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# LES-based validation of a dynamic wind farm flow model under unsteady inflow and yaw misalignment

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# LES-based validation of a dynamic wind farm flow model under unsteady inflow and yaw misalignment

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**Abstract.** This work presents the validation of an extended version of the control-oriented, dynamic wind farm flow solver SPLINTER. The two-dimensional model is applied to use cases of wake steering by yaw misalignment and inflow wind direction variations and the results are compared to large-eddy simulations (LES). While SPLINTER is able to reproduce the antagonal behaviour of decreasing upstream and increasing downstream turbine power under wake deflection, a systematic deviation of the downstream power is detected and quantified, which is connected to underrepresented three-dimensional wake effects. In case of changing inflow wind direction, SPLINTER is capable of computing movement and shape of the bending wakes. The model smooths small-scale turbulent structures and disturbances and does not reproduce wake meandering, but manages to describe the evolution of the mean flow, which is tested by averaging over an ensemble of LES and comparing the resulting flow fields and turbine power time series. Under dynamic inflow conditions, SPLINTER is able to predict at which time intervals and at which rates downstream turbines will be influenced by wakes, which can improve the accuracy of short-term power and load forecasting and enables its application to online model predictive wind farm control.

## 1. Introduction

Wakes of upstream wind turbines can lead to reduced power generation and increased structural loads at downstream turbines due to wind speed deficit and enhanced turbulence. These detrimental effects can be partially mitigated by performing appropriate control actions [1]. On the wind farm level, wake steering [2, 3] and dynamic induction control [4, 5] show potential to optimise farm operation. Model predictive control aims to forecast the influence of applied control actions on the wind farm operation and optimise the control parameter setpoints for a specified objective function. Various sophisticated and efficient wake models have been established to reproduce wake behaviour under steady flow conditions. This includes the analytical Gaussian wake model [6], which has been continuously extended to improve the description of wake shape, velocity deficit, wake deflection and superposition under various atmospheric conditions [7, 8]. For accurate short-term predictions of the wind farm flow field, it is however highly relevant to capture dynamic effects, including changes of wind speed and direction and time variable control actions. Several fast dynamic wake models for control applications have been developed and introduced in recent years [9, 10, 11].

This work presents the extension of the previously introduced efficient, control-oriented, dynamic wind farm flow solver SPLINTER [12, 13] and its application to cases of yaw misalignment and unsteady variations of the wind direction. As a distinction to other models, SPLINTER combines a discretized, two-dimensional velocity field and a Lagrangian particle propagation scheme, which can be used to integrate any kind of flow field measurement sources and generate a time dependent background field by parcel propagation and spatio-temporal interpolation. This structure allows the model to act as efficient 2D Navier-Stokes solver, including turbine-flow momentum exchange by an actuator disc model, and at the same time to propagate any number of additional desired properties with the flow, which potentially can include turbulence and uncertainty measures.

The purpose of this validation study is to assess the limits of the SPLINTER 2D model, i.e., to determine which temporal and spatial scales can be resolved and which uncertainty magnitude can be expected in consequence of insufficiently incorporated effects. This is approached by comparing results for flow and wake behaviour to large-eddy simulations (LES) conducted with the atmospheric PALM environment [14].

The remainder of the paper is organised as follows: Section 2 describes the methodology of the featured SPLINTER model and the reference LES. Case studies for wake deflection and dynamic wind direction change and their validation results are presented and discussed in Section 3. Finally, Section 4 provides conclusions and an outlook for future research.

## 2. Methodology

### *2.1. The SPLINTER flow model*

Flow field evolution is calculated by an extended version of the two-dimensional, step-wise Navier-Stokes solver, presented in [12, 13]. The model uses a discretised spatial grid and features an actuator disk model for turbine-flow interactions, an efficient advection algorithm, viscous fluid effects, 2D-adapted mass conservation and wake dissipation. It is based on the simultaneous evolution of flow field and undisturbed, wake-free, background field. The time-dependent background field can either be prescribed for the simulation duration or reconstructed from measurement data. Since the fluid is propagated through the simulation domain by solving the dynamic flow equations, it is possible to include effects of unsteady inflow conditions, as well as time and space dependent sink and source terms for momentum and turbulence to describe turbine-flow interactions and wake dynamics. Furthermore, it is possible to propagate additional characterizing scalar properties with the flow, like measures for model uncertainty, turbulence intensity and vorticity, and to extract desired quantities at any position in the domain. The model behaviour is steered by several parameters. Compared to the state described in [12], the model was translated from MATLAB to Python. Additionally, a parameter $p$ was added, scaling the turbine power by $(\cos(\gamma))^p$, where $\gamma$ is the yaw misalignment angle. Tuning of all available model parameters, including $p$, was extended for the present atmospheric conditions by comparison to LES data. Furthermore, a functionality was implemented to use slices of LES data as dynamic inflow boundary conditions. In accordance with the reference LES, described in Sec. 2.2, grid cell steps of 5 m and a time step of 0.25 s are used for all SPLINTER simulations.

### *2.2. Large-eddy simulations with PALM*

Large-eddy simulations conducted with PALM [14] are used as validation cases for the SPLINTER model results. PALM is a meteorological modeling system for atmospheric boundary layer flows. An actuator disk model with rotation (ADMR) is utilized for turbine-flow interactions, as described in [15, 16]. In case of the dynamic simulations, a constant rate of wind direction change is specified, and the wind direction variation is propagated with the flow, leading to a realistic velocity distribution throughout the simulation domain. The procedure to impose a propagating wind direction change was developed by [17] and uses the methodology of an artificial Coriolis force introduced by [18]. The full LES domain is illustrated in Fig. 1. The spatial grid step size in $x$- and $y$- direction is set to 5 m and the time step is kept fixed at

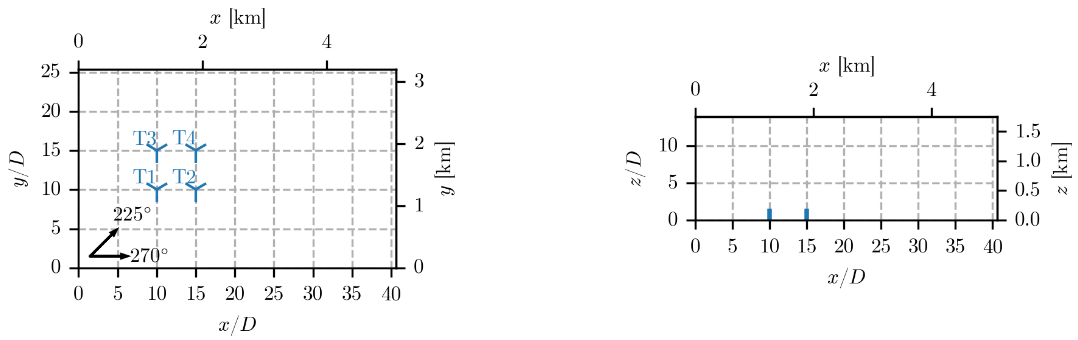


**Figure 1.** LES domain from top and side view. Wind turbines are labeled and indicated in blue. In the dynamic case study, the inflow wind direction changes from 270° to 225°.

0.25 s, which ensures a Courant-Friedrichs-Lewy number smaller than one. The grid step size in $z$-direction amounts to 5 m up to a height of 600 m and is stretched by a factor of 1.08 at higher altitudes. Both of the conducted case studies employ the NREL 5 MW reference turbine [19] with rotor diameter $D = 126$ m and hub height of 90 m. During the dynamic main simulations, a time dependent velocity field is prescribed at the inflow $y$-$z$ plane at $x = 0$ m, and a radiation-type boundary condition is imposed at the outflow ($x = 5120$ m). The boundary conditions at the $x$-$z$ domain borders are periodic. Precursor runs of at least 36 hours are conducted before the main simulations to generate a turbulent, conventionally neutral boundary layer with inversion height of 500 m. The resulting shear exponent of 0.17 and vertical veer of 2° between lower and upper rotor tip correspond to the prescribed roughness length of 0.1 m and average wind speed of 8.3 m/s at hub height. LES are conducted with and without wind turbines present and results from the undisturbed case are used as inflow velocity field for the SPLINTER model.

### *2.3. Fitting of the wake centreline*

The centreline is an important characteristic of the wake. It indicates the general shape of the wake by following the wake core location downstream. Since the wake is highly unsteady, it is difficult to define an instantaneous wake centreline of LES fields. In case of wake models, which aim to describe the average wake effect or impose a smoothing effect, like SPLINTER, the wake shape is better defined. In the following, the wake centreline is determined by fitting Gaussian curves to the wake deficit along lines perpendicular to the local flow. In the nearer wake region (closer than 5 $D$), the actuator disk model induces a wake deficit profile with two peaks. Here, a double Gauss function is used for fitting and the centre point is defined as mean of the two Gauss centres, weighted with their amplitudes. In the far wake regions (further than

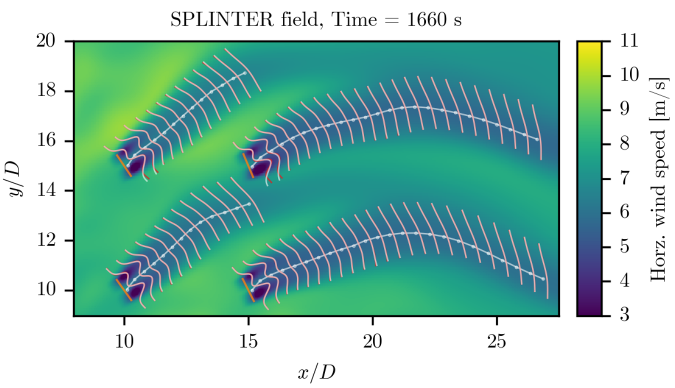


**Figure 2.** Fitting of wake centrelines for the horizontal wind speed field calculated with SPLINTER during wind direction change. The measured wake deficit profiles and corresponding Gauss fits are indicated in red and white, respectively.

$5\,D$), the centre point is defined by a single Gauss fit. The resulting fits and instantaneous wake centre lines produced by the SPLINTER model for a dynamic case with changing wind direction are visualized in Fig. 2. The presented analysis enables a representation, where the LES field snapshot can be overlaid with the instantaneous SPLINTER contour field and centreline. This illustration allows a direct comparison of the flow structure and will be used in the analysis of wake deflection in Sec. 3.1 and for the dynamic case study in Sec. 3.2.

## 3. Case studies

### *3.1. Wake deflection by yaw misalignment*

To study the effect of yaw misalignment, a two-turbine setup is used, including turbines T1 and T2 from Fig. 1, separated by 5 rotor diameters. The turbulent inflow field is steady with an average wind direction of 270°. Simulations of 25 minutes are conducted for 5 different, prescribed yaw angles of upstream turbine T1, ranging from 270° to 290°. This corresponds to average yaw misalignment angles $\gamma$ of 0°, 5°, 10°, 15° and 20° for turbine T1, while turbine T2 is kept at a constant yaw angle of 270°. The first 10 minutes of each simulation are discarded in the evaluation to ensure full flow development.

Figure 3 shows snapshots of the $x$-$y$ flow field generated by LES and SPLINTER for average yaw misalignments of 0° and 20°. The LES resolves a variety of flow structures, including turbulent variations and wake meandering. While the SPLINTER field shows wake characteristics of an actuator disk model, it is not able to reproduce small-scale structures and vortex dynamics. The two-dimensional presentation by SPLINTER can be seen as a smoothing, both in spatial and temporal dimension. When imposing a misalignment between wind and upstream turbine, its wake is deflected partially away from the downstream turbine, which is visible for both, LES and SPLINTER. The turbine power time series for $\gamma = 0°$ and 20° are compared in Fig. 4. As expected, LES resolves higher fluctuation frequencies for both, the upstream and downstream turbines. Since the upstream turbine is close to the imposed

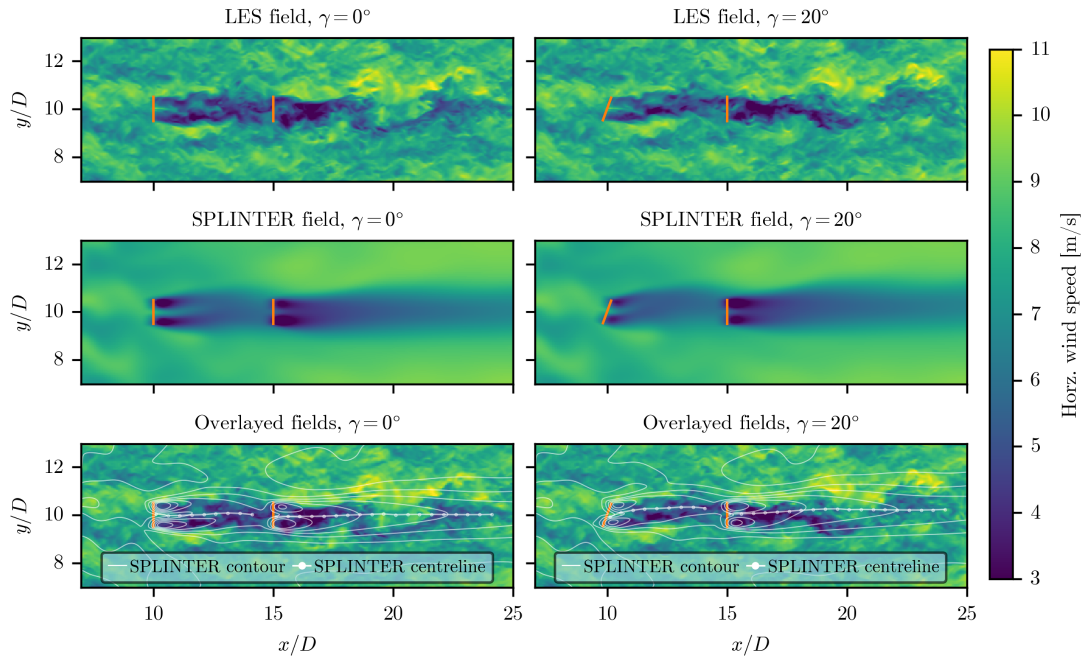


**Figure 3.** Comparison of instantaneous LES and SPLINTER flow fields for 0° and 20° yaw misalignment angle $\gamma$ at an arbitrary simulation time instant of 940 s.

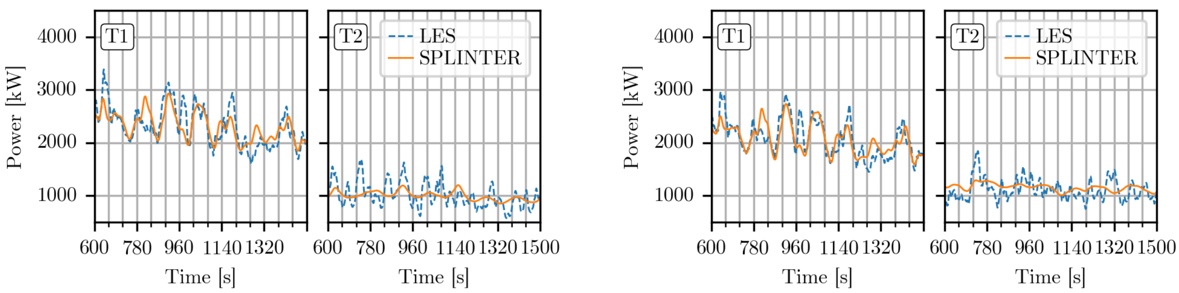


**Figure 4.** Comparison of turbine power for 0° (left) and 20° (right) yaw misalignment.

inflow field, the SPLINTER model can follow some of its power fluctuations, even though the matching of the amplitude varies. At the downstream turbine, however, the fluctuations are mostly induced by wake effects, like meandering, turbulent mixing and break up, which can not be captured by SPLINTER. Here, it is only possible to reproduce mean power and some large-scale fluctuations.

Figure 5 quantifies the validation for the investigated cases of yaw misalignment. As anticipated, the time-averaged power of upstream turbine and downstream turbine decrease and increase with increasing yaw angle, respectively. This behaviour is reproduced by both, LES and SPLINTER. The rate of downstream power increase is however higher for the SPLINTER model, which becomes more evident, when evaluating the relative deviation between the two models. The power deviation of the upstream turbine is well below 1% for all yaw angles. In contrast, the downstream turbine displays systematic behaviour, where the power is overestimated up to 4% for large yaw misalignments. We conclude that the 2D model is not able to fully incorporate 3D effects, especially under yaw misalignment. This includes insufficient description of mass conservation, 3D turbulence, and progressing deformation of the kidney-shaped 3D wake structure, driven by interaction of induced vortices, which was also found and elaborated in [20].

Furthermore, it cannot be neglected that the LES includes sampling over the whole rotor area, which stretches over an altitude range and is thereby influenced by a distribution of wind speeds and wind directions, driven by atmospheric shear and veer. SPLINTER works with a two-dimensional velocity field, which has to represent a vertical flow distribution. While the relative deviation average is reasonably small, the root mean square error (RMSE) between SPLINTER and LES at 4 Hz sampling amounts to roughly 10% of the power average for the upstream

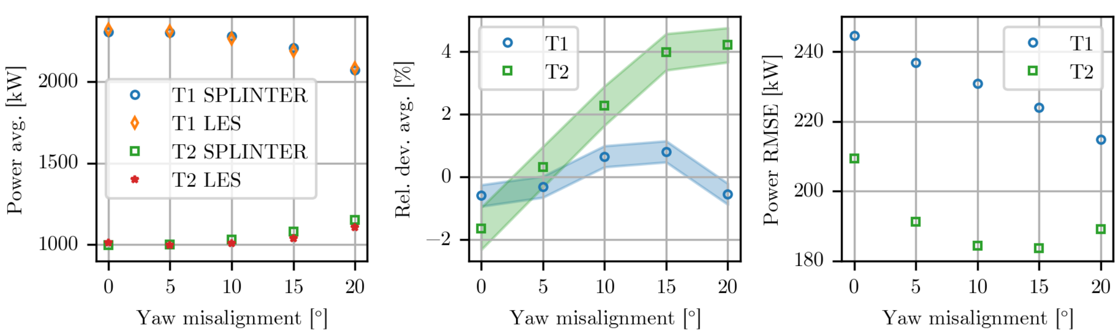


**Figure 5.** Turbine power comparison between SPLINTER and LES for different yaw misalignments of the upstream turbine T1. The shaded areas in the power average relative deviation plot indicate 95% confidence intervals with respect to the investigated time series.

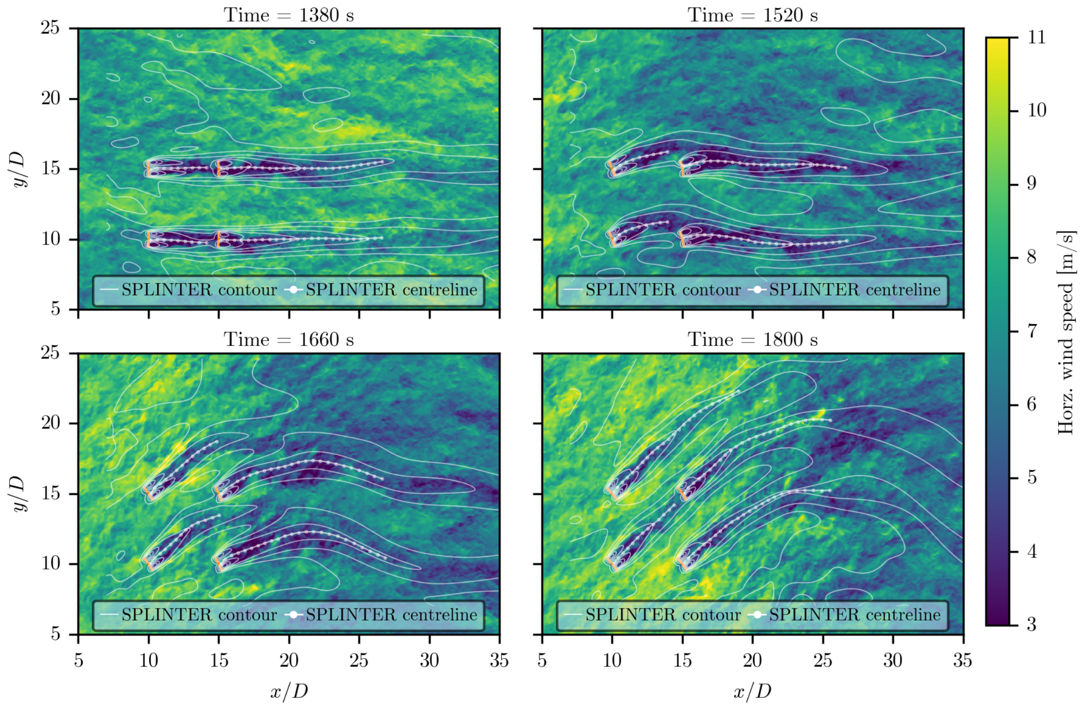


**Figure 6.** Instantaneous LES flow fields with overlay of SPLINTER contours and fitted centrelines during continuous wind direction change.

turbines and up to 20% for the downstream turbines, which coincides with the discussed wake induced fluctuations in the LES time series (see Fig. 4).

### *3.2. Wind direction change*

For the dynamic simulations with changing wind direction, a quadratic four-turbine setup is used, as shown in Fig. 1. The distance between upstream and downstream turbine and between the two upstream turbines is $5\,D$. Greedy control is applied for all dynamic simulations, i.e., the turbines align individually to their effective inflow wind directions. To mimic a realistic controller, a maximum yaw misalignment of up to 3° is tolerated, before the turbine starts yawing into the wind with a rate of $0.3\,°/\mathrm{s}$. After 20 minutes of steady inflow from 270°, a wind direction change with a constant turning rate of $0.2\,°/\mathrm{s}$ is imposed at the $y$-$z$ inflow plane over a time interval of 225 seconds, leading to final inflow wind direction of 225 degree, as indicated in Fig. 1. At the beginning of the simulation, the downstream turbines T2 and T4 are in full wake of the upstream turbines T1 and T3. When steady state is reached at the final wind direction, turbine T4 is now located in wake of turbine T1. Since the turning of the wind direction is propagated through the domain with the flow itself, it reaches the second turbine row later than the first turbine row. This leads to curved wake shapes and introduces the challenge to predict, when the upstream wakes will influence the downstream turbines. The wind direction change starts to influence the upstream turbines after a simulation time of about 1380 seconds.

Figure 6 shows instantaneous LES flow fields overlaid with SPLINTER contours during the wind turning duration. The curved wake shapes are clearly both, LES and SPLINTER. Furthermore, the wind direction change is accompanied by a propagating region with overall lowered horizontal wind speed, which is discussed below. As discussed previously in Sec. 3.1, some of the turbulence and wake effects cannot be reproduced by the 2D SPLINTER model, which again smooths temporal and spatial small-scale structures. The large-scale feature

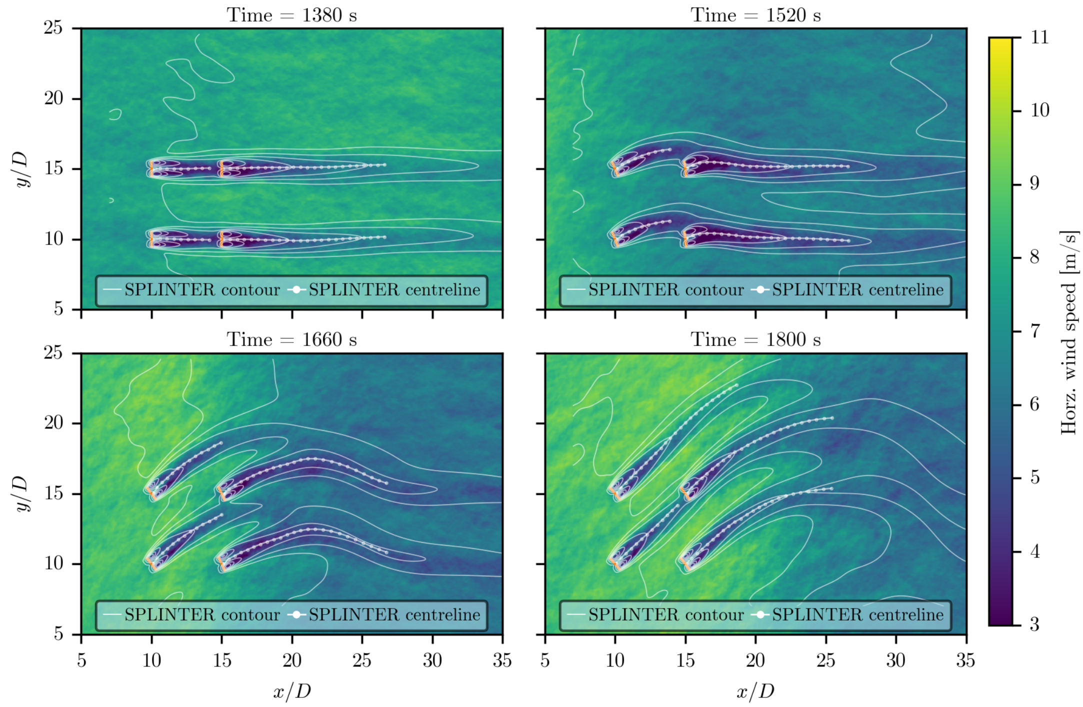


**Figure 7.** Average over an ensemble of 10 LES flow fields with overlay of SPLINTER contours and fitted center lines during continuous wind direction change.

represented by the wind direction change is however well captured by SPLINTER in direct comparison to the LES results. Most significantly, the shape and movement of the wake center line and, consequently, the time instances, when the wake of turbine T1 ceases to influence T2 and starts to influence T4 are well reproduced.

It shall be emphasized that the scope and purpose of SPLINTER, as control oriented, efficient 2D model, is not to resolve flow structures on all scales, but to provide the mean flow and wake behaviour in both, stady-state and dynamic flow situations. In this context, the term 'mean' needs to be understood not as temporal average, but as ensemble average over fluctuations, small-scale structures and wake effects, which are induced by 3D turbulence. To test a wake model in steady-state conditions, it would be sufficient to average over a long time interval and use ergodicity to connect time and ensemble average. In case of dynamic flow conditions, the situation is more complicated, since a time average would generally smear the wake and flow structures over a diffuse region. To investigate, if SPLINTER can meet its objectives and describe the mean flow, we therefore propose the following validation procedure: Ten distinct LES are carried out, each with the same imposed turning of the mean wind direction at the inflow plane, but utilizing the initial precursor simulation at different points in time. Choosing a sufficiently large time separation of 30 minutes leads to effectively independent turbulence states during each individual LES run. Averaging over the set of ten generated LES fields (denoted as LES ensemble) leads to the mean flow and mean power with full time resolution of 4 Hz. The ensemble average is then used to generate inflow conditions for the Splinter model for validation.

The result for the instantaneous, ensemble averaged flow fields can be seen in Fig. 7 and directly compared to the results of a single simulation run from Fig. 6. The mean LES field shows less turbulent structures and sharply defined wake shapes, which correspond well to the SPLINTER simulation results during the whole duration of wind direction shift. As observed for the single simulation, there is a region with overall reduced horizontal wind speed, which

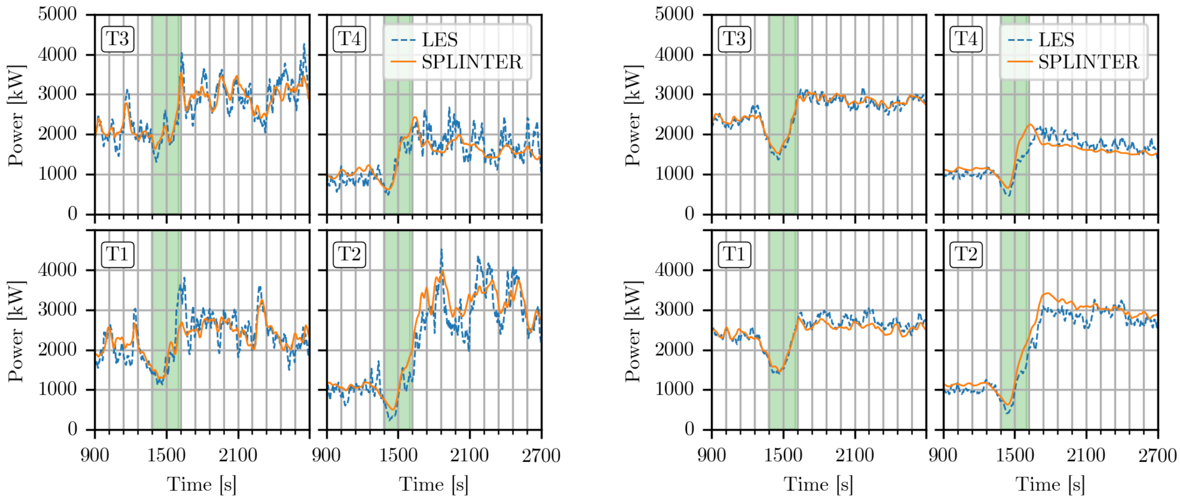


**Figure 8.** Comparison of turbine power between LES and SPLINTER for a single simulation (left) and for the average over an ensemble of 10 simulations (right). The shaded areas indicate the time interval, where the wind direction changes at the first turbine row.

travels slightly ahead of the advected wind rotation.

The graphical observations are supported by evaluating the power time series for both, a single simulation run and the ensemble average, shown in Fig. 8. Before the wind direction change reaches the upstream turbines at approximately 1380 seconds, turbulent fluctuations are visible in all turbine power time series. The major trends of the LES results are followed by SPLINTER, while small-scale fluctuations can not be captured, which is in agreement with the observations from Sec. 3.1. The mean upstream turbine power amounts to approximately 2300 kW, while the downstream turbine power is reduced by the wakes to about 1000 kW. After the wind direction change arrives at the downstream turbines, the wakes are shifting away and a continuous increase in power can be observed. When the final wind direction is established at approximately 1800 s, turbine T2 is not affected by wakes anymore and approaches mean power values similar to the upstream turbines. Turbine T4, on the other hand, is now influenced by the wake of T1. Since the distance from T1 to T4 is 1.4 times larger than the distance from T3 to T4, the wake effect is reduced and the mean power of T4 settles at about 1800 kW.

Comparing results for the ensemble mean, SPLINTER is able to predict the time onset and offset of power variations induced by the movement of the upstream turbine wakes. Furthermore, large-scale fluctuations can be tracked, at least for the upstream turbines. While average power of T2 and T4 are overestimated and underestimated after the wind direction change, respectively, the deviation of mean power remains in reasonable bounds for the intended applications of the flow model. The root mean square errors over the whole simulation amount to 220 kW, 196 kW, 129 kW, and 245 kW for turbines T1 to T4, respectively, i.e., reside between 6% and 11.4% of the average farm power of 2150 kW. Since turbine T4 is exposed to wakes from two different turbines, it shows the largest deviation due to overestimation and underestimation of the power before and after the wind shift. It shall be mentioned that a more extensive model parameter tuning, adapted to the varying atmospheric conditions, could be a way to improve mean power prediction of the SPLINTER model, especially for turbines under wake conditions.

Furthermore, three significant effects are visible in the power time series, shown in Fig. 8. First, fluctuations are enhanced in general after the wind direction shift. Second, there is a reduction in power even before the wind shift arrives at the first turbines. This is due to the overall horizontal wind speed reduction, indicated in Figs. 6 and 7. Third, the mean turbine power of the upstream turbines and of turbine T2 reaches higher values after the wind direction change compared to the initial steady state values. Observing the mean curves, it is evident that this overshoot degrades systematically with time. It would thus be worthwhile to simulate for a longer time after the wind shift termination to investigate whether the mean power settles at the initial values or a higher overall rotor effective wind speed is left as an effect of the imposed wind turning on the atmospheric flow field. This analysis was however out of scope for the presented work. Furthermore, it does not significantly impair the direct comparison of SPLINTER and LES, since the LES field is used as inflow condition for the SPLINTER simulations.

We propose that all three described effects are attributed to induced instabilities in the atmospheric boundary layer. During wind direction change, a horizontal gradient in the mean wind speed $\partial\overline{u}/\partial x$ is imposed, which needs to be compensated by a vertical gradient $\partial\overline{w}/\partial z$ to ensure mass conservation, as discussed in [17]. This interaction leads to the previously mentioned enhancement in turbulence, shifts in pressure as well as horizontal and vertical components of the flow momentum, and the reduction in overall horizontal wind speed. After the wind direction change is completed, flow energy is redistributed between pressure and vertical and horizontal velocity components, which results in the visible overshoot in rotor effective wind speed and thus in turbine power. The results indicate that the atmospheric boundary layer requires a longer time interval to relax back to steady state conditions, supported by the gradual decrease of turbine power after the wind direction change.

## 4. Conclusions and Outlook

An extended version of the previously introduced two-dimensional dynamic wind farm flow solver SPLINTER [12] is validated for cases of yaw misalignment and inflow wind direction change by comparison to LES results. The purpose of SPLINTER is to provide an efficient solver for power forecasting and model predictive control under dynamic wind conditions.

The presented model is able to describe the opposing behaviour of upstream and downstream turbine power under yaw misalignment. While predictions for the upstream turbine are in good agreement with LES results, the downstream average power deviation shows an overestimation of up to 4%, which increases systematically with yaw angle. The 2D model is not able to fully capture turbulence and 3D effects. Knowing the model limitations and the error's order of magnitude enables to estimate the model uncertainty.

A planned approach to incorporate 3D effects is to implement a multi-layer model, introducing a few (3 to 7) horizontal 2D slices along the vertical rotor extension. This would allow to account for atmospheric shear and veer, and for the vertical variation in turbine force distribution and to induce a kind of spatially variable vorticity parameter at the rotor planes, which is propagated with the flow. Mass and momentum exchange between the layers can improve mass conservation and mimic vortex effects, which is expected to lead to a better representation of the wake shape.

SPLINTER is able to compute a time resolved representation of the wake evolution under wind direction rotation. The bending of the wake centreline is well defined and the position and shape of the wake agrees with LES results. This becomes more evident, when comparing SPLINTER results to the average over an ensemble of 10 LES simulations. While larger scale disturbances, like local gusts and turning of the mean wind direction can be captured, smaller scale turbulent structures and fluctuations are smoothed by SPLINTER. Furthermore, wake meandering, mixing and breakup are not represented to full extent. Turbulence and wake induced small-scale fluctuations in the turbine power can thus not be resolved. Nevertheless, it is overall possible to predict at which instants and to which degrees turbines will be influenced by wakes, enabling more accurate power and, potentially, load predictions. Improved short-term forecasting can be used to determine control setpoints, e.g., for wake steering, induction control and active power control to optimise farm power and turbine loads and enhance grid stability.

For the conducted runs of 48 min simulation time with time and grid steps of 0.25 s and

5 m, respectively, computation times amount to 288 min for LES on 128 cores and 30 min for SPLINTER on a single core. The model is not yet tuned for efficiency. By code optimisation and parallelisation, major increase in computational speed is expected in future program versions.

SPLINTER shows promising results for wake and power predictions under unsteady conditions. Nevertheless, the condition of this validation is to know the horizontal components of the inflow plane velocity field at a distance of 5 rotor diameters in front of the upstream turbines during the whole simulation time. In the present case, LES provides the inflow field with a resolution given by its grid spacing and time step. In realistic applications, measurements of the velocity field are limited. Each turbine can act as a measurement point, providing high frequency SCADA data. Furthermore, additional information can be provided by met masts placed in front of the wind farm and LIDAR devices, which can scan over defined angle ranges to deliver velocity field measurements. An algorithm is already implemented in SPLINTER to propagate point measurements and generate inflow and background fields by spatio-temporal interpolation [13]. For future work, we propose to employ not the whole, high frequent information about the inflow plane provided by LES, but to generate point or LIDAR measurements in front of the wind farm and use the internal algorithm to propagate the background flow. This can be combined with utilization of online turbine data, which act as additional measurement points and adds information about the flow state in the wind farm domain. Thus, SPLINTER can be tested under more realistic conditions, leading a step closer to online control applications.

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*Data availability* Samples of the LES and SPLINTER simulation results are available at [21].

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