Spatial-temporal analysis of coherent offshore wind field structures measured by scanning Doppler-lidar

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Abstract. An analysis of the spatial and temporal power fluctuations of a simplified wind farm model is conducted on four offshore wind fields data sets, two from lidar measurements and two from LES under unstable and neutral atmospheric conditions. The integral length scales of the horizontal wind speed computed in the streamwise and the cross-stream direction revealed the elongation of the structures in the direction of the mean flow. To analyse the effect of the structures on the power output of a wind turbine, the aggregated equivalent power of two wind turbines with different turbine spacing in the streamwise and cross-stream direction is analysed at different time scales under 10 minutes. The fact of considering the summation of the power of two wind turbines smooths out the fluctuations of the power output of a single wind turbine. This effect, which is stronger with increasing spacing between turbines, can be seen in the aggregation of the power of two wind turbines in the streamwise direction. Due to the anti-correlation of the coherent structures in the cross-stream direction, this smoothing effect is stronger when the aggregated power is computed with two wind turbines aligned orthogonally to the mean flow direction.

1. Introduction

Wind power very short-term forecasting is becoming of great interest to the wind energy, since it can significantly improve supply reliability, grid stability and additionally provide useful information for the energy spot or balancing market. On a very short-term scale i.e. for periods of less than about 10 min, Nanahara et al. [1] showed that the spatial distribution of a wind farm reduces the impact of power fluctuations from individual wind turbines, as a result of the smoothing effect. Despite this effect, it is becoming essential to understand how wind field structures are affecting a wind farm, depending on atmospheric conditions and the spatial distribution of the wind farm. Moreover, a better understanding of the inflow characteristics enables the wind farm operator to improve wind farm power output and reduce wind turbine loads.

In this regard, Mehrens et al. [2] studied, on a time scale of tens of minutes to several hours, mesoscale wind field spatial fluctuations during cellular convection days in the North Sea. Emeis [3] evaluated the importance of the atmospheric stability on the power output of offshore wind farms. In his analytic wind farm model, the author discovered that large offshore wind farms are more efficient under unstable atmospheric conditions, since the wind speed deficit at hub height increases with increasing stability due to the shadowing effect of upstream neighbour wind farms. Likewise, Dörenkämper et al. [4] found that due to wind shear effects, power output...
below rated wind speed was up to 15% higher in unstable than in stable stratification for wind turbines during non-wake conditions.

In this contribution, long range Doppler-lidar (Light Detection and Ranging) observations are used to evaluate the size of offshore, fluctuating, large coherent structures under neutral and unstable atmospheric conditions. Long range Doppler-Lidar has become an advantageous tool to analyse the inflow field of a wind farm up to several kilometres. Nonetheless, the inherent temporal and spatial averaging process of the lidar results in a source of uncertainty for the measurements [5]. Therefore, two LES have been conducted to simulate the two different stability cases measured by the lidar. In this regard, LES data provide a higher spatial and temporal resolution than lidar measurements. Finally, the effect of large scale structures on a simplified wind farm model is analysed in terms of equivalent power output considering different wind farm topologies.

2. Wind field data
For this study, four data sets of lidar measurements and LES under unstable and neutral stability conditions are considered.

2.1. Lidar measurements
Two Leosphere WindCube 200S long-range Doppler-lidar systems operated in the offshore wind farm ”Riffgat”, located 15 km Northwest of the North Sea island of Borkum. Each lidar system was located on the transition piece of a different wind turbine, at the height of 21.5 m above the sea surface, with the aim of measuring the flow inside and around the wind farm. The positions of the lidars were chosen to allow for inflow measurements in different wind directions, namely the North and West sectors of the wind farm. Due to relative orientation and the distance of 3.87 km of the lidars, no Dual Doppler-lidar measurements were conducted. The two lidars measured the wind inflow in the so-called PPI (Plan Position Indicator) mode, scanning the flow with a wide azimuth range using a small fixed elevation angle. The scanning speed was set to 1°/s with an accumulation time of 1 s. The pulse length of the lidar systems was set to 400 ns, which corresponds to a sample volume length of approximately 60 m. For this work, two data sets of measurements under different stability conditions from each of the lidar systems, measuring in the inflow direction, are examined. Line of Sight (LoS) wind speeds measured with the lidars have been filtered in respect to the Carrier to Noise Ratio (CNR), according to the manufacturer recommendation for the given measurement settings, outliers and hard targets. A sector scan approach based on the VAD (Velocity-Azimuth Display) wind retrieval technique [6], has been applied to determine the global wind direction of the wind fields. Horizontal wind speed \( U_h \) is calculated as in (1) from the LoS wind speed and the angle \( \alpha \) between the beam azimuth angle and the wind direction. The error of this method increases with the angle \( \alpha \) and therefore the data has been properly filtered out using an error propagation law [7], disregarding the data where the relative error \( \Delta U/U > 15\% \). Due to the small elevation angle of the measurement, \( \delta \) is neglected.

\[
U_h = \frac{v_{LoS}}{\cos(\alpha) \cos(\delta)}
\]  

To determine the stability trend, the temperature difference between the water and the air measured by a buoy equipped with two temperature sensors was considered. The water temperature sensor was located right below the water surface and the air temperature sensor was installed one meter above the water temperature sensor.
2.1.1. Unstable stratification case

A data set of one hour of measurements was recorded at the beginning of September 2015. For every measurement beam, 150 range gates were registered, equally spaced from 2000 to 5000 meters. The elevation angle was set to 1.5°, implying PPI scans were performed with a range of heights of [73.85-151.86] m. The lidar system was measuring towards the wind direction. The sector scan approach concluded the prevailing wind direction was North. During this measurement period, the data recorded from the buoy was unavailable. Nonetheless, the averaged wind speed over height during the period showed a wind shear typical of an unstable stratification. In figure 1 top, two consecutive lidar scans of the derived horizontal wind speed are presented, where coherent turbulent structures can be visually tracked. Since the objective of the study is to analyse the effect of coherent structures on a wind turbine rotor (in this case at the hub height of 90 m) it should be necessary to extrapolate the measurements at the hub height using an unstable stratification wind speed profile. Since the structures can be visually tracked in consecutive scans, and an elevation of 1.5° in a structure of 100 m would be translated into a 2.6 m height difference, the authors assume the structures are large enough in the spanwise direction to perform the analysis on the scans. Therefore, no extrapolation was conducted on the data, considering the scans as flat PPI.

2.1.2. Neutral stratification case

In this case, one hour of measurements were registered on April 2016. The small difference between the temperature of the air and the water surface, measured by the buoy located in the wind farm, revealed neutral stability conditions. Here, the lidar system measured with an elevation angle of 1° and it recorded, for every beam, 220 range gates equally spaced from 500 to 5975 m. Due to the differences of height of the lidar measurements, in this case [30.22-125.77] m, all measurement points were extrapolated to \( h = 90 \) m using the logarithmic wind profile for wind neutral conditions (2), where index \( m \) refers to the measured height and \( z \) the extrapolation height. The roughness length \( z_0 = 2 \cdot 10^{-3} \) m, typical of coastal offshore areas has been chosen according to the classification given by Stull [8].

\[
U_z = U_m \frac{\ln \frac{z}{z_0}}{\ln \frac{z_m}{z_0}}
\]  

(2)

2.2. LES wind fields

LES were conducted with the LES model PALM (A Parallelized LES Model). All simulations were run on a volume of 10 x 5 x 3 km to simulate the conditions within the Atmospheric Boundary Layer (ABL), using a grid size of 10 m and a time resolution of 1 s. Simulations were performed for 24 hours to ensure that the flow had achieved its stationary state. An inversion layer between 1.5 and 1.6 km was defined with a gradient aloft of \( d\theta/dz = 8 \) K/km. From those simulations, a volume of 4 x 4 x 0.2 km, during the last hour of every simulation, was extracted. All simulations were performed under cyclic boundary conditions in the horizontal plane using a geostrophic wind, a constant roughness length and a potential temperature profile, in order to achieve similar wind speeds at 90 m as the ones measured by the lidar under the different stability conditions.

2.2.1. Unstable stratification case

To perform the simulation, boundary conditions were defined by a geostrophic wind of \( u_g = -5.52 \) m/s and \( v_g = -1.052 \) m/s. A potential temperature profile for an unstable stratification and a roughness \( z_0 = 2 \cdot 10^{-3} \) m were used. In figure 1 bottom, two snapshots of the horizontal wind speed at 95 m separated in time 70 s are depicted, where the large turbulent
Figure 1. Horizontal wind speed retrieved from the LoS wind speed from two consecutive scans measured by one lidar after filtering out the data (top) and consecutive snapshots of the horizontal wind speed retrieved from the LES (bottom) for the unstable stratification case.

coherent structures can be visualized. Here, the difficulties of simulating a very low wind speed at 90 m resulted in a wind field with an average wind speed of 5.42 m/s at 90 m, which is 0.62 m/s higher than in the lidar measurements data set.

2.2.2. Neutral stratification case

In this case, a geostrophic wind of \( u_g = -8.65 \) m/s and \( v_g = -9.00 \) m/s was used to conduct the simulation. A potential temperature profile for neutral atmospheric conditions and \( z_0=2\cdot10^{-3} \) m were considered. Figure 2 bottom shows two consecutive snapshots of the flow at 95 m, separated in time 70 s. Here, organized elongated structures can be easily identified.

3. Methodology

3.1. Integral length scales

To estimate the size of the coherent structures of the wind fields in the horizontal plane, the spatial coherence of the wind fields scanned with the Doppler-lidar and created with the
Figure 2. Horizontal wind speed retrieved from the LoS wind speed from two consecutive scans measured by one lidar after filtering out the data (top) and consecutive snapshots of the horizontal wind speed retrieved from the LES (bottom) for the neutral stratification case.

LES is analysed. On this subject, integral length scales are a useful term to characterize the structure of the turbulent wind fields depending on different heights and stability conditions [9]. An autocorrelation function (3) is used to evaluate the spatial integral length scales of the horizontal wind speed in the streamwise and cross-stream direction, where \( u \) refers to the horizontal wind speed and \( i \) to the spatial lag in the streamwise (\( x \)) or the cross-stream (\( y \)) direction, referred to the inflow direction. Integral length scales are estimated (4) by integrating the autocorrelation \( r \), only up to the first zero-crossing (\( r=0 \)) of the function, with \( e \) being the unit vector in a given direction.

\[
r_{u,i} = \frac{1}{\sigma_u^2} \frac{1}{N-i} \sum_{k=1}^{N-i} u_{i+k} u_k'
\]

\[
L_{u,i} = \int_0^\infty r_{u,i}(ie) \, di \approx \int_0^{r=0} r_{u,i}(ie) \, di
\]
3.2. Power output fluctuations

A simplified wind farm consisting of two wind turbines, placed in an either streamwise or cross-stream row, is simulated to analyse the effect of the spacing between two wind turbines on their aggregated power output. The following assumptions are made: 1) Vertical wind shear is constant over the entire rotor area and 2) there are no wake losses.

In order to calculate the equivalent power output of a wind turbine, a simplified rotor concept is considered (figure 3). This simplified rotor sweep area is discretised in \( n \) areas \( A_i \) according to (5). Consequently, the rotor wind speed is determined by integrating the horizontal wind speed over the whole rotor, where \( u(\xi_i) \) is the horizontal wind speed in the \( \xi_i \) position of the rotor, \( h = D/n \) is the slice width and \( D \) the rotor diameter. In this analysis we considered \( D=100 \) m.

![Figure 3. Equivalent rotor area.](image)

\[
A_r = \sum_{i=1}^{n} A_i = 2 \sum_{i=1}^{n} \left( h \sqrt{\left( \frac{D}{2} \right)^2 - \xi_i^2} \right)
\]

(5)

Accordingly, the equivalent power output of a single wind turbine is calculated as in (6), where \( u_0 \) is the averaged horizontal wind speed in the entire wind field domain, averaged over the entire period in order to normalize the power.

\[
P_{eq,j} = \frac{8}{\pi D^2 u_0^3} \sum_{i=1}^{n} \left( u(\xi_i)^3 h \sqrt{\left( \frac{D}{2} \right)^2 - \xi_i^2} \right)
\]

(6)

To evaluate the effect of the aggregated power of two wind turbines we calculated first the equivalent power output of a wind turbine for every wind field turbine position and time instant. Wind turbine positions are defined by a grid separation in the wind field of \( G_x=20 \) m in the cross-stream direction and \( G_y=30 \) m in the stream-wise direction. To avoid local influences from the flow, the aggregated power has been calculated by considering all possible combinations of wind turbines given by its rotor spacing. Therefore, we simulated the aggregated power output of two wind turbines, separated \( n \) multiples rotor distances in the streamwise or in the cross-stream direction, by averaging their equivalent power at each time instant. For every time position wind turbines are yawed towards wind inflow mean direction. Turbine distances are...
\( S_y = nD \) and \( S_x = 1.5 \ S_y \). The smoothing effect of the aggregated power of two wind turbines aligned in the cross-stream direction (in \( y \)) or in the streamwise direction (in \( x \)) is analyzed by calculating the standard deviation of the aggregated equivalent power over different scales and distances.

For the analysis of the size of the structures and their impact on the power output with the lidar data, only a rectangular area in the center of the scan with few missing data of \( 2 \times 1.5 \) km (unstable case) and \( 2 \times 2 \) km (neutral case) was considered. For the LES power output analysis, due to the spatial resolution of the LES, the wind fields were selected at 95 m height.

4. Results

4.1. Integral length scales

In figure 4 the distribution of the estimated integral length scales of the horizontal wind speed of the wind fields for the lidar data set and the LES simulations in the unstable (left) and neutral case (right) are shown. We estimated the integral length scales of the wind fields for every LES (snapshot every 70 s) and lidar scans over the whole time period. Integral length scales are represented by blue boxes in the streamwise direction and in red for the cross-stream direction. The boxes range from the 25 % percentile to the 75 % percentile. For the LES we performed the analysis of the integral length scales at three different heights: 65, 95 and 125 meters. Results for the two LES data sets (unstable, neutral) indicate no significant differences in distribution of the structure size over different heights, both in the streamwise and cross-stream direction, what allows for comparison with the lidar measurements despite their non-constant height. For the LES, the distribution of estimated integral length scales over the analysed period revealed larger structures in the unstable case, both in the streamwise and the cross-stream direction. The larger Interquartile Range (IQR) of the box plot for the LES under unstable stratification suggests that, there is a stronger variation of coherent structure sizes under unstable atmospheric conditions at low speed. In the neutral case we have identified smaller structures in the streamwise and cross-stream direction. These results were reported in the early works with LES of Moeng and Sullivan [10]. Here, the authors relate the narrower IQR to the less varying size structure at higher wind speeds with neutral stability conditions.

![Figure 4](image-url)

**Figure 4.** Distribution of integral length scale \( L_{u,x} \) (blue) and \( L_{u,y} \) (red) of the horizontal wind speed from the lidar data sets and the LES at 65, 95 and 125 m under unstable atmospheric conditions (left) and neutral stratification (right).

The distribution of estimated integral length scales of both lidar cases (figure 4) indicates structures in the streamwise direction are slightly larger for the neutral case. Those more elongated structures characteristics of the neutral case can be seen in figure 2 top. Besides,
no structures below 80 m (in the cross-stream direction) can be observed in the lidar data set, which can be explained with the inherent averaging process of the lidar measurements in beam direction, described by Stawiarski et al. [5] in their analysis of surface-layer coherent structures measured with a lidar simulator.

For the lidar unstable case, we found smaller size structures in both directions compared to the LES results. However, due to the process of setting up LES to obtain wind fields with similar properties as the measured in the wind farm, it was not possible to reproduce them. Consequently, the slightly higher wind speed of the LES wind fields does not allow for comparison of the integral length scales of the lidar measurements with the LES simulations, since the integral length scales strongly increase with the wind speed in the region of lower wind speeds (from 2 to 8 m/s) under unstable atmospheric conditions. The variation of the spatial integral length scales under different stability conditions and wind speeds was analysed by Sathe et al. [11], who states similar conclusions, based on Mann turbulence model [12]. Here, the low wind speeds measured by the lidar, in relation to the LoS error, might be a source of uncertainty to the measurements. This finding suggests that wind fields under unstable stratification are very sensitive to slight changes in the atmospheric conditions and that, in order to directly compare LES under similar conditions to the ones from the lidar, there is a need of additional information to make a precise classification of the atmospheric conditions of the lidar data set.

From the estimated integral length scales, we calculated the averaged anisotropy of structures of the data set. The anisotropy $\rho$ is defined as the relation between the integral length scale in the streamwise direction and in the cross-stream direction. In table 1 the averaged integral length scales and the anisotropy of the different data sets are indicated. On this subject, it has been found that, for both the lidar measurements and the LES data sets, the neutral case exhibits a higher degree of anisotropy (see table 1), than the unstable case. Similar results about the stronger elongation of the structures under neutral stratification have been mentioned by Newsom et al. [13] in their analysis of coherent structures in a suburban area. However, it has to be pointed out that the spatial and temporal averaging process of the scanning lidar can be very different for the $x$ and $y$ direction, and can consequently affect the anisotropy of the structures measured. Moreover, during the neutral case, the higher wind speed conditions could as well affect the determination of the integral length scales, since there is a stronger time shift in the measurements than in the unstable case, where coherent structures advect slower.

| Case         | $L_{u,x}$ (m) | $L_{u,y}$ (m) | $\rho$ |
|--------------|---------------|---------------|-------|
| lidar unstable | 135.81        | 76.47         | 1.77  |
| LES unstable  | 209.47        | 92.48         | 2.26  |
| lidar neutral | 179.50        | 89.37         | 2.01  |
| LES neutral   | 127.07        | 54.35         | 2.33  |

4.2. Power output fluctuations
To analyse the effect of the coherent structures on the power output of our simplified wind farm model, we first computed the standard deviation of the equivalent power of a single wind turbine for the LES and lidar data sets over the whole wind field domain. We analysed the following temporal scales. LES: 1 s, 1 min, 5 min, 10 min and lidar: 1 s (70 s between measurements), 5 min, 10 min.
The standard deviation of a single wind turbine is presented in figure 5 at the turbine spacing equal to zero. In the plots, it can be seen the higher standard deviation of the equivalent power for both unstable cases, lidar and LES, compared to the standard deviation in the neutral cases, which can be explained by the higher turbulence, characteristic of the unstable atmospheric conditions.

To evaluate the impact of the aggregated power of two wind turbines as a function of the distance in the streamwise direction and in the cross-stream direction over the different temporal scales, we calculated the standard deviation of the aggregated power over different turbine spacing. Diamond series refer to the standard deviation of the aggregated power of two wind turbines in the cross-stream direction, while star series present the results of the standard deviation of the power of two wind turbines in the streamwise direction.

In the four cases, we found out that there is a stronger smoothing effect, with increasing spacing, in the equivalent power of two wind turbines separated a distance in the cross-stream direction than in the streamwise direction. The result suggests that the elongation of the structures in the streamwise direction produces a prolonged effect of the fluctuation on the aggregated power of two wind turbines. This effect is stronger over higher temporal scales. Nonetheless, the lidar data acquisition period of 70 s does not allow to make a comparison of the effect at smaller temporal scales.

Moreover, in the neutral case, there is a stronger smoothing effect in the cross-stream direction compared to the unstable cases, which can be explained with the larger anisotropy (higher relation of the size of the structures in the streamwise to the cross-stream direction) of the coherent structures under neutral stratification and the smaller turbulence of the wind fields.

Figure 5. Standard deviation of the aggregated power of two wind turbines separated a distance in the streamwise (⋆) and cross-stream (○) direction for LES (left) and lidar (right) in the unstable (top) and neutral (bottom) case.
5. Conclusions and Outlook

Long-range scanning lidar measurements, observed in the offshore wind farm Riffgat, have been used to characterize coherent structures in the inflow of a wind farm under two different stability conditions. LES have been performed based on the measurements to analyse and compare integral lengths scales of the horizontal wind speed. The analysis has shown that coherent structures are elongated in the inflow direction, with a higher anisotropy in neutral conditions. The comparison of the wind fields under neutral conditions showed the nature of the lidar measurements smooths out the smaller turbulent structures. This has not been found in the unstable case, which confirms that, integral length scales of wind fields at low speeds under unstable conditions, strongly vary with small changes in wind speed or in heat exchange and therefore, there is a need of additional information to perform proper LES corresponding to the measured conditions. Further information would be required to determine the exact stability conditions during the lidar measurements in order to make a proper comparison with the LES.

The analysis of the impact of these large structures on a simplified wind farm model reveals, there is a stronger smoothing effect on the aggregated power of two wind turbines aligned in the cross-stream direction compared to the streamwise direction, since coherent structures are larger in the streamwise direction.

Further research will be focused on detailed analysis of coherent structures in different atmospheric conditions, their temporal evolution and the analysis of their impact on a more complex wind farm model where wake losses are considered.

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