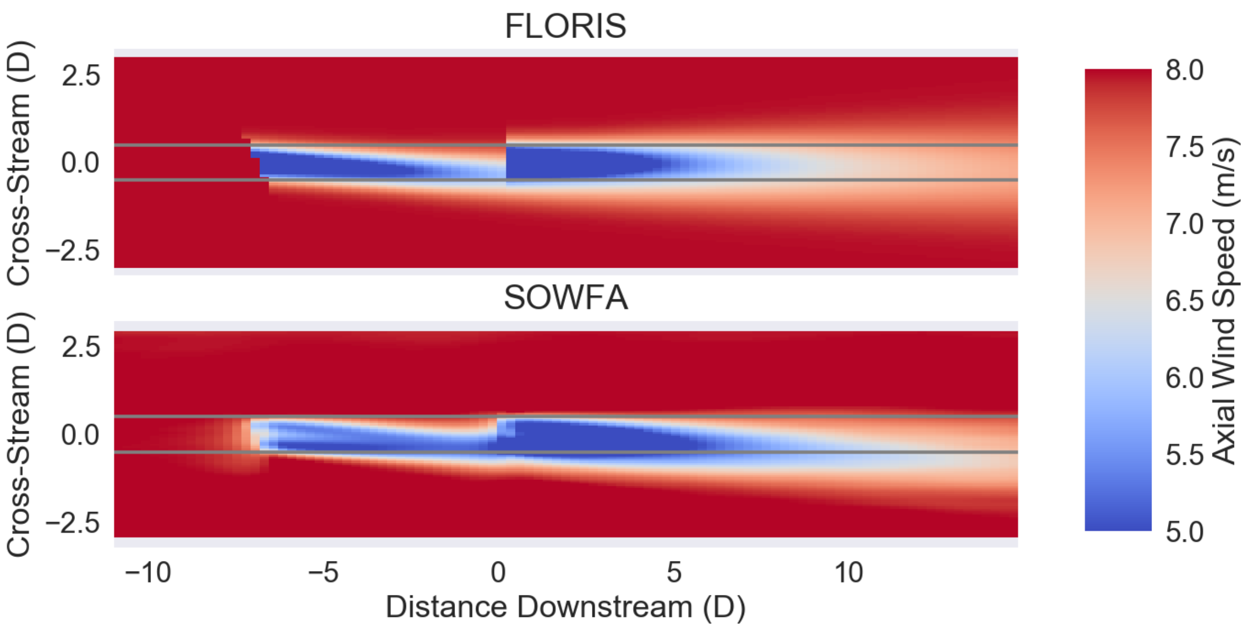

Figure 7. Horizontal cut-through of two-turbine flow in FLORIS and SOWFA. Gray lines pass through edges of rotor to help distinguish flow location relative to rotor.

Horizontal cut-throughs of the flow at hub height in SOWFA and FLORIS are compared in Fig. 7. The most striking observation is that in the SOWFA case, the second wake is impacted by the counter-rotating vortices generated by the first turbine, even though that turbine is aligned to the flow. This is not predicted by FLORIS. If we observe a cut-through at 7 diameters downstream of the second turbine, we see that there is a deflection of the wake of the second non-yawed turbine, see Fig. 8.

Combining observations from Fig. 7 and Fig. 8, we observe that FLORIS expects the wake of the second turbine to be impacted by the first primarily through reduced inflow velocity and increased turbulence. Both of these effects do not lead to the deflection of the second wake. In this case, the second wake is significantly deflected in SOWFA. This deflection appears to be explained as a combination of the rotating wake of the second turbine, with the top vortex generated by the first yawed turbine. Considering the impact on power of a hypothetical third turbine defined 7 diameters downstream of the second, the difference between FLORIS and SOWFA is substantial. As seen in Fig. 9, FLORIS expects a maximum gain for the three-turbine total of approximately 7%, where SOWFA predicts a total power gain of 17%. Also, SOWFA finds some locations where the 3-turbine array loses power, while FLORIS does not.

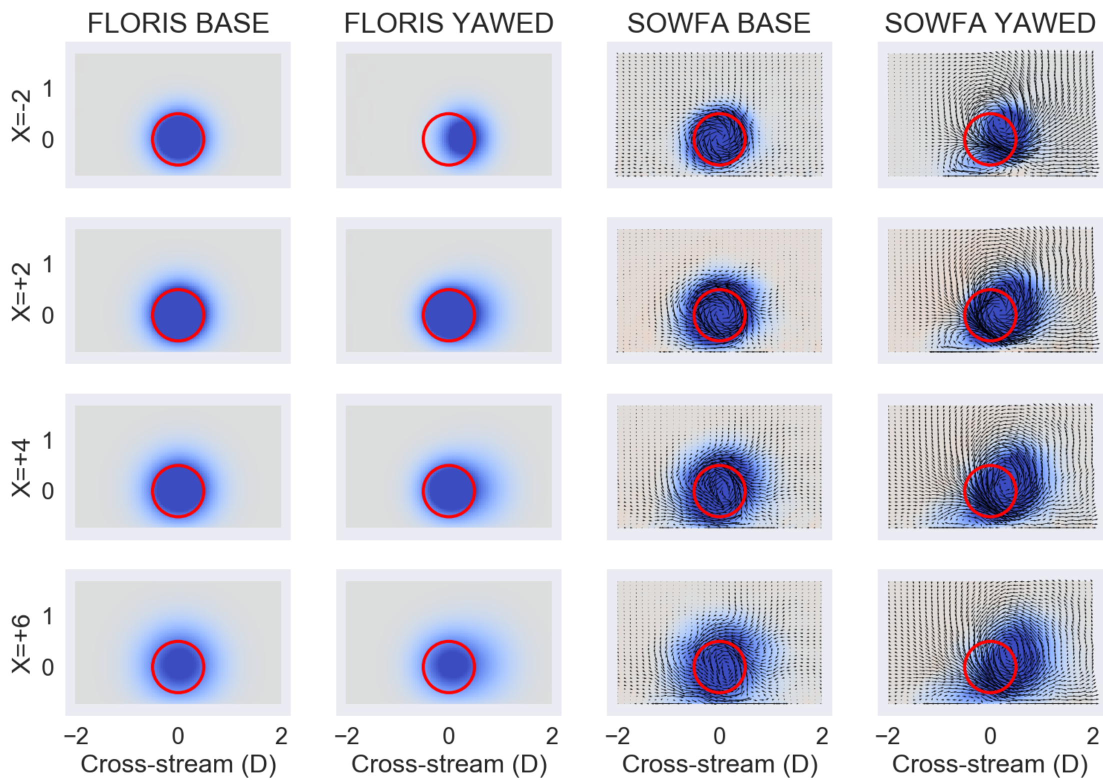

Figure 8. Cut-through visualizations of FLORIS 2D in front of second turbine (top row) and behind the second turbine (remaining rows).

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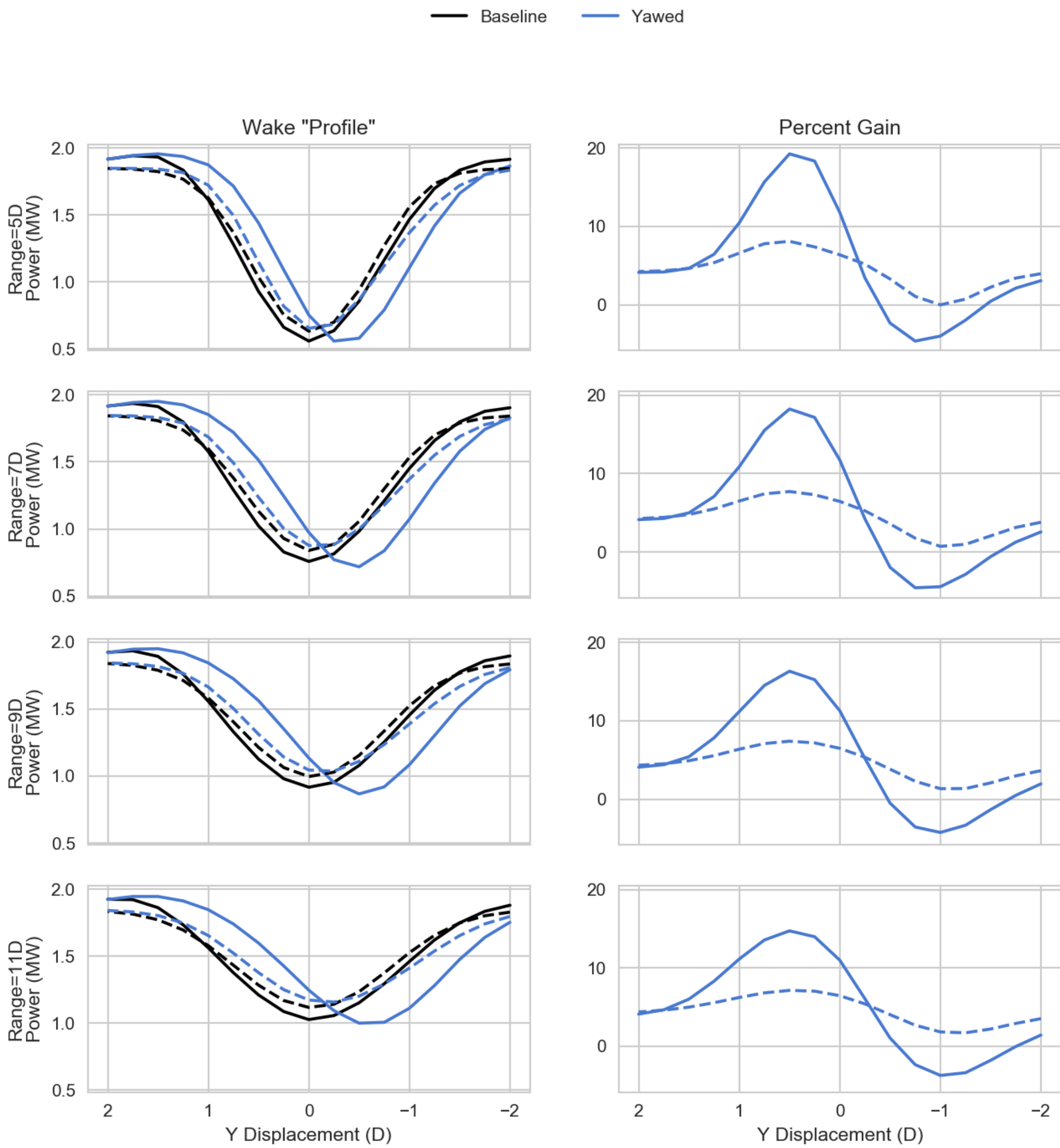

Figure 9. Power of a hypothetical behind the 2nd turbine in SOWFA (solid) and FLORIS (dashed) (left) and percent increase relative to baseline (right). FLORIS has good agreement in the baseline case but misses the change in wake behavior obtained in the yawed case in SOWFA.

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6 Wind turbine array results

Building on the results from the three-turbine case, A final case simulates a tightly spaced wind farm is used to further explore the importance of these counter-rotating vortices generated under yawed conditions. A 12-turbine wind farm, shown in Fig. 10, is modeled in both SOWFA and FLORIS.

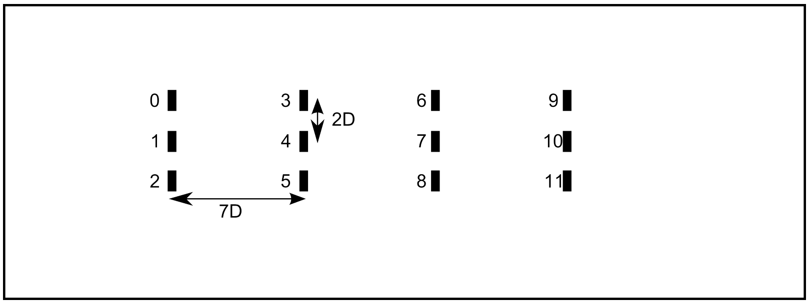

Figure 10. Layout and numbering of turbines in a turbine array case for both SOWFA and FLORIS.

This layout affords the opportunity to assess how the consideration of vortices impacts previous assumptions of wake steering. If wake steering only deflects wakes to the right or the left of a downstream turbine, then it is possible to incidentally steer a wake into a different turbine operating nearby. This description suggests that wake steering will be difficult in situations where a turbine's wake cannot be directed easily into empty space.

However, noting that vortices and wakes combine in a profitable manner when wakes interacted going downstream, we can observe that vortices can provide a constructive mechanism for wakes located near to each other laterally as well.

Additionally, in FLORIS as currently modeled, it is expected that although the three horizontal rows of turbines are tightly spaced, the effect of simultaneously applying wake steering to turbines 0, 1, and 2, would be equivalent to the super-position of applying wake steering to each row individually. However, in SOWFA, the generation of these large-scale structures, i.e. counter-rotating vortices, influence each other and can combine in ways that are not captured in the current engineering model.

We ran five simulations of the scenario in Fig. 10, one in which all turbines operate aligned ("baseline"), there where only one of the upstream turbines is yawed ("yaw0," "yaw1," and "yaw2"), and a final where all three are yawed ("yawAll"). Then in the analysis, we can compare the results of summing the effects of individually yawed turbines ("sumInd") in post-processing to the case of simultaneously yawing all turbines.

Fig. 11 shows the change in power from baseline, for each turbine, for SOWFA and FLORIS. We note that the power predicted for the baseline case is 13.05 MW for FLORIS, and 13.107 MW for SOWFA, which indicates good agreement.

For the first row, which is the upstream turbines implementing the yaw misalignment, the losses between SOWFA and FLORIS are similar, and small differences between individual and simultaneous yawing is observed. However, in the second row, while FLORIS continues to show no difference between individually and simultaneously yawed conditions, SOWFA shows a consistent gain when yawing is simultaneously applied versus summing of individual yaw misalignment effect ("yawInd".)

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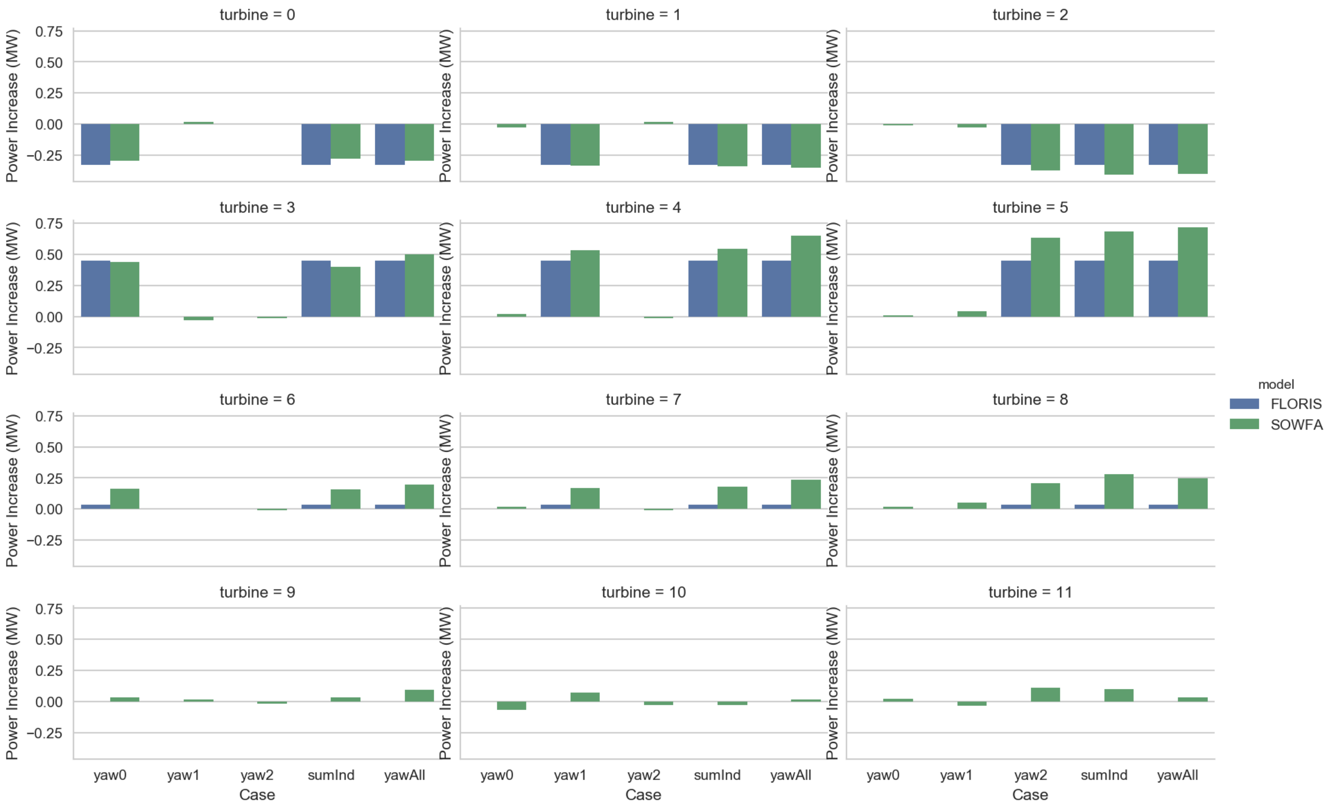

Figure 11. Change in turbine power relative to baseline for each turbine across the various scenarios in both SOWFA and FLORIS.

In the third row, as indicated in the earlier three-turbine analysis, FLORIS sees no impact on turbine power, whereas SOWFA observes an increase, and a difference between individual and simultaneous yawing. This continues to a lesser extent in the fourth row, now a full 21 diameters behind the yawed turbines.

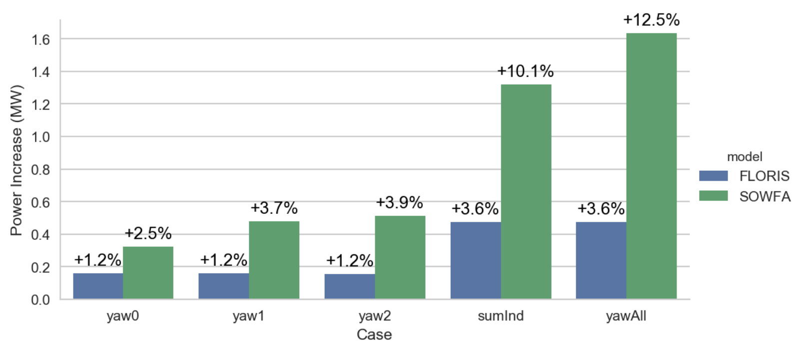

Figure 12. Change in total power for SOWFA and FLORIS across the cases.

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The summed turbine power is shown in Fig. 12. Again, FLORIS underestimates the power increase from the later rows, and assumes that individually applied yaw offsets can be summed to the whole, while SOWFA shows an increase from simultaneous application. Fig. 13 shows cut-throughs following each of the rows in the simulation. Most notably, it appears that the counter-rotating vortices that are generated from the three upstream turbines are combining to have a larger impact on the downstream turbines. Just by operating the upstream turbines under misaligned conditions, these large-scale structures are generated and propagate throughout the farm.

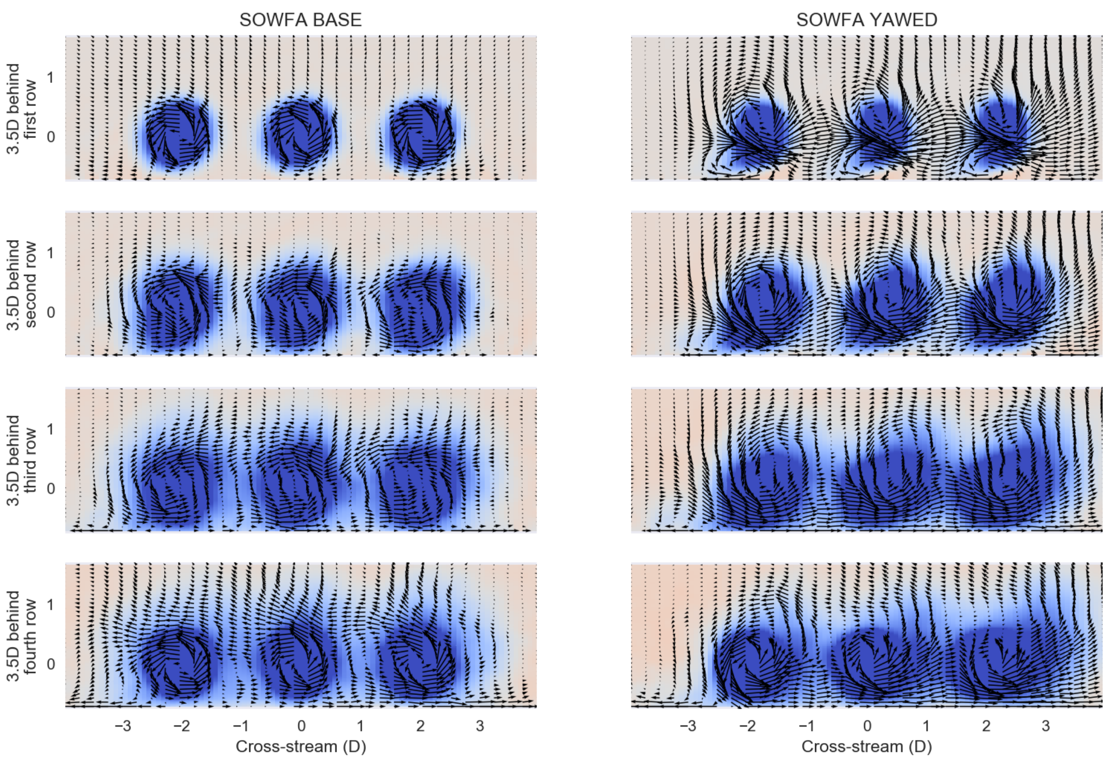

Figure 13. Cut-through visualizations of SOWFA following each row in the turbine array scenario.

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7 Conclusions

In this paper, the role of flow structures, particularly this pair of counter-rotating vortices, generated in wind farm control through yaw misalignment was investigated. These vortices were shown to be important in deforming the shape of wake, in explaining the asymmetry of efficacy in wake steering of oppositely signed yaw angles (rather than the currently used natural deflection angle), and in understanding how a "steered" wake interacts with a downstream wake and with laterally adjacent wakes.

A first result of the paper is a motivation to develop new physics for a control-oriented model of wind farm control, which includes the effects of these counter-rotating vortices. This is in fact a focus of ongoing efforts at NREL. Such a new model should improve predicting the SOWFA cases presented in this paper. More importantly, it is clear that wind farm control strategies based on such models would pursue different, and perhaps more effective, wind farm control strategies than are currently designed.

A second result is the suggestion that wind farm control and wake steering should be thought of, not as a geometrical redirection of wakes but, as the generation of large-scale flow structures that will aid in the improved performance of wind farms. In other words, emphasis should shift from controlling the wakes, which are only deficits, to controlling the entire flow. In flow control, positive effects such as entrainment of new flow and creation of large-scale flow structures can be modeled and affected in addition to wake properties.

Future work should strive to better model these structures in control-oriented models, and to design controllers that seek to use these models to maximize the impact of control using minimal effort.

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