

Wake Measurements in ECN's Scaled Wind Farm

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Wake Measurements in ECN's Scaled Wind Farm

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Abstract. In ECN's scaled wind farm the wake evolution is studied in two different situations. A single wake is studied at two different locations downstream of a turbine and a single wake is studied in conjunction with a triple wake. Here, the wake is characterized by the wind speed ratio, the turbulence intensity, the vertical wind speed and the turbulence (an)isotropy. Per situation all wake measurements are taken simultaneously together with the inflow conditions.

1. Introduction

In wind farms, especially the turbines in the inner part of the farm face the wakes of the upwind turbines. Wakes are, among others, characterized by a lower wind speed and an increased turbulence intensity as compared to ambient conditions. Therefore, turbines that are facing these wakes produce less power and suffer from a higher loading. Wakes could be regarded as the way turbines communicate with each other. It is therefore of utmost importance to understand these wakes. In addition detailed knowledge of the wakes inside a farm can be used to greatly improve wind farm models on for instance energy production and to optimize wind farm control strategies. Much research in this field has already been carried out, an example is the research in the EU project UpWind [1].

In full scale wind farms detailed measurements inside a farm are scarce because large meteorological masts are very expensive and permits are needed to build them. On the other hand the value of wind tunnel data is limited due to scaling effects. ECN's scaled wind farm overcomes these problems, because its scale is not too small to alleviate the dominant scaling effects and the scale is not too large to permit the building of sufficient meteorological masts. It consists of 10 turbines with a hub height of 7.5m in separate rows with many meteorological measurements inside, around and above the farm.

In this paper the wake evolution is studied in ECN's scaled wind farm. Single wakes are studied at various distances as well as multiple wake situations. The remaining of this paper is organized as follows: section 2 contains a description of the scaled wind farm and the situations considered and section 3 contains the details about the data and the data selections. The results are described in section 4 and they are summarized and concluded in section 5.

2. The Scaled Wind Farm facility

ECN's scaled wind farm was introduced in 2008 [2] and consists of 10 Aircon 10P turbines divided over the park in three lines of 2, 3 and 4 turbines and one single turbine; a layout of which is given in figure 1. The turbines have a diameter of 7.6 m and a hub height of 7.5 m. 15 small and large meteorological masts are placed within and around the farm which measure the wind velocity field from 3.6m to 19m height. These measurements, especially in the wakes of the turbines, include many 3-dim sonic anemometers. An extensive description of the instrumentation of the scaled wind farm is given in [3]. Additional information on the farm and about performed research in the farm can be found

in [4]. The farm is located on ECN's test field EWTW in between locations for prototype turbines. The test field and its surroundings are characterised as flat terrain near the lake "IJsselmeer". The layout of the farm (turbines and meteorological masts) also makes it possible to simultaneously measure free wind conditions, single and/or multiple wake conditions at various spacing together with wind conditions above the park. We stress that this is a very unique situation.

In the analysis two wake situations are considered, i.e. the single wake at multiple distances and the multiple wake situation; see the ovals in figure 1. With respect to the single wake situation (left) the inflow conditions are measured with the sonic anemometer on meteorological mast 1 at 7.5m height (indicated with sonic 1). The distance between meteorological mast 1 and turbine 1 is 13.9m (=1.8D). The wake is measured at two distances from turbine T1 with sonic anemometers on meteorological mast 2 and 3 both being 7.5m high (sonic 2 and sonic 3, respectively). The distance between the turbine and the meteorological masts 2 and 3 is 14.2m (=1.9D) and 31.6 (=4.2D), respectively. The positions of meteorological masts 2 and 3 are in the following denoted as 'location 1' and 'location 2', respectively.

With respect to the multiple wake situation the inflow conditions are measured with the sonic anemometers on meteorological mast 9 at 7.5m height and the sonic anemometer on meteorological mast 13 at 7.5m height (indicated with sonic 9 and sonic 13, respectively). The mean of these two is considered to be representative for the inflow at turbine T6. The distance between meteorological masts 9 and 13 to turbine T6 is 31.4m (=4.1D) and 31.6m (=4.2D), respectively. The single wake, i.e. the wake directly behind turbine T6, is measured with a sonic anemometer on meteorological mast 10 being 7.5m high (sonic 10), where the distance between the turbine and the masts is 13.3m (=1.8D). The triple wake, i.e. the wake behind the third turbine T8, is measured with a sonic anemometer on meteorological mast 12 being 7.5m high (sonic 12), where the distance between turbine T8 and meteorological masts 12 is 13.4m (=1.8D). The distance between turbine T6 and meteorological masts 12 is 69.3m (=9.1D). The spacing of the turbines in the row, i.e. turbines T6, T7 and T8, is 3.7D.

Unfortunately, the sonic anemometer suitable for measuring the double wake (not indicated in figure 1, but named meteorological mast 11) has not performed well during the considered period. Therefore, the double wake could not be studied.

A comparison of the turbines T6, T7 and T8 showed that the measured power of turbine T7 needs to be corrected by subtracting 300W from it (rated power is 10kW). After this correction the power of the turbines compare quite well. In addition it is noted that the rotational speed of turbine T7 is a bit higher and the rotational speed of turbine 8 is a bit lower than that of turbine T6. However, the differences are considered to be acceptably small.

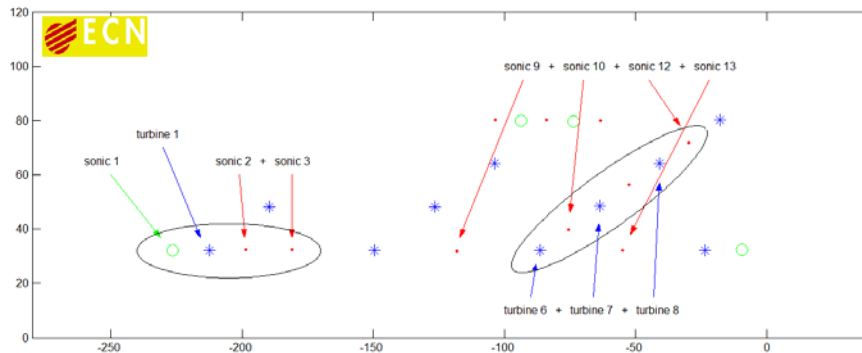


Figure 1. Layout of the scaled wind farm. The blue stars represent the turbines, the green circles the large meteorological masts and the red dots the small meteorological masts. The ovals indicate the two considered sonic wake situations.

3. Data taking and selection

For the single wake analysis 10 minute statistical data are considered from the 10th of November 2011 until the 18th of April 2012 and from these data valid results have been selected for the sonic anemometers 1, 2 and 3 (see figure 1) and valid data have been selected for the turbine. Here, valid turbine data means that the turbine is producing power, the rotor is rotating and the pitch angle is such that the turbine operates optimal below rated. Furthermore, only wind directions and yaw angles between 230 degrees and 300 degrees have been considered and inflow wind speeds below 13 m/s. This yields a dataset of 2643 data points in total. It is noted that the line: sonic 1, turbine 1, sonic 2 and sonic 3 is the line from 270° to 90°.

For the multiple wake situation 1 minute statistical data are considered, where data are taken from the 6th of April 2011 until the 1st of June 2011. Furthermore, valid sonic data have been selected for all the considered sonic anemometers: 9, 10, 12 and 13 (see figure 1) and all considered turbines: T6, T7 and T8 (see figure 1). Here, again, valid turbine data means that the turbines are rotating, the power of turbine T6 is above 50W and the corrected power of turbine T7 as well as the power of turbine T8 is above zero. For the analysis only wind directions between 190° and 270° have been considered, where it is noted that the turbines lay on the line 235°-55°. In order to exclude data points with strange turbine behavior no data have been considered between the 27th of April 2011, 10:00 hours and 21:00 hours (UTC) as well as between the 20th of May 2011, 0:00 hours and 10:00 hours (UTC). This yields a dataset of 2102 data points in total. It is noticed that for the resulting data set the turbines operate all below rated.

An averaging time of 1 minute has been chosen. On the one hand this is because not enough 10 minute statistical data are present to properly perform the analyzes. Therefore, in order to generate more data, a lower averaging time was chosen. On the other hand the scales in the scaled wind farm are smaller as compared to full size farms (i.e. of the order 80m to 100m). Comparing to the full scale ECN research turbines also present at the test field (see [3]) scaling down with a factor of 10 seems appropriate. These research turbines have a rotor diameter of 80m, which is about a factor of 10 larger than the rotor diameter of the scaled turbines, i.e. 7.6m. The resulting data set is not very rich, however it is considered complete to perform the analyses.

4. Results and Discussion

4.1. Single wake at multiple locations

4.1.1. Wake measurements

The wake is characterized by means of wind speed ratio, turbulence intensity, vertical wind speed and turbulence (an)isotropy. Here, the wind speed ratio is defined as the wind speed as measured in the wake divided by the inflow wind speed. The turbulence intensity is defined as the standard deviation of the wind speed (σ_U or σ_{vhor} in the figures) divided by the mean wind speed (U) ($TI = \sigma_U/U$, or multiplied by 100% to obtain percentages) and the turbulence isotropy is defined as the standard deviation of the vertical wind speed divided by the standard deviation of the horizontal wind speed (isotropy = σ_w/σ_U). These wake characterizations are shown in figure 2 where they are given as function of the inflow wind direction and where they are binned in wind direction bins of 2°. It is recalled that the wake center line is at 270°.

From the relative wind speed plot it is noted that in the center of the wake the wind speed ratio is about 0.46 for location 1 (1.9D) and about 0.74 for location 2 (4.2D). This latter location is further from turbine T1 and the wake has already recovered a bit due to (turbulent) mixing with the ambient air flow. Therefore, more energy is present in the wake and the wind speed deficit is less, leading to a higher ratio, as compared to location 1.

It is noted that there seems to be a small deviation from a fully symmetric wake profile; this was also noticed in [5]. In addition a little overshoot is seen for location 2 at the border of the wake at higher wind directions. It is believed that these issues are the result of the wind shear in conjunction with the vertical wind speed (see [5]). The latter issue is treated below in more detail.

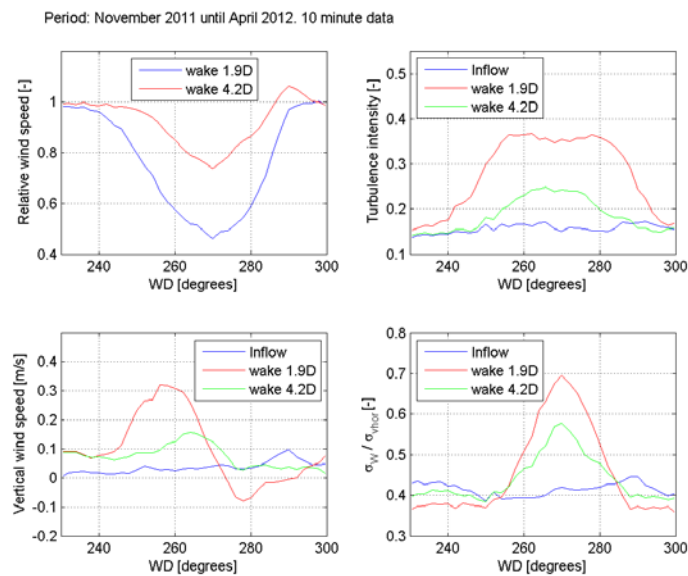


Figure 2. Relative wind speed (upper left plot), turbulence intensity (upper right plot), vertical wind speed (lower left plot) and turbulence isotropy (lower right plot) as function of the inflow wind direction at two locations in the wake.

From the vertical wind speed plot it is clearly seen that the vertical wind speed in the wake of the turbine is increased for wind directions less than the center line (270°) and decreased for wind directions larger than the center line¹. Furthermore, the (absolute value of the) vertical wind speed for location 1 is larger than for location 2. This is, because location 2 is further from the turbine and the wake has already recovered a bit due to (turbulent) mixing with the ambient air flow, as mentioned before. Therefore, the vertical wind speed is less

¹Taking into account that the wake rotates in the opposite direction as the turbine rotor, we conclude from the observations that the rotor rotates clockwise, which is indeed the case.

at larger distances in the wake. It is noted that the negative vertical wind speeds, i.e. for wind directions larger than the center line, are less pronounced, especially for location 2.

As mentioned above it is the vertical wind speed in conjunction with the vertical wind shear that is responsible for the slightly asymmetric shape of the wind speed deficit wake profile [3] and perhaps for the overshoot. This is, because upward winds at wind directions less than the center line transport low momentum from lower altitudes to higher altitudes and vice versa for downward winds at wind directions larger than the center line. Therefore, the horizontal wind speed receives low momentum and high momentum contributions, respectively, reducing and increasing the horizontal wind speed.

From the turbulence intensity plot it is clearly seen that the turbulence intensity in the wake of the turbine is increased with respect to the inflow turbulence intensity. This, because the turbine adds turbulence to the ambient conditions. The inflow turbulence intensity is about 15% and the maximum turbulence intensity for location 1 and location 2 (in the wake) is about 37% and 25%, respectively. Furthermore, the symmetric, two peak structure is more pronounced for location 1, where this two peak structure is due to the tip vortices. Due to turbulent mixing with the ambient flow the turbulence intensity is less further downstream the turbine, in this case location 2.

The turbulence ratio is about 0.4 outside the wake. This is a bit lower than the values indicated in [6] (0.52), in [7] (~ 0.5) as well as in [5] (0.5-0.6), where the former value is for uniform terrains. It is noted that the terrain of the scaled wind farm is flat and is the same as the one in [5]. The only difference is the height: 7.5m vs. 52m, 80m and 108m. From the turbulence ratio plot it is furthermore clearly seen that the turbulence ratio in the wake of the turbine is symmetrically increased about the center line (270°) to values of about 0.7 and 0.6 in case of location 1 and location 2, respectively. This means that the turbulence becomes more isotropic in the wake, which was also concluded in [5]. The effect of increase is stronger for location 1 than for location 2 due to the wake recovery at the latter location.

4.1.2. Wind speed and turbulence intensity dependence

In the following analyses the data set is divided in high and low wind speed and turbulence intensity. Borders are set at a wind speed of 6.5m/s and a turbulence intensity of 17%, because these values are considered as median values of the datasets. A median value of 17% for the turbulence intensity is rather high for full scale conditions. However, due to the small scale the hub height is relatively close to the ground, where the turbulence intensity is higher. From now on turbulence intensities above and below 17% will be considered as high and low, respectively. The same applies for wind speeds above and below 6.5m/s. In figure 3 the same plots are shown as in figure 2, however, here the data have been selected for high and low wind speed and for high and low turbulence intensity.

Period: November 2011 until April 2012. 10 minute data. Wind speed and turbulence intensity selection.

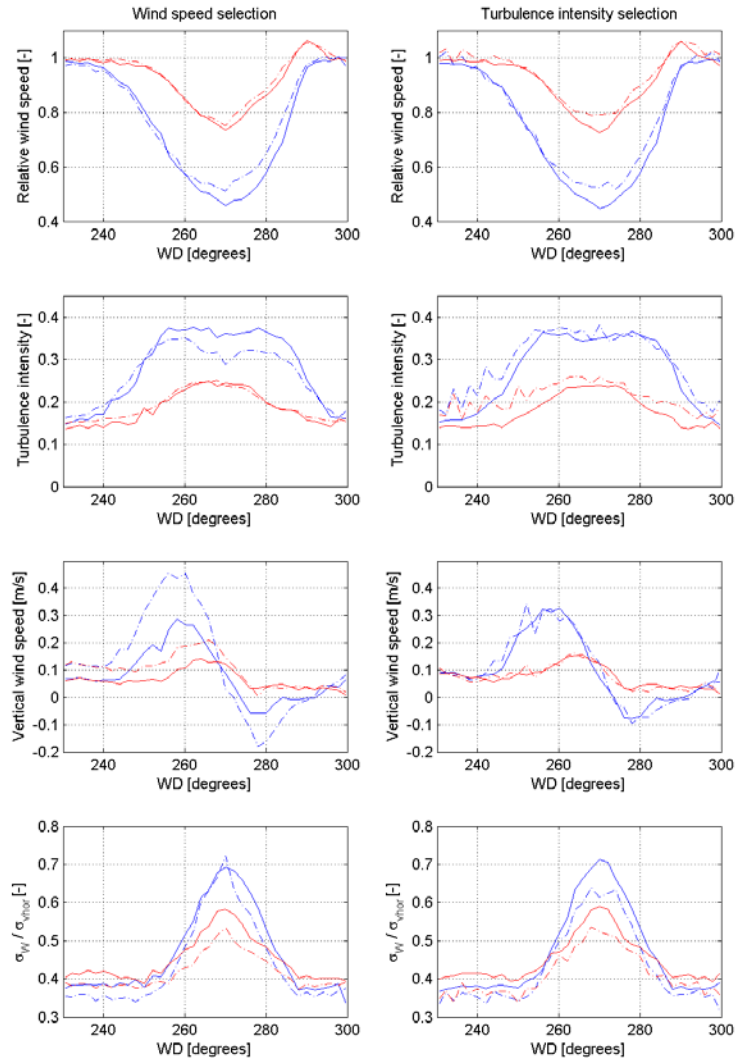


Figure 3. Relative wind speed (upper plots), turbulence intensity (upper middle plots), vertical wind speed (lower middle plots) and turbulence isotropy (lower plots) as function of the inflow wind direction. Specific wind speed selections are indicated in the left plots and specific turbulence intensity selections in the right plots. The solid lines represent low wind speed and turbulence intensity selections and the dashed dotted lines the high wind speed and turbulence intensity selections. The two locations in the wake are indicated with blue (location 1) and red (location 2).

The relative wind speed plots in figure 3 reveal that the wind speed deficit is larger for lower wind speeds. This is clearly seen for location 1 and perhaps, to a certain extent, also for location 2. It is, because for lower wind speeds the thrust coefficient (C_T or $C_{D,ax}$) of the turbine is larger. Therefore, more wind is blocked and less wind speed is available in the wake. It is also seen that the wind speed deficit for both locations is less for higher turbulence intensities. This is because turbulence mixing is stronger for higher inflow turbulence intensities, resulting in a faster recovery of the wake. Therefore, more energy is available in the wake.

Regarding the turbulence intensity plots it is clearly seen for location 1 that the turbulence intensity is less for higher wind speeds; for location 2 this is not seen. An increase in turbulence intensity for larger inflow turbulence intensities may be seen, especially for location 2. However, this may also be due to the scatter in the data. A possible explanation of this phenomenon is that the turbine

adds turbulence to the ambient turbulence, as mentioned before. Therefore, if the inflow turbulence intensity is already higher, then this will also be the case in the wake.

For the vertical wind speed it is noted that selecting higher wind speeds increases the (absolute value of the) vertical wind speed, which applies for both locations in the wake. This is obvious from the fact that the rotor speed of the turbine is increased for higher inflow wind speed (below rated) and, therefore, also the vertical wind speed in the wake. It is concluded from the plot with the specific turbulence intensity selections that considering these selections do not have any effect on the profiles.

With respect to the specific turbulence intensity selections it is seen that the turbulence is more isotropic, i.e. an increased ratio, for lower inflow turbulence intensities. Most probably this is due to the fact that when the inflow turbulence intensity is lower the wake recovers more slowly and the turbulence ratio remains increased longer. For the wind speed selections it may be that the turbulence is slightly more isotropic for lower inflow wind speeds.

4.2. Single and triple wake

4.2.1. Wake measurements

The single wake and the triple wake are characterized in the same way as above: wind speed ratio (deficit), turbulence intensity, vertical wind speed and turbulence ratio. These wake characterizations are shown in figure 4, where they are given as function of the inflow wind direction (mean of the measurements of sonic anemometer 9 and 13) and where they are binned in wind direction bins of 2°. All presented plots contain inflow wind directions up to 270°. It should be noted that for larger wind directions and yaw angles the downstream turbines and sonic anemometers are facing disturbed winds from other turbines (see figure 1). The boundary is set by the readings of sonic anemometer 12 and from that it is concluded that the measurements (of sonic anemometer 12) from 252° and beyond are affected by other wakes. It is recalled that the turbine line is 235°.

It may be expected that the results to a certain extent coincide with the results obtained in the previous section (section 4.1); in both cases single wakes are investigated. Nevertheless, we will report the observed phenomena and indicate what the similarities and the differences are.

From the wind speed deficit plots it is observed that the minimum wind speed ratio for the single wake is comparable to the wind speed deficit of the triple wake, being about 0.56. This wind speed ratio is somewhat higher as compared to the single wake of turbine T1 (see section 4.1). The reason is sought in the difference in atmospheric and turbine conditions, although with respect to the latter point it is seen that the (power) performance of the turbines compare quite well. With respect to the atmospheric conditions it is noted that the distributions of the inflow wind speeds differ significantly in both situations; the mean wind speeds of these distributions are about the same. With respect to distance to the mast it is noted that sonic anemometer 10 is a bit closer to turbine T6 (13.3m) than sonic anemometer 2 to turbine T1 (14.2m). Last but not least we mention the difference in averaging time, i.e. 10 minutes in the single wake situation (turbine T1) and 1 minute in the multiple wake situation (turbines T6, T7 and T8). It is believed that the differences in the wind speed deficits when comparing both single wakes is also seen in the other wake characterizations (turbulence intensity, vertical wind speed and turbulence ratio) and that the same explanations apply.

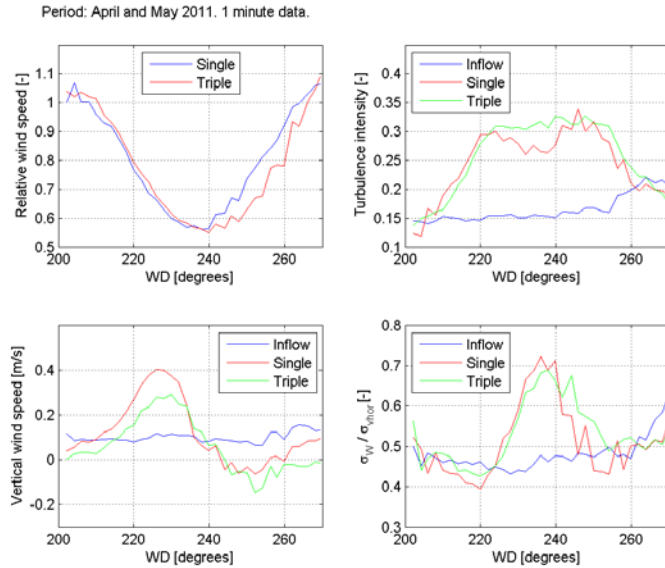


Figure 4. Relative wind speed (upper left plot), turbulence intensity (upper right plot), vertical wind speed (lower left plot) and turbulence ratio (lower right plot) as function of the inflow wind direction for the single wake as well as the triple wake situation.

As compared to the single wake situation in section 4.1 again a slight deviation from the symmetric wake profile is seen for the single wake. As indicated above sonic anemometer 12 suffers from other wake situations as well, therefore deviations from a symmetric profile are hard to determine for the triple wake situation. A larger wind speed deficit may be expected in the triple wake situation as compared to the single wake, because two more turbines (T7 and T8) have extracted energy from the wind flow. However, this is not very clear from the plots and may as well be the result of the scatter in the data.

As was the case in the previous section it is clearly seen that the vertical wind speed in the wake of the turbine is increased for wind directions less than the center line (235°) and decreased for wind directions larger than the center line. However, a significant amount of these latter measurements are for the triple wake situation influenced by other disturbed winds as indicated above. Furthermore, the (absolute value of the) vertical wind speed in the single wake seems to be larger than in the triple wake. This could be explained by the fact that there is less energy available for the third turbine in a row, which causes it to rotate slower. Therefore, the (absolute) vertical wind speed in its wake is less.

For the turbulence intensity plots it was already concluded that the turbulence intensity in the wake of the turbines is increased with respect to the inflow turbulence intensity reaching, in this case, values of 30% to 35%. In addition, the turbulence intensity in the triple wake is larger than in the single wake, especially in the center of the wake. Related to that, the symmetric, two peak structure is present in the single wake, but is hardly or not seen at all in the triple wake. Apparently, the triple wake is too mixed to sense the two peak structure.

Similar conclusions for the turbulence ratio as in the previous section are drawn: a turbulence ratio in the range 0.4-0.5 outside the wake and a turbulence ratio in the wake of the turbines, which is symmetrically increased about the center line (~235°) to values of about 0.7. The effect of increased ratio seems slightly stronger for the single wake than for the triple wake, although this may also be the result of the scatter in the data.

4.2.2. Wind speed and turbulence intensity dependence

The same high and low wind speed and turbulence intensity selections have been applied for the multiple wake situations as for the single wake situation in

section 4.1. The results are shown in figure 5 and figure 6 for the single wake and triple wake, respectively. Again, the wind speed ratio, the turbulence intensity, the vertical wind speed and the turbulence ratio is considered.

It is noticed that the wind speed deficit in both the single wake and the triple wake is larger for lower inflow wind speeds. This complies with the observations seen in section 4.1 and is due to the increased value of the thrust coefficient as indicated before. With respect to the turbulence intensity selections a slight decrease in wind speed deficit may be seen for larger turbulence intensities for single and triple wake situation. This could be explained by the earlier mentioned wake recovery due to turbulent mixing. However, it is acknowledged that the effect is small and it may also be due to the scatter in the data.

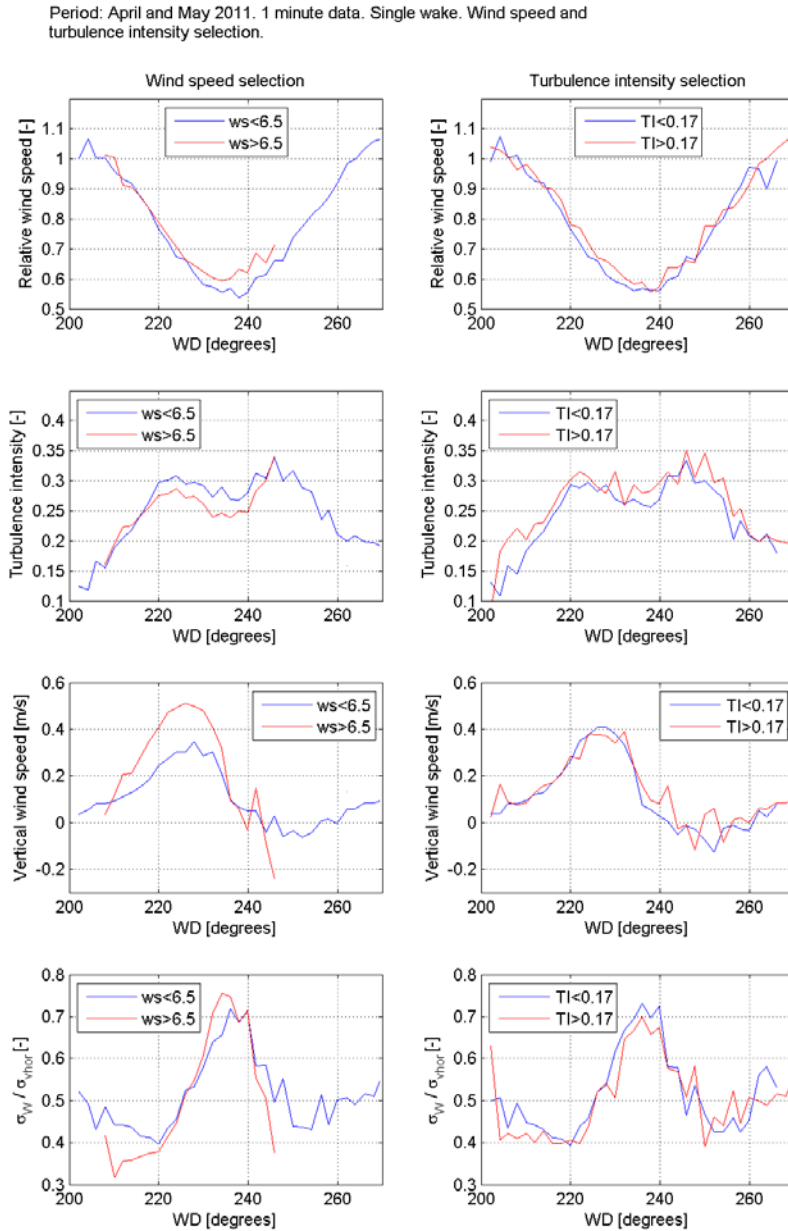


Figure 5. Relative wind speed (upper plots), turbulence intensity (upper middle plots), vertical wind speed (lower middle plots) and turbulence isotropy (lower plots) as function of the inflow wind direction. Specific wind speed selections are indicated in the left plots and specific turbulence

intensity plots in the right plots. The red lines represent high wind speed and turbulence intensity selections and the blue lines the opposite. The results are for the single wake situation, only.

The turbulence intensity is for both single and triple wake situation reduced for higher wind speeds. For the single wake situation in the previous section this was also observed, but only for location 1. The effect of turbulence intensity selections is not so pronounced; a small increase in turbulence intensity for larger inflow turbulence intensities may be seen for the single wake. However, for the triple wake this is not seen at all. An increase in turbulence intensity for larger inflow turbulence intensities was also observed in the previous section.

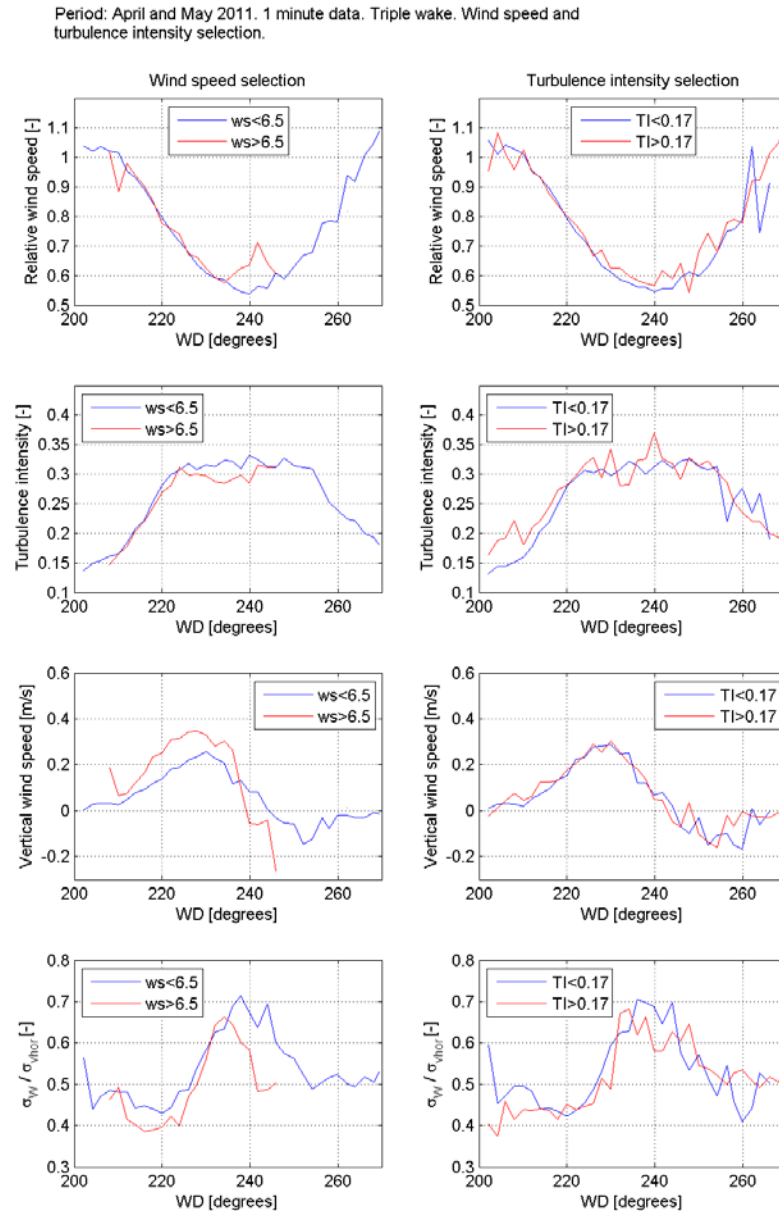


Figure 6. Relative wind speed (upper plots), turbulence intensity (upper middle plots), vertical wind speed (lower middle plots) and turbulence isotropy (lower plots) as function of the inflow wind direction. Specific wind speed selections are indicated in the left plots and specific turbulence intensity plots in the right plots. The red line represent high wind speed and turbulence intensity selections and the blue line the opposite. The results are for the triple wake situation, only.

Considering the vertical wind speed it is for both single and triple wake situation clearly seen that the (absolute value of the) vertical wind speed is increased for higher wind speeds. This is obvious from the fact that the rotor speed of the turbine is increased for higher inflow wind speed, as was explained before. Therefore, also the vertical wind speed in the wake is increased. Complying with the single wake situation of the previous section considering the specific turbulence intensity selections do not have any effect on the profiles.

For the turbulence ratio some trends may be observed for specific inflow wind speed and turbulence intensity filtering. However, it must be said that the scatter in the data with which these figures were obtained is pretty large. Therefore, no definite statements are made concerning these results.

5. Summary and Conclusions

Wake studies have been performed where two situations have been considered. In one case the single wake of a turbine was studied at two different locations downstream of the turbine (1.9D and 4.2D). In a different case the single wake as well as the triple wake was studied, where the measurements were taken 1.8D behind the first and third turbine. A unique feature is the extensive instrumentation of the farm by which wake and inflow measurements can be studied simultaneously.

The wakes were studied by means of the wind speed deficit, the turbulence intensity, the vertical wind speed and the turbulence (an)isotropy as function of the wind direction. Generally, the following features of the wake have been found: The wind speed ratio is decreased with a minimum at the center of the wake. The turbulence intensity is increased with a two peak structure, due to the tip vortices, centered about the wake center. On one side of the wake center the vertical wind speed is increased and on the other side it is decreased. This corresponds to a clockwise rotating turbine (and counter clockwise rotating wake). Last but not least the turbulence ratio is increased; apparently turbulence is more isotropic in the wake.

More specifically it is noted that the wind speed ratio is somewhat asymmetric and exceeds the value one at one side of the profile. It is believed that this is due to the vertical wind speed in conjunction to the vertical wind shear. On one side upward winds transport high momentum to higher altitudes and vice versa on the other side. Therefore, the horizontal wind speed receives contributions from higher or lower altitudes, increasing or decreasing its value.

Specific selections on inflow turbulence intensity have been made and in the wake it is seen that a higher inflow turbulence intensity leads to a smaller wind speed deficit, a slightly higher turbulence intensity and less isotropic turbulence, i.e. a smaller turbulence ratio. A higher inflow turbulence intensity leads to more turbulence mixing in the wake and hence a quicker wake recovery. Therefore, a smaller wind speed deficit in the wake is observed. A slightly higher turbulence intensity in the wake is most probably due to the fact that the turbine adds turbulence to the ambient conditions. Any effect on the vertical wind speed is not observed.

Specific selections on inflow wind speed have been made and in the wake it is seen that a higher wind speed leads to a smaller wind speed deficit, a lower turbulence intensity, a higher (absolute) vertical wind speed and less isotropic turbulence, i.e. a smaller turbulence ratio. For higher inflow wind speeds the thrust coefficient is smaller and more wind passes the rotor, therefore the wind speed deficit in the wake is smaller. Obviously, a higher inflow wind speed causes the rotor to rotate faster (under rated), leading to increased (absolute) vertical wind speed in the wake.

From the single wake measurements further downstream the turbine it is clearly seen that the wake has recovered to a certain extent as compared to the

wake measurements closer to the turbine. This is concluded from less wind speed deficit, less increased turbulence intensity, less (absolute) vertical wind speed and less isotropic turbulence. In addition the two peak turbulence intensity structure is less pronounced, if visible at all.

The wind speed ratio in the triple wake situation does not differ very much from the ratios in the single wake situation. One would expect larger deficits in the former case, because additional turbines have already extracted energy from the wind flow. Main difference in the turbulence intensity for the single and triple wake situation is that in the latter case the two peak structure is hardly visible. In addition the vertical wind speed has decreased and the turbulence ratio seems less isotropic in the triple wake.

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