The effects of Open Cellular Convection on Wind Farm Operation and Wakes

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Abstract. Majority of the severe variability in power production of an offshore wind farm occurs when open cellular convection (OCC) is observed. With a diameter of 10 – 80 km, the open cells are essentially the main drivers of hour-scale wind fluctuations passing through the wind farm. Here we aim to quantify the impact of the OCC on Horns Rev-I offshore wind farm located in the North Sea, in terms of variance in the power production and turbulence intensity. Using mesoscale simulations, met-mast measurements and high frequency (1 Hz) SCADA data from all the operating turbines, the behaviour of power deficit and added turbulence intensity is explored comparatively with and without presence of open cells. The investigation is a case study performed on a ‘day-to-day’ basis with an in depth analysis of the in-farm effects, such as the wake behaviour and smaller scale atmospheric structures. For the investigated event, the study shows striking difference in wind farm operation under the open cell structures and underlines the importance of taking local mesoscale phenomena into account for wind farm operation monitoring and control, short-term wake estimation, forecasting and market participation.

1. Introduction

Open cellular convection (OCC) is three dimensional convective circulation of air that commonly occurs behind cold fronts over warmer water. Open cells are often present over the North Sea, e.g. (1; 8; 6). They can be observed in satellite images as hexagonal cloud patterns, as shown in Figure 1 in the west of Denmark. There is also a storm centre visible in Figure 1 northwest of Norway. In the open cells, the edges are cloudy, corresponding to upwards vertical velocity, and the centres of the cells are clear with downwards vertical velocity. Previous studies claim that the majority of the severe variability in power production of an offshore wind farm occurs when OCC is observed (9). With a diameter of 10 – 80 km, the open cells that are passing through the wind farm substantially enhance the variance over the timescales of minutes to hours (9; 5).

Here in this study, we aim to analyse the impact of the OCC on Horns Rev-I offshore wind farm in terms of variance in the power production and turbulence intensity within the wind farm. The behaviour of the wake effects with regards to the power deficit and added turbulence...
intensity on the downstream turbines within Horns Rev-I is investigated comparatively with and without the presence of open cells. Although the wind farm level hourly \((9; 8)\) and intrahourly \((10; 3)\) wind speed and power fluctuations driven by OCC have been investigated thoroughly, the corresponding impact to the wind farm operation and wakes is not previously explored. This study, therefore, aims to bring this mesoscale phenomena to the attention of offshore wake modelling and operation monitoring community, underlining the significance of OCC quantified via the case study in Horns Rev-I.

2. Methodology

Using met-mast measurements and high frequency (1 Hz) SCADA data from all the operating turbines in Horns Rev-I, a day of operation with OCC presence (2005/05/18, referred as OCC day as seen in Figure 1), is compared with a **No-OCC** day when the phenomena is not observed (2005/10/22). Both days have similar inflow conditions. The investigation is performed with an in depth analysis of the inflow as well as the in-farm effects, such as the wake behaviour and smaller scale atmospheric structures.

Horns Rev-I Wind Farm Layout & Surrounding Met-Masts

Horns Rev-I is an offshore wind farm located in west of Denmark, with 80 Vestas 2MW V80 turbines. The layout of the wind farm together with the surrounding met-masts is shown in Figure 2. The signals extracted from the SCADA system of the turbines for this analysis are the wind speed and direction, together with the active power produced by the turbines. SCADA wind speed and direction is measured with sonic anemometers placed at the nacelle behind the rotor at 70 m a.s.l. From the met-masts M2, M6 and M7 the wind speed and direction are investigated. The meteorological masts are equipped with cup anemometers from which the wind statistics (mean and standard deviation) are extracted every 10-min. The considered measurement heights vary among the explored features and are indicated in the relevant legends of the time series analysis.

Mesoscale simulations of the OCC and wind farm wakes are performed with the Weather Research and Forecasting (WRF 3.7.1, (7)) limited area model with two nested domains and activated Explicit Wake Parameterization (EWP, (11)) in the innermost domain, i.e. closer to
the wind farm. The horizontal resolutions of the three domains are 9 km (outermost), 3 km (1st nest) and 1 km (innermost domain). The model was initialised at 2005-05-17, 1200 UTC and ran for 36 hours. Settings regarding the selection of physics schemes and the initial and boundary conditions are as indicated in (4).

3. Results and Discussion
In addition to the satellite images, the OCC structures can also be observed in higher resolution mesoscale simulations. Figure 4 shows a 10-min snapshot of the large scale wind speed gradients all around and approaching Horns Rev-I. It also highlights the substantial wind speed difference across the wind farm, with turbines in the north experiencing lower than 5 m/s wind speed as opposed to approximately 13 m/s observed at the western part of the farm.

![WRF results @ 2005/05/18, 02:40 UTC](image)

Figure 4: WRF 10-min snapshot during the OCC Day on 2005/05/18 at 02:40 UTC, approximately an hour after the cloud picture in 1. The red dots indicate the turbine locations in Horns Rev-I. The solid lines on the east of Horns Rev-I show the coastline of western Denmark. For the full video of 10-min resolution flow development as modelled in WRF with EWP (11), see the link: OCC event at Horns Rev-I with WRF @ 2005/05/18

OCC induces severe fluctuations in the incoming wind speed and direction, as recorded by the met-masts at microscale level, shown in Figure 5. Note that the cloud picture in Figure 1 is taken around 01:30 UTC on that day, where the first peaks in 10-min standard deviation of wind speed are observed. The effects of the OCC last until approximately 16:00 UTC, where the difference in the sequential 10-min mean wind directions reduces from more than 35° (i.e. between 05:00 – 05:10 UTC) to about 10° levels.
The turbulence intensity, which is both physically and statistically highly correlated to the measured fluctuations in wind direction, increases almost to 40% at M6 at around 05:00 UTC; where the standard deviation of wind speed is the highest. It is estimated using the standard deviation and mean wind speed over 10-min periods.

Despite differences in the scale compared to met-mast measurements, Figure 6 shows that the severe fluctuations under open cells are captured with mesoscale WRF simulations extracted at the met-mast locations. Note that the shift of approximately 2-hours in the time scale (i.e. x-axis) for WRF results compared to local measurements is commonly observed and addressed in similar studies, e.g. (8). This relatively successful representation of the trends in very high variability in wind speed and direction highlights the potential added value of including mesoscale models into microscale plant-level assessments under OCC.

Regarding the behaviour of the flow within the wind farm, these fluctuating effects of the OCC are manifested with enhanced turbulent mixing. Firstly, Figure 7 shows the daily median of wind speed measured by the nacelle anemometers at the turbines in Horns Rev-I, as well as the daily median of the wind direction represented in arrows, for two separate days of operation:
OCC day (2005/05/18) and No-OCC day (2005/10/22). Since the main focus of this case study with day-to-day comparison is to investigate the potential change in wake behaviour for deep arrays under OCC, 2005/10/22 with similar incoming wind direction and less than rated wind speed (approximately 15 m/s for Vestas V-80 2MW, see Figure 3) is investigated. Although the wind speed observed in no-OCC day is higher, for majority of the time it is still safely lower than the rated region where the expected variance in power is zero. The velocity deficit in the first few rows on the other hand are lower due to lower $c_t$ for the majority of the no-OCC day, which also suggests reduced wake-added turbulence intensity. However, Figure 8 suggests a 'systematic' increase in turbulence levels further downstream for no-OCC day, as opposed to consistently very high turbulence observed from the second row of turbines to the last during the OCC day. It points to a potentially dominating effect of OCC to the wake induced, small-scale fluctuations for both the single wake and multiple wake events. Such an effect is typically not included or investigated in wake research.

Figure 7: Daily Median of the wind speed per turbine on 2005/05/18 and 2005/10/22 in Horns Rev-I. Arrows: Median of the available Wind Direction signal from SCADA. Note that the scales in the contour plots are not equalised to represent the difference in wind speed among the turbines clearly.

Figure 8: Daily Median of the turbulence intensity (TI) estimated via the nacelle anemometers at the turbine locations on 2005/05/18 and 2005/10/22 in Horns Rev-I. Arrows: Median of the available Wind Direction signal from SCADA.

Figure 9 compares the daily median of the 10-min power fluctuations during for the OCC and No-OCC days. Under OCC, the added turbulence due to wake effects is less visible as seen in Figure 8 and the difference in power fluctuations between the upstream and downstream turbine(s) is accordingly lower. However, as stated by the previous studies mentioned earlier, the overall fluctuations in power production are higher, especially for the upstream turbines.
For the upstream turbine HR 1101, the substantial increase in the fluctuation for the same wind speed in the presence of open cells is shown in Figure 10(a) within a 10-min time window. Accordingly, there is also much more fluctuation in the wind power, as shown in Figure 10(b). Power saturation towards 2 MW (rated power of Vestas V80 2MW turbines located in Horns Rev-I) can also be observed.
The high correlation between the variability in wind speed and active power at the open cell scales can be seen in Figure 11 in the power spectrum at different frequencies. Note that the spectrum for wind speed is multiplied with $10^6$ to visualise the correspondence between the two variables. Note that, the wind speed signal corresponds to the point-wise measurements collected at the nacelle anemometer of turbine HR1101, where the power signal includes the inertia of the turbine converting this wind speed to power. In other words, the power signal is a spatially averaged quantity of the wind speed profile along the rotor which can explain the energy difference for faster time scales than 100-seconds.

The enhanced variability in wind speed in the presence of open cells is also shown in the frequency domain in Figure 12.

The extra energy at lower frequencies related to open cells are also compared with climatological wind spectrum (Figure 12(a), (5)) and a typical boundary-layer turbulence model (Figure 12(c), (2)). This additional contribution in lower frequencies is reflected in the active power fluctuation shown in Figure 12(b). Note that the No-OCC case corresponds to overall stronger winds.

Figure 13 shows the level of spectral energy of various observed winds speeds on 2005/05/18 and points to extraordinary energy for $f < 0.007$ Hz under open cell presence compared to the typical boundary-layer turbulence model introduced by Kaimal et al. (2). It is consistent with the met-mast M2 and upstream turbine HR 1101. Further downstream, the turbine in the third row (HR 1222, see Figure 2) experiences more enhanced turbulence at $f < 0.007$ Hz. For this frequency region, the turbulence level seems to sustain further in the wind farm as seen in comparison with turbine HR 1588. It should be noted that, for a normal operation No-OCC day, the small scale turbulence levels are expected to increase with deep array effects. Therefore,
similar to the daily median investigation in Figure 9, the spectral analysis also suggests that the OCC induced turbulence enhances the mixing and dominates the wake added turbulence effects within the large scale offshore wind farms.

Figure 12: Power spectra $fS(f)$ vs. frequency $f$: (a) wind speed and (b) wind power in the presence and absence of open cells at T1. The straight line in (a) shows the level of the climatological wind speed power spectrum. (c) Various data sources show the extraordinary energy for $f < 0.007$ Hz for the open cell case at both upstream turbine HR 1101 and met-mast M2, in comparison with a typical boundary-layer model by Kaimal et al. (2).

Figure 13: Power spectrum $fS(f)$ vs. frequency $f$ of wind speed from the met-mast M2 and turbines HR 1101 and HR 1594 @ OCC Day 1 2005-05-18

4. Conclusion
For the investigated event, it is shown that the open cell effect is dominating the wake induced fluctuations for frequencies lower than 0.008 Hz (or about 2-min). In other words, the wake induced turbulence effects might not be visible during OCC days, which underlines the importance of analysing higher frequency data, clearly higher than commonly studied 10-min SCADA signals. Furthermore, a mitigation in the wake induced turbulence is observed. That is particularly interesting as the overall power fluctuation at the wind farm level increases under OCC, while the difference in fluctuations at the individual turbines decreases significantly. The study shows potentially striking difference in wind farm operation under OCC conditions and underlines the importance of taking local mesoscale phenomena into account for wind
farm operation monitoring and control, short-term wake estimation, forecasting and market participation. The case study presented here motivates for further investigation of OCC events on large offshore wind farms and their influence on wind farm operation and turbine-turbine interaction.

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