RAMP EVENT ANALYSIS FOR WESTERN MISSOURI

A Thesis Presented to the Faculty of the Graduate School at the University of Missouri

In Partial Fulfillment of the Requirements for the Degree Masters of Science

by

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July 2013

The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

RAMP EVENT ANALYSIS FOR WESTERN MISSOURI

Presented by Adam Balbi,

a candidate for the degree of master of science,

and hereby certify that, in their opinion, it is worthy of acceptance.

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Acknowledgments

I would first like to thank my family for supporting me in my decision to go back to school for something I’m passionate about.

I am very appreciative of the friends and colleagues that have helped me through this program. Without their support and guidance this would have been infinitely more difficult.

Dr. Fox, Dr. Lupo, and Dr. Market have made the master’s experience rich with learning, and with friendly and selfless dedication have led me to the completion of the program.

Lastly I would like to thank the Mizzou Advantage for funding me. Without this program I would not have gotten this opportunity and for this I am eternally grateful.

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Abstract

Advances in wind power technology are needed for further growth and lower costs in the field. One aspect needed is improved forecastability of the variable winds. This work focuses on rapid increases and decreases in wind speed that produce “ramps” which affect wind power calculations and planning. Average wind speeds are predicted with a high level of accuracy; however variable winds that contain ramp events are not represented very accurately. To better understand variability in western Missouri a statistical analysis was conducted to identify ramp events in various capacities based on time and strength. 10 minute average wind speeds were collected at 7 sites on the western half of Missouri. From these wind speeds applicable wind turbines were selected to represent realistic conditions for comparative analysis. Ramp events were identified with 30 minute, 1 hour, 2 hour, and 4 hour temporal scales and 20%, 30%, 40%, and 50% power difference scales between rated turbine power and actual power output. To reflect the available wind power in Missouri the 30% power change and 1 hour counting was implemented. Results were broken down by season, month, day, and time of day. For this region of Missouri seasonal and time of day effects are evident. The winter and spring months and the time period of 0-12Z produce the majority of events. The Low Level Jet was assumed to be the largest contributor of ramp events during the evening

hours and was verified with a 68%-92% correlation for all sites using a comparative analysis of Low Level Jet days and times. This information can lead to the informed development of wind farms in this region with an understanding of when ramp events will occur most. Power managers can intelligently plan for times of greater variability thus saving money.

Chapter 1 - Introduction

There are many benefits for utilizing weather dependent renewable energy. Wind power is produced domestically which increases energy independence, national security, and economic growth. It has been shown by the Department of Energy (DOE) that it is both possible and plausible to reach 20% of electricity generated in the U.S. to come from wind power (Lindenberg 2008). While there is the technology to implement renewable energies, penetration into the mainstream market is still difficult due to the variable nature of the resources. Increased predictability of the wind can allow for higher integration into the power grid allowing operators to balance different resources. Forecasting for ramp events in wind energy is particularly important. Ramp events are large changes in energy production which are caused by changes in wind speeds. Proper understanding and parameterization of these events would allow operators and power authorities to manage other energy reserves. Ramp events are difficult to forecast because they have many different causes. These include synoptic scale forcing such as high/low pressure systems and fronts. On smaller scales they are created by thunderstorms, boundary layer processes including vertical mixing and diurnal heating as in the Low Level Jet (LLJ), complex terrain, and thermally forced flow. To better forecast for these events observations, data assimilation, and numerical weather prediction (NWP) configurations are needed. Current forecasting a few days out can appear to correlate very well with observed conditions. In times that have relatively constant wind errors in wind power prediction can be as low as 10%, but during ramp events in this scenario the model can be off by more than 80%.

1.1 Objectives

This research is designed to identify significant fluctuations in the wind for sites in western Missouri and their association with the nocturnal Low Level Jet (LLJ). Ramp events occur everywhere in the world but due to the unique circulations and terrain effects in the Midwestern United States, the area is hypothesized to have a large number of ramps. It is hypothesized that seasonal effects associated with the LLJ would have the most ramp events occur in the winter and spring months, with the least occurring in the summer. As for time of day for these ramps it is hypothesized that most up ramps will occur during the formation period of the LLJ (18-0 CT) and most down ramps occurring during the dissipative period of the LLJ (0-6 CT). There was also interest in the total number of ramp events as well as the temporal variation of these occurrences. Due to the sites' geographical distribution, determining which sites have the most ramp events is important. Lastly, finding if there is the same number of up ramps and down ramps and if they occur complementary will allow for energy managers to better plan for events. To accomplish this, a wide range of data computation and parameterization was needed as follow:

- Find 10 minute average wind speed for an entire year for each site
- Identify an applicable wind turbine based on average wind speed
- Create calculated power generated by the turbine based on observed wind speeds versus rated power of turbine

- Identify percent change thresholds between observed and rated power that will indicate a ramp
- Create a counting methodology that incorporates different duration thresholds
- Separate computed data into season, month, day, and time of day categories
- Analyze seasonal peaks for ramp activity
- Analyze time of day occurrences for ramps
- Analyze LLJ connection to ramp events

1.2 Thesis Outline

The literature review of this thesis begins with the explanation and understanding of boundary layer mechanisms that create the Low Level Jet (LLJ). It then transitions into a section concerning the renewable energy that can be extracted from the wind. This section shows the governmental support for and applicability of widespread implementation of wind farms. Forecasting the wind and the difficulty of forecasting ramp events is then described. Studies conducted by Storm et al. (2009), Greaves et al. (2009), and Deppe et al. (2012) regarding ramp events and forecasting are analyzed.

The methodology section describes the seven locations in the study, the equipment used, and the way data was broken down into useful parts. The locations in western Missouri include exact coordinates, height above sea level, height of instruments, and orientation of instruments. The systems used to collect the 10 minutes average wind speeds are described. From this overall average wind speeds, statistical algorithms, and ramp identification methods are employed. The determination of an appropriate representative wind turbine is discussed based on average wind speeds.

The results and discussion section shows which counting method and percent power change was chosen to best represent ramp events. Statistical breakdowns are shown based on which turbine was used, season, month, and time of day. From this it was shown that the winter and spring months contain the largest number of ramps, as do the nocturnal hours.

The conclusion section shows that there is a difference in up ramp and down ramp occurrence and these are not necessarily linked to the same event. The nocturnal ramps when compared to days with LLJs showed a high probability that the LLJ was the cause of the events. This will be important for energy managers who extract energy from these areas. Other work to be done include documenting all the causes for the ramp events, looking at a longer period of time for the area, and having exact definitions and conditions for ramp events be universal.

Chapter 2 - Literature Review

2.1 The Low Level Jet

The Low Level Jet (LLJ) is a commonly observed relative maximum in the vertical profile of wind speed occurring in the lower levels of the atmospheric boundary layer (ABL). LLJs occur all over the globe and are important atmospheric features in their respective areas. In particular the LLJ over the North American Great Plains is responsible for significant moisture and temperature advection from the Gulf of Mexico. These allow for higher convective available potential energy (CAPE) and shear values which produce convection and ultimately precipitation. The LLJ's ability to produce low level wind maxima has made it appealing to wind energy companies as well. The Great Plains have become the centerpiece for American renewable energy endeavors with the LLJ as a major factor. Fully understanding, documenting, and predicting the North American LLJ is integral for maximizing efficiency for wind energy collection.

The LLJ was studied intensely in the mid 1960's by many atmospheric scientists and has proved to be the basis of modern research. The first widely accepted explanation of the LLJ came from Blackadar (1957) who, through experimentation with radiosonde data, concluded a wind maximum was accompanied by a nocturnal inversion. There were five conditions associated with the development of the nocturnal LLJ. The first condition was the temporal element 8 p.m. (local time) to 8 a.m. (local time). This twelve hour window allowed for different initial conditions related to night time inversions to be included. The second condition was a temperature profile that increased to a single maximum in the lowest 1000m above the surface. This marked the top of the inversion where turbulent mixing effects were no longer contributing. The third condition was a wind maximum less than 1000m from the surface. Blackadar (1957) found the wind maximum would be at the top of the thermal inversion. The fourth condition required that the temperature decrease up to 2000m above sea level sometime during the previous afternoon. This setup allows for a nocturnal temperature inversion. The last condition was that no air masses pass through the area during the night or afternoon. Synoptically forced wind maximums were not part of the study (Blackadar 1957).

From previous work Blackadar (1957) found three larger circulations gave the Midwestern United States a setup for the LLJ. The three included a circulation between the dry region in the southwestern United States, the circulation between the plains and the mountains to the west, and the circulation between the sea and the continent; in particular the occurrence of the Bermuda high (Blackadar 1957). While these do explain the general flow, they do not explain the supergeostrophic nature of the LLJ. Blackadar (1957) then postulated that boundary layer mixing and vertical turbulent mass exchange could explain the phenomenon. After the nocturnal inversion first begins turbulent mixing dramatically drops off above the inversion. Some turbulence is still present due to large wind shear. Heat, lost from radiative cooling, at the surface rises and momentum lost from the inversion leads to a pronounced jet-like profile around the inversion level. The loss of turbulence under the wind maximum is explained by downward transport of momentum which is dissipated at the surface with frictional effects (Blackadar 1957).

This explanation allows for an oscillating ageostrophic wind vector to create supergeostrophic flow (Fig 2.1) (Monteverdi 2011). The removal of frictional forces creates a force imbalance in the geostrophic wind that works to balance itself. Through the night adjustments are made that create supergeostrophic flow followed by subgeostrophic flow. This nocturnal system ceases when turbulent mixing and friction are reintroduced once the sun comes up.

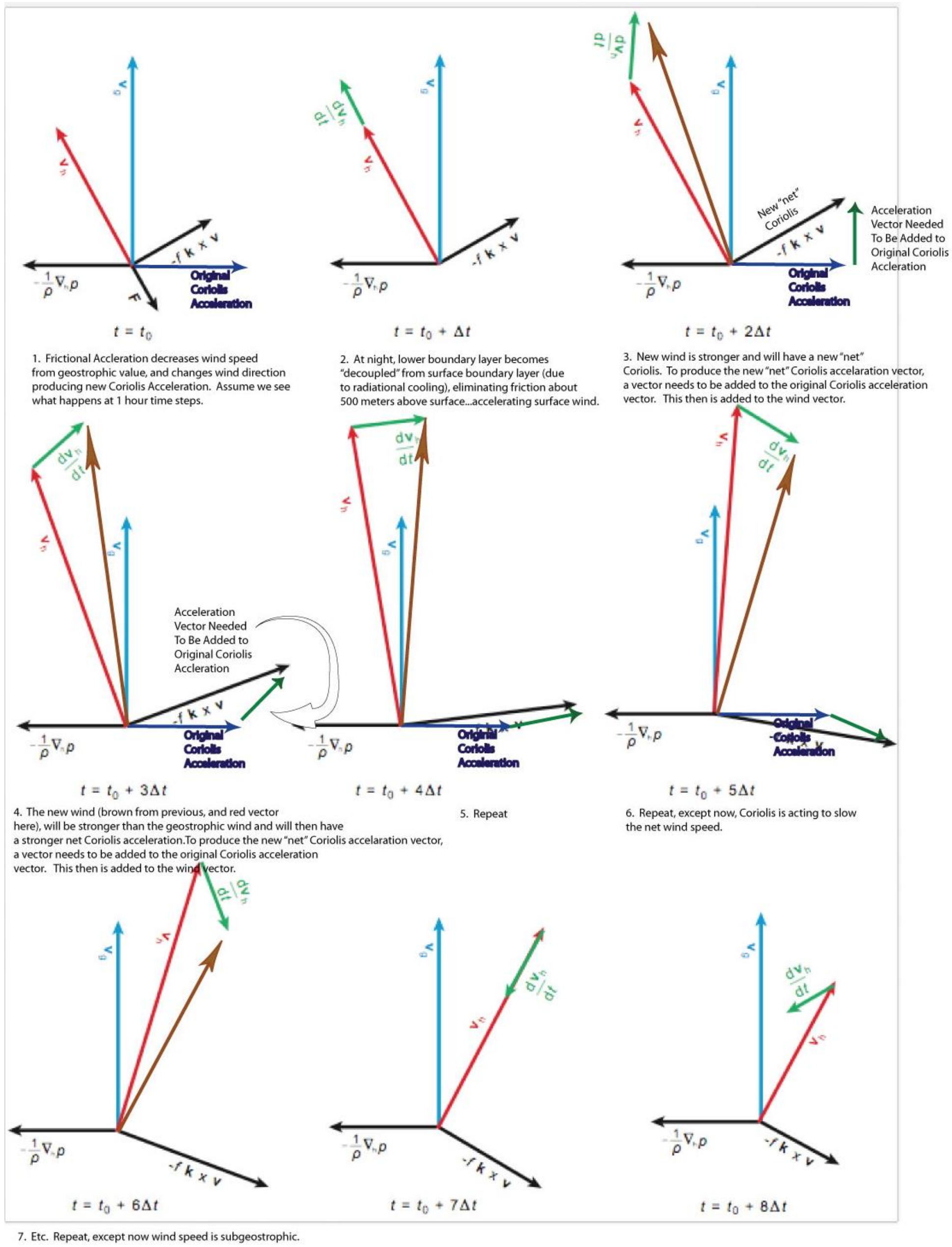


Figure 2.1 Explanation of the LLJ formation from Monteverdi (2011)

Bonner et al. (1968) also made interesting contributions to the understanding of the LLJ. He concurred with Blackadar's (1957) oscillating ageostrophic wind vector calculations, but considered that the boundary layer oscillation was more complicated than previously thought (Bonner et al. 1968). Blackadar's (1957) constant geostrophic wind was also questioned by Bonner (1968). Bonner et al.'s (1968) aim was to parameterize the southerly LLJ using radiosonde data from 8 sites over one year as well as punch card data from 47 stations over a two year period. His first conclusions were about the ageostrophic winds. The first statement was that the largest contributor to the ageostrophic winds was the local turning of the wind. The second was that at the jet core and downstream wind is either increasing or decreasing less rapidly than the upstream of the jet. This allows for wind maximas spreading downwind during the morning hours. Third was that convective accelerations were smaller than local accelerations of the wind (Bonner 1968). They should be included for modeling purposes though.

Bonner (1968) then sought to find a definitive upper boundary for the LLJ. Using Blackadar's (1957) analysis of finding the maximum within the first 1000m above the ground, Bonner set his observation height at 2.5 km. This was to ensure Blackadar (1957) did not underestimate. Five levels were identified between 500m and 2500m with equal spacing. He found that there was a high concentration of jets in levels 1 and 2 with a sharp drop off between level 2 and 3. With this data he chose 1.5 km as the upper limit for the LLJ. Bonner (1968) also sought to refine Blackadar's (1957) definition of jet maxima being greater than 5 knots. Using data collected and a subjective procedure that had minimal effects on seasonal, geographic, or diurnal differences he came up with 4 criteria (Bonner 1968). These criteria are:

Criteria 1: The wind at the level of maximum wind must equal or exceed 12 m/s and must decrease by at least 6 m/s to the next higher minimum or to the 3 km level.

Criteria 2: The wind at the level of maximum wind must equal or exceed 16 m/s and must decrease by at least 8 m/s to the next higher minimum or to the 3 km level.

Criteria 3: The wind at the level of maximum wind must equal or exceed 20 m/s and must decrease by at least 10 m/s to the next higher minimum or to the 3 km level.

Criterion 0: Data examined using all information levels and tabulating all wind maxima without regard to speed within the first 1.5 km (Bonner 1968).

Using this system Bonner (1968) was able to break down LLJ occurrences based on speed and geographical location. The location of most occurrences was around the Oklahoma-Kansas border. His findings also show that criteria 1 were met most often, followed by criteria 2 and 3 respectively. Considering criterion 0 it was clear that nocturnal jets far exceeded daytime jets in both strength and occurrence (Bonner 1968). This finding showed a connection to Blackadar's (1957) inertial oscillation explanation. Bonner (1968) also found that the jet was more frequent and stronger during the summer months with a southerly flow. This was attributed to larger diurnal effects at this time as well as the influence of the Bermuda high. During the winter months he found a bimodality in wind direction. From Kansas and south there was a general southerly to southwesterly flow. He said another pattern from the Dakotas to Texas had northerly flow which is caused mainly by cold fronts and shallow cold highs (Bonner 1968).

The overall mean altitude from all stations reporting a LLJ was 785m with a standard deviation of +/- 127m. He also found that regardless of station the LLJ tends to form at a constant level above the ground. Following Blackadar's (1957) findings, Bonner (1968) found the temperature inversion to be an important aspect of the study. However, he found that the maximum wind was located above, below, and at the same level as the inversion for different cases (Bonner 1968). Blackadar's (1957) data showed that the temperature and wind profiles take on a stable configuration, but Bonner (1968) was able to determine that jet maxima can exist at almost adiabatic lapse rates.

Uccellini (1980) has done research investigating the connection between upper tropospheric jet streaks and leeside cyclogenisis with LLJ development. With Bonner's (1968) assertion that on 60% of days where LLJs were present there was a cold front or low pressure system less than 350 miles away, Uccellini (1980) hypothesized that synoptic scale events could be linked to the LLJ as a response mechanism to leeside cyclogenesis (Uccelini 1980). To analyze this he took 15 cases of the LLJ that had been explored by both Blackadar (1957) and Bonner (1968). He found that there were two upper flow regimes. The first (type 1) accounted for 12 of the 15 cases and consisted of a trough over the Rockies and ridge in the eastern third of the country with upper tropospheric jet streaks coming toward the Great Plains from both the California region and Arizona-Mexico region (Uccellini 1980). This type of setup was consistent with seeing a development of a leeside cyclone generated from the tropospheric flow. The other setup (type 2) accounted for 3 of the 15 cases had a strong ridge located over the front range of the Rockies with weak tropospheric flow over northern Texas (Uccellini 1980). This flow was more associated with a diurnal wind oscillation with wind maxima coinciding with boundary layer inversions.

Uccellini's (1980) study showed the two different setups produced different dynamical causes to the LLJ. Type 1 had LLJs located in the exit region of an upper level jet, were directed to the cyclonic side, and deviated from the classic pattern of LLJs (Uccellini 1980). The deviation is made by the LLJ being more persistent even during the afternoon and extends beyond the planetary boundary layer (PBL). With this finding he stated that boundary layer and terrain forcing in diurnal oscillation are not the only mechanisms to create the LLJ. Other factors such as the retraction of the Bermuda high, synoptic scale interactions, and isallobaric wind events which account for mass adjustments should be analyzed to fully understand the forcing behind the LLJ (Uccellini 1980).

A study conducted by Stensrud (1996) investigated the importance of LLJs to climate. Using the previous knowledge gathered by Blackadar (1957), Bonner (1968), and Uccellini (1980) he was able to separate LLJs and low level jet streams (LLJS). A LLJ was analyzed by taking the vertical profile of the horizontal wind to see if a wind maximum occurs. A LLJS was defined as a narrow horizontal zone of high-speed flow that extends for some considerable horizontal distance. It also does not have a significant diurnal cycle and is coupled with an upper tropospheric jet stream (Stensrud 1996). This definition can be used to better define Uccelini's (1980) results. Stensrud (1996) came up with five mechanisms of LLJ formation. The first was inertial oscillation which was originally described by Blackadar (1957). The next was shallow baroclinicity which includes regions of dynamic and changing surface features. The differences in these features, whether land to sea or ice to dry land, have different sensible and latent heat fluxes causing LLJs from strong geostrophic forcing. This factor also includes effects of sloping terrain. The horizontal thermal gradient causes a diurnal cycle in the geostrophic wind which can be seen in the thermal wind. The next factor is terrain effects which include slope and valley wind systems as well as the creation of boundary currents. The fourth factor documented by Stensrud (1996) was isallobaric forcing which have been previously discussed by Uccellini (1980). The last factor was vertical parcel displacement. In a previous study (Stensrud 1996) it was shown that as parcels approached a developing cyclone, it changed the pressure gradient force in the parcel. The change was modest in the horizontal but large in the vertical which led to a rapid increase in the ageostrophic wind component. From this parcels were accelerated vertically thus rapidly creating a LLJ (Stensrud 1996).

Banta et al. (2003) studied the relationship between LLJ properties and turbulence kinetic energy (TKE) in the nocturnal stable boundary layer. Turbulence is generated by vertical shear and horizontal winds that is enhanced in the presence of the LLJ. Knowing the height and intensity of the LLJ would then lead to a direct measurement of TKE (Banta et al. 2003). The data was taken from the Cooperative Atmosphere-Surface Exchange Study-1999 (CASES-99) which collected high resolution horizontal winds and height, U_x and Z_x respectively. Shear was then calculated (U_x/Z_x) over 15 minute intervals on a 60 m tower. 20 Hz sonic anemometers were used to calculate TKE and two slow response aspirated temperature sensors at 5 m and 55 m were used for vertical potential temperature gradient. A bulk jet Richardson number was created to display dynamic stability for the height and speed of the jet, and is defined here as:

$$Ri_j = \frac{g}{\theta}\frac{\Delta\theta/\Delta z}{(\Delta U_x/\Delta Z_x)^2} \qquad (1)$$

In Eq (1), Θ is the potential temperature, U_x is the maximum horizontal wind speed, Z_x is the height of the jet, Δz is the change in vertical height, and g is the acceleration due to gravity. His results showed that shear values tended to gather around a constant value when some turbulence was present. This would mean Ri_j could be calculated with better accuracy if the stability could be well represented, along with accurate radiation and energy budgets being represented. He also showed that it would be beneficial to determine gross LLJ properties from larger scale meteorological quantities such as ageostrophic wind profile, surface cooling rates, and the vertical profile of horizontal pressure gradients to relate them to turbulence fluxes (Banta et al. 2003). Banta et al. (2003) also found that moderately stable conditions where turbulent mixing is continuous, $Ri_j < 0.25$-0.30, turbulence could be diagnosed from bulk properties of the LLJ. However in the very stable case with higher values of Ri_j where turbulent mixing is patchy other factors such as aerial coverage, spatial frequency, and effectiveness of mixing patches must be examined (Banta et al. 2003).

2.2 Renewable Wind Energy

2.2.1 Importance of Forecasting for Wind Energy

There are many benefits for utilizing weather dependent renewable energy. Wind and solar power are produced domestically which would increase energy independence, national security, and economic growth. It has been shown by the Department of Energy (D.O.E.) that it is both possible and plausible to reach 20% of electricity generated in the U.S. to come from wind power alone (Lindenberg et al. 2008). While there is the technology to implement renewable energies, penetration into the mainstream market is still difficult due to the variable nature of the resources. Increased predictability of the wind can allow for higher integration into the power grid allowing operators to balance different resources.

The Department of Commerce in 2011 signed a memorandum of understanding (MOU) to corroborate the accuracy, precision, and completeness of renewable energy resource information. This MOU calls for improvements in observations, modeling, numerical weather prediction, and climate research (Lindenberg et al. 2008). This shows the importance and dedication to the idea that renewable energy will be the direction that the nation moves. Three studies analyze variable renewable energy feasibility and what is needed to grow the industry.

The first study written by the U.S. D.O.E. entitled *20% wind by 2030* looked at all aspects involved in expanding wind power potential to 305 gigawatts (GW) (Lindenberg et al. 2008). It calls for new transmission lines, larger batteries, and better regional planning to account for 251 GW generated from land based wind farms and 54 GW from offshore farms (Lindenberg et al. 2008). Environmental benefits include emission reduction, water usage reduction, and fossil fuel reduction. While the initial investment is steep the costs can be significantly reduced with improved short term wind production forecasts.

Enernex in 2011 released the *Eastern Wind Integration and Transmission Study* that compared similar costs, challenges, and benefits of the previous D.O.E. (Lindenberg et al. 2008) study, but focused on operating implications for the Eastern Interconnect by a date of 2024. It concluded the need for new transmission lines, increasing the size of batteries, and the need for improved wind forecasts (Corbus et al. 2011).

The Western Wind and Solar Integration Study examined the feasibility of having 30% wind and 5% solar capacity on a power system run by WestConnect along with 20% wind and 3% solar for the remaining western interconnection (Lew et al. 2010). The study, like the previous two, did find it feasible to accomplish assuming substantial increases in cooperation, coordination, increased sub-hourly scheduling for generation, and utilization of transmission lines. They also found that depending on the cost of natural gas, CO_2 emissions could be reduced between 25%-45%. A high gas price means wind and solar would displace gas usage, whereas a low gas price would lead to the displacement of coal, leading to further carbon emission reduction (Lew et al. 2010). This report assumed state of the art forecastability, but also said this was the most difficult aspect in terms of integration. Overall the three studies come to the conclusion that infrastructure is necessary, but the single greatest improvement would be the short term forecasting of wind (Lew et al. 2010).

Forecasting for ramp events in wind energy is particularly important. Ramp events are large changes in energy production which are caused by changes in wind speed. Proper understanding and parameterization of these events would allow operators and power authorities to manage other energy reserves better. Ramp events are difficult to forecast because they have many different causes. These include synoptic scale forcing such as high/low pressure systems and fronts. On smaller scales they are created by thunderstorms, boundary layer processes including vertical mixing and diurnal heating as in the LLJ, complex terrain, and thermally forced flow (Lew et al. 2010). The wind power community uses forecasts produced by the National Weather Service (NWS), however these models are inadequate due to the fact the power equation is based on the cube of the velocity as the main component.

$$P = {}^{1}\!/_{2}\,\rho A v^3 \qquad (2)$$

In Eq. 2, P represents the power output, ρ is the density of the air, A is the swept area of the turbine blades, and v is the velocity of the wind. To further the importance of an accurate forecast it has been found through engineering analysis, that no turbine can achieve an efficiency value of more than 0.59, [called Betz's Law] (C_{pmax} = 59%) (Ragheb and Ragheb 2011). When real world factors are incorporated the best designed turbines can achieve 30%-45% efficiencies. Given the other mechanical components associated with the turbine such as gear box, rotors, and bearings, only 10%-30% of the power of the wind is ever converted into usable electricity. The final equation includes the Betz's Law factor (C_p);

$$P = {}^{1}/_{2}\, \rho A v^3 C_p \qquad (3)$$

which makes any fluctuation in wind speed vitally important to capture accurately (Ragheb and Ragheb 2011). Within the Lew et al. (2010) study it was shown that a model overestimated the next day wind forecast to produce 18,771 MW when the actual output was 7,000 MW. This forecast was off by 11,771 MW and greatly affected energy managers when they made energy balancing decisions (Lew et al. 2010). When managers miscalculate the wind resource, compensating with other resources come at a premium price if not planned for. This makes the industry volatile in the face of ramp and unpredicted events.

To better forecast for these event observations, data assimilation, and Numerical Weather Prediction (NWP) configurations are needed which are can be accomplished with research studies. Improved resolution for current models such as the High-Resolution Rapid Refresh (HRRR) and boundary layer parameters will lead to better results (Lew et al. 2010). Current forecasting a few days out can appear to correlate very well with actual winds. Times that have relatively constant winds have errors that can be as low as 10%, but during ramp events, in this scenario, the model can be off by more than 80% in wind power generation. Next hour forecasts can have this type of error and when forecasts for 6 h, 12 h, or longer are used the error grows (Lew et al. 2010). Wind energy integration charges and curtailments make it difficult economically to implement nowcasts with longer lead times unless solutions are found. These solutions to forecasting will allow a robust mixture of both renewable and traditional resources to be used together. The need for expanded forecasts from minutes to decades will need expanded cooperation between public, private, and academic entities as well as a commitment to the expanded implementation of wind power technologies. The first step to becoming more productive is analyzing regional tendencies and quantity of ramp events as this study does. After this is completed a better model can be implemented and energy managers can act accordingly with improved data.

2.2.2 Forecasting Model on Forecasting LLJs: Implications for Wind Energy

A case study conducted by Storm et al. (2009) aimed at reproducing observed conditions using modern modeling capabilities in order to accurately predict wind power. The driver for this was to both forecast wind power potential but also to understand the boundary layer. An LLJ has significant effects on vertical wind shear and nighttime turbulence that can be detrimental to turbine rotors. The International Electrical Commission's Normal Turbulence Models, which provide inflow conditions for wind turbine design, do not represent strong shear or turbulence bursts associated with stable boundary layers (Storm et al. 2009). Failures of turbines and suboptimal generation have been reported by several Great Plains wind farms based on poor forecasting parameters. The Weather Forecasting and Research (WRF) model was recently developed to forecast severe weather events, but the model's ability to forecast LLJs is mainly undocumented. The Storm et al. (2009) study aimed to fill in the void of prediction validity and accurate representation of the stable boundary layer.

To test the capabilities of the WRF model for LLJs two events over west Texas and southern Kansas that had been previously observed were simulated. The Texas event occurred from 00:00 to 12:00 UTC on 2 June 2004 at Texas Tech University's Wind Science and Engineering (WISE) Research Center. The WISE center includes a boundary layer wind profiler with 55m vertical resolution and a 30 minute average data output. It also has the Reese Mesonet station, from the West Texas Mesonet network, which consists of 50 automated 10m tall towers that measure 15 meteorological and 10 agricultural variables every 5 and 15 minutes respectively (Storm et al. 2009). The Kansas event was observed on the night of 2 October 2006 at the Atmospheric Radiation Measurement (ARM) facility in Beaumont. This facility also has a boundary layer profiler. Both events were modeled using version 2.2 of Advanced Research WRF. The model had 4km spacing with 36 levels being observed. In order to capture the LLJ 13 of these levels were less than 1km AGL (Storm et al. 2009).

The Texas event recorded two LLJs with wind speeds greater than 16 m/s with the first occurring between 5:30 and 6:30 UTC and the second between 8:30 and 9:30 UTC. The first LLJ had a generally easterly direction at about 0.5km above the ground. The second was southerly with a range of 0.3-0.9km above the ground. The first LLJ was attributed to dryline motion westward with the second LLJ the product of inertial oscillation (Storm et al. 2009). In Figure 2.2 wind speed and direction time-height profiles are shown using different runs of the MYJ, YSU, and the onsite boundary layer wind profiler. The MYJ and YSU are planetary boundary schemes used by the model (Storm et al. 2009). It can be seen that both the MYJ and YSU represented the LLJ fairly well. The MYJ forecasted stronger but more accurately for the first LLJ while the YSU captured the second LLJ winds more accurately although the timing was a bit behind. Unfortunately neither captured the >14m/s winds below 0.2km during 5:00 and 6:00 UTC.

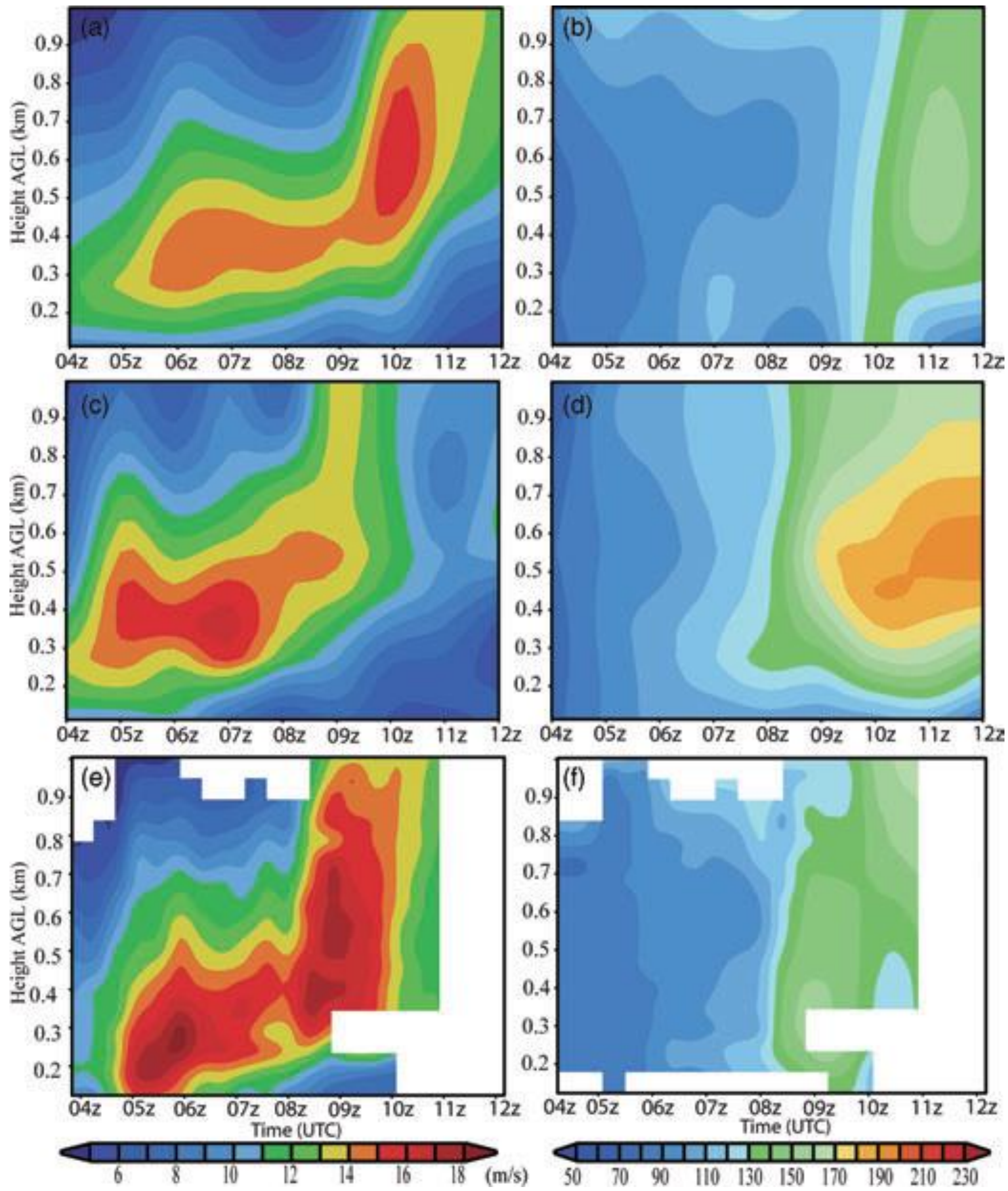


Figure 2.2 Simulated wind from Figure 1 of Storm et al. (2009) where the left column shows wind speed time-height plotsof (a) hourly output of the YSU run, (c) hourly output from the MYJ, and (e) half hourly averages from the Texas Tech boundary layer wind profiler. The right column is the wind direction time height plots that correspond with (b) the YSU, (d) the MYJ, and (f) profiler runs.

The next aspect examined was the power law relation:

$$U(z) = U_r \left(\frac{z}{z_r}\right)^{\alpha}, \qquad (4)$$

where in Eq. (4), U_r and z_r are the wind speed and height at a reference point, U(z) is the wind speed at some height z, and α, the shear exponent, is typically assumed to be 1/7 (Storm et al. 2009). This equation is typically used by the wind energy community to estimate wind speed in the boundary layer. Figure 2.3 shows the observed α time series along with the WRF simulated α time series. Both the MYJ and YSU captured the evolution of α but underestimated the magnitude. This can be blamed on the nocturnal effects in the boundary layer increasing α to greater than 1/7 the entire night.

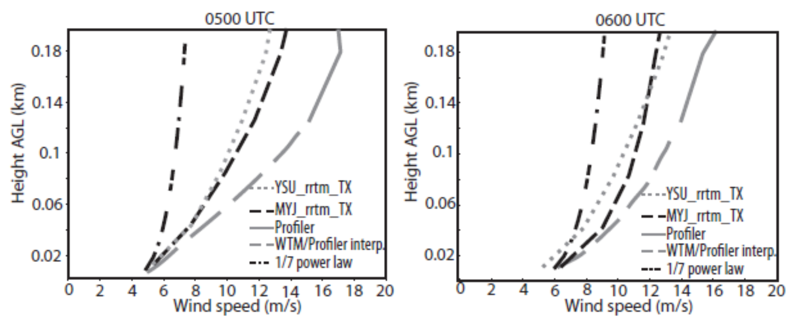


Figure 2.3 Vertical Wind Speed Profiles from Figure 2 of Storm et al. (2009)

The southern Kansas case was similarly simulated to confirm validity of the model runs. During the October 2, 2006 event a southerly LLJ with 24m/s winds between 0.3 and 0.4km AGL starting around 2:00 UTC and ending at 10:00 UTC was observed (Storm et al. 2009). Both the YSU and MYJ models had similar results. The researchers only reported what the YSU model determined in the report. Figure 2.4 shows that the YSU model was able to forecast the vertical and temporal characteristics well, however as with the Texas runs the model overestimated the LLJ heights and underestimated the wind speeds.

This study has important implications for the future of wind energy. Both models were able to represent the actual events. Where they did not perform ideally was in boundary layer mechanics where much more data is needed to accurately represent LLJ events. High-resolution spatiotemporal observations and innovative forecast verification metrics will be needed before declaring which model is the best WRF configuration (Storm et al. 2009).

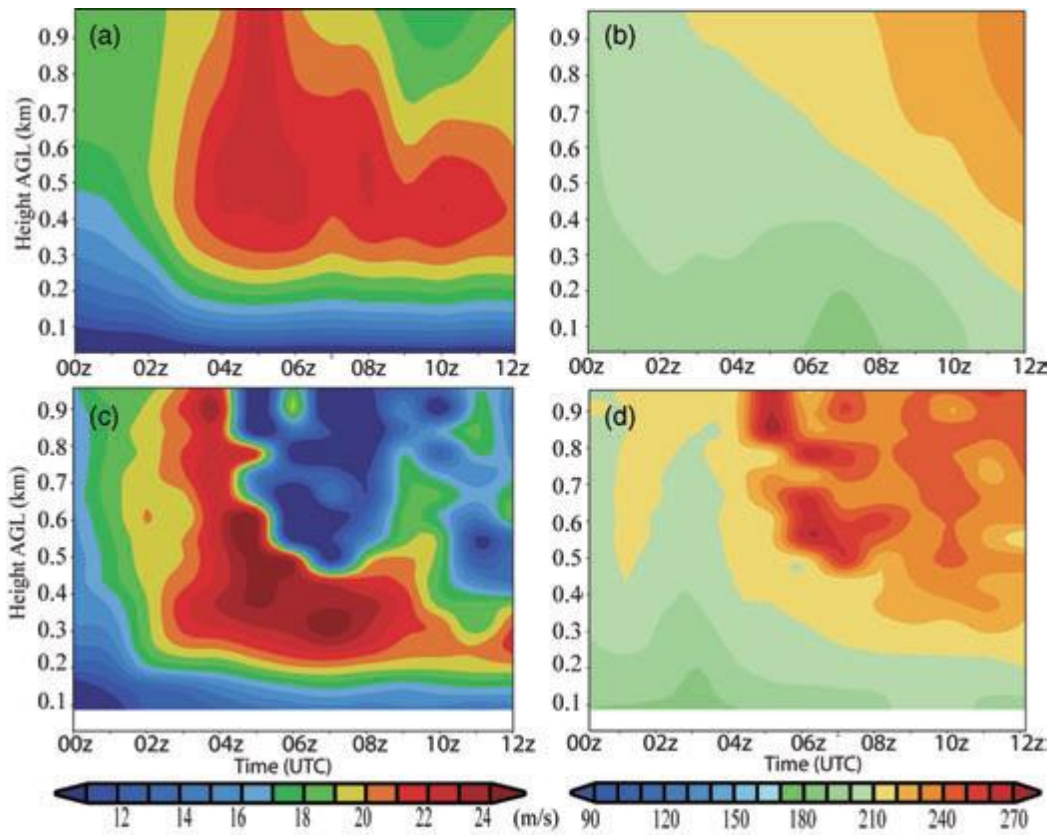


Figure 2.4 Simulated and observed wind speeds from figure 5 of Storm et al. (2009) showing simulated and observed wind speed and wind direction for 00:00–12:00 UTC on 02 October 2006. The left column shows wind speed time–height plots (unit: m s^{-1}) of (a) hourly output from the YSU run and (c) hourly averages from the Beaumont ARM profiler. The right column shows wind direction time–height plots of (b) hourly output from the YSU run and (d) hourly averages from the Beaumont ARM profiler

2.2.3 Temporal Forecast Uncertainty for Ramp Events

The majority of work done on wind energy forecasting has been on the average wind speed that is available at a particular site. There has been limited research into effectively defining the timing of significant wind energy events. The study conducted by Greaves et al. (2009) focused on methods for determining forecast uncertainty. It defined ramp events, provided calculated uncertainty values, and presented this data in a way that is easily decipherable by the end user.

A ramp event is a large change in power production over a short period of time. These events can cause large amounts of energy to be collected in a short period, but are also capable of causing failures to wind turbines and high speed shutdowns. Ramp events are rare comparatively to normal winds but uncertainty in forecasts leads to problems with grid operators. These unpredicted events are passed on negatively to energy traders who receive penalties or lowered market values for wind energy. Economically it is necessary to be able to effectively determine ramp events.

In Greaves et al. (2009) a ramp is defined as the change in power output greater than a minimum size, s_{min}, over a time less than or equal to a maximum duration, d_{max}, as seen in figure 2.5 (Greaves et al. 2009). The data used for this study came from a number of wind farms in the United Kingdom with each farm being analyzed individually, not as a portfolio. For determining forecast accuracy of ramp events, a ramp was defined as a change in power of 50% of capacity or more over a period of 4 hours or less (Greaves et al. 2009). From figure 2.5 it can be seen that such events happen only 6% of the time, but are very influential.

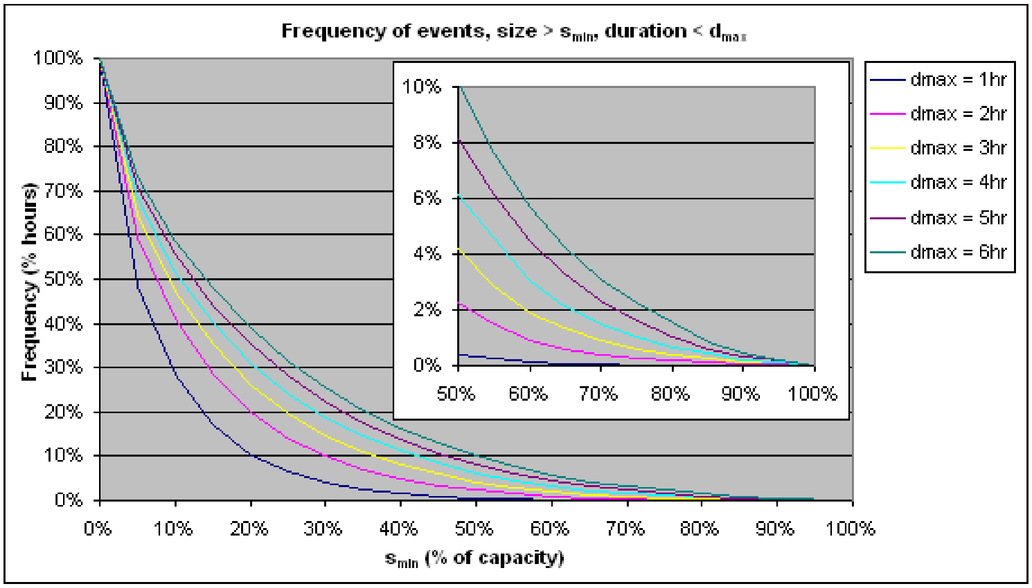


Figure 2.5 Frequency of power changes with varying size and duration constraints from figure 2 of Greaves et al. (2009)

Data was collected from the forecasting model which incorporates NWP sources and on-site sources. From this three outcomes were possible with the forecast which were true forecast, false forecast, or missed ramp. Forecast accuracy and ramp capture parameters were then derived;

$$forecast\ accuracy = \frac{true\ forecasts}{true\ forecasts + false\ forecasts} \quad (5a)$$

$$ramp\ capture = \frac{true\ forecasts}{true\ forecasts + missed\ ramps} \quad (5b)$$

Table 1 shows how the frequencies of forecast and measured ramp events were portrayed by the model for an individual UK farm, a portfolio of UK farms, and an individual US site.

Wind farms	Individual UK sites		UK Portfolio		Individual US sites	
Forecast horizon (hrs)	3	24	3	24	3	24
Number of true forecasts	894	700	21	18	384	323
Number of false forecasts	436	484	43	30	266	236
Number of missed ramps	1099	1300	21	24	699	769
Forecast accuracy (%)	67.2%	59.1%	32.8%	37.5%	59.1%	57.8%
Ramp capture (%)	44.9%	35.0%	50.0%	42.9%	35.5%	29.6%

Table 2-1 Ramp frequencies and forecast accuracies for individual wind farms and portfolios from table 2 of Greaves et al. (2009)

For an individual site in the UK a plot of power was measured and forecasted over a 9 day span in December. In figure 2.6 it can be seen that the model does track the general trends of the power output but lacks the ability to forecast maximums, minimums, and short term variation accurately. Figure 2.7 is a representation of power and probability of a ramp over an 8 day period in January. This particular format is the best method for displaying temporal uncertainty on a plot for forecast power.

The study concluded that the temporal uncertainty of current ramp event forecasting is about a normal distribution around the mean time difference between forecast and measured ramps (Greaves et al. 2009). The rarity of ramp events affects the ability to acquire sufficiently large data sets for analysis. The mean value of time difference between forecasted and measured ramps was negative which can be attributed to feedback data and was more pronounced in the shorter forecast horizon. In terms of future work it will be essential to improve the ability to capture ramp events. The other improvement would be an optimization of the NWP combination model for predicting models.

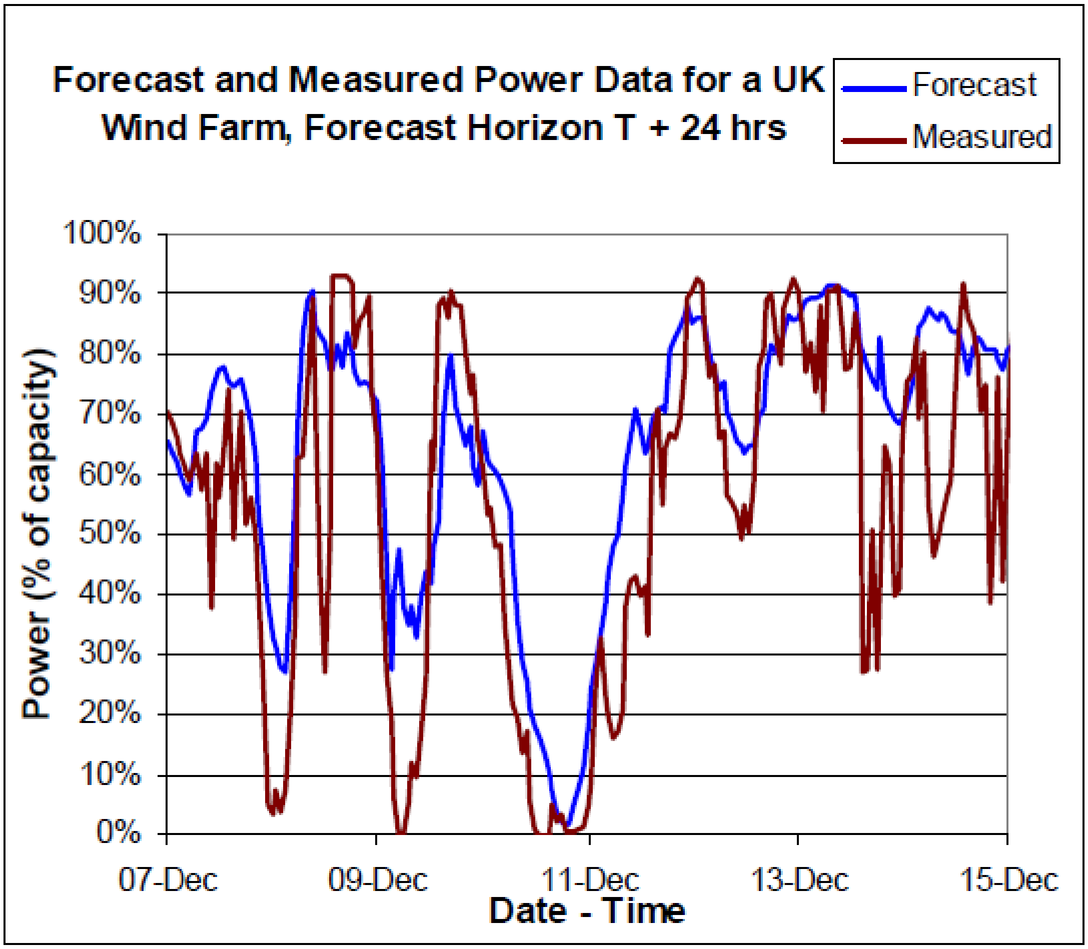


Figure 2.6 Time history of forecast and measured power for a single wind farm from figure 7 Greaves et al. 2009

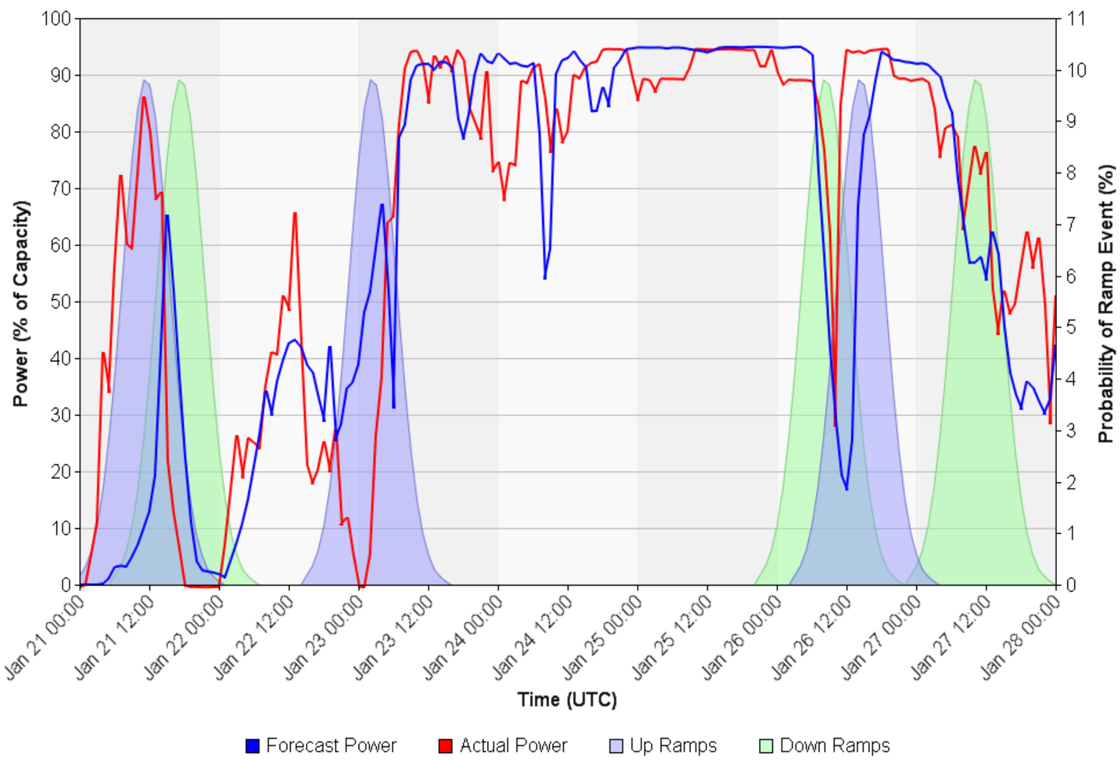


Figure 2.7 Forecast power with ramp event temporal uncertainty for a horizon of 24 hours from figure 9 of Greaves et al. 2009

2.2.4 A WRF Ensemble for Improved Wind Speed Forecasts at Turbine Height

The Deppe et al. (2012) study was conducted due to the lack of evaluations of model forecasts of winds at 80 m. This height not only coincides with the height of modern turbines, but also has influences of turbulent fluxes of momentum, heat and moisture from the surface, and vertical temperature stratification. Even fewer studies have examined the forecasting of ramp events. These events are both rare and difficult to forecast, as shown from the previous Greaves et al. (2009) study where only 36% of ramp events were captured by a private company when forecasting for six wind farms in the United States.

In the study version 3.1.1 of the WRF was used to reproduce the 80 m winds. Along with this model 6 different planetary schemes were compared to the wind speeds collected at the Pomeroy, Iowa site (Deppe et al. 2012). For most of the simulations, 10 km grid spacing was used with domains of 47 vertical levels. To effectively capture low level jet activity and influence 16 levels were below 1300 m with an average spacing of 15 m in the lowest 100 m. The winds were evaluated from June 2008 through September 2010 with 58 cases over 116 days from June 2008 to June 2009 analyzed for ramping events (Deppe et al. 2012).

Two evaluations were made for the study (Deppe et al. 2012). The first utilized mean absolute error to evaluate the speed forecasts. Within the first evaluation there were three tests. The first set looked at pre-run modification, time initializations, and grid spacing. The second set looked at three techniques which were the neighborhood approach, training of the model, and bias correction. The results from these techniques led to a final ensemble to be used operationally known as final OP. The second evaluation was forecast accuracy for ramp events at 80 m. An example of a ramp event is shown in Figure 2.8. This study utilized the Greaves et al. (2009) definition previously stated and further used a definition where if an area with 6-12 m/s winds had a change +/- 3 m/s in four hours or less it was considered a ramp. Ramp ups and ramp downs were identified using 10 minute data, but hourly data was focused on due to the model only accepting hourly data (Deppe et al. 2012).

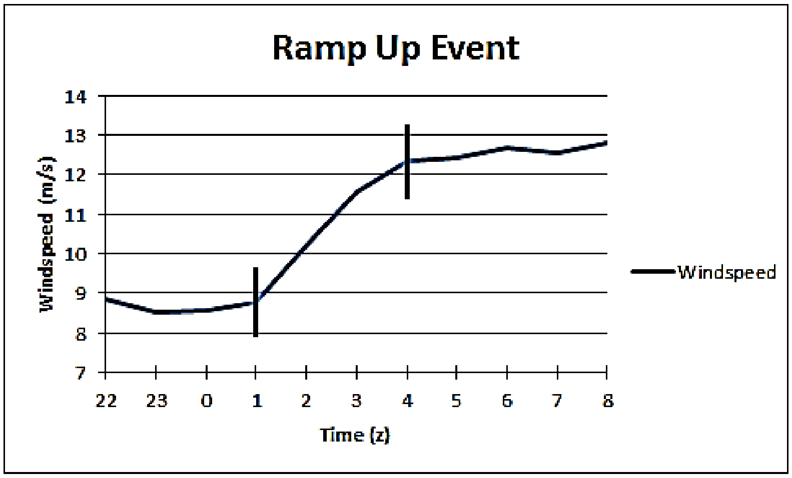


Figure 2.8 Example of ramp event

The observations for the ramp up events showed maxima in December and June at a frequency of 1.35 per day with a smooth decrease to minima in February and August at a frequency of 0.9 per day. Ramp down events had a frequency of 1.4 per day during December and June and a minima of 0.8 per day during March and August as seen in figures 2.9 and 2.10 (Deppe et al. 2012). For the analysis of 2 hour events vs. 4 hour events the trends were very similar. The colder months have longer ramp events compared to the warmer months. This can be explained by increased convective activity during the summer in Iowa. Ramp up events occurred most commonly at 1801-2100 LST which coincides with the timing for the decoupling of the boundary layer creating the LLJ as shown in figure 10. Ramp down events occurred between 0601-0900 LST which coincides with the coupling of the boundary layer. While there is no definite interval to explain a ramp, the change from 2 hours to 4 hours only produces a 10-20% increase in number of ramps (Deppe et al. 2012).

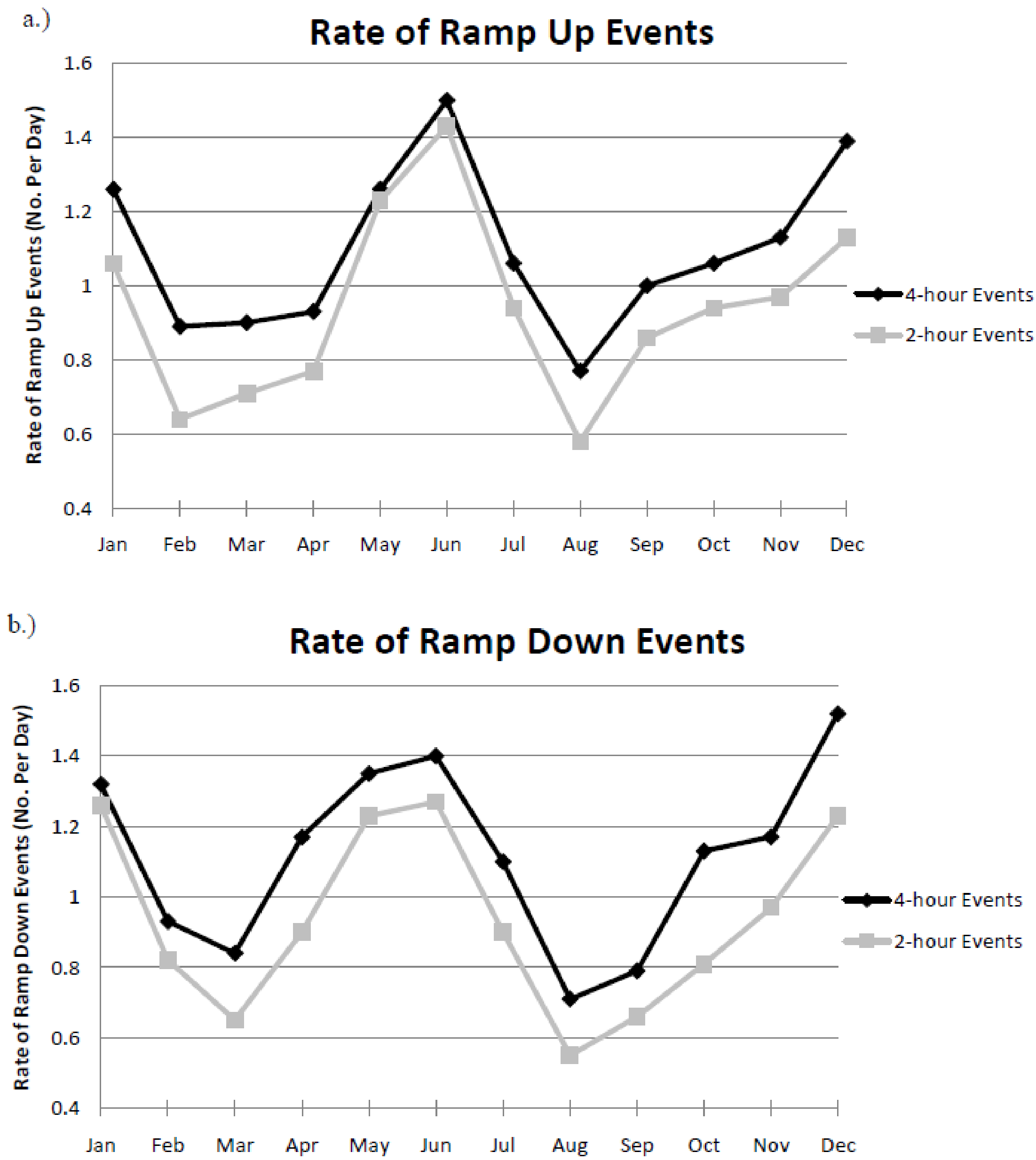
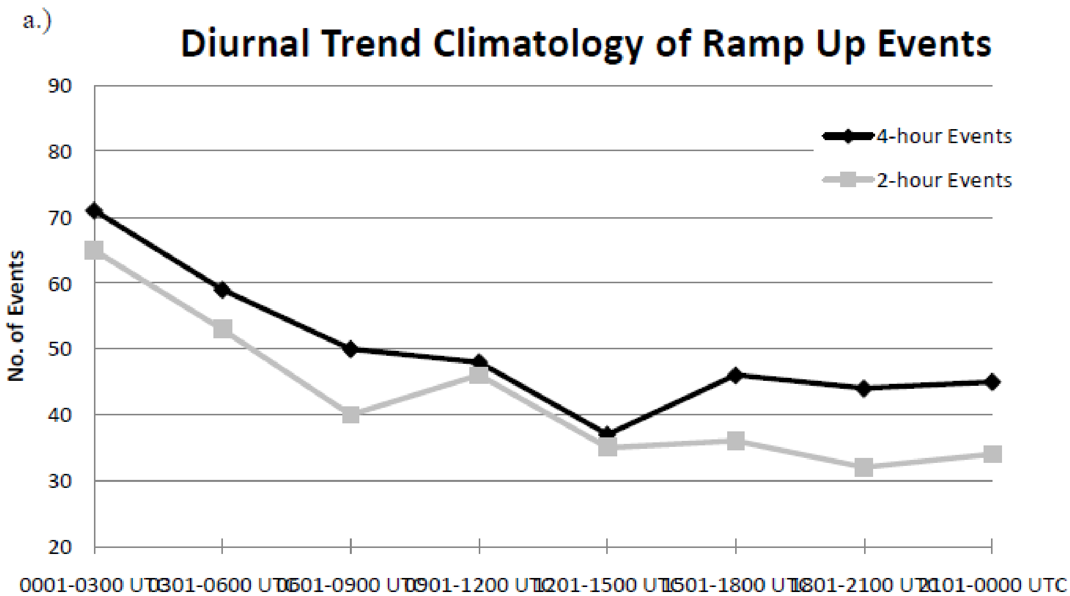


Figure 2.9 Monthly climatology of 2 and 4 hour ramp events from figure 7 Deppe et al. (2012)



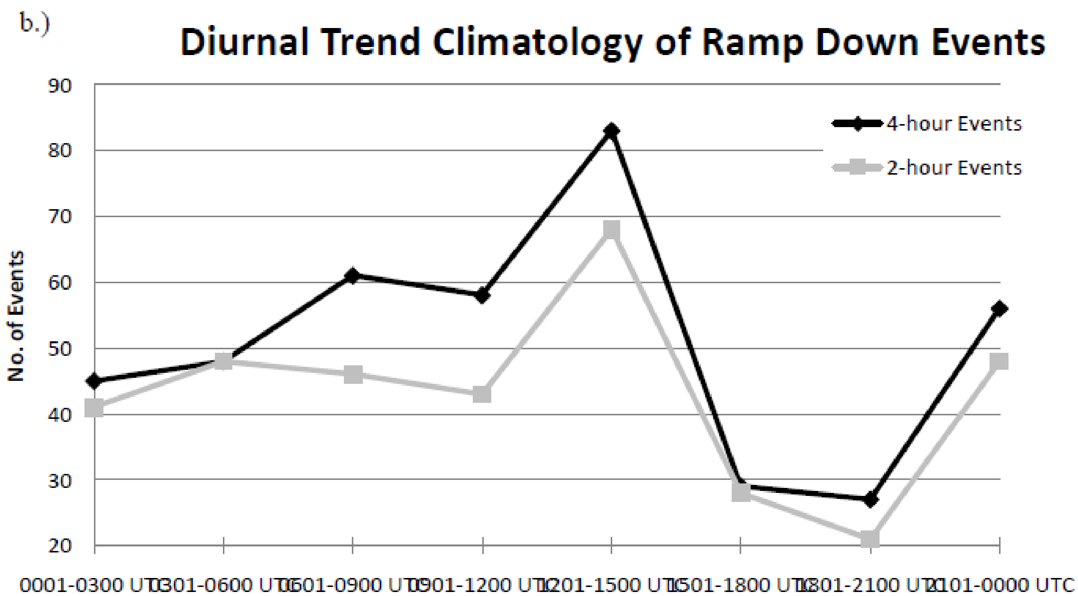


Figure 2.10 Diurnal trend climatology of ramp events from figure 8 of Deppe et al. (2012)

Initially ramp events were assumed to be most associated with frontal passages or local thunderstorms, however this proved to only explain for 16% and 12% respectively of all 4 hour ramps (Fig 2.11). 28% of all 4 hour events had no known cause. 29% of events were associated with a LLJ and mechanical mixing was theorized to have brought down higher winds. 15% were associated with the growth of the PBL where surface winds will raise rapidly (Deppe et al. 2012).

For the 2 hour events frontal passage and thunderstorms are responsible for more ramp events at 17% apiece. 24% occurred with no known cause. 34% were attributed to the LLJ and 10% were caused by the PBL growth. Further analysis explaining the large number of unknown events should be explored (Deppe et al. 2012).

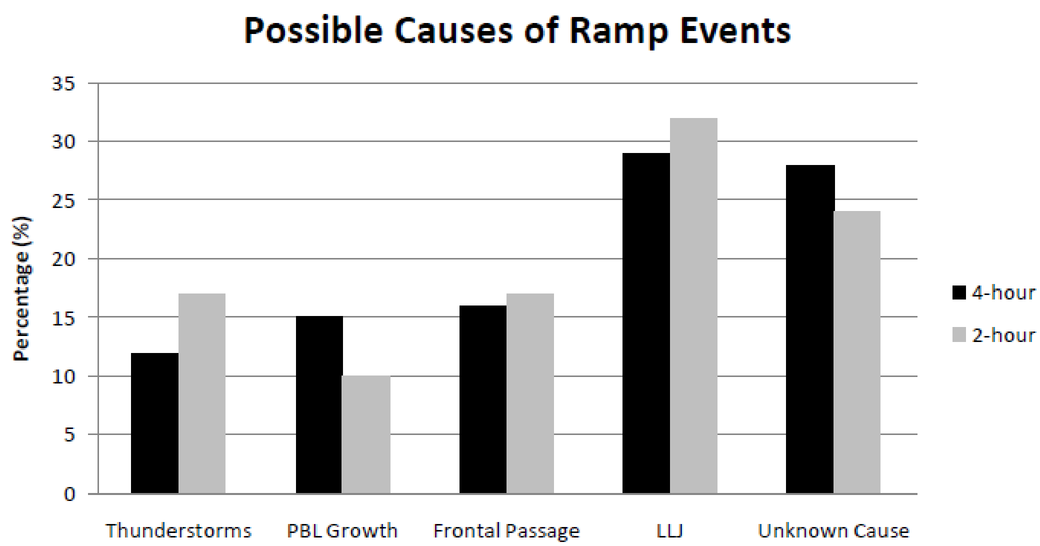


Figure 2.11 Causes of ramp events from Deppe et al. (2012) Figure 9.

In the model interpretation the midpoints of the ramp events were used. This was used to compare to the observational data for both ramp ups and ramp downs (Fig 2.10). All six PBL schemes underestimated the number of ramp up and ramp down events (Deppe et al. 2012). However the models did capture the correct timing of the LLJ compared to the observed results which was around 1600 LST and 1900 LST. This leads to the conclusion that vastly more observations of wind and temperature in the lowest 500 m of the PBL are needed under all conditions. With this data the representations for turbulent processes in models need to be reevaluated.

With an understanding of the LLJ, wind energy growth, and previous studies conducted involving ramp events this study aims to show the variability of the wind in western Missouri as it pertains to wind power. This is an important regional resource that can be implemented to help decrease the cost of power and lower dependence on other forms of energy. The LLJ plays a large role in this variability and is important to understand the exact level of involvement for energy managers. With renewable energy resources becoming more legitimized and funded there are two areas that can be improved which are engineering and forecasting. Forecasting is the more difficult than engineering and if it can be more accurate will lead to an efficient and predictable flow of wind power. The various studies conducted on ramp events show the importance of this subject. For a comprehensive understanding and implementation of wind farms all regionally dissimilar areas should be investigated. This study accounts for an area that has transitional conditions from very favorable for large wind farms to marginally favorable for small individual wind turbines.

Chapter 3 - Methodology

3.1 Study Focus

The goal of this research was to investigate and analyze the observed tall-tower data for trends and intensities of ramping events. It is thought that ramping events are often caused by the nocturnal LLJ and this research will either support or refute this assumption. This type of analysis has been done both domestically (Kamath 2010) and internationally (Greaves et. al 2009), but not for Missouri. Ramping events are of immense importance for energy operators to understand. With more knowledge they can balance the appropriate amounts of other energies when wind speeds are either high or low.

3.2 Area of Study and Instrumentation

Turbine heights have increased in the past few years to capture winds at higher heights which translate to higher power. With this growth the documentation of these winds is also needed to allow for wind farm placement. Towers from sites in northwestern and southwestern Missouri were analyzed for this project; the specific information is located in Table 3-1. Each tower at every location was instrumented with 2 anemometers and a single wind vane at 3 different heights: close to 70 m, close to 100 m, and the highest available location on the tower, with exception of the Monett tower. Each anemometer was mounted on a boom 113” long. They were situated 180 degrees apart from each other at each level. This configuration reduces error generated from the effects of the tower, boom, and other mounting arrangements on the wind flow. Due to tower differences the instruments were not all mounted at exactly the same heights. The lower and middle level instruments are relatively close but the upper level is dependent on the tower height, which was different at each location. For the Monett location the height of the tower data restricted the height the instruments could be placed and are significantly lower than other sites as seen in Table 3-2. See the study conducted by Fox et al. (2010) for more detail.

Tower Location	FCC #	Date Equipped	Latitude	Longitude	Elevation (m)
Blanchard	1003309	8/4/2006	40-33-34	95-13-28	328
Maryville	1002208	8/3/2006	40-21-36	94-53-01	353
Mound City	1007070	8/6/2006	40-04-11	95-11-41	340
Chilicothe	1002160	10/4/2006	39-48-48	93-35-26	244
Miami	1029923	6/30/2006	39-16-49	93-13-44	236
Raytown	1230974	7/25/2006	39-02-29	94-29-19.8	265
Monett	1042598	11/13/2006	36-58-30	93-54-55	415.2

Table 3-1 Tall tower information for each of the sites to be used in this study

Tower Location	Tower Height (m)	Lower Height (m)	Middle Height (m)	Upper Height (m)
Blanchard	155	61	97	137
Maryville	151	61	93	117
Mound City	126	61	97	117
Chilicothe	152	61	97	137
Miami	122	67	93	114
Raytown	152	67	93	142
Monett	77.4	50	60	70

Table 3-2 Tall-tower information specific to tower and instrumentation heights

3.3 Data Collection and Processing

The observational data was collected during the period of September 2006 through August 2007. Once the data was gathered, NRG software was used to convert the raw ten-minute averaged data into scaled text files. These files could either show the 10 minute or 60 minute averages of the wind data. The 10 minute data was utilized for this project to identify rapid changes in wind intensity for each month. The files were then imported into Microsoft Excel for statistical analysis. The data were separated by location and put in chronological order. The overall average wind speeds shown in Table 3-3 were used to select applicable turbines for analysis.

	Average wind speed at ~90m (m/s)
Blanchard	7.7
Chillicothe	6.3
Maryville	7.5
Miami	6.7
Mound City	6.6
Raytown	5.9
Monett (70m)	6.3

Table 3-3 Average wind speeds from September 2006 – August 2007 at about 90m using 10 minute averaged data (70m for Monett).

3.4 Statistical Algorithms and Ramp Identification

The challenge of identifying ramps lies in parameterizing what a ramp is and how to count them. On a time series graph it should be easy to identify a jump in wind speeds from the data. A mathematical representation is more difficult to produce due to there being no universal definition for ramp events and the subjective nature of determining wind turbines based on average wind speeds. The aim of this analysis was to portray ramp events as power spikes that exceed a percentage of rated power by a selected turbine within a given time.

The first process that needed to be addressed was finding the average wind speeds at turbine hub heights. The middle height was chosen for this analysis (highest for Monett) because it best represents the appropriate height for turbines utilizing the speeds found in the data. After finding the average wind speed for each site over an entire year, a specific turbine was chosen to maximize wind power production. To minimize comparative differences sites with similar wind speeds used the same turbine. Due to the large power differences based on velocity, sites with either higher or lower wind speeds used different turbines. The calculated power difference equation only needs the difference in cubed observed wind speeds versus the cubed rated wind speeds of the turbines used. All other factors in the power equation presented in the previous section (eq. 2 or 3) are identical on both sides of the equation. The turbines include the Vestas(V)90 2MW Gridstreamer turbine, used at Blanchard and Maryville, and the Wind Energy Resource's 50kW turbine, used at the other 5 sites. These particular turbines were chosen for their power production potential and had ideal operating parameters for the conditions at the sites. The Gridstreamer turbine has a swept area of 6,362 m^2, cut-in wind speed of 3.5 m/s and a rated wind speed of 13.5 m/s (Vestas 2013). Using the Electrotechnical Commission standard (IEC) 61400-1 wind class table (Table 3-4), Blanchard and Maryville average wind speeds do meet the requirements to be in the IEC III Low Wind category.

Wind Class/Turbulence	Annual average wind speed at hub-height (m/s)	Extreme 50-year gust in meters/second (miles/hour)
Ia High wind - Higher Turbulence 18%	10.0	70 (156)
Ib High wind - Lower Turbulence 16%	10.0	70 (156)
IIa Medium wind - Higher Turbulence 18%	8.5	59.5 (133)
IIb Medium wind - Lower Turbulence 16%	8.5	59.5 (133)
IIIa Low wind - Higher Turbulence 18%	7.5	52.5 (117)
IIIb Low wind - Lower Turbulence 16%	7.5	52.5 (117)
IV	6.0	42.0 (94)

Table 3-4 IEC 61400-1 wind class definitions for wind turbine generators (Vestas 2013)

This is important because this is the ideal operating conditions for the V90 2MW Gridstreamer also falls into the same IEC category (Vestas 2013). The other turbine selected, the Wind Energy Resources 50kW turbine, has a significantly lower power output. It has a swept area of 133 m^2, cut in speed of 3 m/s, and a rated wind speed of 12 m/s (Wind Energy Resources 2010). Although operating conditions for the two turbines are similar the 50kW turbine is designed to work with the IEC's class IV or lower wind speeds, which the remainder of sites fall into. Percentages of 20%, 30%, 40%, and 50% of the rated power output were also found to evaluate ramps based on intensity. Both the rated power of the turbine and theoretical power generation from the data have the same equation (see eq. 3) except for the wind speed. With this a direct comparison of cubed wind velocities was made. Power output based on the site specific ten minute winds and turbine information was calculated for the entire year.

3.4.1 Ramp Definition

The definition of a ramp was chosen based on statistical analysis by Kamath (2010). In the study there were three possible definitions. The definition used in this study was also the first definition in Kamath (2010) which stated, "A ramp event is considered to occur at the start of an interval if the magnitude of the increase or decrease in generation at a time, t, ahead of the interval is greater than a pre-defined threshold". The time parameters chosen to identify ramp events were 30 minutes, 1 hour, 2 hours, and 4 hours. Looking at multiple time scales allows for the identification of ramp events over longer periods and it also increases the likelihood that a change in wind will be observable. The threshold of power is subjective in that it will be based off the turbine chosen previously. To allow for objective analysis with subjective parameters, all time periods were analyzed using each percentage of rated power value. For the 2MW Gridstreamer, with a rated wind speed of 13.5m/s, a 20% change shows a flux of 2.7m/s, a 30% change is 4.1m/s, a 40% change is 5.4m/s, and a 50% change is 6.8m/s. For the Wind Energy Resources 50kW turbine a 20% change is a flux of 2.4m/s, 30% change is 3.6m/s, 40% change is 4.8m/s, and 50% change is 6.0m/s. This can show if particular sites have the potential for more severe ramps at greater intervals. The values of 1,-1, and 0 are assigned to up ramps, down ramps, and null events respectively. These values are determined by the difference between the rated power of the wind turbine and the power produced at a specific time with data provided. If the difference is greater than a particular percentage it is considered a down ramp and if smaller an up ramp. The majority of values fall between the percentage gates are assigned 0.

3.4.2 Counting Ramps

Once the definition of a ramp was found the next task would be quantifying how many ramps exist in the data. From the study conducted by Kamath (2010), there are three methods to count ramps where the first and third methods were not selected. The first counting method involves explicitly counting all the intervals which start a ramp event during a period. This can lead to over counting because there is not a count of the events but the intervals which comprise the event (Kamath 2010). The third option involves a binary count in which a check for whether a ramp did or did not occur during a particular time of day. This would be considered under-counting because if multiple ramps occurred in a time period only one would be counted. In options 1 and 3 if a ramp event straddles a time period boundary it can get counted in two time periods. For this study option 2 was chosen to most accurately count ramps. Kamath (2010) states, "Instead of counting all intervals which form a ramp event, which would result in longer ramp events contributing more to the count, we count only the first interval in a series of consecutive intervals which form a ramp event. Thus, an interval will be considered if it starts a ramp interval, and the previous interval is not the start of a ramp event, or is part of a ramp event of the opposite sign". Counting method 2 in Kamath (2010) was determined to be the optimal counting method.

There is a distinct increase in ramps when looking at longer time scales so an attempt to adjust this was made. In the case of the 30 minute observations a ramp was counted if 3 consecutive values, either positive or negative, were found. For the 1 hour observations a ramp was counted if 5 consecutive values were found. For the 2 and 4 hour observations ramps were counted if 9 and 14 consecutive values were identified, respectively. These values were chosen arbitrarily based on the first dataset's maximum number of consecutive values then divided by two. With a limited number of ramp event studies in circulation, there is room for interpretation for the most effective method for counting ramps. With this method it allows for the count of ramps that may not last the entire duration of the counting period, but do last for the majority of the period. While every site will have a different maximum number of consecutive values, they can all be judged comparatively using a set methodology. Table 3-5 shows a representation of counting method 2 using a 1 hour parameter. The first counted ramp has 5 consecutive "1" values which meets the criteria for an up ramp in this period and would be counted as 1 up ramp. The second counted up ramp has 6 consecutive "1" values which meet the criteria for an up ramp and would be counted as 1 up ramp. The counting methodology is if 5 out of 6 consecutive time period have consecutive up or down ramps they will be counted. If the value at 4:20 PM in table 3-5 was "1" then there would only be one continuous ramp counted instead of two. Figure 3.1 graphically shows ramps are counted using data from table 3-5.

Counting method 2 with 1 hour parameter							
Time	Wind Speed m/s	Ramp	Count		[illegible]	Ramp	Count
3/31/07 3:30 PM	9.90E+00	1	1		[illegible]	0	0
3/31/07 3:40 PM	9.30E+00	1	0		[illegible]	-1	0
3/31/07 3:50 PM	1.01E+01	1	0		[illegible]	1	0
3/31/07 4:00 PM	1.02E+01	1	0		[illegible]	1	0
3/31/07 4:10 PM	1.09E+01	1	0		[illegible]	1	0
3/31/07 4:20 PM	1.24E+01	0	0		[illegible]	1	0
3/31/07 4:30 PM	1.19E+01	1	0		[illegible]	0	0
3/31/07 4:40 PM	1.30E+01	1	1		[illegible]	-1	0
3/31/07 4:50 PM	1.35E+01	1	0		[illegible]	-1	0
3/31/07 5:00 PM	1.37E+01	1	0		[illegible]	0	0
3/31/07 5:10 PM	1.29E+01	1	0		[illegible]	-1	0
3/31/07 5:20 PM	1.41E+01	1	0		[illegible]	-1	0
3/31/07 5:30 PM	1.51E+01	-1	0		[illegible]	1	0

Table 3-5 Illustrates counting method 2 with the 1 hour parameter for data taken from March 31 from 3:30 PM to 7:40 PM.

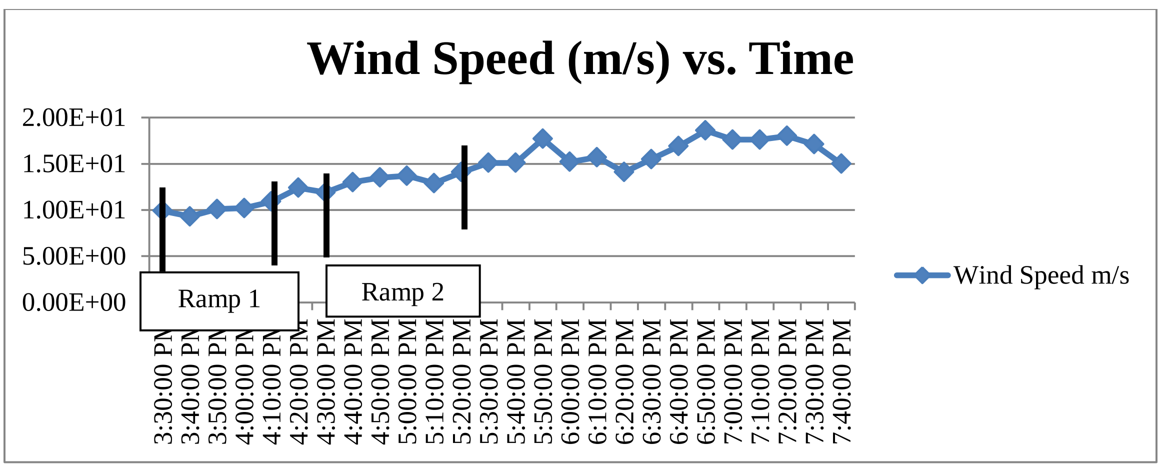


Figure 3.1 Wind speed vs. time for data in table 3-5 to show graphically how a ramp is counted. Counted ramps 1 and 2 are displayed.

Chapter 4 - Results and Discussion

4.1 Initial Investigation

Using the methods described in the previous section, a detailed analysis depicting ramp events was conducted for seven locations in western Missouri from September 2006 to August 2007. These events were identified using a variety of different temporal and power gauging methods. In the Greaves et al. (2009) study, a change in 50% of power capacity over a 2 or 4 hour period was determined to be a ramp. The cases used by Greaves et al. (2009) were also industrial power capable locations with higher mean winds and gradient changes than locations used in this study. With this in mind and knowledge of Missouri's less capable power production, the counting method producing the most ramps, 1 hour, was used to give the most data points. Using the 1 hour counting method also reduces the time the wind could change as much as the Greaves et al. (2009) analysis, so to remain comparable the 30% power change was utilized. This decision will capture rapidly occurring ramps as well as events that happen more gradually such as the LLJ. Table 4-1 shows the total number of ramps identified for the entire year of data for 1 hour events at four different power thresholds. As seen in Table 4-1, the 30% power change does not have as many ramps as the 20% power change, but it is a more realistic change in power that may affect power managers. When stepping up to 40% there is a significant reduction in ramps making analysis less insightful. The research conducted does include 30 minute, 1 hour, 2 hour, and 4 hour temporal scales, as well as 20%, 30%, 40%, and 50% power changes. See Appendix A for figures A.1-A.4 representing the other temporal counting methods.

	1 hour							
	20%		30%		40%		50%	
	+	-	+	-	+	-	+	-
Blanchard	131	111	63	58	28	21	16	10
Chillicothe	88	81	30	34	10	20	5	7
Maryville	122	105	56	53	25	21	14	10
Miami	204	234	94	102	49	48	21	22
Mound City	135	159	63	77	34	37	24	24
Raytown	220	210	99	95	48	50	27	31
Monett	119	118	46	48	24	23	14	13

Table 4-1 Total number of up(+) and down(-) ramp events using 1 hour counting

On top of total overall ramp events, a seasonal analysis with time of day information was accomplished. The seasonal variability of ramp events has an effect on energy managers who, with more predictive knowledge, will be more prepared to accommodate their occurrence. The last analysis regarding time of day can be a proxy determinant for LLJ induced ramp events. Figures A.5-A.8 show the seasonal relationships to ramps during LLJ and non-LLJ times. These show a majority of ramps to occur during LLJ times. This is an important finding because power used is generally during the day. To make wind power efficient and viable the power generated in the evening hours needs to be stored until peak usage hours. To show the more specific times of the nocturnal LLJ and other factors to ramps, the data was broken into 4 sections. 0-6 (12 a.m.- 6 a.m. UTC), 6-12 (6 a.m.- 12 p.m. UTC), 12-18 (12 p.m.- 6 p.m. UTC), and 18-0 (6 p.m.- 12 a.m. UTC) were chosen due to emphasize diurnal effects on the winds. To more accurately show comparative analysis the sites using the same turbine will be analyzed together.

4.2 Ramp Analysis with the V-90 2 MW Gridstreamer

Due to the higher overall wind speeds at the Blanchard and Maryville locations a larger industrial wind turbine was chosen. For comparative analysis showing these two locations alongside the other sites does not show equal power in ramp events. These two sites must produce more dynamic ramps for them to be recorded by the counting algorithm because of the higher power capacity of the turbine. The average wind speeds seen at these sites were in the class III wind classification, which this turbine was designed to operate in. Fig. 4.1 shows the monthly variation for ramp distribution during 2006-2007 for Blanchard and Maryville. Winter and spring months contained the majority of ramp events.

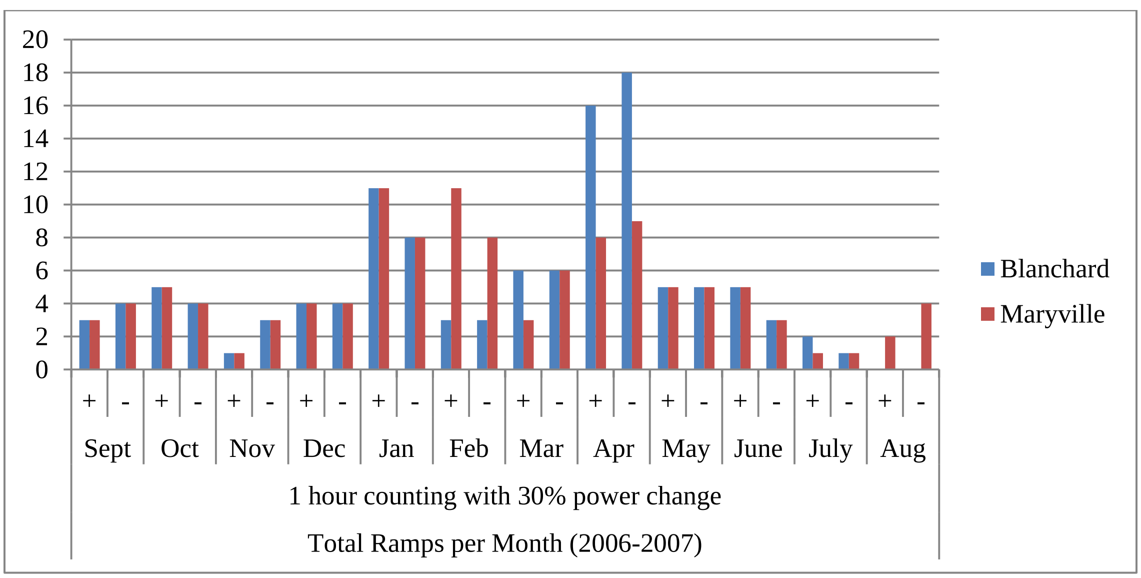


Figure 4.1 Monthly distribution for ramp events at the Blanchard and Maryville towers with 1 hour counting and 30% power change parameters.

4.2.1 Seasonal Ramp Event Analysis

A seasonal analysis is important for power operators to know and plan for high volatility and integration of other power sources. Breaking a year's worth of data into spring, summer, fall, and winter seasons allows for a better understanding of synoptically based forcing mechanisms. Depending on the time of year, higher or lower reserves of other sources of energy can be stockpiled and a heightened preparedness for changes can be achieved.

4.2.1.1 Spring Time of Day Analysis

Spring is taken to be the months of March, April, and May. The LLJ typically forms and is sustained during the 18-0 and 0-6 hours respectively. Other forcing mechanisms do occur during this time, but the largest contributor is thought to be the LLJ. Also the LLJ can occur at any time during the day so this analysis does not differentiate from the day time jets. Table 4-2 shows the spring of 2007's data for Blanchard and Maryville.

	0-6 CDT		6-12 CDT		12-18 CDT		18-0 CDT	
	+	-	+	-	+	-	+	-
Blanchard	6	8	8	8	11	5	2	8
Maryville	4	5	5	5	9	4	1	6

Table 4-2 Blanchard and Maryville ramp data in the Spring of 2007 for 1 hour counting and 30% power change

Starting with the 18-0 time period, when the LLJ typically forms, results show a significantly greater number of down ramps than up ramps during this period for both sites. While the days are increasing in length at this time of year, sunsets could be affecting the time that the LLJ may be forming. This result goes against what would be expected.

The next section, called the 0-6, is where the LLJ should be at its greatest strength. The data shows more down ramps than up ramps as before, but the numbers are closer together. During this time of year many nocturnal storm systems move through the area due to the LLJ, giving explanation to both up and down ramps.

The 6-12 section is the time period where turbulent mixing will begin again with the rise of the sun. This usually is accompanied by a drop in wind speeds as the LLJ fades. The data from this time period however, shows an equal number of up and down ramps for both sites. In fact this time period has more up ramps than the previous period. While this analysis doesn't account for strength it does show slightly more variability in this period than the 0-6.

The last period is the 12-18 where the majority of up ramps reside. Both sites recorded their highest number of up ramps at 11 and 9 for Blanchard and Maryville respectively. The down ramps are about half these values. This trend would suggest a general increasing of wind speeds during this time. This may be explained by the earlier setting of the sun transitioning during this time of year or a considerable amount of storms moving through the area.

4.2.1.2 Summer Time of Day Analysis

Table 4-3 shows the summer of 2007 ramp event analysis. Summer is considered to be June, July, and August (JJA). This time of year typically is accompanied by lower winds and storms as reflected by the difference in ramp events compared to the spring.

	Early AM 0-6 CDT		Late AM 6-12 CDT		Early PM 12-18 CDT		Late PM 18-0 CDT	
	+	-	+	-	+	-	+	-
Blanchard	4	2	1	2	1	0	1	0
Maryville	5	4	2	4	1	0	0	0

Table 4-3 Ramp events for Blanchard and Maryville in the summer of 2007 for 1 hour counting and 30% power change

The 18-0 period only recorded 1 up ramp total for both sites. This may be explained by the ground being heated enough to subdue the nocturnal inversion from taking full effect until later in the evening. When there is a greater amount of sensible heating it leads to more convection and turbulence at the surface. This in turn increases the friction at the surface hindering boundary layer decoupling. If the following period has more ramps this theory could be considered.

The 0-6 period has more up and down ramps than the 18-0 period and more ramps than the other periods as well. There are also more up ramps than down ramps for both sites with Maryville having more of both. The data shows that the LLJ at Blanchard and Maryville will occur most frequently at this time period during the summer.

The 6-12 period recorded more down ramps than up ramps but the values are close. From this data it can be shown that the LLJ dissipates in this period. While it has exactly the same number of down ramps as the 0-6 period, it does not match the up ramps. Therefore it can be theorized that the ramp frequency observed in the 0-6 period is based on fluctuations of the wind and this period is dissipative.

The 12-18, much like the 18-0, is largely uneventful. Both sites only recorded one up ramp for the entire season. Turbulent mixing most likely persists during this period not allowing for the decoupling stage and the formation of the LLJ. These conclusions are tentative based on the results and are based on a general understanding of typical atmospheric processes.

4.2.1.3 Fall Time of Day Analysis

During the fall season in Missouri increased gradients of temperature occur compared to the summer. This change should lead to a higher number of wind events and frontal passages. Table 4-4 shows ramp events for Blanchard and Maryville during the fall of 2006 with 1 hour counting and a 30% power change. This particular season recorded identical ramp events for both sites possibly showing that either there were larger systems affecting the area or a specific flow intersected this area.

	Early AM 0-6 CDT		Late AM 6-12 CDT		Early PM 12-18 CDT		Late PM 18-0 CDT	
	+	-	+	-	+	-	+	-
Blanchard	4	9	3	0	0	1	2	1
Maryville	4	9	3	0	0	1	2	1

Table 4-4 Ramp events for Blanchard and Maryville in the Fall of 2006 for 1 hour counting and 30% power change

In the 18-0 period there 2 up ramps and 1 down ramp for each site which could be used to show LLJs are developing. This does not definitively prove this due to the low number of ramps and similar number of down ramps though.

During the 0-6 period there are the most up and down ramps. The down ramps outnumber the up ramps by 9 to 4. This may point to down ramps occurring more rapidly than the up ramps for this period.

For the 6-12 there are 3 up ramps with no down ramps which could indicate wind speeds increasing rapidly and then decreases gradually. This would be counterintuitive for the timing of the nocturnal LLJ, but, as previously stated, the LLJ can occur during the day. Another explanation could be frontal passages which are typically accompanied with strong initial winds and as the front passes a gradual slowing.

The 12-18 period there is only 1 down ramp recorded. No conclusion can be made from only one event other than this is the calmest period of day during the fall season.

4.2.1.4 Winter Time of Day Analysis

The winter time for this region can be influenced by strong frontal passages, cyclones, and two LLJs. The more common southerly LLJ is seen in all seasons, but the northerly LLJ occurs during this time of year as well. Table 4-5 shows ramp events for Blanchard and Maryville during the winter months of December, January, and February in 2006. This time of year recorded the second most ramp events behind the spring.

	Early AM 0-6 CDT		Late AM 6-12 CDT		Early PM 12-18 CDT		Late PM 18-0 CDT	
	+	-	+	-	+	-	+	-
Blanchard	5	6	3	3	3	1	7	5
Maryville	5	8	5	2	6	2	10	8

Table 4-5 Ramp events for Blanchard and Maryville for the winter in 2006 using a 1 hour count and 30% power change

The 18-0 period had the most ramp events and more up ramps than down. With the number of up ramps being higher it can be argued that the LLJ is occurring and that there are significant fluctuations due to the high number of down ramps.

The 0-6 has more down ramps during this period than up ramps but they are similar for both sites. The down ramps could be caused by the LLJ dissipating with the up ramps occurring earlier representing supergeostrophic winds, or high variability in the area.

In the 6-12 for Blanchard there are an equal number of up and down ramps with 3. In Maryville there are 5 up ramps and 2 down ramps. From this it can be assumed that an event such as a gust front passed through Maryville and not Blanchard, despite their close proximity. It also might suggest the LLJ did not include Blanchard during a particular night or week.

The 12-18 looks similar to the 6-12 period except Maryville had 1 more up ramp and both sites had less down ramps. The up ramps can be explained with the sun setting earlier in the day and activating the LLJ earlier in the evening.

4.2.2 Ramp Analysis using Wind Energy Resources 50kW Wind Turbine

The wind speeds at Chillicothe, Mound City, Monett, Miami, and Raytown were not considered to be class III. For this reason another turbine was selected to maximize wind power potential given the average wind speeds collected. There is a larger difference in wind speeds and location with these sites, so more variability should be seen. Sites with higher winds should capture more ramps as well as those that have significant terrain effects that channel and concentrate flow near the tower. The Wind Energy Resources 50kW wind turbine was selected and used to compare ramp events for the remaining sites in the study. Fig. 4.2 shows the monthly variation for ramp distribution during 2006-2007 for Chillicothe, Miami, Mound City, Monett, and Raytown. Winter and spring months contain the majority of ramp events as seen previously at Blanchard and Maryville.

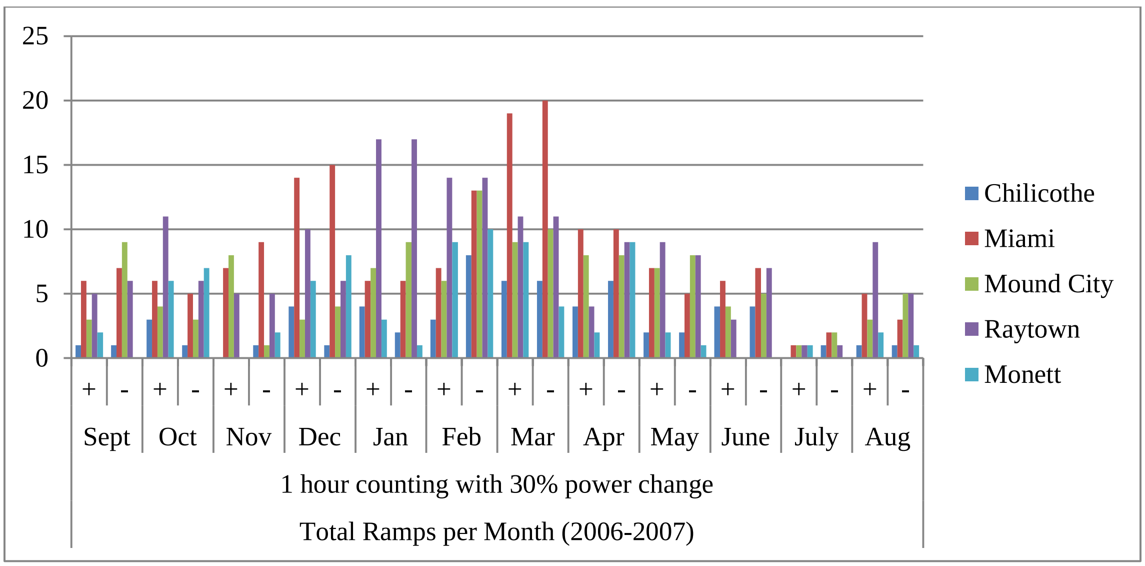


Figure 4.2 Monthly distribution for ramp events at for remaining 5 towers with 1 hour counting and 30% power change parameters.

4.2.2.1 Spring Time of Day Analysis

Table 4-6 shows the distribution of spring 2007 ramp events for the Chillicothe, Miami, Mound City, Raytown, and Monett sites.

	Early AM 0-6 CDT		Late AM 6-12 CDT		Early PM 12-18 CDT		Late PM 18-0 CDT	
	+	-	+	-	+	-	+	-
Chillicothe	0	3	6	2	2	5	1	4
Miami	16	13	6	14	9	5	5	3
Mound City	6	7	4	4	10	7	4	8
Raytown	8	9	7	6	5	6	4	7
Monett	3	3	5	1	2	3	3	7

Table 4-6 Ramp events in the spring of 2007 using 1 hour counting and 30% power change for 5 sites shown

Geographic location will also play a factor in the number of ramp events observed, as seen in the above table. During the 18-0 period all sites recorded more down ramps than up ramps except for the Miami location. The other sites consistently have 3 or 4 more down ramps which may suggest similar events, and judging from the distance between the sites, this would most likely be due to the LLJ. The Mound City site is closest to the Blanchard and Maryville locations and should resemble their results.

For the 0-6, Mound City, Raytown, and Monett have about the same number of up and down ramps. Chillicothe recorded no ramp ups during this period and 3 ramp downs. For this time of year and time of day it is surprising that no up ramps occurred. Miami captured many more than the other sites with 16 up ramps and 13 down ramps. This is either a function of the turbine size chosen and to minimize ramp events for this location a larger turbine may be used, or significant events passed through this area more frequently.

In the 6-12 all sites recorded between 4 and 7 ramp ups but had a larger separation in number of down ramps. Monett and Chillicothe recorded 1 and 2 down ramps respectively with Miami showing 14. This period would be more associated with down ramps from the LLJ dissipating, but judging from the ramp ups could be associated with prolonged LLJs, storms, or frontal passages.

The 12-18 has a mixture of results. The Miami and Mound city sites both have a high number of up ramps with a lower number of down ramp. Raytown and Monett both have one more down ramp than up ramps. Chillicothe has 3 more down ramps than up ramps. While the sites could have been affected by the same large scale events such as frontal passage or LLJ it seems that individual storms may have played a part for this time period. During the spring, this would be the time period in which storms initiate, further explaining the result.

4.2.2.2 Summer Time of Day Analysis

The summer season, as in the Blanchard and Maryville cases, produced the fewest number of ramps. Figure 4-7 shows the results from the 2007 summer season.

	Early AM 0-6 CDT		Late AM 6-12 CDT		Early PM 12-18 CDT		Late PM 18-0 CDT	
	+	-	+	-	+	-	+	-
Chillicothe	2	1	2	0	1	3	0	2
Miami	3	3	2	5	6	1	1	3
Mound City	4	4	2	5	1	2	1	1
Raytown	6	3	3	6	4	2	0	2
Monett	1	0	1	1	0	0	2	0

Table 4-7 Summer of 2007 ramp event results with 1 hour counting and 30% power change for the sites above

For the 18-0 period there are at most 2 recorded up ramp events, which occurred in Monett. Miami had the most recorded down ramps with 3. Each site, except for Monett, had more down ramps associated with them.

In the 0-6 more events were captured than the previous period and all sites had either more up ramps or an equal number to down ramps. Raytown had the most up ramps with 6 and had the greatest differential with 3 down ramps.

The 6-12 generally had more down ramps except for Chillicothe. For Miami, Mound City, and Raytown there were 3 more down ramps than up ramps. Monett recorded an equal number at one apiece and Chillicothe had only two up ramps. This would typically show a decline in LLJ activity given the time of day and down ramp values.

For the 12-18 there are mixed results. For Chillicothe and Mound City there are more down ramps recorded but the values are close. For Miami and Raytown there are more up ramps with ratios of 6 to 1 and 4 to 2 respectively. Monett did not record any ramp events during this time of day in the summer. The higher degree of variability also occurred during this time for the spring season.

4.2.2.3 Fall Time of Day Analysis

The fall season did record more ramp events than the summer, as shown in Figure 4-8, which agrees with the Blanchard and Maryville data.

	Early AM 0-6 CDT		Late AM 6-12 CDT		Early PM 12-18 CDT		Late PM 18-0 CDT	
	+	-	+	-	+	-	+	-
Chillicothe	0	1	1	0	1	0	2	2
Miami	10	10	5	6	1	3	3	2
Mound City	6	9	4	2	2	1	3	1
Raytown	7	3	4	9	5	0	5	5
Monett	3	4	3	1	2	1	0	3

Table 4-8 Fall season of 2006 ramp events using 1 hour count and 30% power change for the sites listed above

The 18-0 shows about an equal distribution of ramps events with maximum values occurring in the Raytown location. Monett did not follow this trend with having no recorded up ramps and 3 down ramps.

During 0-6 most locations saw a similar number of both ramps. Miami recorded 10 of each showing a high fluctuation in the wind. Mound City recorded more down ramps during this period but also had a significant number of up ramps as well. Raytown had the greatest differential with 4 more up ramps than down ramps showing a greater degree in increasing wind speeds most likely due to the LLJ.

The 6-12 span has a mixed trend. Chillicothe and Miami have a differential of 1 between up and down ramps, but Miami recorded 11 total events to Chillicothe's 1. Mound city and Monett both had 2 more up ramps than down ramps and similar total values. Raytown observed 5 more down ramps with 9 than its up ramps at 5. The mixed values could indicate storm events or dissipation of the LLJ.

The 12-18 was a mixed period as well but had less variability than the previous period. The only stand out site was Raytown which recorded 5 up ramps and no down ramps. This could mean very slow relaxing of the winds after up ramps. The other sites varied less having mostly a differential of one for either ramp type.

4.2.2.4 Winter Time of Day Analysis

The winter of 2006 was very close to being the most active season for this study. It produced the greatest single site up ramp count and every time period had at least one event. Figure 4-9 shows this season's ramp event totals.

	Early AM 0-6 CDT		Late AM 6-12 CDT		Early PM 12-18 CDT		Late PM 18-0 CDT	
	+	-	+	-	+	-	+	-
Chillicothe	2	3	6	1	2	5	1	2
Miami	10	13	8	6	4	7	5	8
Mound City	9	6	2	7	2	8	3	5
Raytown	19	11	10	12	8	5	4	9
Monett	5	1	7	5	4	8	2	5

Table 4-9 Winter of 2006 ramp events using 1 hour counting and 30% power change for the sites listed above

For the 18-0 period every site produced more down ramps. The differential ranges from 1 to 5 more down ramps than up ramps. This result is directly opposed to the findings at Blanchard and Maryville. The down ramps are similar for all sites however the Blanchard and Maryville sites had a greater number of up ramps.

During the 0-6, Raytown recorded 19 up ramps which is the highest total for any time or season. It also had a high number of down ramps with 11. Miami and Mound City had 9 and 10 up ramps respectively. They differed in down ramps with Miami recording 13 and Mound City with only 6. Monett and Chillicothe were the least fluctuating stations. Monett did record 5 up ramps with only 1 down ramp though, and Chillicothe had 2 up ramps with 3 down ramps. The occurrences at Miami and Raytown show an interesting high frequency of ramp events.

The 6-12 varies from site to site. Miami, Raytown, and Monett all have a differential of 2 between ramps events. Monett has more up ramps with the other two having more down ramps. Raytown again records the highest number of up ramps with 10 and also has the most down ramps with 12. Chillicothe had 6 up ramps with only 1 recorded down ramp and Mound city had an opposite effect with 2 up ramps and 7 down ramps.

The 12-18 was the least active period but still relatively active overall. All sites except Raytown experienced more down ramps. The differential for those was from 3 to 6. Raytown had the most up ramps in this period as well with 8 and only 5 down ramps. This trend would show a lowering in wind speeds in general which theoretically is supposed to occur.

4.3 Up Ramp Correlation with LLJ presence

If there is a link between the LLJ and ramps, then a forecast of the LLJ can be used as a proxy to predict ramps. To determine the correlation between up ramps and nocturnal LLJs a comparative analysis was conducted. Previous research conducted by Koleiny (2009) was able to determine LLJ activity for the region including the seven towers in this study. He identified occurrences of the nocturnal LLJ for this region for the time of September 2006 to August 2007 using upper-air observational winds from the National Centers for Environmental Prediction (NCEP). Three criteria had to be met to be considered a nocturnal LLJ in his study. The first was a wind speed greater than 16 m/s at or below 700mb. The second was the vertical wind shear between the level of strongest wind and the earth's surface equaled or exceeded 4 m/s. The last parameter was that these events happen between 0Z and 12Z. The result was 205 unique LLJs for the year.

To make a direct comparison the data collected in this study from the previous sections had to be further broken down. The dates on which ramps occurred were found. Once this was completed individual up ramps were represented by their date and time for every ramp. To best identify the increasing wind speeds accompanied with the LLJ only up ramps from 0Z-12Z were used to match Koleiny's (2009) study. Table 4.10 shows a statistical analysis of the relationship between the up ramp occurrences and the LLJ activity. Comparing dates for matches in Koleiny's (2009) study and the data from this study was convincing that there is a strong relationship between up ramps and the nocturnal LLJ. Table 4-10 shows the results in which the lowest correlation was 69% showing a high correlation of up ramps during the night hours being related to the nocturnal LLJ.

	LLJ matches	LLJ misses	No LLJ w/ up ramp	% LLJ caused
Blanchard	22	4	2	79%
Maryville	25	3	0	89%
Chillicothe	6	0	1	86%
Miami	41	8	4	77%
Mound City	11	2	3	69%
Monett	34	1	2	92%
Raytown	53	6	4	84%

Table 4-10 The relationship between the up ramps recorded between 0Z-12Z and the LLJ over the period of September 2006 to August 2007.

Chapter 5 - Conclusions and Future Work

5.1 Conclusions

For wind power to be an effective resource in Missouri it is necessary to know both average and variable conditions. Average wind speeds can determine exact locations for wind farms and the size of the turbines to be used. The variability of the wind has more of an effect on day to day operations when energy managers need to plan for wind power usage.

This investigation into ramp events and their association with the LLJ for a 12-month period (September 2006 through August 2007) in Missouri has led to some insights that can be applicable to wind power development in the state.

- Analysis of 10 minute averaged wind speeds and appropriate wind turbine selection for given average.
- Overall there were a total of 451 up ramps and 467 down ramps recorded with one hour counting and 30% power change.
- The spring and winter months have the most total ramps events with 318 and 319 respectively.
- The fall and summer months are significantly less active in terms of ramp events with 170 and 113 respectively.

- Ramp events occur most frequently during 0-6 CT in March with 41 events.
- Ramp events occur the least during 0-6 CT in July with no events.
- For LLJ times (18-06 CT), ramp events were determined to have been caused by the LLJ between 69% (at Mound City) and 92% (at Monett).

These findings can be useful for wind farm developers as well as energy managers that will utilize the power generated. For the spring and winter seasons they can schedule to use more wind power resource and be on alert for quick and numerous changes. In the summer more traditional resources will be needed to be accounted for to make up for the lack of wind.

Climatologically the LLJ is prominent in western Missouri. The ramp events documented in this study have been shown to coincide with the LLJ as well. It does make sense that a high correlation percentage would be seen using any particular data set. Unfortunately only using one year a data hinders the effect of large scale circulation changes that affect the LLJ. Since the LLJ has been documented, tracked, and studied for many years, it can be said that the sites used in this study will be affected by the LLJ. The further east in Missouri sites are located the low level jet should have less correlation.

In Deppe et al.'s (2009) study there was a relationship to ramps caused by the LLJ. Figure 2.11 shows that with 2 hour counting 34% were attributed to the LLJ and with 4 hour counting 29% were attributed. Deppe et al. (2009) used a different counting method than used in this study which will affect the count of ramps as well as a different temporal scale. Another difference is this study looked at the correlation of the LLJ to recorded up ramps rather than Deppe et al. (2009) looking at total ramps with a more specific breakdown into boundary layer causes. Even with these differences in methodology it can be seen that the LLJ for this area in the Midwest is the largest contributing factor in ramp events.

5.2 Future Work

This study looked at many different methods for counting and analyzing ramp events. There have been studies that have used similar and different methods to quantify the magnitude of wind speed change and duration. However there is no universal definition or methodology into determining ramp events at the moment. The goal in future work would be to collaborate with wind power organizations to parameterize ramp event identification so it can be translated through multiple disciplines involved in power production. Another aspect to look at is how certain power grids and infrastructure can handle ramp events. Some locations may only be affected by 50% power changes while others would have significant issues with a 20% change. By having a universal definition it would allow for an easier transmissibility of information for all parties.

This study only looked at data over one year which may be enough to identify what size turbine to use but it isn't enough to understand variability completely. A larger dataset would allow for understanding of larger circulation pattern's effect on local winds and a more definite knowledge of the average wind speeds.

The LLJ contribution to ramp events was highlighted in this study, but other aspects could be explored. The climatology for this area allows for other explanation which can be investigated further.

Thunderstorms, PBL growth, frontal passage, and other natural phenomena all contribute to ramp events and to further accurate wind power forecasting should be explored. Once these elements can be positively identified as causes for ramp events, direct comparisons with other studies can be made to better understand the full impact and climatology of the LLJ and the generation of ramp events.

Appendix A

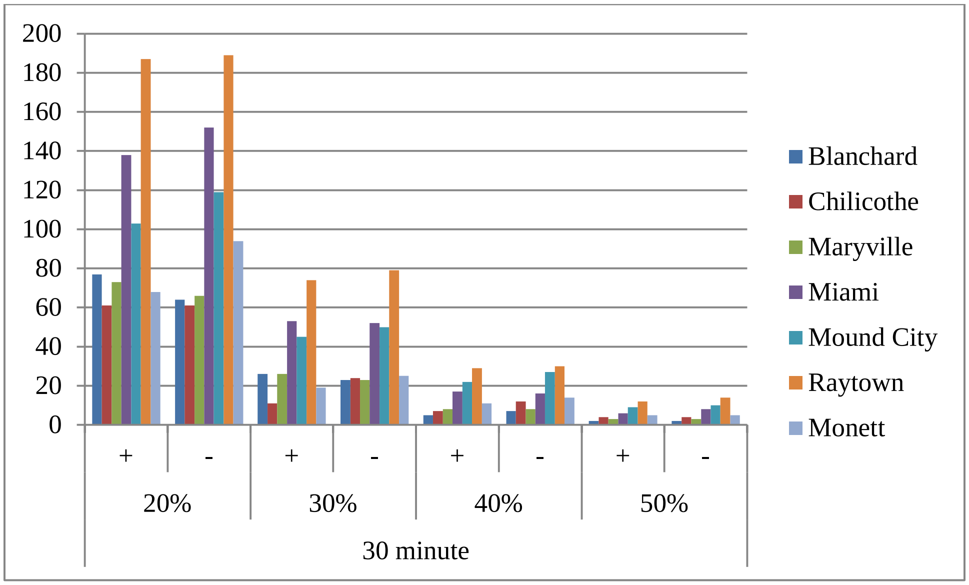


Figure A. 1 Alternative temporal counting method of 30 minutes for all sites including all power thresholds, up ramps, and down ramps

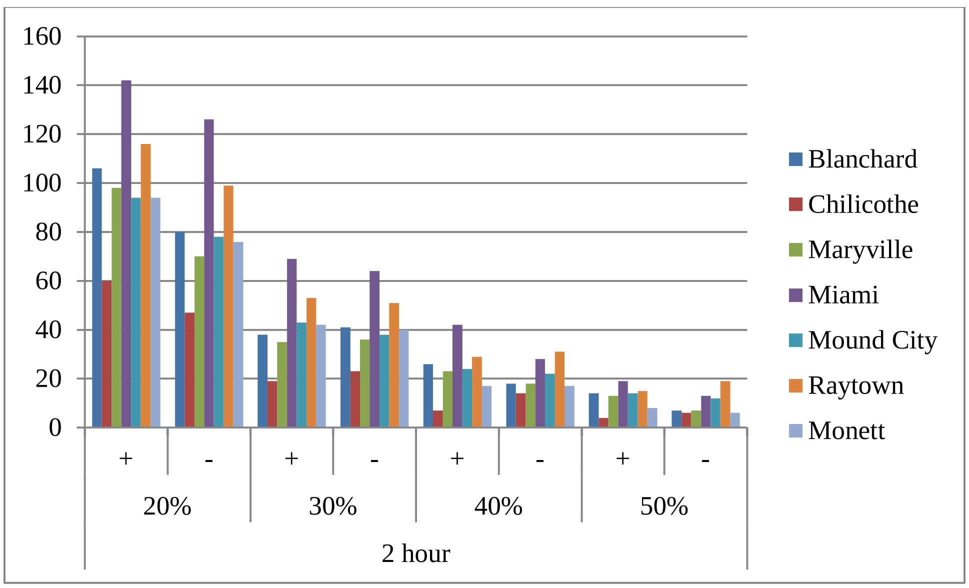


Figure A. 2 Alternative temporal counting method of 2 hours for all sites including all power thresholds, up ramps, and down ramps

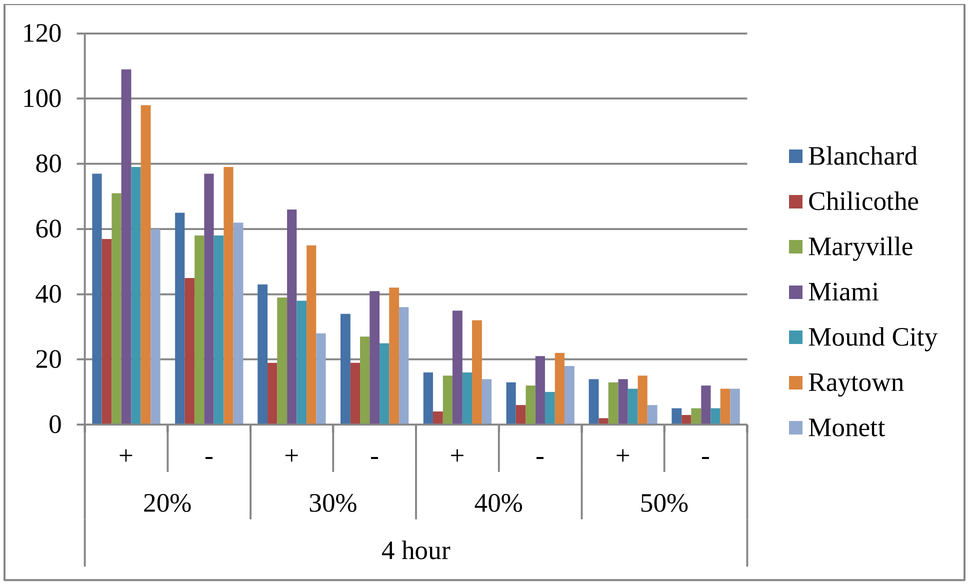


Figure A. 3 Alternative temporal counting method of 4 hours for all sites including all power thresholds, up ramps, and down ramps

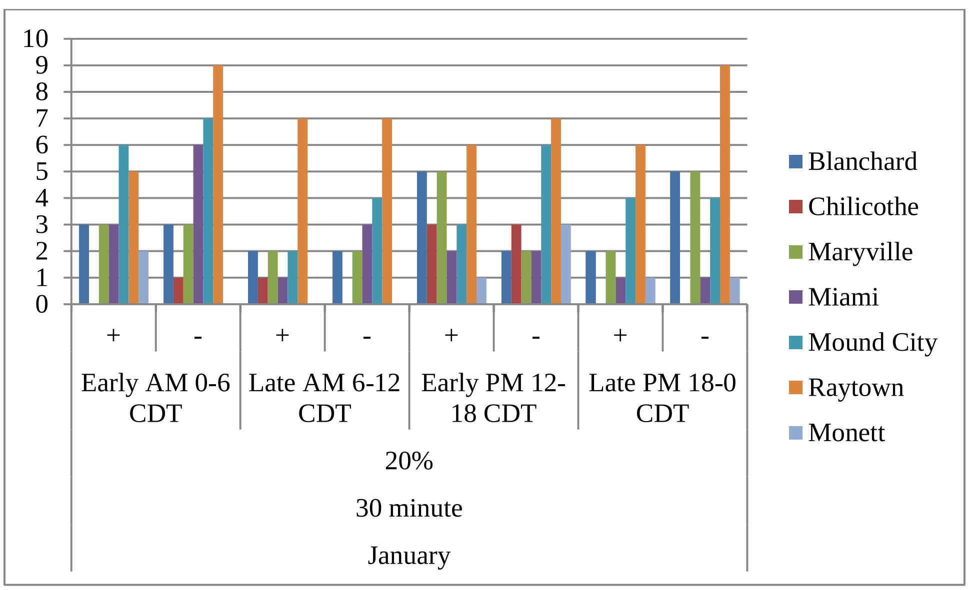


Figure A. 4 Alternative temporal counting method of 30 minutes with the 20% power threshold in January 2007 for all sites. It also includes up ramp and down ramp differentiation as well as time of day segmentation.

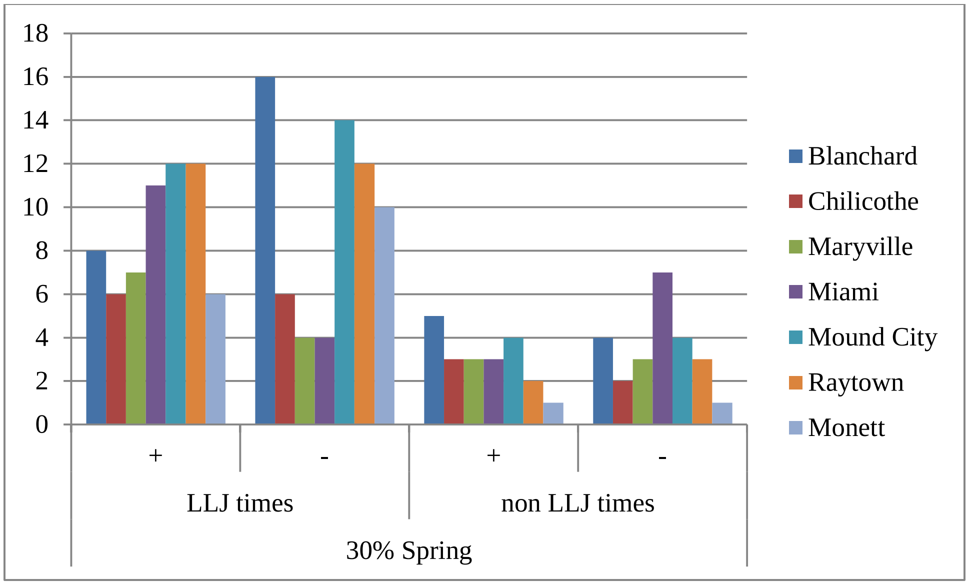


Figure A. 5 Ramp events recorded with 1 hour counting and 30% power threshold for LLJ times and non LLJ times in the spring. For every site the LLJ times have more ramps.

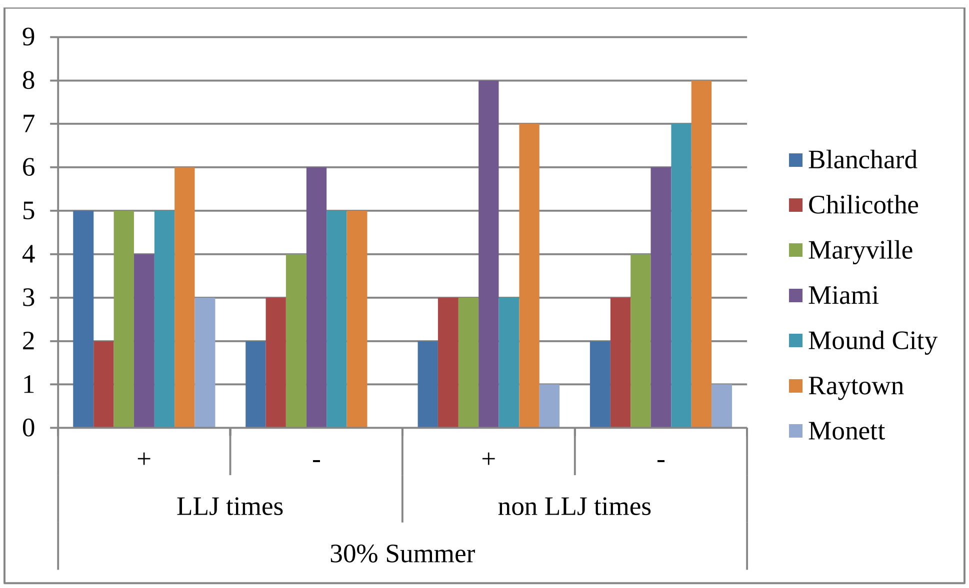


Figure A. 6 Ramp events recorded with 1 hour counting and 30% power threshold for LLJ times and non LLJ times in the summer. The non LLJ times have more ramps however this period had the least amount of ramps.

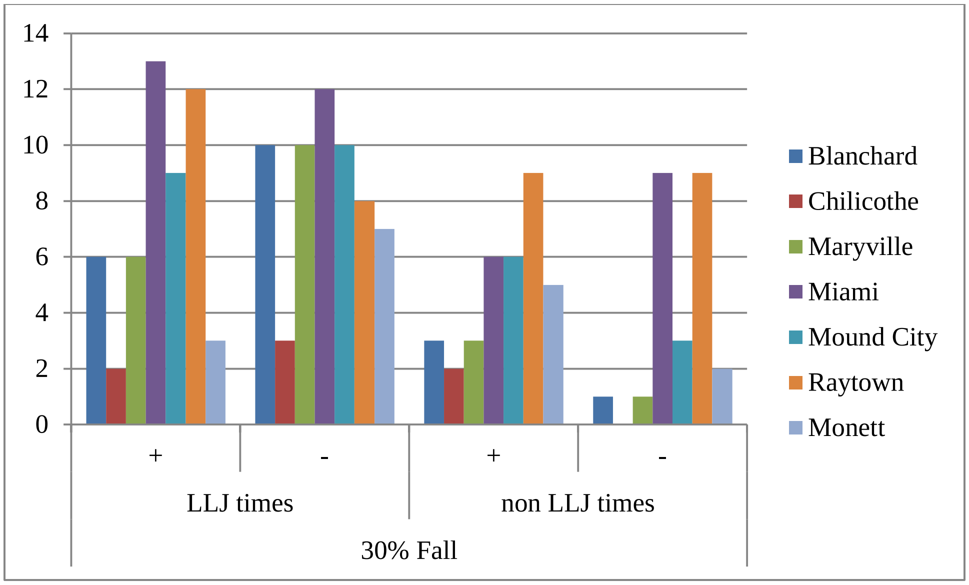


Figure A. 7 Ramp events recorded with 1 hour counting and 30% threshold for LLJ times and non LLJ times in the fall. For every site the LLJ times have more ramp events.

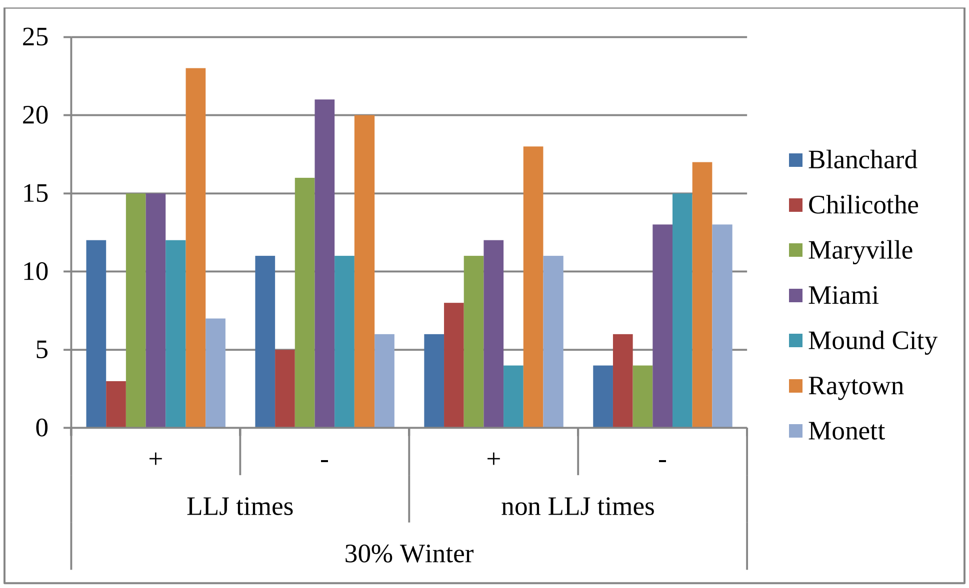


Figure A. 8 Ramp events recorded with 1 hour counting and 30% threshold for LLJ times and non LLJ times in the winter. Over all more ramp events were recorded during the LLJ times, however Monett and Chillicothe recorded more ramps during non LLJ times.

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