Meteorological Phenomena Impacting Spatial Consistency of Ramp Events in Wind Farms

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1. Introduction

Wind energy is one of the fastest growing forms of energy generation in the United States and around the world. A Department of Energy report states that from 2004 to 2009 wind was the second largest resource added to the electric grid in the U.S. behind natural gas. It also projects, going at that pace, about 35% of the increase in electric generation in the U.S. will be met by wind energy by 2035 (Wiser & Bolinger, 2011). Even with this boom in the industry, wind energy is a technology still considered in its infancy and is not without its problems.

One problem with this energy source is its inherent variability. This variability puts wind energy in the category of variable renewable resources (VRE's) (Marquis et al., 2011). This variability can lead to unexpected rapid increases and decreases in power output, which are known as wind ramp events. These ramp events can cause power curtailment for wind farms, where the wind farms are producing electricity but are not allowed to put it on the grid due to transmission overloads. This is very costly to utilities (Marquis et al., 2011). Deppe et al. (2013) defined a ramp event as a minimum change of ±3 m/s between 6 m/s and 12 m/s in wind speed over a 4 hour period. A positive change is labeled a "ramp up" and a negative change a "ramp down." The range between 6 m/s and 12 m/s is usually when a wind turbine has its most variable power output. quick changes in this range can cause problems in the power grid (Ferrier et al., 2010). Better predictions on when wind ramps may occur will be beneficial to utilities. A Department of Energy report (Schreck et al., 2008), states that a 1% error in wind estimation could lead to about $12,000,000 loss over the lifetime of a 100-MW wind plant.

Previous research focused on when these ramp events occurred and different methods of predicting their characteristics. Deppe et al. (2013) found that most planetary boundary layer schemes in the prediction models did not lead to well-predicted ramp events. The most successful scheme, the MYNN 2.5, only predicted ramp up events 50% of the time. For most schemes the mean average error (MAE) was larger than the calculated biases, meaning that the schemes predicted times for the ramps that were off from the times the ramps actually happened (Deppe et al., 2013). Showers Walton et al. (2012) also found difficulties in predicting ramp events, with a persistence model showing a hit rate (HR) never exceeding 45% and a false alarm rate (FAR) between 50-70%. That study also found that in one wind farm not all turbines were ramping at the same time or having the same type of ramp.

Deppe et al. (2013) found only 17% of ramp events could be accounted for by the passage of frontal system. 32% occurred during the presence of a low level jet (LLJ) and 10% were likely related to the growth of the planetary boundary layer (PBL). Another 24% of ramps could not be explained by obvious causes using standard observational networks.

The present study will seek physical explanations for the 24% of ramps that Deppe et al. (2013) failed to explain, and will also explore why turbines in the same wind farm can be ramping in opposite directions.

2. Data and Methods

Data were taken from the nacelles of thirteen wind turbines in a wind farm close to central Iowa. The thirteen turbines included two lines of turbines, eight from the "B" line, which was at the south edge of the wind farm and five from the "A" line which was one line north of the "B" line (see Figure 1). Data were taken every ten minutes between 29 June, and 16 August, 2011. The nacelle data included, for each individual turbine, the wind speed (in m/s) at turbine height, yaw angle of the turbine (in degrees), ambient temperature (in ºC), and active power (in KW).

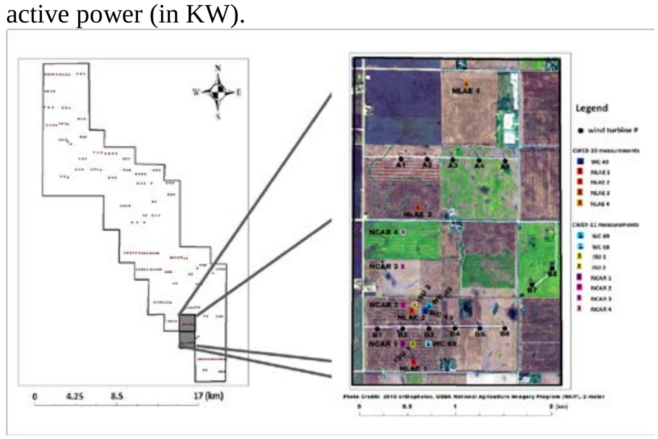

Figure 1. Turbine Locations (photo from Rajewski et al., 2013)

The nacelle data were first searched to identify wind ramp events. The definition of a wind ramp has been debated, and different studies have used different

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definitions of a wind ramp event (Ferrier et al., 2010). For this study the definition of a ±3 m/s change in wind speed between 6m/s and 12 m/s over a 4-h period was used (as in Deppe et al. (2013). Wind ramps identified by Showers Walton et al. (2012) were used as examples for identifying ramps in this research.

Ramp events were divided into 5 categories: all the turbines simultaneously ramping up ("All up"), all the turbines ramping down ("All down"), a mix of up ramps and no ramps ("Some-up"), a mix of down ramps and no ramps ("Some-Down"), or a mix of up, down and no ramps ("Mixed").

Meteorological data were collected for the start times of these group ramp events from the Iowa State University's Mtarchive data server [Available online at http://mtarchive.geol.iastate.edu/]. Measurements examined included: surface pressure (mb), 850-mb wind speed (knots) and wind direction (degrees). Looking at archived maps the ramps were also classified by the turbines' relative position to synoptic features: east of high or low pressure ("Ahead"), west of high or low ("Behind"), or in the middle of high or low ("Mid"). Ramps were classified by the curvature of the isobars near the turbines, cyclonic, anti-cyclonic, or straight, which implies the likelihood of ascent and descent. For some dates where group ramps occurred, not all of the meteorological data could be obtained due to missing information in the archive.

Atmospheric stability and net radiation readings were acquired from research done by Rajewski et al. (2013). Net radiation data were taken from a net radiometer placed 4.5 m above the ground on a tower just south of the "B" line (labeled ISU-1 on fig. 1). Stability was measured using the z/L_0 calculation, where z is the height of the sonic anemometer (also located 4.5m above the ground at the ISU-1 site) and L_0 is the Obukhov length:

$$L_0 = \frac{-\theta_v u_*^3}{kg(w'\theta'_v)_s}$$

Where θ_v is the virtual potential temperature, u_* is the friction velocity, k is von Karman's constant (0.4), and $(w'\theta'_v)_s$ represents the surface moist sensible heat flux (Rajewski et al., 2013).

Group ramp events were classified in ranges of stability following the convention laid out in Rajewski et al. (2013), and ranges in net radiation by guidelines laid out upon personal conversation with Dan Rajewski. Atmospheric stability was separated into 3 categories: stable atmosphere ($z/L_0 > 0.05$), neutral atmosphere ($-0.05 < z/L_0 < 0.05$), and unstable atmosphere ($z/L_0 < -0.05$). Net radiation, R, was divided into three categories: day time conditions ($R > 300$ W/m^2), transition period ($0 < R < 300$ W/m^2), and night time conditions ($R < 0$ W/m^2).

3. Results

Table 1 shows the number of ramps identified in the different group ramp classifications. There were 127 groups identified overall. Figure 2 shows the percentages of each classification. "Some-up" is the largest class, with 40%, meaning that when winds were ramping up at the

Table 1: Breakdown of group ramp events into five different classifications

	Totals:
All_Up	12
All_Dwn	15
Some_Up	51
Some_Down	42
Mixed	7
Overall	127

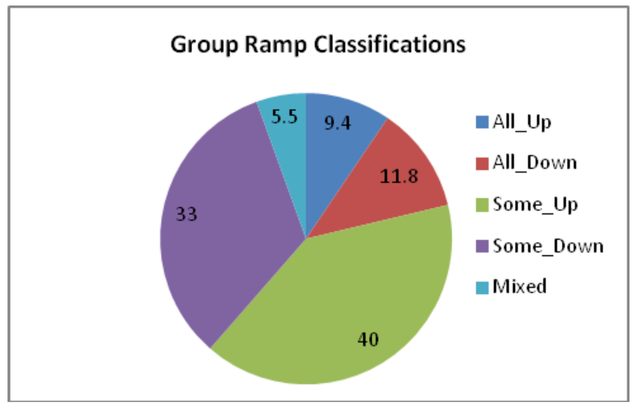

Figure 2: Pie-chart showing percentages of group ramps events in the different five classification

wind farm, most of the time several, but not all, wind turbines were ramping up. The next most common classification (33%) were identified as "Some-Down". This suggests that when ramps happen in a wind farm there is usually variability and not all turbines will ramp.

It is useful to notice the smallest classification is when turbines are simultaneously ramping up, down and not ramping. These events suggest that while there could very be small scale phenomena affecting wind ramps in a wind farm, most of the ramps (about 94.5%) occur over a large enough scale that opposing ramps within the same farm are rare.

For each ramp classification an average pressure (mb), average wind speed (knots), average wind direction (degrees), and average stability were identified. Table 2 shows each of the group ramp classifications along with the respective averages. Figures 3-6 show a comparison between the classifications and respective averages. The error bars represent the standard deviation from the average. It should be noted that out of the 127 group ramp events, 1 was missing meteorological data and was not included in the averages.

No clear signals are seen comparing average stability and wind direction. The average stability seems fairly clustered. The “Some-up” class seems to have the highest stability, looking at the standard deviation; it seems to be affected by some outliers. The argument could be made that the higher stability leads to more variance in which turbines ramp, because the “Some-up” and “Some-down” classifications’ average stability is higher than either of the “All” classes. However this is contradicted by the “Mixed” average which is lower than the “All” classes (See Figure 6).

The average wind speed does shed some light on what might cause the variability. Higher wind speed at the 850-mb level does seem to suggest more uniform ramping (see Figure 4). The “All” classifications have higher average wind speeds then the variable ramp classifications. This could be explained by the idea that with strong winds at higher levels there is more uniformity through the atmosphere and at turbine height the effects of the higher winds can be seen. However, lower wind speeds higher up in the atmosphere might suggest less potential for higher speeds to affect turbines, and maybe small scale phenomena would play a bigger role in getting ramps.

Average pressure also shows a reasonable distinction between the “All” classes and the “Some” and “Mixed” classes. The “All” classes have a lower average pressure than the variable classifications (see Figure 3). This suggests that more uniform ramping occurs during lower pressures and more variable ramping in a wind farm would happen at higher pressures. This result suggest more organized weather systems, accompanied by lower pressure, result in more uniform ramping.

Table 2: Measurement averages for each group ramp classification

	Avg. Pressure	Avg. Wind Speed	Avg. Wind Dir.	Avg. Stability
All_Up	1009.8	23.8	232.1	0.1
All_Dwn	1008.6	25	242.5	0.03
Some_Up	1011.4	14.7	219.4	0.4
Some_Down	1011.6	16.3	221.6	0.1
Mixed	1011	20	226.4	0.02

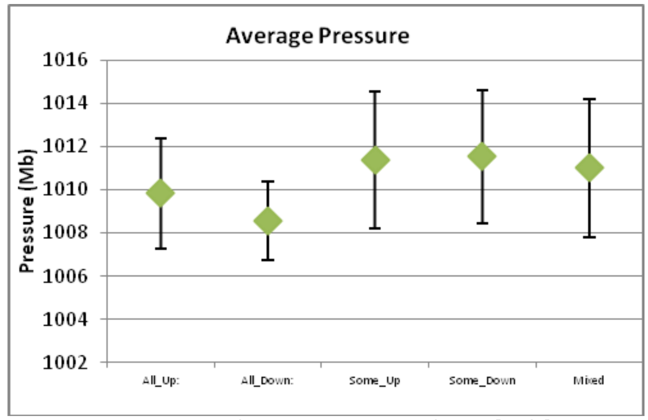

Figure 3: Comparison of average pressures for each of the different group ramp classifications

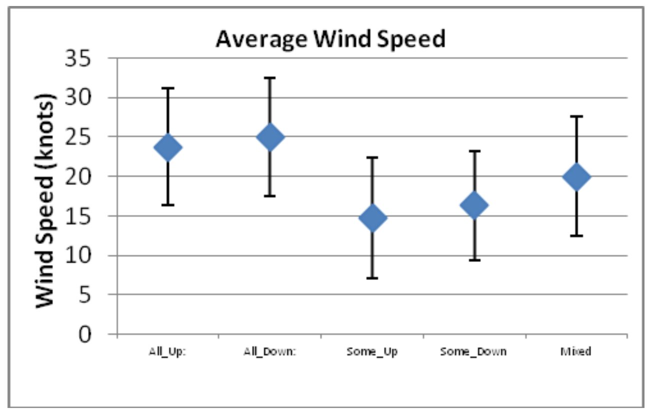

Figure 4: Comparison of average wind speed for each of the different group ramp classifications

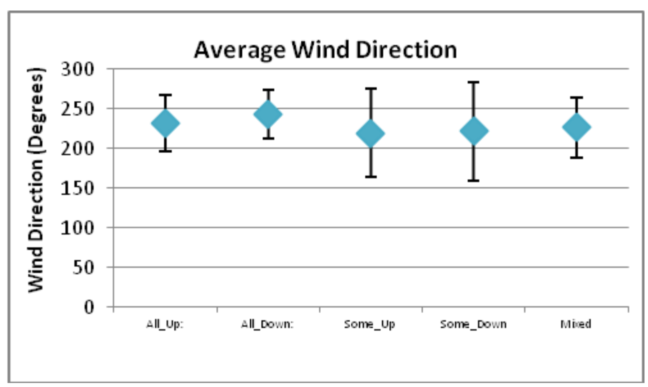

Figure 5: Comparison of average wind direction for each of the different group ramp classifications

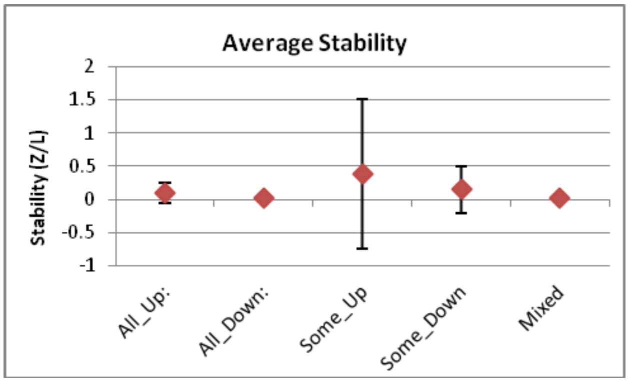

Figure 6: Comparison of average stability for each of the different group ramp classifications

Table 3 shows the number of times group ramps were classified as a function of their position relative to major synoptic features. As some occurrences could be put in two different categories, weighting was used such that if a turbine was said to be Ahead of a Low and Behind a High, 0.5 was put into each category. Table 4 shows the percentages of each occurrence. Position relative to synoptic features does not seem to differentiate between types of ramps. All classifications seem to have roughly the same probability of being in one of the synoptic classifications ("Ahead of Low" etc.). In the broad picture, however, ramp events seem to occur when turbines lay ahead of low pressure systems and behind high pressure systems. Both of these scenarios typically support warm air advection which by itself usually favors upward motion and reduced mixing near the surface. This could be significant if it is not simply reflecting a tendency for turbines to more often lay in that position relative to those pressure systems.

Table 3: Group ramp events classified by their position to synoptic features

	Ahead Low	Behind Low	Mid Low	Ahead High	Behind High	Mid High
All_Up	4.5	1	1	0.5	4	1
All_Dwn	4.5	1	2	1	3.5	2
Some_Up	23.5	2	3	2.5	14	6
Some_Down	17	3	4	2.5	10.5	5
Mixed	2.5	0	1	0	2.5	1
Total	52	7	11	6.5	34.5	15

Table 4: Percentages of group ramp events by their position to synoptic features

	% Ahead Low	% Behind Low	% Mid Low	% Ahead High	% Behind High	% Mid High
All_Up	37.5	8.3	8.3	4.2	33.3	8.3
All_Dwn	32.1	7.1	14.3	7.1	25	14.3
Some_Up	46.1	3.9	5.9	4.9	27.5	11.8
Some_Down	40.5	7.1	9.5	6	25	11.9
Mixed	35.7	0	14.3	0	35.7	14.3
Total	41.2	5.6	8.7	5.2	27.4	11.9

Curvature of isobars fluctuated more substantially with group ramp classification than with synoptic feature position. Table 5 shows the number of occurrences of each of the different curvature classifications. Table 6 shows the respective percentages for each category. The "Total Ramp" data (group ramps as a whole) looks almost identical to the probability in the "All Up" classification, with a maximum variation of about ±4% of each classification of curvature. "All Down" sees more cyclonic curvature (42%), and when comparing it to the "Some-down" classification they do not seem to compare (23.8%), so it cannot be confidently said that cyclonic curvature would be more related to down ramps. Reasons for variability of ramps are equally as muddled. The even 38.1% split between Anticyclonic and Straight curvature in the "Some-down" classification does not mesh with the "Some-up" classification, which is more dominated by Cyclonic curvature (42.9%). The fact that this classification can be such a subjective measurement and that there appears no concise pattern in the data makes it difficult to confidently draw conclusions.

Table 5: Group ramp events organized by curvature of isobars

	Cyclonic	Anticy	Straight
All_Up	4	5	3
All_Dwn	6	3	5
Some_Up	11	27	13
Some_Down	10	16	16
Mixed	5	2	0

Table 6: Percentages of ramps occurring with certain curvature of isobars

	% Cyclonic	% Anticy	% Straight
All_Up	33.3	41.7	25
All_Dwn	42.9	21.4	35.7
Some_Up	21.6	52.9	25.5
Some_Down	23.8	38.1	38.1
Mixed	71.4	28.6	0
Total	28.57	42.06	29.37

Stability measurements were not available for every time nacelle data were available, so some group ramps were not included in the stability analysis. One hundred thirteen group ramps were examined with stability. 41 ramps occurred in a "stable" atmosphere, 72 in a "neutral" atmosphere, with 0 group ramps starting in an "unstable" atmosphere. Since 0 ramps started in unstable atmospheric conditions, we examined if any part of any ramp occurred at all in unstable conditions. The stability data were on the same time step as the nacelle data. It was found that periods said to be part of a ramp occurred 38.6% of the time in stable atmospheric conditions, 61% of the time in neutral atmospheric conditions, and only 0.17% of the time in unstable conditions.

This same type of analysis was done for the different ramp group classes. Table 8 shows the percentages of stability for each of the group ramp classifications.

Stability seems to influence wind ramping markedly, both in the existence of ramps and also the variability. Before considering the results of the stability data it is important to know what the climatology of stability looks like (was that atmosphere mostly neutral? etc.). It was found that for the time period over which the nacelle data were taken the atmosphere was neutral 43% of the time, unstable 18%, and stable 39% of the time. It would follow that if ramps had no real correlation to stability that overall we would see ramps occurring at around those percentages. This is not what the data show. It is seen that only 0.17% of ramps happened in an unstable atmosphere. We also considered what happened as neutral stability trended toward unstable ($-0.05 < z/L_0 < 0$). It was found that only about 25% of ramps that occurred with values in the negative neutral range occurred with reading less -0.025, suggesting strongly that as neutral readings tend toward unstable there is a considerable drop off in ramping. Unstable atmospheres are not conducive to ramp events.

Stability was also considered in relation to variability of the ramp events. The "All" classes are dominated (over 70%) by a neutral atmosphere (Table 7), while in the "Some" classifications there is a more even 50-50 split, between neutral and stable. Here it suggests that neutral atmospheres might be better for uniform ramping and that more stable atmospheres lead to more variability.

Table 7: Percentages of ramps occurring in different stability classifications

	% Unstable	% Neutral	% Stable
All_Up	0.29	73.1	26.6
All_Dwn	0.0	79.7	20.3
Some_Up	0.4	49	50.6
Some_Down	0.0	54	46
Mixed	0.0	100	0.0

Net Radiation was looked at in the same way as atmospheric stability. Without considering group ramp classification it was found that 58% of the time ramps were occurring during nocturnal conditions, 23% were occurring during transitions period conditions, and 19% of ramps occurred during daytime conditions. Each group ramp classification was also analyzed (Table 8). The "All" categories evidenced a three way split between the net radiation classifications. This is clearly not true when analyzing the "Some" and "Mixed" categories. The "Some-up" classification had over 70% of its ramps happening at night and the both "Some-down" and "Mixed" classifications had over 60% of their ramps at night. "Mixed" had 0% happen during daytime. These data suggest that more variable ramping occurs during the night.

Table 8: Percentages of ramps occurring in different net radiation ranges

	% Night	% Trasition	% Day
All_Up	37.4	33.7	28.8
All_Dwn	44.5	28.4	27.1
Some_Up	74.6	13.8	11.6
Some_Down	61.1	24.4	14.5
Mixed	67.9	32.1	0.0

4. Conclusions

Improved wind forecasting and wind ramp forecasting would improve the economics of wind energy (Marquis et al., 2011). Understanding and predicating wind ramp events is very complex and difficult (Francis 2008). Wind ramp events can have unknown causes (Deppe et al., 2013) and are variable around the wind farm (Showers Walton et al., 2012). Patterns in meteorological data were examined to better understand small-scale spatial variations in ramping. As a result the following conclusions were made: Location relative to synoptic weather systems and isobar curvature do not differentiate the amount of spatial ramp variability. On average lower pressures are related to uniform ramping along with higher wind speeds at the 850mb heights. Nighttime radiation conditions usually correlate to higher variability in ramps. Unstable atmospheric conditions produce barely any ramp events, and even as the atmosphere tends toward being unstable (negatively neutral) the occurrence of ramp events drops off. Neutral conditions are more likely to result in uniform ramping across a wind farm. Stable conditions are seen more frequently in the variable cases.

Opportunity for future research is apparent, both in terms of looking deeper into the data acquired in this research and utilizing the conclusions made in this research. The classifications of "Some-up" and "Some-Down" could be further broken down into subcategories relating to how many turbines were actually ramping up or down. For example, in this research if all but one turbine was ramping it was still considered a "Some" ramp. If the "Some" classifications was better defined one could compare the cases where all turbines were ramping to cases where "most" turbines were ramping. Organizing the data relative to wind direction may reveal further difference between the uniform and variable categories. Wind direction was only looked at in a cursory fashion in this research. In all areas, looking at more data would be beneficial. A better understanding of small-scale ramp variability might ultimately lead to improved forecasting of power production.

Acknowledgements

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References

Department of Energy, 2008: 20% wind energy by 2030. Energy Efficiency and Renewable Energy Rep. DOE/GO-102008-2567, 1-2.

Deppe, A. J., W. A. Gallus, Jr., and E. S. Takle, 2013: A WRF ensemble for improved wind speed forecasts at turbine height. *Wea. Forecasting*, **28**, 212–228.

Ferreira, C., J. Gama, L. Matias, A. Botterud, and J. Wang, 2010: A survey on wind power ramp forecasting. *Argonne National Laboratory. ANL/DIS*

Francis, N., 2008: Predicting sudden changes in wind power generation. *North American Windpower*. **5**, 58-60.

Marquis, M., J. Wilczak, M. Alhstrom , J. Sharp, A. Stern, J. C. Smith, and S. Calvert, 2011: Forecasting the wind to reach significant penetration levels of wind energy. *Bull. Amer. Meteor. Soc.*, **92**(9), 1159–1171.

Rajewski, D., E. Takle, J. Lundquist, S. Oncley, J. Prueger, T. Horst, M. Rhodes, R. Pfeiffer, J. Hatfield, K. Spoth, & R. Doorenbos, 2013: Crop wind energy experiment (CWEX): Observations of surface-layer, boundary layer, and mesoscale interactions with a wind farm. *Bull. Amer. Meteor. Soc.*, **94**(5), 655-672.

Schreck, S, J. Lundquist, and W. Shaw, 2008: U.S. Department of Energy Workshop Report - Research needs for wind resource characterization. NREL Rep. TP-500-43521, 81-82.

Showers Walton, R., W. Gallus Jr., and E. S. Takle, 2012: Analysis of ramp events and two-day WRF wind forecast accuracy at 80 m. *Proc. Wind Energy Science, Engineering, and Policy National Science Foundation Research Experiences for Undergraduates Symposium*, Ames, IA, NSF and Iowa State University, 3/1-3/11. [Available online at http://www.meteor.iastate.edu/windresearch/resources/Binder1.pdf].

Wiser, R., and M. Bolinger, 2011: 2010 wind technologies market report. , *U.S. Department of Energy, Energy Efficency & Renewable Energy.* [Available online at http://www.windpoweringamerica.gov/pdfs/2010_annual_wind_market_report.pdf]