Farm to farm wake interaction in WRF: impact on power production

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Abstract. This work focuses on the study of interactions between neighboring wind farms through a mesoscale numerical modelling approach. High resolution simulations with three wind farm parameterizations (WFP, EWP and IAWFP), implemented on the WRF model, over a set of “real world” neighboring onshore wind farms are performed. The sensitivity of the three parameterizations to wake development is analyzed. The older version of the WFP is also included to account for differences between versions in terms of wake length and intensity, and TKE production and advection. Finally, the impacts of upstream wind farms are studied through a series of simulations where they are “disabled” and the increases in power at downstream farms are quantified. These results and the adopted methodology have direct application and are highly relevant for the feasibility assessment of new wind farms in the shadow of other existing ones.

1. Introduction

In a context of steady wind energy growth, where the wind farm global coverage is increasing, with bigger parks, turbines with greater height and rotor swept area and with wind farms located closer to each other, an accurate estimation of farm wake intensity and extension is needed. The increase in the density of wind farms per unit area makes potential interaction between them a clear possibility, because wind farm wakes produce a reduction of the incident wind on those that are located downstream. These interactions between farms have the potential to reduce the energy production of individual wind farms [1, 2], especially in stable environments or situations where, as demonstrated in [3, 4], wakes tend to be more persistent downstream. These phenomena are beginning to be studied with greater attention due to the higher density of installed capacity in the world and their unintended consequences related to power losses. In this sense, the National Renewable Energy Laboratory (NREL) researchers projected in 2019 that more than 50 % of new installed capacity in the U.S. will be in the “shadow” of another already existing wind farm [5]. Moreover, one of the biggest offshore wind farms developers, Ørsted, announced in 2019 a downgrade on its anticipated internal rate of return, due mainly to the underestimation of energy losses produced by wakes within wind farms and between
neighboring wind farms [6]. Nowadays, there are some efforts to explore these interactions through an observational approach, like the American WAKE ExperimeNt (AWAKEN) [7]. However, due to the time and costs of these campaigns high fidelity simulations are also appreciated and required to assess power projections for new developments or expansions of the existing ones.

Owing to the distance between neighboring wind farms and the time scale of the interaction processes, a mesoscale modelling approach is required. In this sense, the Weather Research and Forecasting (WRF) regional model [8] has a wind farm parameterization implemented on its standard version that represents the presence of wind turbines (WT) in the atmospheric flow, the Wind Farm Parameterization (WFP) developed originally by [9] (from now on, Old WFP). This scheme was updated last year by [10], where two modifications around the turbulent kinetic energy (TKE), the magnitude and its advection, were implemented. On the other hand, there are another two wind farm parameterizations implemented in the WRF model but not distributed on its standard version, the Explicit Wake Parameterization (EWP) [11] and the Induction Aware Wind Farm Parameterization (IAWFP) [12].

This work aims to address the potential interactions between neighbouring onshore wind farms through high resolution WRF simulations. In order to achieve this goal two different experiments are performed. First, with the objective of exploring the differences between the four wind farm parameterizations mentioned above, single wind farm simulations are conducted and the behaviour of the wind speed and TKE vertical profiles deficits over the wake region downstream are studied. This experiment, from now on Experiment A, is performed for a single wind farm placed in Patagonia, where a westerly flow day is analyzed as a study case. Then, the interaction problem between wind farm arrays, from now on Experiment B, under varying wind farm parametrizations is analyzed. For this experiment, a region with high wind farm density near the Buenos Aires maritime coast in Argentina is considered. The interaction between six wind farms located in this area for a winter week study case is conducted. Finally, impacts of the farm to farm wake interaction on the power production are analyzed through a series of simulations where some farms are “disabled” and the changes in downstream farms power production are quantified. As mentioned in [1], assessments of wake impacts on power production are rare. While in that work the WFP was used to assess the downwind wake impact over a wind farm in Western Texas in the present work two different wind farm parameterizations are used to estimate the impacts of a single wind farm or a cluster of them on the power production of downwind waked wind farms placed near the ocean in the center-east of Argentina.

2. Methodology

In order to explore wake differences from the four distinct wind farm parameterization schemes and to account for the interactions between neighbouring wind farms, experiments A and B respectively, high resolution WRF simulations were performed. As it was highlighted in [12] there is a need to conduct simulations with horizontal resolutions around 300 m - 500 m, to capture the “real” layout of wind farms and consequently represent in a more accurate way their wakes development. Therefore, in both experiments, configurations of four nested domains with resolutions of 9 km, 3 km, 1 km and 333 m were proposed for all simulations. Other settings that were common to both experiments are described hereafter. The initial and boundary conditions were provided by the ERA5 reanalysis dataset [13]. This dataset was selected for being one of the reanalyses that best represents near surface winds [14]. The top of the model was located at 50 hPa, with 41 vertical levels below and with a higher density of levels in the first few hundred meters. The details of the model configuration in relation to nudging technique and selected parameterizations can be found in Table 1. All of these settings are in agreement with those proposed, after several sensitivity experiments, for the New European Wind Atlas (NEWA) production [15].
Table 1. Model configuration.

| Configuration                                      | Details |
|----------------------------------------------------|---------|
| Nudging technique in the outer domain (d01):       | Spectral |
| Radiation scheme:                                  | RRTMG [16] |
| Land surface scheme:                               | NOAH-LSM [17] |
| Surface layer scheme:                              | Monin Obukhov (Eta) [18, 19] |
| Boundary layer scheme:                             | MYNN 2.5 [20] |
| Cumulus scheme in d01:                              | Kain-Fritsch [21] |
| Microphysics scheme:                               | WSM5 [22] |

Regarding each experiment, their particular configurations, as well as their locations and wind farms considered, are described below.

2.1. Experiment A

As mentioned before, in order to explore the differences between wind farm parameterizations, in terms of wind speed deficit and TKE source, a single wind farm experiment was proposed. For this experiment one of the main and oldest wind farms in Argentina was selected. The Rawson Wind Farm (RWF) is located in the southern region of the country and is composed of 43 wind turbines Vestas V90. Its layout and location can be observed with black dots in Figure 3 and more detailed specifications can be found in [12]. For this experiment, several simulations were performed for a day which showed a strong west wind component, in pursuance of having a clear mean wake towards east to study its averaged behaviour. Within the chosen day five simulations were conducted, four of them activating each wind farm parameterization: the Old WFP, the newer version of this one developed by [10] (from now on, the WFP), the IAWFP and the EWP. One last simulation not considering the presence of the wind farm (No_WT) was included in order to account for the differences between the schemes and the free flow. Two-day long simulations were performed for the selected day and the day before and the first simulated 24 hr of each simulation were discarded as model spin-up time.

2.2. Experiment B

On the other hand, as already mentioned, for the wind farms interaction problem, an area with high density of wind farms was chosen. This region is located near to the city of Bahia Blanca, in the south of Buenos Aires Province in Argentina. In this 50 km by 55 km area there are six wind farms, totaling 175 wind turbines and 643 MW, placed over a terrain with a slight slope towards northeast, Figure 1. All of these wind farms came into operation in the last two years. A description of each of them, including installed capacity and type of turbines can be found in Table 2 while their locations and respective layouts are presented in Figure 1.

From the study of the region’s wind resource, through the last two years of ERA5 reanalysis data, it was found that the prevailing wind directions in the area came from the NNW-N sector. Taking this into account, the fact that wind farm wakes can reach distances exceeding the 20 km, even achieving longitudes of 70 km under stable conditions [23, 1], and the geographical location of these wind farms placed in the surroundings of Bahia Blanca city, it is feasible to assume that there might be interactions among some of them. Therefore, to study these potential interactions a winter week simulation with prevailing NNW - N wind directions was selected. The choice of a winter week is connected to the fact that during this season there is a
Figure 1. Location of the main wind farms at the surroundings of Bahia Blanca city and terrain height above sea level.

Figure 2. Wind direction and wind speed at 100 m height from the ERA5 time series for the winter week.

Table 2. Wind farm characteristics.

| Wind Farm         | Capacity [MW] | WT model       | Hub height [m] |
|-------------------|---------------|----------------|----------------|
| 3 Picos (3PWF)    | 214           | V136 - 4.2     | 130            |
| Energética (EWF)  | 99            | AW 132/330     | 120            |
| G. del Río (GRWF) | 10            | EN 2.5-110     | 90             |
| La Genoveva (LGWF)| 120           | V126 - 3.5     | 110            |
| Corti (CWF)       | 150           | V126 - 3.5     | 90             |
| de la Bahía (BWF) | 50            | V126 - 3.5     | 117            |

greater probability of occurrence of stable conditions. Therefore, longer wake developments are expected and consequently greater potential interactions between wind farms. The wind speed and direction, at 100 m above ground, for that 2019’s winter week from the ERA5 data are shown in Figure 2.

The simulations for this week were set up in two overlapped segments of 5 and 4 days, discarding the first day of each segment as model spin-up time. To represent the presence of wind turbines in the mesoscale model and also to evaluate differences between them, the Old WFP, WFP, IAWFP and EWP parameterizations were used. The inner of the four nested grid domains was configured to be coincident with the region shown in Figure 1.

Finally, to assess the potential interaction among farms and to study its consequent impact on energy production, four different experiments were devised. A first experiment where all the farms were included in the simulation (FULL), a second experiment in which the 3PWF
was excluded (No 3P), a third experiment in which the cluster of wind farms located in the northwest were excluded from the simulation, that is, the 3PWF, the GRWF and the EWF, this was called No NW and a last experiment in which only the presence of de la Bahia Wind Farm (PB) was considered. The intention behind “removing” farms from the simulations is to quantify how the energy production of downstream farms is modified when they are not under the influence or do not perceive the impact of wind farms that are upstream.

3. Results
3.1. Single wind farm simulations (Experiment A)
To illustrate the differences in the wake characteristics within the RWF and its downstream propagation and recovery, for each of the 4 parameterizations, the vertical profiles of wind speed and TKE deficit were estimated at different points within the farm and downstream. As already mentioned, this was made for a particular day with a strong west wind component. Figure 3 shows the wake regions for that day and for each parameterization, and the location of the seven points along the transect chosen to calculate the different vertical profiles. In the figure, analyzing from west to east, it can be observed that the first three points are within the RWF while the remaining points are downstream of it. It is evident, for all the parameterizations, that the last point is outside the region where the average velocity differs in more than 5% from the free flow, and in the case of the EWP the previous point is also located outside this region. It can also be observed that the WFP and the Old WFP wakes are quite similar, while the IAWFP wake seems to be the most intense and prolonged one. On the other hand, the EWP presents the weakest and shortest wake.

Then, with the objective of assessing in greater detail the observed differences for each parameterization, the analysis of the wind speed and TKE deficits profiles were performed. For this, the vertical profile pairs of velocity and TKE were used to estimate the deficits, i.e. \( \Delta \{ \text{Spd} | \text{TKE} \} = \{ \text{Spd} | \text{TKE} \}_{\text{param}(x,y,z,t)} - \{ \text{Spd} | \text{TKE} \}_{\text{No wT}(x,y,z,t)} \). With the resulting time series, the median and interquartile range were computed for each selected point, Figures 4 and 5. The first thing to be observed in Figure 4 is that the larger deficits for all parameterizations are found at the last point within the farm (0 km), downstream they begin to decrease reaching values close to zero at the last point (11 km). It can also be noticed that both versions of the WFP and the IAWFP exhibit similar behaviors, with slightly higher deficits for the IAWFP due to its formulation. On the other hand, the EWP imposes smaller deficits in the rotor area within the wind farm region but greater in the near surface levels. This was also observed in 24. On the contrary, for the last point inside the wind farm (0 km), it can be observed that deficits but wind speed acceleration close to the surface for both versions of the WFP and the IAWFP. This is consistent with the fact that the thrust force is applied at the rotor disc and that makes more fluid to pass underneath, as previously also observed for the WFP in 5 24.

Probably, the main differences between parameterizations are presented for the TKE deficits, Figure 5. It can be observed that while the WFP and the IAWFP exhibit maximum mean values around 0.5 m²/s² for the last point within the farm (0 km) and above the hub, the EWP and Old WFP show values close to zero. However these differences quickly disappear and from the fifth point (5 km) on, around six turbine diameters downstream the farm, all TKE deficit profiles resemble each other and get closer to zero.

3.2. Multiple wind farms simulations (Experiment B)
As already mentioned the region around Bahía Blanca city was selected to study the farm to farm wake interactions. As a first exploratory analysis of the interaction between these wind farms located in an area with a radius of less than 30 km, the wind speed field at 100 m height resulting from the simulations considering all the farms and using the four parameterizations, were evaluated. Although in almost all the cases some kind of interaction among farms could be
Figure 3. Mean wakes for the 4 wind farm parametrizations. The black dots represent the position of the wind turbines and the red points the cells selected to estimate the vertical profile deficits.

Figure 4. Vertical profiles of the median and interquartile range of velocity deficits, for the seven points located on the transect represented in Figure 3. The labels are set according the distance of each point to the last row of turbines. As a reference the wind farm size is 4 km x 4 km. Dotted lines represent the limits of the rotor area while the broken line shows the RWF hub height (≈ 80 m).
Figure 5. Same as Figure 4 but for TKE deficits.

observed, Figure 6 shows, as an example, the velocity fields at 100 m height for some selected moments in the simulated winter week, where the impact of one farm or cluster of farms over another can be appreciated.

One of the most visible outcomes is the lowest intensity presented by the speed deficit regions, which occur downstream each wind farm, in the simulations using the EWP versus those using the Old WFP, the WFP or the IAWFP. Regarding these last three, their velocity fields are quite similar, with a slightly greater wake intensity in the case of the IAWFP. This behavior is related to that observed in experiment A, where the greatest speed deficits at levels close to hub height were imposed by the IAWFP while the EWP was the parameterization that imposed the lowest ones. In this Figure, it can also be observed, in all panels, the impact of the 3PWF onto the GRWF and the EWF. Also, for July 16th (first row) it can be clearly seen the impact of the LGWF over the BWF, while in the second row (July 18th), the interaction between this last one and the CWF is reflected. Moreover, for July 19th (third row), the joint impact of the farms located in the northwest on LGWF is shown. On the other hand, although it was sought to evaluate interactions between farms when the wind came mainly from the NW-N sector, in the analyzed week there was one day where the wind rotated and presented an east component. This day as it can be observed in Figure 2 was the 20 of July. As a consequence of this wind rotation it was possible to observe situations like the one presented in the fourth row, where the impact of GWF over CWF is exhibited.

3.2.1. Impact on power production

Even though Figure 6 exhibits interactions among different wind farms, by showing regions of lower wind speed produced by wind farms that are capable of reaching other farms located downstream, the impact of these interactions on the power production will depend on the intensity of the wake when reaching the farms. As can be seen in Figure 6, the deficit magnitude in the wind speed depends on the wind velocity upstream, on the stability conditions and also, in the case of simulations, on the wind farm parameterization used.

For this reason, in order to assess the impact of some farms on the power production of the others located in their surroundings, different simulations, “disabling” certain farms, were performed in order to quantify the power production of the remaining farms and compare them with the production resulting from simulations where all the farms were considered. Hence, the experiments mentioned in Section 2 were carried out, but only for the parameterizations that presented the greatest differences in the wake development, the IAWFP and the EWP.
Figure 6. Velocity fields at 100 m height, resulting from FULL simulations, Old WFP (left), WFP (center left), IAWFP (center right) and EWP (right), for 03 UTC July 16th (a), 22 UTC July 18th (b), 21.10 UTC July 19th (c) and 12.50 UTC July 20th (d).

Table 3 presents the percentage differences in power production for each wind farm, by omitting the presence of 3PWF (first column), the north west (NW) wind farm cluster (second column) and all wind farms but the BWF (third column), resulting from the simulations with the IAWFP and the EWP, for the full winter week. As it can be observed all values present
Table 3. Percentage difference in power production for each of the wind farms in relation to the different experiments for the winter week.

|                   | No\_3P/ FULL [%] | No\_NW/ FULL [%] | PB/ FULL [%] |
|-------------------|-------------------|-------------------|--------------|
|                   | IAWFP             | EWP               | IAWFP        | EWP          | IAWFP        | EWP          |
| EWF               | 5.79              | 3.10              | -            | -            | -            | -            |
| GRWF              | 3.94              | 2.25              | -            | -            | -            | -            |
| CWF               | 1.44              | 0.56              | 1.53         | 1.14         | -            | -            |
| LGWF              | 0.74              | 0.32              | 0.98         | 0.79         | -            | -            |
| BWF               | 0.38              | 0.21              | 0.76         | 0.23         | 1.37         | 0.68         |

positive signs, meaning that when a wind farm or a cluster is not present a positive impact in the production of the remaining farms is seen. This is due to these farms having a higher incident wind than the one they would have had if considering the presence of the omitted farms. On the other hand, the EWF and the GRWF are the ones with major percentage differences due to 3PWF proximity. When assuming the absence of this last one, a positive impact results on EWF and GRWF with increments in power production of around 6 % and 4 %, respectively, from the IAWFP simulations. On this last point, it is important to emphasize that the EWP shows, in every case, lower values than the IAWFP, due to the stronger and larger wakes produced by this last one in relation to the EWP. Furthermore, the No\_NW experiment shows that not considering the presence of 3PWF, EWF and GRWF, represent an increase of 1.5 % and around 1 %, in the CWF and LGWF productions, respectively. Finally, the BWF may have produced 1.37% more energy if it had not been affected by the other 5 wind farms, according to the IAWFP simulations.

4. Conclusion, discussion and further work
The significant growth in the number of wind farms in the world, with a higher density of farms per unit area, added to the continuous technological development that allows wind turbines to have even greater heights and greater diameters, raises the need to study the interaction between wind farms located close to each other, as these interactions can produce important power losses. In this sense, a farm to farm wake interaction study, through a numerical modelling approach, was conducted for a set of six onshore wind farms located in the southeast of Buenos Aires Province in Argentina.

As the selected mesoscale model, the WRF model, has several options for parameterizing wind farms, and because it was found, last year, that the one distributed with its standard version and the most popular one presented a code bug and an overestimation of the TKE produced, there was a need to compare the outcomes of the older and newer versions of the WFP, as well as the results of two other parameterizations such as the IAWFP and the EWP. Therefore, the behavior of these four parameterizations was explored for a single wind farm case and the development of its wake was studied for a particular day. The intensities and lengths of the wakes at hub height were analyzed as well as the structure of the vertical profiles of wind speed and TKE deficits. It was found that the parameterization that imposed the greatest deficits at hub height was the IAWFP while the EWP was the one that reported the lowest values. Regarding the differences between the two WFP versions, both schemes exhibited similar results in terms of extension and intensity of the mean weak, and also for the wind speed deficit profiles. The bigger differences were found for the TKE deficit vertical profiles but only for the region inside the wind farm, as downstream the signal is quickly lost and all values become very close to zero. This is consistent with the hypothesis stated in [10] where it is suggested that the two
errors found in the Old WFP, the code bug related to the advection and the excessive TKE coefficient, compensated each other, giving rise to realistic profiles of wind speed and TKE and consequently to reasonable wakes.

These four schemes were also used to study the potential wake interactions between the set of farms in the proximity of Bahia Blanca city. High resolution simulations were carried out in order to capture in the most accurate way the wake shapes and their development, but avoiding to reach LES resolutions (less than 100 m according [25]). During the winter week simulated, multiple interactions were found among these farms located in some cases at distances greater than 20 km. These interactions were shown for the wind speed fields at 100 m (≈ the average hub height of the wind turbines involved in the study). Then, the impact of these interactions on power production were analyzed. As it was expected, the main impacts were reported for the farms located closer to each other, with power reductions of up to 6 %. However, impacts were also found in farms further away. It should also be mentioned, that even though the two parameterizations employed for this power impact study exhibited different results, in both cases the effects were significant.

This type of analysis would become extremely important in the design, operation and even expansion stages of wind farms, because it allows to represent the “shadow” effects and quantify the losses in terms of energy production, therefore becoming a vital tool for decision making. Regarding the PPA (Power Purchase Agreement) price for the energy produced by the Energetica Wind Farm (EWF) of 37.3 dollars per MWh and considering that in one week the presence of the 3 Picos Wind Farm (3PWF) resulted in a reduction in energy generation in the EWF of around 650 MWh, this phenomena would have produced losses of USD 24,000 during that week. If this situation were representative of what happened throughout the year, for which analysis the study period would have to be extended, the annual economic losses would be over one million dollars.

Future work will attempt to extend this power impact assessment and, on the other hand, to conduct similar studies over other regions. For example, the Patagonian region that comprises the cities of Rawson, Puerto Madryn and surroundings, where the RWF is located, presents a considerable wind farm density, even stronger winds and a greater tendency to stable conditions due to its location at high latitudes.

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