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Influence of Wind Turbines on the Vertical Component of Ambient Atmospheric Turbulence as Measured by w'2

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ABSTRACT

More and more is becoming known about how wind turbines impact the atmosphere and surface around them. Researchers have studied turbulence and its interactions in the boundary layer for many years and how it affects different atmospheric variables. Introducing mechanically-induced turbulence from wind turbines directly influences the atmospheric turbulence, altering the transport of heat, momentum, and moisture fluxes. For this study, multiresolution decomposition was applied to data taken from a wind farm in Central Iowa for the summer months of 2013, with a focus on nighttime events with flow disrupted by several turbines deep in the wind farm (i.e. northerly wind directions). Initial analysis investigated the magnitude of the variances of the vertical velocity component of ambient atmospheric turbulence (w'^2) as a function of an averaging timescale to determine influences of turbine turbulence or mesoscale interactions. These interactions were compared to wind direction, turbine status, and time throughout the night to determine correlations of these variables with turbine influence. Whether or not there was direct turbine influence on the vertical velocity component appeared to depend mostly on specific wind directions. Measurement stations directly downwind of the wind turbines were found to be the most influenced, but the degree of influence is sensitive to station location and wind direction.

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1. Introduction

The desire for renewable energy has grown over the past several years. One of the cleanest, most environmentally-friendly sources of energy known today is wind energy (U.S. Department of Energy, 2008). Wind farms have been rapidly expanding over the past few years and more questions arise regarding how the expansion of these wind farms impacts the area surrounding the wind turbines. These turbines operate in the lower part of the planetary boundary layer (Sanderse, 2009) which is an important contributor to the effects of the atmosphere. The boundary layer is the part of the troposphere that is directly impacted by forcing at the surface on about a one-hour time scale. As the surface is heated by solar radiation, it alters the boundary layer through transport processes. One of the most important of these processes for affecting the boundary layer is turbulence. (Stull, 1988). The turbulence in this layer transports moisture, heat, and momentum in the vertical direction. Wind turbines generate mechanically-induced turbulence which can directly alter the local atmospheric circulations in the boundary layer. Boundary layer variations in mean wind, pressure, and natural turbulence modify surface heat, moisture, and momentum fluxes (Fitch et al., 2013). This is of interest because wind turbines and wind farms are generally located in crop fields, and these mechanically-induced changes in turbulence and flux influences can affect agricultural processes (Rajewski et al,. 2013).

The effects of wind farms throughout a diurnal cycle was studied by Fitch et al. (2013) and they determined that a wind farm covering an area of 100 square km had a significant effect at night on atmospheric flow locally and in areas up to 60 km downwind. The Crop Wind Energy Experiment (CWEX) (Rajewski et al., 2013) determined that wind turbine wakes can continue to exist up to a distance of 15 rotor diameters downwind of a turbine. For their study, the wind farm consisted of 200 General Electric 1.5-MW super long extended and extra-long extended wind turbines with 80 meter hub heights and rotor diameters ranging between 74 meters and 82.5 meters. The interaction of the turbine wakes reaching up to 15 rotor diameters (1,110 – 1237.5 meters) downwind could have a significant impact on the localized climate extended well beyond the turbines. (Rajewski et al., 2013).

It is important to understand how turbines influence the atmosphere and surface around them, and there are different ways to analyze this problem. One such method is multiresolution decomposition. Vickers and Mahrt (2003) used multiresolution decomposition to study the cospectral gap scale, which is a timescale that separates turbulent fluxes and mesoscale fluctuations of heat, moisture, and momentum. The multiresolution technique is useful because of the capability to isolate low frequency and high frequency turbulence scales each caused by different sources of turbulence. It is of interest to separate the turbulent and large-scale variations because the turbulent fluxes are associated with wind shear and temperature stratification, and the mesoscale fluxes are not (Vickers and Mahrt, 2003). Using the spectral or cospectral gap scale identifies the mesoscale interference (Vickers and Mahrt, 2003). A study done by Chloe Dedic (2015) applied multiresolution decomposition to data from the CWEX-13 project (Lundquist, et al., 2014, Rajewski et al., 2015) to investigate turbulence from the boundary layer and nearby wind turbines.

While a lot is known about how turbines affect the atmosphere, there are questions that still need to be answered regarding the influence of turbines. This project uses multiresolution decomposition to determine how wind turbines affect ambient turbulence in the surface layer. The vertical component of turbulence among natural and wind turbine-forced sources of turbulence will be evaluated to determine the impact of flux modification deep within a utility-scale wind farm.

2. Methods

The 20-Hz resolution of sonic anemometer 3-dimensional wind speed (u, v, w) and virtual temperature from the CWEX-13 project were used for the multiresolution decomposition analysis. A sonic anemometer was positioned at 8 meters on seven surface flux stations to measure atmospheric turbulence differences inside versus outside of a Central Iowa wind farm containing 200 wind turbines (Fig. 1). This data was collected from July 3, 2013 to September 19, 2013. For this particular study, thirty data sets were analyzed, each set spanning a four-hour period, with a focus on nighttime events (between 6 PM CST and 5 AM CST) and northerly winds (including NW, NNW, N, NNE, NE). The focus on nighttime events was chosen because the data for this time would not be obscured by

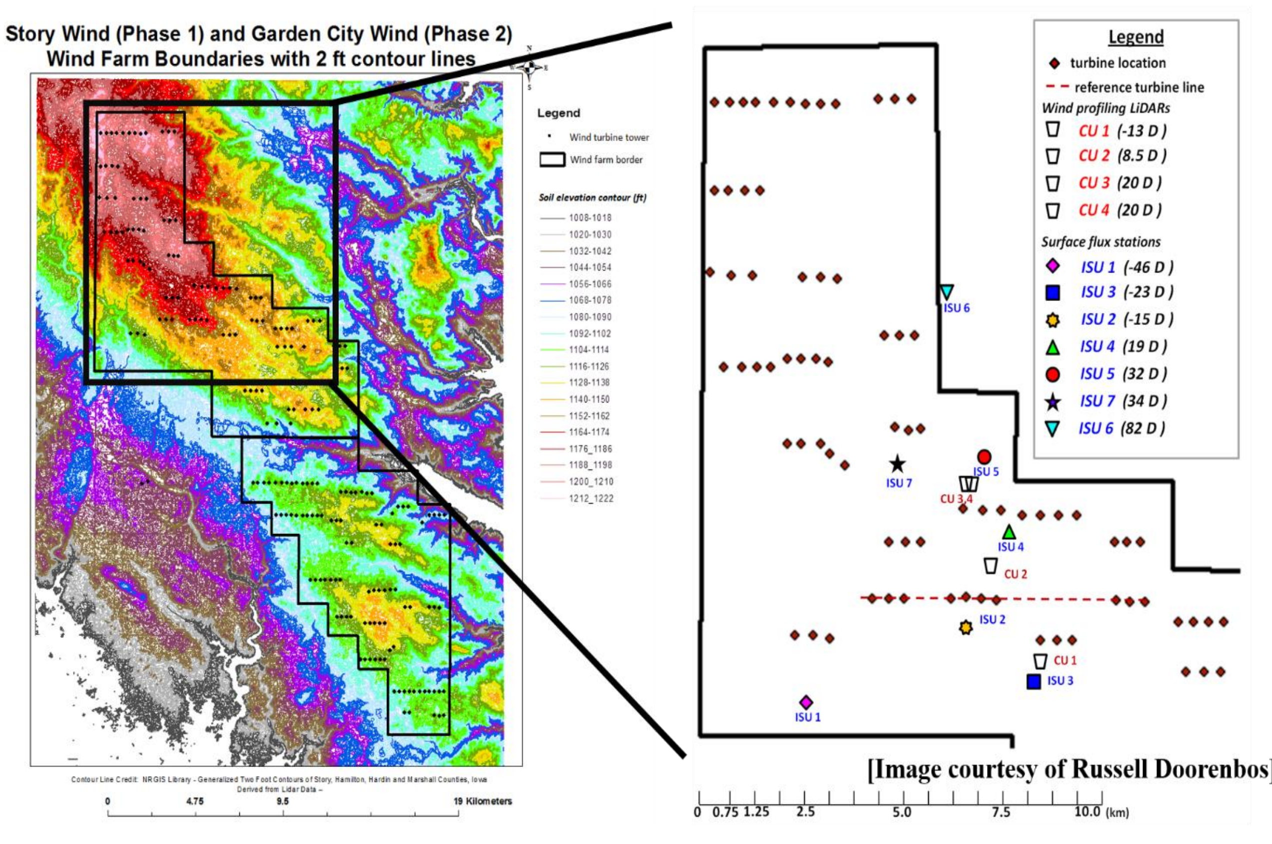


Fig. 1. Wind farm in Central Iowa, the site of the Crop Wind Energy Experiment–13 project and the site of which the data for this project comes from. The flux measurement stations are located in the northern section of the farm, highlighted on the right side of the figure labeled ISU 1 – ISU 7.

daytime convection, which strongly affects the vertical velocity power spectra (w'^2). Northerly winds were chosen based on the curiosity of how this particular wind direction would influence the spectrum of interest, w'^2.

Matlab was used to employ multiresolution decomposition on the 20-Hz flux station data to analyze w'^2. Multiresolution decomposition, which separates turbulent and mesoscale fluctuations, was used to study the cospectral gap scale. To isolate the two variations, the positive and negative turbulent fluctuations can be averaged out by averaging a variable over a one-hour period, giving a mean component $\overline{w}$, for example, which can be subtracted from the actual variable, w, resulting in a turbulent component, w':

$$w' = w - \overline{w} \qquad (1)$$

The spectral gap is what allows this separation to be done. The component w' represents flow variation on scales shorter than an hour (turbulent fluctuations), and the mean component, $\overline{w}$, represents that which varies over a period longer than one hour (mesoscale fluctuations). (Stull, 1988). This averaging can be done for variables in the horizontal and vertical directions and for variables such as momentum, moisture, and temperature fluxes.

Multiresolution decomposition satisfies Reynold's averaging at all scales, which uses equation (1). Looking at the vertical wind ($w' = w - \overline{w}$) and temperature ($\theta' = \theta - \overline{\theta}$) components for example, Reynold's averaging is satisfied by:

$$\Sigma\, D_w\,(m) = \overline{(w - \overline{w})^2} = \overline{w'w'} = \overline{w'^2} \qquad (2)$$

$$\Sigma\, D_{w\theta}\,(m) = \overline{(w - \overline{w})(\theta - \overline{\theta})} = \overline{w'\theta'} \qquad (3)$$

Where D is the multiresolution spectrum. These equations give vertical momentum flux and vertical temperature flux respectively. Mesoscale fluctuations can be filtered out by summing up the multiresolution spectrum to a specific averaging time scale. Using this method still satisfies Reynold's averaging, but only the flux contributions from time scales below a given level are calculated, instead of overall flux (Dedic, 2015). This is desirable as it is the turbulent scales that are being focused on.

In order to perform the decomposition on the four-hour datasets used in this study, each time series must include 2^M samples, where M is the number of decomposition modes.

$$M = \log_2(4hr*3600s/hr*20samples/s) = 18.14 \qquad (4)$$

Rounding this down to 18 results in 2^{18} points which trims the dataset causing it to last 3.64 hours instead of 4 hours. Instead of averaging the datasets over the entire four-hour period, each set was broken down into 4 subsets, resulting in a 54.6 minute (3.64 hr/4 hr*60 min) time series length. The number of decomposition modes was then decreased from 18 to 16, which removed any mesoscale effects that occur on a time scale larger than an hour, but still included the spectral gap. The multiresolution decomposition was applied to CWEX-13 data by Dedic (2015), whose code was altered and reused for this project.

Specifically for this project, the magnitude of the vertical velocity power spectrum (w'^{2}) flux, or variance, near the surface was plotted as a function of the averaging time. This averaging time scale is equal to inverse frequency. The magnitude of the variance at any given inverse frequency indicates the importance of that frequency to the total turbulence being measured. The high frequency variances are at small averaging times and the left-most part of the plot. These variances are very fast fluctuations of wind speed generated by natural turbulent eddies near the measurement station. The low frequency variances are at large averaging times and displayed toward the right-most part of the plot. The low frequency variances are generated by isolated events, like mesoscale influences (e.g. advection in mean wind), landscape features, large structures, or some form of a flow disturbance maybe a mile or several miles away. The plots usually have a spectral gap separating these mesoscale and turbulent features (Fig. 2).

30 datasets were used spanning the months of July 2013 through September 2013 that were taken at 5-7 measurement stations between 6 PM CST and 5 AM CST with northerly winds. Measurement stations ISU 1 and ISU 6 were offline until July 22 and August 15 respectively, so certain datasets only include five or six stations instead of all seven. 194 plots were generated after applying multiresolution decomposition to the datasets. Each plot contained four, one-hour

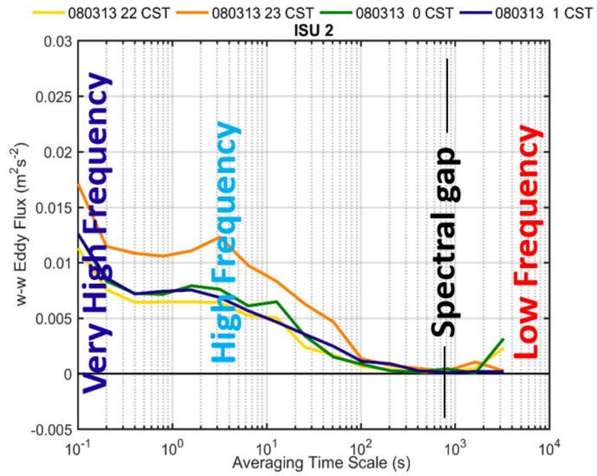


Fig. 2. Locations of very high, high, and low frequencies, and location of the spectral gap relative to the plots.

time series, each one-hour time series treated as a singular case, resulting in a total of 776 cases. Specific wind directions at each measurement station (NW, NNW, N, NNE, and NE) were noted for each case. The plots were analyzed for peak fluctuations to determine whether there was high or low frequency influence, or whether the peak of the variances shifted from lower to higher frequencies. That shift is a good indication of turbine influence. Over the four hours, for each hour, the flux starts at the smallest time scale, generally reaches a peak corresponding to a maximum turbulence fluctuation, and declines to zero at the spectral gap. However, for the vertical velocity spectrum, the flux peaks were not always shown on the plot, but rather had higher frequency peaks extending further left than the scope of these graphs. (Fig. 3). These peaks will be referred to as higher or very high frequency peaks. A very high frequency flux peak is another indication of wind turbine influence.

Excel was used to keep track of which plots had these very high frequency peaks and the wind directions corresponding to them. Whether there was a general shift of the flux peaks from low to high frequency was also tracked.

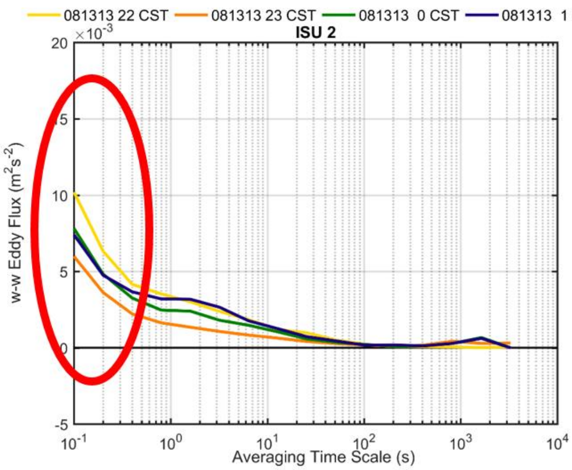


Fig. 3. Example of a plot at measurement station ISU 2 showing a clear very high frequency peak, with the highest flux values at the smallest averaging time scale.

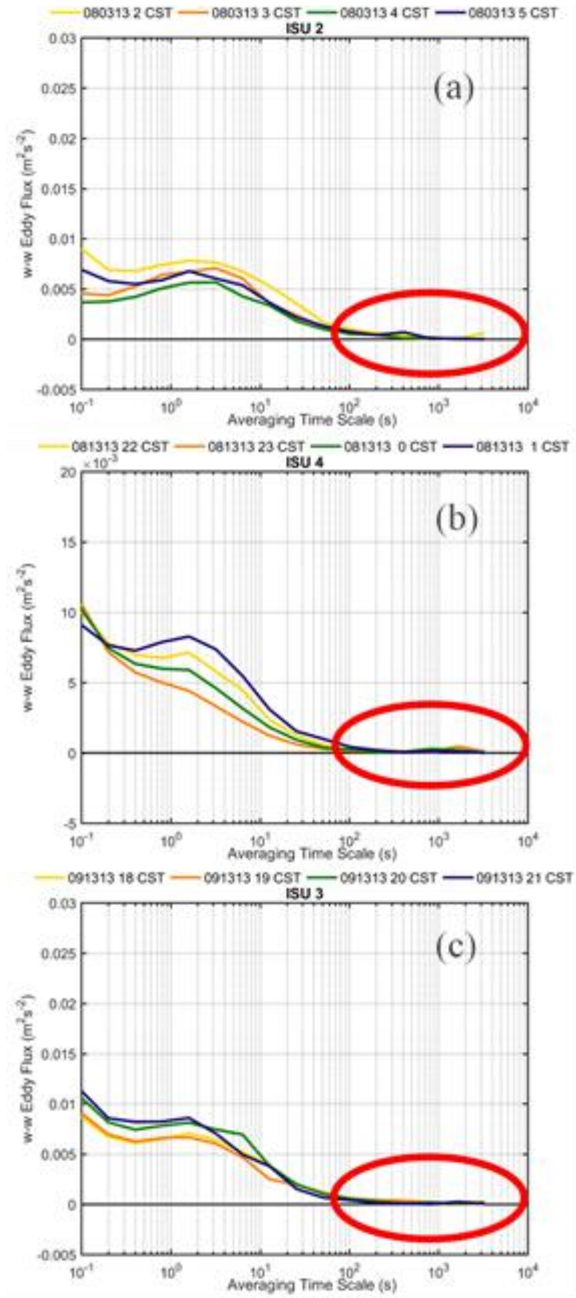


Fig. 4. 4(a), (b), and (c) show examples of how the w'^{2} spectra are not influenced on the low frequency end, implying that there are no mesoscale contributions to the overall turbulence measured.

3. Results and Analysis

After analyzing the plots, it was found that there was very little to no activity at the low frequency end of the w'^{2} spectrum for all cases examined. This suggests that at night with northerly winds, there are no mesoscale contributions to the low frequency end of the spectrum, indicating that w'^{2} is not affected at lower frequencies under these conditions. (Fig. 4a, b, c)

The number of cases with very high frequency peaks were compared to wind direction to look for correlations. (Table 1). Of the 776 cases, 293 (37.8%) of them had north winds, 167 (21.5%) had northeast or north-northeast winds, 141 (18.2%) had northwest or north-northwest winds, 93

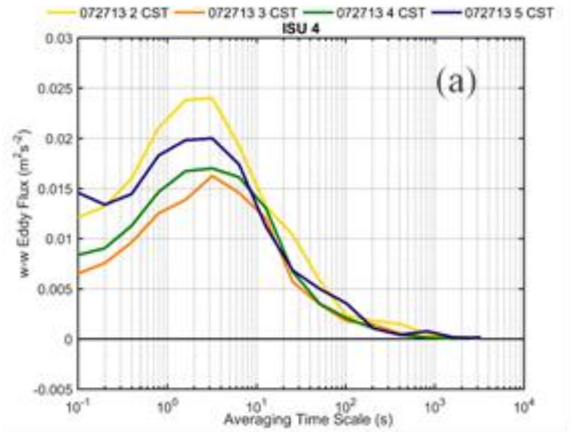
Table 1. Summary of the total cases corresponding to different categories of wind direction. The number of cases with very high frequency peaks were compared to those without. A percent of very high frequency peaks was computed for each wind direction category and for the total number of cases.

Wind Direction	Total Cases	Cases w/ Very High Frequency Peaks	Cases w/out Very High Frequency Peaks	Percent of Very High Frequency Peaks
N	293	271	22	92.49
NE, NNE	167	5	162	2.99
NW, NNW	141	40	101	28.37
Mixed (e.g., NNE-N)	82	37	45	45.12
W influences	93	9	84	9.68
TOTAL CASES	776	362	414	46.65

(12%) cases contained too much of a westerly wind influence, and 82 (10.5%) cases contained mixed northerly winds over an hour-long period (e.g., NNE-N). There were 362 cases with very high frequency peaks. Of these 362 cases, 271 of them had directly north winds. There appeared to be a correlation between north wind directions and very high frequency peaks. 92.49% of the north wind cases had very high frequency peaks. On the opposite side of the spectrum, cases with north-northeast or northeasterly winds tended not to have very high frequency peaks. Only about 3% of the cases looked at with these wind directions showed peaks at the desired higher frequency. Looking at the next-largest set of cases, those with northwest or north-northwest winds, only 28.37% of these cases had very high frequency peaks. Instances containing a mix of variable wind directions over the hour-long period had almost 50% of its cases with very high frequency peaks. When there was too much of a westerly component to the wind direction over the hour, it resulted in only 10% of the cases having very high frequency peaks.

Of the plots without a higher frequency peak, few showed a prominent flux peak shift over the four-hour span from lower to higher frequencies. Most cases without a very high frequency peak (Fig. 5a) had peak magnitudes at around the same averaging time, which for NW or NNW winds was usually around 3 seconds for a majority of those cases. (Fig. 5b).

The 30 datasets that were looked at had time spans of four hours each. 10 of these cases started at 0000 UTC, 12 cases began at 0400 UTC, and 8 started at 0800 UTC. Comparing the time of the cases during the night to those with higher frequency flux peaks appeared to be particularly variable and insignificant, and wind direction alone seemed to have much more of an impact on whether there was an influence or not.



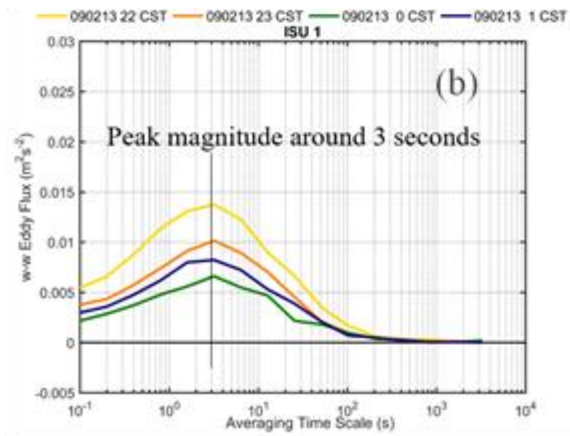


Fig. 5. 5(a) and (b) are examples of plots without the very high frequency peaks. The peaks of these plots generally appeared around 2 or 3 seconds. Those specifically with NW or NNW winds had peaks stacked at 3 seconds, shown in figure 5(b).

The cases evaluated that ended up containing too much of a westerly wind influence appeared to have a majority of the fluxes show very low magnitudes on both the high and low frequency ends of the spectrum (Fig. 6). Evaluating turbine activity showed that for these specific cases, the turbines were off or at very low power. This suggested a relationship between westerly winds and turbine status. This could be due to the fact that there are very few turbines located to the west of the measurement stations. However, there were not enough cases in this specific project under these conditions to make any determinations, and looking specifically at westerly winds was not the focus of this particular study, but could be considered for future work.

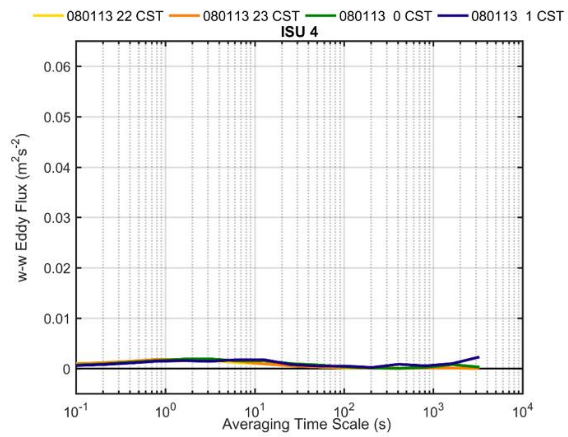


Fig. 6. Example of one of the westerly wind-influenced cases. Shows very low activity on both the low and high frequency ends.

212 cases with southerly winds from a separate project using the same multiresolution decomposition and analysis methods were evaluated to compare whether these datasets included the higher frequency peaks as well. After analyzing these southerly wind cases, it was found that none of them contained very high frequency peaks, but rather only high frequency peaks near an averaging time of 3 seconds.

Results show that the most notable factors in determining wind turbine influence on the vertical component of atmospheric turbulence, w'^2, are location of the measurement stations and wind direction through the wind farm.

4. Discussion and Conclusions

Plots generated after the application of multiresolution decomposition of flux data displayed the magnitudes of the variances, or fluctuations, of the vertical velocity power spectrum, w'^2, as a function of averaging time, which is equivalent to inverse frequency. After evaluating these plots it was determined that there were no low frequency contributions to the vertical velocity power spectrum, w'^2. This suggests that w'^2 is not affected by mesoscale or isolated events.

Flux peaks on the very high frequency scale are a good indication of wind turbine influence. Only about half of the cases analyzed had these higher frequency peaks. 92.49% of the very high frequency peak cases were cases taken with north winds. This indicates that the w'^2 is influenced by wind turbines in this particular wind farm when there are north winds. Only 3% of the cases having north-northeast or northeast winds had very high frequency flux peaks, which suggests that there is very little influence of wind turbines on w'^2 under those conditions.

A shift in the flux peaks from lower to higher frequencies is also a good indication of turbine influence. Most of the plots that did not have a higher frequency peak did not appear to have any distinguishable peak flux shifts which suggests that there was little turbine influence of w'^2. The magnitudes of the variances in these cases usually appeared to be at about the same averaging time.

For all of the plots, except those cases with the more westerly influences, there were notable magnitudes of vertical velocity flux contributing to the overall turbulence. However, for the cases without very high frequency flux peaks or peak variances shifting from low to high frequency over the time period, the vertical velocity component of the atmosphere may not be specifically impacted by wind turbines in these instances. With only about half of the 776 cases having the very high frequency flux peaks and therefore only around half of the cases appearing to be influenced by wind turbines, it can't be concluded that w'^2 will always be influenced specifically by the turbines. It can be concluded that turbine influence appears to depend much more on wind direction than on the time of which the data was taken during the night. This could likely be due to where the measurement stations are located in reference to the wind turbines. There was a significant percent of cases with north winds that had the very high frequency peaks, indicating that the vertical component of the ambient atmospheric turbulence is influenced by wind turbines at night under north wind conditions. Under these conditions, this would put a majority of the measurement stations downwind of the turbines. A more general conclusion can be noted that w'^2 is influenced most in areas downwind of the wind turbines, and that this influence is sensitive to wind direction and dependent on the measurement location in the wind farm relative to the turbines. Since these wind farms are generally located in crop fields, the conclusions from this study imply that the vertical velocity component of the atmospheric turbulence would be most influenced by the wind turbines at a point in the field downwind from them. Knowing this, and how mechanically-induced turbulence impacts these atmospheric fluxes, which can affect agricultural processes, a more careful consideration can be made of crop placement in wind farms.

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