AN INVESTIGATION INTO THE CONTRIBUTION OF THE LOW-LEVEL JET (LLJ) TO THE AVAILABLE WIND RESOURCE IN MISSOURI

A Thesis
Presented to
The Faculty of the Graduate School
At the University of Missouri–Columbia

In Partial Fulfillment
Of the Requirements for the Degree

Master of Science

By
ALI KOLEINY

Dr. Neil I. Fox, Thesis Supervisor

May 2009

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

AN INVESTIGATION INTO THE CONTRIBUTION OF THE LOW-LEVEL JET (LLJ) TO THE AVAILABLE WIND RESOURCE IN MISSOURI

Presented by Ali Koleiny

A candidate for the degree of Master of Science

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

Dr Neil I. Fox

Dr Anthony R. Lupo

Dr Steven C. Borgelt

Acknowledgements

Wow, it is kind of hard to believe I even made it to this point. Back when I was receiving the Bachelors degree, I swore I would never continue my education and pursue my Masters degree but it looks like it happened. There are so many people who made my journey easier along the way. I would like to acknowledge those who played a vital role in supporting me, especially during some of the roughest moments of my life.

First and foremost, I would like to thank God for putting me in all the right places at the right times so that I could meet the demands of this degree adequately over the last couple years. His guidance allowed me to be surrounded and supported by all the necessary professors, family and friends at the appropriate times. Special thanks goes to my advisor, Dr. Neil Fox, for having faith in me enough to give me this opportunity to perform such interesting research over the last couple years. I would also like to thank my other two committee members, Dr. Anthony Lupo and Dr. Steven Borgelt, for their interest in my research while improving the quality of my thesis along the way.

The Atmospheric Science Department as a whole is one of the better ones around the country. The support and wisdom of the professors makes this a great atmosphere in which all of the students feel they can truly excel in anything they want to. It also helps to have the support of fellow graduate students in working towards a common goal. Special thanks to Mr. Marc Dahmer, Ms. Katie Crandall, Mr. Shawn Riley, and Mr Eric Weber for giving me the necessary push and helping me to keep the faith! More thanks also goes out to the undergraduates who never failed in always keeping me entertained.

My family must be given strong credit for always keeping my spirits up throughout. I owe so much to my father, Jalil, and my mother, Linda, for giving me the chances and opportunities to prove myself and for never giving up on me. My sister, Leila, also deserves credit because her personal strength always pushes me and motivates me to cross that finish line. I wish to give further credit to my aunt Becky and my uncle Mansoor and his family for their never-ending love and encouragement.

Last, but definitely not least, I would like to thank those responsible for the funding necessary to perform this research. Without the financial support, much of the research in this study may never have been conducted. With that, I would like to thank Empire District, the Missouri Department of Natural Resources and the U.S. Department of Energy for their continued support of this research.

Table of Contents

Acknowledgements ii

List of Figures..vii

List of Tables xi

Abstract..xiii

Chapter 1 Introduction..1

1.1 Statement of Thesis 2

1.2 Objectives 3

Chapter 2 Literature Review 4

2.1 The Wind and How it Works 4

2.2 An Overview of the Planetary Boundary Layer 6

2.2.1 Turbulent Motions……………………………………………….....7

2.2.2 Stability…………………………………………………………12

2.2.3 Diurnal Variations in the PBL………………………………….14

2.2.4 The Low-Level Jet……………………………………………...16

2.3 Previous Research…………………………………………………………...19

2.3.1 The Lamar Low-Level Jet Program…………………………….20

2.3.2 Tall-Tower Climatology Studies……………………………......21

2.3.3 Previous Investigations Using the RUC………………………....24

2.4 Summary………………………………………………………………...28

Chapter 3 Data and Methodology 29

3.1 Study Focus...29

3.2 Area of Study and Instrumentation 29

3.3 Data Collection and Processing 32

3.4 Observational Wind Data Analysis and MATLAB 33

3.5 Selection and Verification of LLJ Events 36

3.5.1 LLJ Identification Process……………………………………….....37

3.5.2 Identified LLJ Event Summary…………………………………......40

Chapter 4 Results and Discussion 43

4.1 Initial Investigation 43

4.2 Monthly Tall-Tower Wind Speeds 44

4.2.1 Maryville………………………………………………………………44

4.2.2 Blanchard…………………………………………………………......47

4.2.3 Mound City……………………………………………………........50

4.2.4 Chillicothe……………………………………………………….......53

4.2.5 Miami………………………………………………………………….55

4.2.6 Raytown……………………………………………………………....58

4.2.7 Monett……………………………………………………….........61

4.2.8 Tower Comparison……………………………………………….....63

4.3 Monthly Tall-Tower Wind Shear…………………………………………......67

4.3.1 Mound City, Maryville, and Miami Comparison……………………67

4.3.2 Blanchard, Raytown, and Chillicothe Comparison……………….......70

4.3.3 Monett……………………………………………………….......73

4.4 Friction Velocity Comparisons 74

4.3.1 Mound City, Maryville, and Miami Comparison……………………..75

4.3.2 Blanchard, Raytown, and Chillicothe Comparison……………….......78

4.3.3 Monett……………………………………………………….......81

4.5 Strong Jet Cases vs. Weak Jet Cases 82

4.5.1 Maryville……………………………………………………........84

4.5.2 Blanchard……………………………………………………......85

4.5.3 Mound City…………………………………………………......86

4.5.4 Chillicothe………………………………………………………....88

4.5.5 Miami………………………………………………………………...89

4.5.6 Raytown…………………………………………………….......91

4.5.7 Monett………………………………………………………........93

Chapter 5 Conclusions and Future Considerations…………………………...95

5.1 Jet Events Versus Non-Jet Events………………………………………....95

5.2 Alpha Versus Friction Velocity………………………………………………97

5.3 Strong Jet Events Versus Weak Jet Events………………………………..98

5.4 Future Work…………………………………………………………………...100

References…………………………………………………………………...102

List of Figures

		Page
Figure 2.1	The geostrophic wind results as the magnitude of the pressure gradient force balances the magnitude of the Coriolis Force.	5
Figure 2.2	Stability variation curves of the logarithmic wind profiles.	12
Figure 2.3	Diurnal variations in mean wind speeds at different heights within the PBL near Oklahoma City, Oklahoma (adapted from Arya (1998)).	15
Figure 2.4	Seasonal variability in alpha parameter at 3 locations across the Great Plains (adapted from Schwartz and Elliot (2006)).	24
Figure 2.5	RUC model analysis of average wind speeds (m s^{-1}) at 100 m when LLJ is active (adapted from Dahmer (2009)).	25
Figure 2.6	RUC model analysis of average wind speeds (m s^{-1}) at 100 m when LLJ is not present (adapted from Dahmer (2009)).	26
Figure 2.7	Average wind shear (s^{-1}) between 60 m and 140 m AGL when the LLJ is active (adapted from Dahmer (2009)).	27
Figure 2.8	Average wind shear (s^{-1}) between 60 m and 140 m AGL when the LLJ is not present (adapted from Dahmer (2009)).	27
Figure 3.1	The green stars represent the location of the ten tall-towers in Missouri overlaid on the AWS Truewind map of wind speeds at 100 m.	30
Figure 3.2	Examples of graphics produced using MATLAB that show **a)** diurnal wind speeds at 3 heights, and **b)** diurnal variation in alpha, at the Blanchard site in February 2007 where hour is in UTC.	34
Figure 3.3	An example of a strong jet event day affecting all tower locations at 06Z on 11 January 2007.	39
Figure 3.4	An example of a non-jet event day in which none of the towers seem to be affected at 06Z on 17 January 2007.	40
Figure 4.1	A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Maryville.	47

Figure 4.2	A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Blanchard.	50
Figure 4.3	A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Mound City.	53
Figure 4.4	A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Chillicothe.	55
Figure 4.5	A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Miami.	58
Figure 4.6	A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Raytown.	60
Figure 4.7	A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Monett.	63
Figure 4.8	A comparison of the mean winds (m s^{-1}) between the low-level winds at Raytown and Miami compared to the high-level winds at Monett during jet events.	64
Figure 4.9	A comparison of the mean winds (m s^{-1}) between the low-level winds at Maryville, Blanchard, Mound City, and Chillicothe compared to the mid-level winds at Monett during jet events.	65
Figure 4.10	A comparison of the mean winds (m s^{-1}) between the low-level winds at Raytown and Miami compared to the high-level winds at Monett during non-jet events.	66
Figure 4.11	A comparison of the mean winds (m s^{-1}) between the low-level winds at Maryville, Blanchard, Mound City, and Chillicothe compared to the mid-level winds at Monett during non-jet events.	66
Figure 4.12	A graphical display of alpha values for the entire period at Mound City, Maryville, and Miami during jet events.	68
Figure 4.13	A graphical display of alpha values for the entire period at Mound City, Maryville, and Miami during non-jet events.	70
Figure 4.14	A graphical display of alpha values for the entire period at Blanchard, Raytown, and Chillicothe during jet events.	71
Figure 4.15	A graphical display of alpha values for the entire period at Blanchard, Raytown, and Chillicothe during non-jet events.	72

Figure 4.16 A graphical display of alpha values for the entire period at Monett during both jet and non-jet events. 74

Figure 4.17 A graphical display of friction velocity (m s^{-1}) values for the entire period at Mound City, Maryville, and Miami during jet events. 76

Figure 4.18 A graphical display of friction velocity (m s^{-1}) values for the entire period at Mound City, Maryville, and Miami at during non-jet events. 77

Figure 4.19 A graphical display of friction velocity (m s^{-1}) values for the entire period at Blanchard, Raytown, and Chillicothe during jet events. 79

Figure 4.20 A graphical display of friction velocity (m s^{-1}) values for the entire period at Blanchard, Raytown, and Chillicothe during non-jet events. 80

Figure 4.21 A graphical display of friction velocity (m s^{-1}) values for the entire period at Monett during both jet and non-jet events. 82

Figure 4.22 Mean monthly wind speeds (m s^{-1}) at Maryville during strong jets. 84

Figure 4.23 Mean monthly wind speeds (m s^{-1}) at Maryville during weak jets. 85

Figure 4.24 Mean monthly wind speeds (m s^{-1}) at Blanchard during strong jets. 86

Figure 4.25 Mean monthly wind speeds (m s^{-1}) at Blanchard during weak jets. 86

Figure 4.26 Mean monthly wind speeds (m s^{-1}) at Mound City during strong jets. 87

Figure 4.27 Mean monthly wind speeds (m s^{-1}) at Mound City during weak jets. 88

Figure 4.28 Mean monthly wind speeds (m s^{-1}) at Chillicothe during strong jets. 89

Figure 4.29 Mean monthly wind speeds (m s^{-1}) at Chillicothe during weak jets. 89

Figure 4.30 Mean monthly wind speeds (m s^{-1}) at Miami during strong jets. 90

Figure 4.31 Mean monthly wind speeds (m s^{-1}) at Miami during weak jets. 91

Figure 4.32 Mean monthly wind speeds (m s^{-1}) at Raytown during strong jets. 92

Figure 4.33 Mean monthly wind speeds (m s^{-1}) at Raytown during weak jets. 92

Figure 4.34 Mean monthly wind speeds (m s^{-1}) at Monett during strong jets. 93

Figure 4.35 Mean monthly wind speeds (m s^{-1}) at Monett during weak jets. 94

List of Tables

		Page
Table 3.1	Tall-tower information for each of the sites to be used in this study.	31
Table 3.2	Tall-tower information specific to tower and instrumentation heights.	32
Table 3.3	Identified LLJ events throughout observational period.	41
Table 4.1	Frequencies of jet and non-jet event days listed by month.	43
Table 4.2	Observed mean wind speeds (m s^{-1}) for jet events at Maryville.	45
Table 4.3	Observed mean wind speeds (m s^{-1}) for non-jet events at Maryville.	46
Table 4.4	Observed mean wind speeds (m s^{-1}) during jet events at Blanchard.	48
Table 4.5	Observed mean wind speeds (m s^{-1}) during non-jet events at Blanchard.	49
Table 4.6	Observed mean wind speeds (m s^{-1}) during jet events at Mound City.	51
Table 4.7	Observed mean wind speeds (m s^{-1}) during non-jet events at Mound City.	52
Table 4.8	Observed mean wind speeds (m s^{-1}) during jet events at Chillicothe.	54
Table 4.9	Observed mean wind speeds (m s^{-1}) during non-jet events at Chillicothe.	54
Table 4.10	Observed mean wind speeds (m s^{-1}) during jet events at Miami.	56
Table 4.11	Observed mean wind speeds (m s^{-1}) during non-jet events at Miami.	57
Table 4.12	Observed mean wind speeds (m s^{-1}) during jet events at Raytown.	59

Table 4.13 Observed mean wind speeds (m s^{-1}) during non-jet events at Raytown. 60

Table 4.14 Observed mean wind speeds (m s^{-1}) during jet events at Monett. 62

Table 4.15 Observed mean wind speeds (m s^{-1}) during non-jet events at Monett 62

Table 4.16 Monthly calculated average alpha values at Mound City, Maryville, and Miami during jet events. 68

Table 4.17 Monthly calculated average alpha values at Mound City, Maryville, and Miami during non-jet events. 69

Table 4.18 Monthly calculated average alpha values at Blanchard, Raytown, and Chillicothe during jet events. 71

Table 4.19 Monthly calculated average alpha values at Blanchard, Raytown, and Chillicothe during non-jet events. 72

Table 4.20 Monthly calculated average alpha values at Monett during both jet and non-jet events. 73

Table 4.21 Monthly calculated average friction (m s^{-1}) velocity values at Mound City, Maryville, and Miami during jet events. 75

Table 4.22 Monthly calculated average friction velocity (m s^{-1}) values at Mound City, Maryville, and Miami during non-jet events. 77

Table 4.23 Monthly calculated average friction velocity (m s^{-1}) values at Blanchard, Raytown, and Chillicothe during jet events. 78

Table 4.24 Monthly calculated average friction velocity (m s^{-1}) values at Blanchard, Raytown, and Chillicothe during non-jet events. 80

Table 4.25 Monthly calculated average friction velocity (m s^{-1}) values at Monett during both jet and non-jet events. 81

Table 5.1 Tower location rankings for the mean wind speed (m s^{-1}) at all three heights during low-level jet periods. 96

Table 5.2 Tower location rankings for the mean wind speed (m s^{-1}) at all three heights when the LLJ is not present. 96

Abstract

This work uses data from a network of tall-towers to investigate the impact of the nocturnal low-level jet (LLJ) on near-surface winds in Missouri. Of particular interest is the contribution of the nocturnal jet to wind speeds at operational turbine heights. Significant LLJ contributions to the wind resource should allow for utilization of wind turbines in producing energy in a more efficient manner. However, these higher contributions in wind speeds may have potential drawbacks in the form of increased shear induced within the planetary boundary layer. This shear may result in adversely affecting operational turbines, as suggested by Pichugina et al. (2004). Therefore, measurements of shear were also calculated to qualitatively and quantitatively describe the turbulent nature of the boundary layer within part of the state. This study is part of a larger one which seeks to improve the wind resource assessment in Missouri.

The period of wind observations begins 1 September 2006 and stretches through August of 2007 so that a complete annual cycle of near-surface winds is observed. Analysis of 158 potential jet events reveals that the LLJ increases the mean wind speeds by at least 2 m s^{-1}, and sometimes 3 m s^{-1} compared to times when the LLJ is not actively present, depending on tall-tower locations across Missouri. Comparison of two different measures of shear reveal that the alpha parameter, commonly used in the wind energy sector, may not be the best indicator of shear within the jet environment.

Chapter 1 Introduction

As the planet continues to age and evolve, so must the people. Regardless of if one is a proponent of viable alternative sources of energy or a skeptic, research into these alternative energy sources is necessary to justify the usage of such options.

Therefore, the objective of this study is to further investigate the available wind resource in the state of Missouri, particularly as influenced by the presence of the nocturnal low-level jet (LLJ). Knowledge of the LLJ contribution to the wind resource at turbine-level heights should provide valuable insight into the prospects of harnessing wind power more efficiently. This insight should further allow America to push and find viable alternative sources of energy, for purposes of cleaning up the environment and reducing utility costs.

The LLJ is believed to contribute to the amount of wind resource. However, there is another face to the coin of wind energy that must be investigated before making key decisions regarding implementation of wind farms. Not only does an increase in wind speeds lead to an increase in the amount of energy that can be produced by wind farms, but consequently also brings an increase in the amount of turbulence that exists at turbine heights. This increase in shear can have adverse effects on turbine rotors, leading to more costly repairs in the future. Hence, it would be foolish to invest valuable money into such projects without better understanding of the true nature of the available wind resource.

1.1 Statement of Thesis

Regional reanalyses acquired from the National Centers for Environmental Prediction (NCEP) were used to identify potential nocturnal LLJ events affecting tall-tower locations between the times of 00 Z and 12 Z (approximately between 6 PM and 6 AM CST, or between 7 PM and 7 AM CDT) using a modified version of criteria used by Walters and Winkler (2004). The number of nocturnal jet events identified each month out of the 12-month period (September 2006 through August 2007) were then compared with an even number of days when the LLJ is not thought to be present. Comparisons of alpha (a dimensionless quantity) and friction velocity (m s^{-1}) will also accompany calculations of average wind speeds for jet and non-jet event days each month. Discussion will follow about whether the traditional alpha parameter used in wind energy applications better represents the turbulent nature existing at turbine hub-heights. Further work is also presented in quantitatively comparing wind speeds during strong jet events and weak jet events, both of which will be described in further detail in Chapter 3. Results of the above inquiries will be presented in Chapter 4 and conclusions of the results in that chapter will be mentioned in Chapter 5 along with other suggestions of future work which can be done to further investigate and add to knowledge of the available wind resource that exists within Missouri.

1.2 Objectives

The objectives of this study are to:

i. Analyze mean wind speeds in jet and non-jet event cases each month

ii. Analyze two measures of wind shear during the same 12-month period

iii. From identified jet events, investigate differences in strong events and weak events

More specifically, the questions which this research will attempt to answer are:

(1) How often is a LLJ identifiable in Missouri during a one-year period?

(2) What is the average difference in wind speed at turbine heights in different parts of the state between times when the jet is present compared to times when it is not?

(3) What is the average difference in wind shear at these same heights during similar time periods?

(4) Do different measures of shear provide reasonable indications of turbulence within the turbine height layer?

Chapter 2 Literature Review

2.1 The Wind and How it Works

To understand how wind energy works, it helps to look at those physical processes which act to influence the wind observed in the atmosphere. For purposes of simplification, we will restrict our view of the wind patterns in the troposphere to the planetary boundary layer (PBL) as this is where the observational data for this study is taken.

The uneven heating of the earth's surface is the primary mechanism responsible for the development of the wind. Different parts of the earth heat at different rates and therefore give rise to uneven heating. These horizontal differences of temperature lead to horizontal differences of atmospheric density and pressure (mass distribution) as well. These differences in physical characteristics allow, and give rise to, motion of the air within and above the PBL. The earth's rotation, topographical features (i.e. mountains, valleys, rivers, etc.) and surface roughness are believed to impact wind velocity throughout the atmosphere.

The Coriolis force (CF) arises solely due to the fact that the earth rotates. The geostrophic wind, in Figure 2.1, results when the horizontal pressure gradient force (PGF) balances the CF (represented in equation 2.1 below) in the large-scale general circulation of the atmosphere.

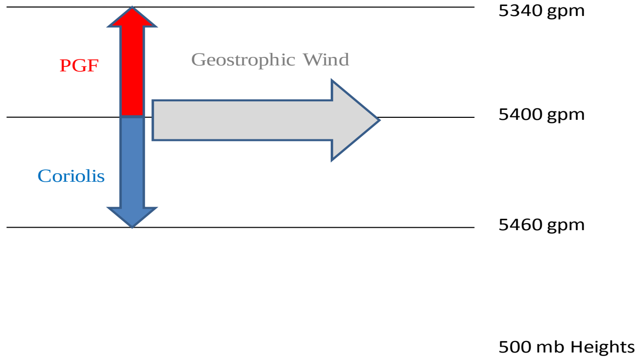


Figure 2.1. The geostrophic wind results as the magnitude of the pressure gradient force balances the magnitude of the Coriolis Force.

This geostrophic wind is typically observed at the top of the PBL as it gets further away from the effects of friction near the surface, and an approximation of the geostrophic wind speed (V_g) in natural coordinates is given in Equation 2.1.

$$|V_g| = \frac{g}{f}\frac{\partial z}{\partial n} \quad \textbf{(2.1)}$$

In this equation for the geostrophic approximation, g is the acceleration of gravity, f represents the Coriolis parameter, and $\partial z/\partial n$ is the slope of the constant pressure surface normal to the contour lines.

The horizontal PGF is responsible for causing wind to accelerate from zero meters per second (m s^{-1}) and to move from an area of higher pressure to lower pressure, while the CF tends only to deflect the wind to the right of its intended path in the northern hemisphere, all the while not affecting the magnitude of the wind speed. The CF is proportional to the magnitude of the wind speed, and therefore only increases in strength as the wind speed increases. Meanwhile, the speed of the geostrophic wind is determined purely by the strength of the PGF.

The geostrophic wind most closely approximates the synoptic-scale observed wind in the mid-latitude and polar regions, where the CF is known to be strongest. Also as previously alluded to, the geostrophic approximation is valid at higher altitudes in order to properly avoid the influences of friction (Rochette and Market, 2006).

2.2 An Overview of the PBL

The PBL is defined as the part of the troposphere that is directly influenced by the presence of the earth's surface and responds to surface forcings with a time scale of an hour or less (Stull, 1988). The troposphere consists of the following sublayers: the planetary boundary layer (PBL), the free atmosphere (FA), the surface layer (SL), and the roughness layer (RL).

The PBL makes up roughly the lowest 10% of the whole troposphere (approximately 10 km), and hence the top of the PBL extends upwards of about 1 kilometer above the earth's surface (Ahrens, 2007). Frictional sources within the PBL have a noticeable impact on the observed winds. As friction acts to retard the flow of air, a new balance between the CF, PGF, and friction must be achieved. Consequently, cross-isobar flow results across the pressure contours and the observed winds become subgeostrophic within the PBL.

The free atmosphere (FA) is the layer found directly above the PBL and extends upwards to the tropopause. A geostrophic approximation to the wind can be applied near the top of the PBL where this interface exists with the FA as the effects of friction are reduced and the CF has more influence on the observed wind.

The PBL also consists of a few sublayers: a surface layer extending up to 100 m above ground level (AGL), and a roughness layer extending up to 10 m AGL. These sublayers are highly influenced by the frictional effect of surface obstructions such as trees and buildings, which is where most human activities take place. The surface layer is still highly dependent upon the earth's surface forcings, where the sharpest variations in temperature, pressure, and moisture also exist. Consequently, the most significant exchanges of momentum, heat, and mass also occur in this layer. The roughness layer close to the surface is a function of surface vegetation. In areas where the land surface is bare, the roughness layer can be considered negligible. For grasslands and other vegetated surfaces, the height of the roughness layer is approximated to be 1.5 times the average height of vegetation. In the cities, the height may depend on the spatial distribution and height of buildings.

The depths of these different layers within the atmosphere are more typical under near-neutral stability, along with strong winds and overcast skies. So it is important to understand that these respective heights are highly variable in both space and time (Arya, 1998).

2.2.1 Turbulent Motions

Solar heating, friction, moisture, and orographic effects due to trees, mountains and hills, and sky-scrapers can all contribute to modifying airflow within the PBL. Such factors are capable of producing varying amounts of turbulence which can affect a vast array of day-to-day human operations, especially with respect to operational wind farms. Therefore, a sufficient knowledge of turbulence is vital in hopes of maximizing the energy production output of such wind farms.

Turbulence can be defined in many ways. Arya (1998) notes that turbulence refers to the apparently chaotic nature of many flows, which is manifested in the form of irregular, almost random fluctuations in velocity, temperature, and scalar concentrations around their mean values in both time and space. Meanwhile, Stull (1988) classifies turbulence as the gustiness superimposed on the mean wind, which can be visualized as consisting of irregular swirls of motion called eddies. Such eddies appear responsible for effectively transporting heat, moisture, and momentum throughout the boundary layer. There are two primary sources of turbulence in the PBL: thermal and mechanical turbulence.

Thermal turbulence is more of a warm season event, and occurs mostly during the day as incoming net radiation is maximized and results in turbulent mixing of the atmosphere. After the air at the surface is effectively heated, it rises up to the high end of the PBL. Depending on the amount of moisture present, some of this rising air will begin to condense and form into clouds. Colder, drier air typically rushes down from the upper portion of the PBL to replace the rising thermal air. A circulation results, thereby producing enough turbulent mixing to generate an efficiently mixed layer in the lower part of the troposphere during the afternoon.

On the other hand, mechanical turbulence results simply as airflow is slowed down by surface friction. As layers of air slide over one another at different speeds (due to wind shear), each layer exerts a viscous/shear stress on one another causing air parcels to deform. This type of stress tends to act parallel to the direction of motion. The Reynolds stress is a similar type of stress which results under turbulent conditions as a result of mechanical shear. This type of turbulence predominantly resides in the lowest part of the PBL. In this surface layer is where the greatest increase in wind speed with height occurs directly above the surface. In theory, friction should act to dissipate horizontal air motions with wind speeds going to zero right at the surface-air interface. This type of turbulence is greatest when near surface wind speeds are high and the terrain is rough.

In fact, this turbulent mixing is responsible for vertical transport/distribution of energy/heat, moisture, momentum, and pollution dispersion throughout the boundary layer. As turbulence acts to mix out momentum in the daytime, this results in less of a difference between the momentum at 2 levels within the mixed boundary layer. As such, more turbulent motions during the daytime lead to lesser amounts of vertical wind shear.

However, turbulence proves to be difficult to measure over time and space. Much of our understanding of turbulent motions and fluxes of heat and momentum within the boundary layer is based largely on similarity theory and dimensional analysis. The Monin-Obukhov (M-O) similarity theory is the basic similarity hypothesis for a horizontally homogeneous surface layer.

The M-O similarity theory employs four key independent variables or parameters: z (the height above the surface), $\frac{g}{T_v}$ (the buoyancy parameter ratio, where g is gravity and T_v is the virtual temperature), $\frac{\tau_0}{\rho}$ (the kinematic surface stress/drag, where τ_0 is the surface shear/Reynolds stress and ρ is atmospheric density), and $\frac{H_{v0}}{\rho c_p}$ (the surface virtual temperature flux, where H_{v0} is the sensible heat flux at the surface and c_p is the specific heat capacity at constant pressure).

Each of these key parameters can then be used to define a set of four dimensional scales (covering length, velocity, and temperature). The friction velocity is calculated by using the Reynolds stress, and a calculation for the frictional velocity is given in Equation 2.2.

$$u_* = \sqrt{\frac{\tau_o}{\rho}} \qquad \textbf{(2.2)}$$

Jacobsen (1999) describes this friction velocity as a measure of the vertical turbulent kinematic wind flow within the surface layer. Typical roughness elements such as rocks, trees, vegetation, buildings, and grass all impact wind flow nearest to the surface via friction. Even hills or anything that contributes to an uneven surface can be considered a roughness element. This creates vertical wind shear between slower winds near the surface relative to those aloft. The greater the height of surface roughness elements, the greater the resulting wind shear and mechanical turbulence in the form of eddies. It is then expected that high wind shear in a single layer induces stronger turbulence, and thereby increases the friction velocity.

Equation 2.3 shows the temperature scale of the surface layer:

$$T_* = \frac{H_o}{u_*} \qquad \textbf{(2.3)}$$

The eddy length scale is represented by the Obukhov length shown by Equation 2.4,

$$L = \frac{-u_*{}^3 T_v}{kgH_0}, \qquad \textbf{(2.4)}$$

where k is the dimensionless von Karman constant and has an empirical value of 0.4. The last scale is the height above ground, z.

Each of these four key scales can then be used in dimensional analysis to get an expression for all surface-layer flow properties as dimensionless universal functions of z/L, a stability parameter. Arya (1998) refers to this dimensionless function as the buoyancy parameter, where:

$$\zeta = \frac{z}{L} \qquad \textbf{(2.5)}$$

This stability parameter is then related to the gradient Richardson number by means of the Monin-Obuhkov similarity theory. With the key parameters and scaled equations above, along with the assumption that the fluxes in the surface layer are uniform with height, fluxes of momentum, heat and moisture can be calculated (AMS Glossary).

The Monin-Obuhkov similarity theory can then be used to estimate the wind profile of the boundary layer. Integration of a generalized equation for the dimensionless wind shear gives the equation for the logarithmic wind profile:

$$\mathrm{u(z)} = \frac{u_*}{k}\left[\ln\left(\frac{z_2}{z_1}\right) - \psi_m\right] \qquad \textbf{(2.6)}$$

Jacobsen (1999) notes that ψ_m is an influence function of momentum. This parameter accounts for atmospheric stability; when ψ_m=0 in equation 2.6, the atmosphere is considered neutral. However, when the parameter is negative (positive) the atmosphere is considered stable (unstable).

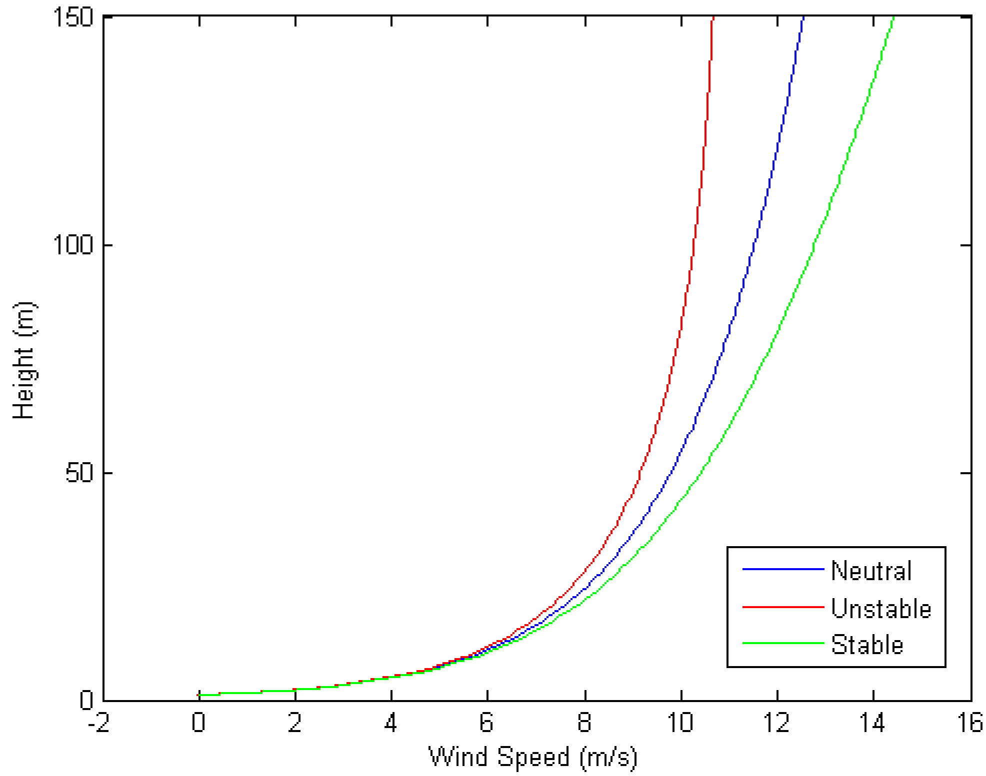


Figure 2.2 Stability variation curves of the logarithmic wind profiles.

The above curves for the logarithmic wind profile assume a constant stability over the depth of a layer. Realistically, the atmosphere rarely behaves as such and this is something one must keep in mind when looking at how wind speeds change with height.

2.2.2 Stability

Static stability can be defined as the difference between the dry adiabatic lapse rate (-9.8°C km^{-1}) and the observed environmental lapse rate. More simply stated, the stability of the air can be determined by comparing the temperature of a rising parcel of air to the air that surrounds it. If rising air is warmer than that of its surroundings, the layer is referred to as unstable and the air continues to rise until it reaches a point where it is cooler than its surroundings. At this point, the air begins to sink back down and the air is considered to be stable. Where the temperature of the parcel is equal to that of its environment, the air has attained neutral stability.

Stability can be measured in different ways. Arya (1998) defines local static stability as:

$$a_b = \frac{-g}{T_v}\left(\frac{\partial T_v}{\partial z} + \Gamma\right)\Delta z = \frac{-g}{T_v}\frac{\partial \Theta_v}{\partial z}\Delta z\,, \qquad \textbf{(2.6)}$$

where Γ represents the temperature lapse rate, $\partial\Theta_v / \partial z$ is the change in virtual potential temperature with respect to height, and Δz is the total change in height within a specific layer.

From equation 2.6, the stability parameter, s, can be defined as,

$$s = -\frac{g}{T_v}\frac{\partial \Theta_v}{\partial z} \qquad \textbf{(2.7)}$$

In a qualitative sense, the atmosphere is considered unstable (buoyant) when s is negative and stable when s is positive; hence, when s is zero the stability is considered neutral. This measure of static stability is good in cases of weak wind shear only, since no term exists in the equation above to effectively represent wind shear.

Another approach which actually incorporates wind shear into its calculation is the dimensionless gradient Richardson number Ri:

$$R_i = \frac{\dfrac{g}{T_v}\dfrac{\partial \Theta_v}{\partial z}}{\left(\dfrac{\partial V}{\partial z}\right)^2} \qquad \textbf{(2.8)}$$

The gradient Richardson number is a ratio of turbulence generation by the buoyancy force (numerator) to a wind shearing force (denominator). The buoyancy term contributes to the generation of turbulence when it is negative, and acts to dampen the turbulence when positive. Therefore, turbulence is usually enhanced when the boundary layer is relatively unstable during the daytime and suppressed during stable conditions overnight. This concept will further be explained in the following sections.

2.2.3 Diurnal Variations within the Boundary Layer

Turbines should be located in areas which experience and receive higher wind speeds. Therefore, sufficient knowledge of diurnal wind patterns in the boundary layer is key to the placement of wind farms. Winds may be stronger at certain altitudes at different times of the day. Assuming the wind results primarily due to the uneven solar heating of the surface, it would seem logical that wind speeds would maximize during the daylight hours when solar heating is expected to be at a maximum; meanwhile, wind speeds would be minimized overnight as there is no incoming solar radiation. To effectively paint a realistic picture of the diurnal wind pattern within the boundary layer, the wind profile must be averaged over a lengthy period, such as a month or greater. Averaging the wind speeds over a longer time period effectively eliminates the influence that synoptic weather patterns may have on the diurnal pattern from day to day.

Figure 2.1 shows wind speed observations over a year period from a 500 m tower near Oklahoma City (Arya 1998). This observational wind data verifies the above assumption that wind speeds are generally stronger beginning after sunrise through the late afternoon hours, before weakening around sunset. However, this appears only true for the layers nearest to the surface. As the surface heats up more quickly compared to the overlying air, more momentum is transferred down and mixed down towards the surface, resulting in these stronger wind speeds near the ground. On the other hand, wind speeds tend to increase in the evening hours around and above 100 m, often as a result of the formation of the low-level jet (discussed below). As the surface cools off faster than the overlying air, an inversion above the surface results, acting as a lid to suppress turbulence along with any vertical mixing that may have taken place earlier in the day. At this point, the boundary layer then is referred to as the nocturnal/stable boundary layer.

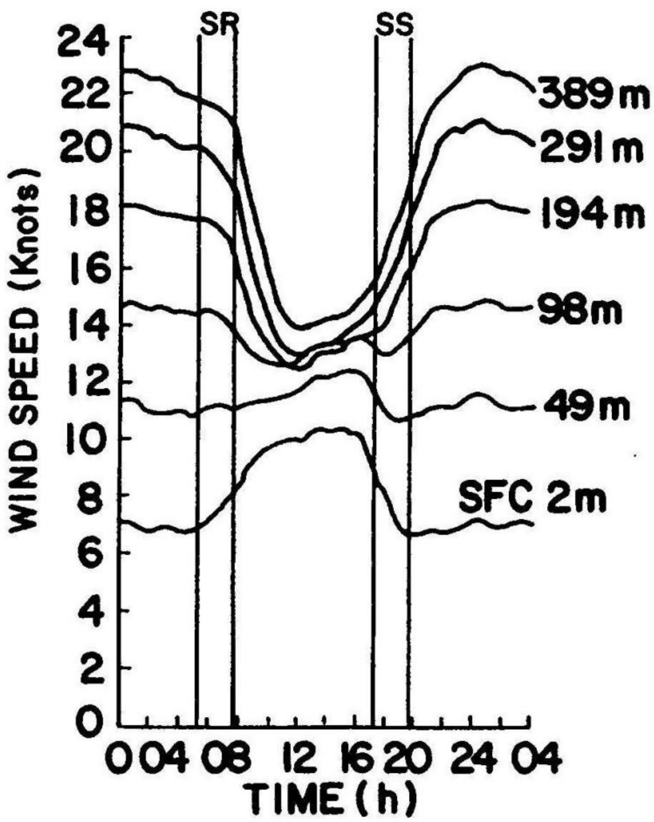


Figure 2.3 Diurnal variations in mean wind speeds at different heights within the PBL near Oklahoma City, Oklahoma (adapted from Arya (1998)).

2.2.4. The Low-Level Jet

The low-level jet (LLJ), a common phenomena existing in but not exclusive to the Great Plains, is a fast moving stream of air that exists in the lower levels of the atmosphere. The LLJ provides a significant contribution to the available wind resource for producing wind energy as it acts to enhance wind speeds above the surface. Other than the LLJ being a valuable source of wind energy, it also has other roles. It is primarily responsible for temperature and moisture advection in synoptic mid-latitude cyclones. Additionally, the LLJ plays a key role in convergence and organization of convective weather via speed and directional wind shear. However, these other roles of the LLJ will not be discussed any further for this research.

Several mechanisms have been verified in the evolution of the low-level jet in a variety of environments. One mechanism analyzed by Holton (1967) explains that the formation of the LLJ is driven by the terrain as it slopes from a lower elevation in the eastern Great Plains and gradually increases westward toward the Rocky Mountains. This orographic effect results in a reversal of temperature gradients throughout the entire day. In the daytime scenario, the surface and the overlying air tend to warm up faster in the east relative to out west, resulting in a negative temperature gradient from east to west. This creates a PGF between relatively lower pressure (warmer temperatures) in the east compared to relatively higher pressure (cooler temperatures) out to the west. This daytime scenario leads to a northerly component of the winds over the Central Plains, which along with the turbulent mixing tends to mask the presence of a LLJ. When nighttime comes, the temperatures to the east are relatively cooler compared to those out west, partially as a result of the sun setting earlier. This leads to a reversal in the existing temperature gradient, and the resulting PGF as well. In this situation, relatively higher pressure sets up to the east along with lower pressure out to the west. This setup allows for more prevalent southerly return flow over the Central Plains. Coupled with a stable boundary layer during the evening, this leads to an acceleration of the geostrophic winds at the top of the boundary layer, which accounts for the presence of the nocturnal jet.

Blackadar (1957) proposed the inertial oscillation as a means of explaining how the nocturnal LLJ forms and evolves. During the daytime, the depth of the boundary layer increases as a result of the incoming solar insolation. Wind flow is restricted to sub-geostrophic wind speeds in the boundary layer as a result of the turbulent mixing of atmospheric variables such as temperature, moisture and energy become effectively mixed out. As the PBL cools after sunset, the depth of the boundary layer begins to "collapse" and becomes much thinner than its mixed layer counterpart during the daytime. The surface cools relatively faster than the overlying air immediately above, resulting in a temperature inversion and a stable boundary layer above the surface. The surface layer begins decoupling from other layers above, as fluids of different densities would do as if they settled out into a glass of water. This frictionless layer near the surface begins accelerating due to an existing pressure gradient force. To counter this, the Coriolis force acts to induce an inertial oscillation in which the wind speeds associated with the jet near the top of the nocturnal boundary layer reach a supergeostrophic state a few hours later. The air above the surface is no longer subjected to frictional drag associated with the surface. This leads to an acceleration of night-time winds to supergeostrophic wind speeds above the stable boundary layer a few hours later. This mechanism accounts for the daily oscillation in jet intensity along with the supergeostrophic wind speeds observed during the nighttime hours. Oftentimes, both the Blackadar (1957) and sloping terrain mechanisms appear to work together in the formation of the nocturnal jet.

As a result of decoupling within the stable boundary layer, the amount of wind shear (how wind speed, and even direction changes with respect to height) increases as well. The basic equation represented by equation 2.9 for wind shear (s^{-1}) is given by the difference in wind speed divided by the difference in height:

$$s = \frac{u_2 - u_1}{z_2 - z_1} \qquad \textbf{(2.9)}$$

Here, two wind speeds (u_1 and u_2) are measured at their respective heights (z_1 and z_2).

A traditional measure of shear in the wind energy field is the shear exponent alpha (α) used in the power law equation:

$$\frac{u_2}{u_1} = \left(\frac{z_2}{z_1}\right)^{\alpha} \qquad \textbf{(2.10)}$$

where z_1 is some reference level height corresponding to a wind speed v_1. Typical standard reference heights of 10 m are commonly used (Arya, 1998). The numerator on both sides of the equation represents the elevation of a higher anemometer and its corresponding wind speed. Assuming all heights and wind speeds are known, equation 2.10 can be manipulated to determine the shear parameter α :

$$\alpha = \frac{\ln\left(\frac{u_2}{u_1}\right)}{\ln\left(\frac{z_2}{z_1}\right)} \qquad \textbf{(2.11)}$$

The shear parameter α does not calculate for turbulent intensity at different levels, but a higher value indicates a higher amount of shear is present. This shear exponent proves highly dependent on both the surface roughness elements and stability within the boundary layer.

These values can change from location to location, but a traditional value of α is 0.143 (particularly in neutral stability conditions). The IEC (1998) defined the Normal Wind Profile (NWP) as having a standard value of 0.2, representative of onshore flow. Meanwhile values are smaller with respect to offshore flow, as less friction exists over water compared to the amount on land.

This increase in wind shear generates bursts of turbulence which is a primary concern for wind turbine operation. Of particular concern is the shear-induced turbulence in the vicinity of the turbine hub height, which has proven detrimental to the existing turbine rotors. Pichugina et al. (2004) noted that jets with speed maxima greater than 10 m s^{-1} could potentially damage wind turbines. Furthermore, the higher wind speed maxima along with the resulting increase in shear below the height of the jet were correlated with smaller gradient Richardson numbers. This is indicative of turbulent motions at very low levels where turbine rotors exist.

2.3. Previous Work

Up until just a few years ago, studies of observational winds near turbine hub heights proved to be sparse and close to non-existent. Initially back in the 1990s, turbine hub heights were on the order of 40-60 m AGL. Recent technological advances have increased the size of turbines and have helped capture the available wind resource in a more efficient manner.

Early studies involved instrumented tall-towers (~50 m and lower) to collect observational wind data. The observed wind speed data was then extrapolated up to the hub height. However, this technique proved much less reliable for heights above 80 m due to the reduction of friction above the surface layer. Features like the LLJ and other thermal circulations make basic extrapolations up to hub heights difficult and prove less reliable (Schwartz and Elliot, 2005).

2.3.1. The Lamar Low-Level Jet Program

The Lamar Low-Level Jet Program (LLLJP) was formed to study characteristics of turbulence induced by the low-level jet at local turbine heights for the purpose of improving operational reliability and overall lifetime of future turbines. General Electric Wind Energy supplied the 120 m tower by installing it at a potential wind farm site just south of Lamar, Colorado. The National Renewable Energy Laboratory (NREL) was in charge of mounting cup anemometers at heights of 3, 52, and 113 m along the tower. This observational data was used in conjunction with SODAR (Sound Detection and Ranging) derived wind profiles and high-resolution Doppler LIDAR (HRDL) to effectively measure turbulence at turbine rotor heights. The HRDL provides a more accurate depiction of the nocturnal LLJ in the stable boundary layer because of its high temporal and spatial resolution.

After one year of statistical data analysis (October 2001 through September 2002), Kelley et al. (2004) concluded that the peak of available energy at the LLLJP site occurs between April and June. Meanwhile, the peak in turbulence intensities occurred in the warm season (April through September) with the highest mean values in the months of June and July. This peak in turbulence intensities coincided when the gradient Richardson number in the 52-113 m layer is in the range of $0 < Ri < 0.25$. A last, but still important conclusion from this data, illustrated that higher values in the shear exponent alpha resulted at times when wind speeds were weaker.

Also during the warm season in the presence of LLJ's, they noticed that winds blew predominantly out of the south. Given the right atmospheric conditions, the presence of the LLJ at the site can cause intense shears to become unstable and breakdown into intense coherent turbulence. However, the presence of the jet does not always result in organized turbulence, as evidenced in three case studies within the scope of the project. For further detailed explanation of the objectives and results of the LLLJP, refer to Kelley et al. (2004).

2.3.2 Tall-Tower Climatology Studies

In the second half of 2006, the state of Missouri began acquiring tall-tower data in areas where the best wind resource was thought to exist. The hopes were to gain a more precise understanding of wind climatology for future wind farm development. Prior to that, few studies looked at observational wind characteristics (i.e. speed, power density, and wind shear) at heights above 80 m across the Great Plains. One such study peformed by Schwartz and Elliot (2005) investigated the available wind resource at various tall-towers in Kansas, Indiana, and Minnesota.

Six tall-tower stations were setup in Kansas with anemometers and wind vanes at 50, 80, and 110 m AGL. These towers became operational between April and July in 2003, with five having observations through June of 2004; the last station had observations through the early part of April of 2004. The average 110 m wind speeds at the six sites ranged from 8.4 m s^{-1} to 9.4 m s^{-1}. Annual wind speeds above 8 m/s at such a level generally attract wind farm developers to that region. Another observation of the Kansas towers revealed that the diurnal maximum wind speeds peaked between 2100 and 2400 Local Standard Time (LST). Locations appearing to have the strongest nocturnal winds will likely have the greatest 110 m wind resource. This conclusion highlights the importance of the strength of the LLJ in contributing to the available wind energy resource in Kansas.

Five tall-towers in Indiana were instrumented with anemometers and wind vanes at roughly 10, 49, and 99 m AGL. The raw data collected for analysis is from 2004; three of them (Haubstadt, Carthage, and Goodland) collected a full year of data, while the other two attained around seven months of data. The diurnal wind speed at the highest level follows a similar pattern to the towers in KS, with Goodland experiencing stronger upper-level winds. However, the spread for the three towers that have complete 2004 data with respect to diurnal maximum and minimum wind speeds is much larger when compared to the Kansas sites. Exposed sites in northwest Indiana, like Goodland, may have the best available resource at higher altitudes.

Nine tall-towers in Minnesota were originally included as part of the study. However, only three in southwestern Minnesota were included in the analysis, for the purpose of data completion (during 2001 and 2002). Anemometers were installed at 30, 60, and 90 m, and wind vanes were only instrumented at the top and bottom levels. Results from the three towers indicate that all three sites appear favorable for future development of wind farms based on the diurnal pattern. It appeared that subregional terrain can influence the available wind resource in southwestern Minnesota. The two sites on the downslope side of Buffalo Ridge had average wind speeds 0.5 m/s higher than the site on the upslope side at the 90 m level. This difference appears to be a result of stronger nighttime and southerly winds at the Marshall and Currie towers.

In another study, Schwartz and Elliot (2006) investigated wind shear characteristics at various tall-towers across the Central Plains. The primary objective is to gain specific knowledge of wind shear characteristics in the vicinity of turbine hub heights to optimize turbine design and wind farm layout. Thirteen towers were spread out in Texas (2), Oklahoma (2), Kansas (6), Colorado (1), South Dakota (1), and North Dakota (1). Eleven of the sites had the highest anemometer at a level above 100 m, while two sites had their highest anemometer level between 70 m and 85 m. Twelve of the towers had approximately 2 years of reliable data to investigate.

Despite a bit of uncertainty in the exact shear statistics due to tower and instrumentation effects on observed winds, the shear alpha values provided some key insight into wind shear climatology in the Central Plains. The annual average wind shear was found to be generally between 0.15 and 0.25, which can be seen in Figure 2.4. This value proves to be greater than the traditional 1/7 power law value of 0.143.

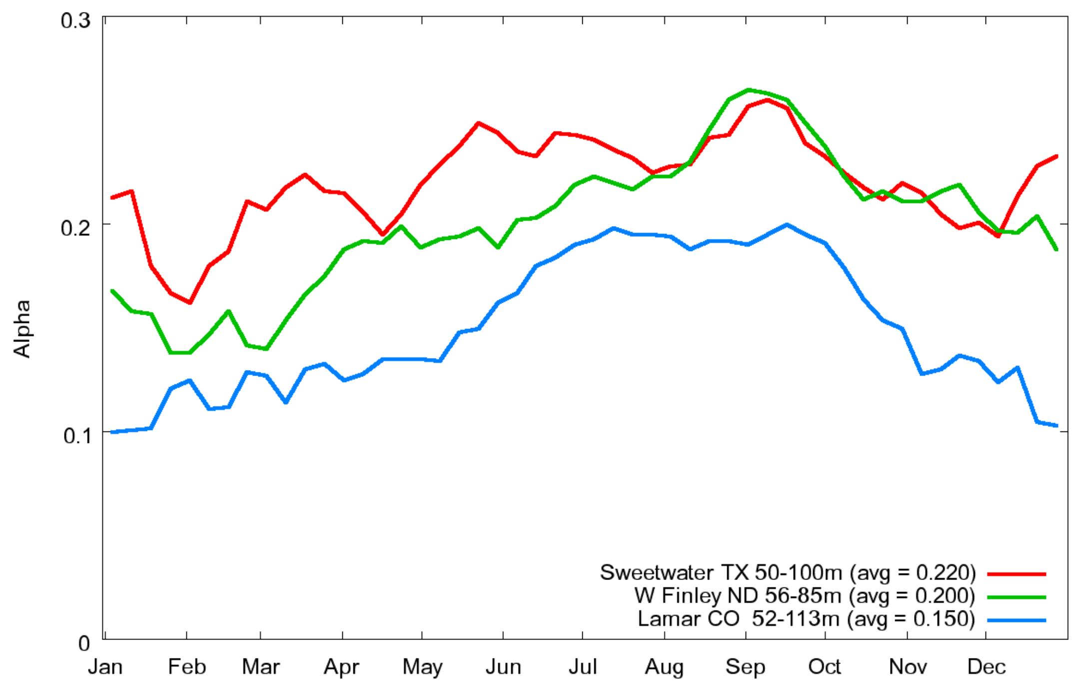


Figure 2.4 Seasonal variability in alpha parameter at 3 locations across the Great Plains (adapted from Schwartz and Elliot (2006)).

There also was little difference in alpha values between the northern and southern Central Plains. Diurnal patterns revealed that daytime alpha values were around 0.1, whereas nighttime alpha values ranged anywhere from 0.25 to 0.4. Due to tower and instrumentation effects and their influences on wind speeds, one must not take wind shear information at face value and must also carefully consider such effects.

2.3.3 Previous Investigations Using the RUC

Previous research investigating the contribution of the active LLJ to lower-level wind characteristics in Missouri was performed by Dahmer (2009) using RUC model analysis/initialization fields for an earlier time period (May 2003 through April 2004). There were 68 LLJ events identified using plan-view maps of the wind fields at 925 mb and 850 mb twice daily along with observed soundings available from Springfield, MO.

Each identified event met the criteria that the winds at 925 mb were stronger than those winds at 850 mb. The majority of these events were found to occur closer to 12Z as opposed to 00Z**.** These events were then analyzed using RUC model output for the corresponding times to better understand the contribution and role of the LLJ to the low-level wind field over the whole state.

Figure 2.5 shows that, during times when the LLJ is active, 100 m wind speeds are greater than 7 m s^{-1} across most of the state, with the exception of southeast MO. When the LLJ is not present however, wind speeds are between 3 m s^{-1} and 4 m s^{-1}, as indicated in Figure 2.6.

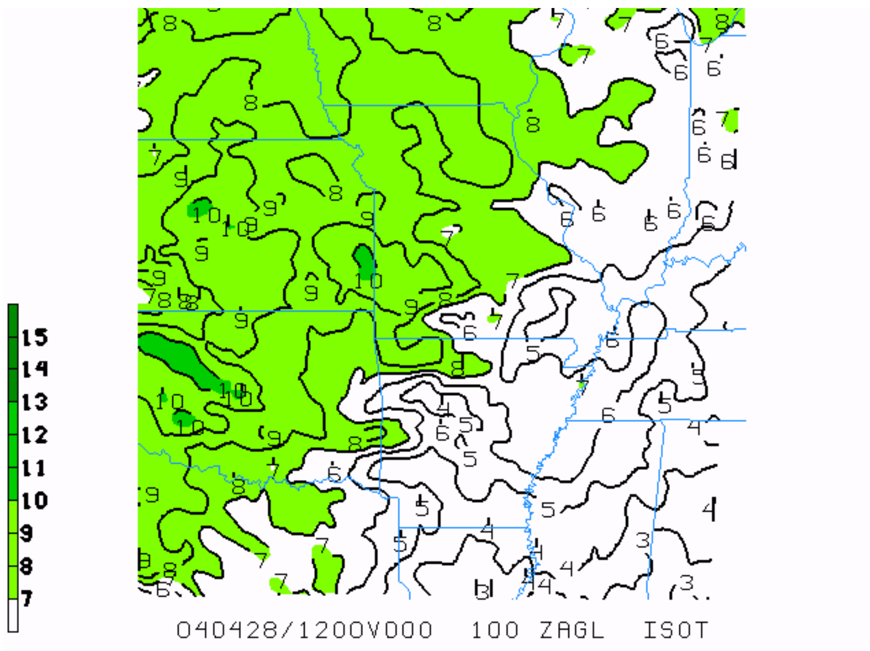


Figure 2.5 RUC model analysis of average wind speeds (m s^{-1}) at 100 m when LLJ is active (adapted from Dahmer (2009)).

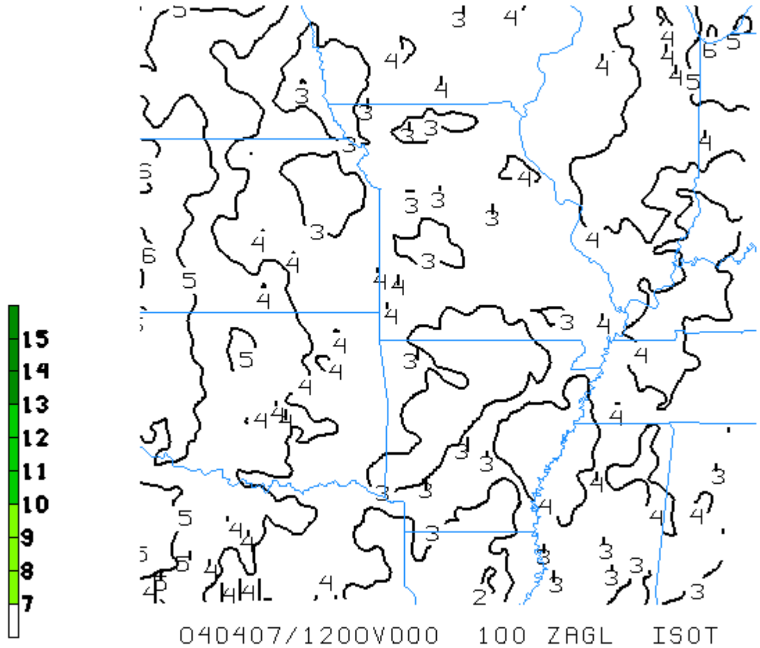


Figure 2.6 RUC model analysis of average wind speeds (m s^{-1}) at 100 m when LLJ is not present (adapted from Dahmer (2009)).

In the case of wind shear, the wind shear is much greater at 100 m across the state when the LLJ is considered active, with higher values located in southwest MO on the order of 0.045 s^{-1}. This can be seen in Figure 2.7. On the other hand, Figure 2.8 shows that the wind shear is much weaker and less variable across the state when the LLJ is not present, with higher values on the order of 0.01 s^{-1}.

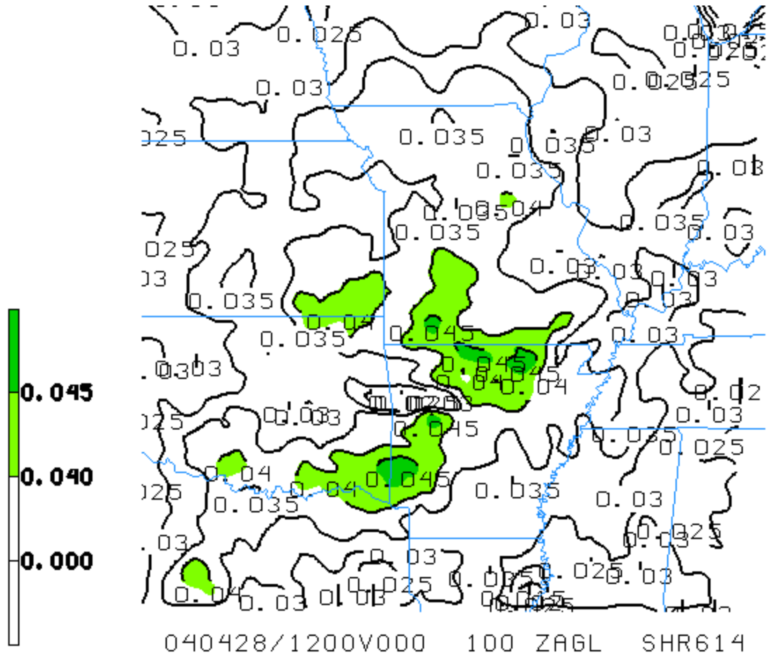


Figure 2.7 Average wind shear (s^{-1}) between 60 m and 140 m AGL when the LLJ is active (adapted from Dahmer (2009)).

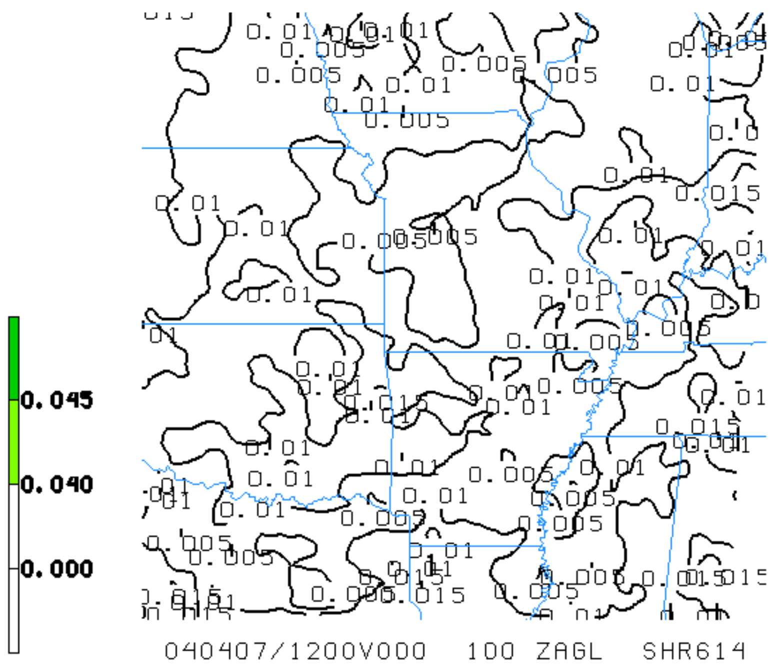


Figure 2.8 Average wind shear (s^{-1}) between 60 m and 140 m AGL when the LLJ is not present (adapted from Dahmer (2009)).

2.3.4 Summary

The LLLJP study and the tall-tower studies provide good background knowledge of upper-air wind climatologies across the Great Plains. The LLLJP study focuses on the activity of the nocturnal LLJ, which was the primary focus of the current study. More recently, relevant research of LLJ activity shown by RUC model output data in Missouri can be used to gain some insight into the contribution of the LLJ to the wind resource available at turbine heights.

The analysis of the RUC model initialization fields can then be used as a baseline for the tall-tower wind observations collected for this research, even though two different periods are investigated. It is hoped then that the results and analysis of this research should provide a good qualitative and quantitative idea of the existing wind resource in the state of Missouri.

Chapter 3 Data and Methodology

3.1 Study Focus

Selecting periods when the nocturnal LLJ is active will help characterize its contribution to producing wind power and verifying wind resource assessment. The goal of this research is then to investigate and analyze the observed tall-tower data and determine differences in wind characteristics between times when the LLJ is thought to be active and times when it does not appear to be present. Very few studies have investigated the activity of the LLJ in the state, especially with regard to wind energy applications. As the LLJ contributes to the available wind resource, it is of interest to know how the LLJ influences the wind speed and shear within the lower boundary layer. These observations can prove useful to future wind farm operations in the state.

3.2 Area of Study and Instrumentation

Pre-existing communication towers have been instrumented to obtain wind measurements throughout parts of Missouri. Achieving this first requires knowledge of where the wind resource is expected to be greatest. To accomplish this, AWS Truewind Ltd produced an Arc GIS wind map, seen in Figure 3.1, to establish areas where stronger wind speeds are expected. This map was produced by the Mesoscale Atmospheric Simulation System (MASS) numerical weather model in conjunction with another program, WindMap, to meet high computational demands. The map can display mean wind speeds at heights of 30 m, 50 m, 70 m and 100 m. For further specifics of the

MASS model and the production of the actual Arc GIS wind map, refer to Brower (2005).

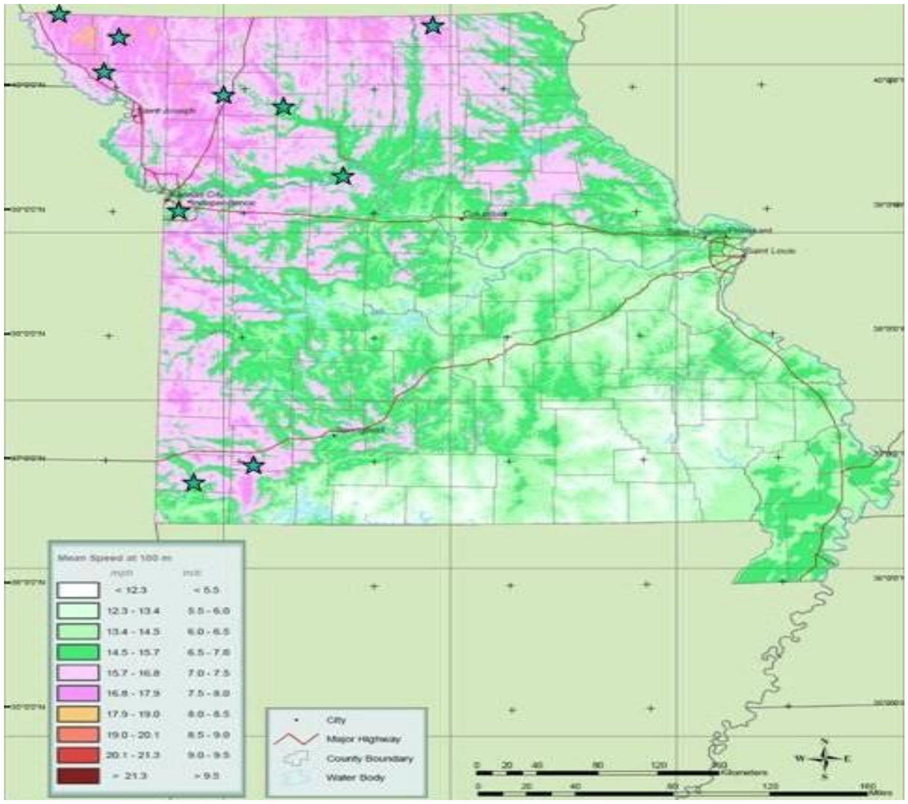


Figure 3.1 The green stars represent the location of the ten tall-towers in Missouri overlaid on the AWS Truewind map of wind speeds at 100 m.

The map in Figure 3.1 represents a fifteen-year climatology of the 100 m wind speeds. It shows an area of much stronger winds located in northern and western Missouri, indicated by the pink shading. To verify areas of stronger winds in Missouri, Redburn (2007) initially investigated observations from six towers in the northwestern part of the state: Blanchard, Maryville, Mound City, Miami, Chillicothe, and Raytown. Since then, one communication tower was instrumented near the town of Santa Rosa to compliment the other towers that Redburn (2007) initially studied in northwest Missouri. Further instruments have been added onto additional communication towers near Neosho and Monett in southwest Missouri. One last communication tower was instrumented north and east of Kirksville, near the town of Lancaster, Missouri. Specific information relevant to each tower location is shown in Table 3.1.

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
Chillicothe	1002160	10/4/2006	39-48-48	93-35-26	244
Santa Rosa	1005778	1/6/2007	39-57-28	94-06-56	298
Lancaster	1007392	8/7/2007	40-31-47	92-26-30	278
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
Neosho	1042598	10/29/2007	36-52-47	94-25-34	372.8

Table 3.1 Tall-tower information for each of the sites to be used in this study.

As turbine hub heights have increased over the last couple years, measurements of wind characteristics at a higher altitude are becoming highly relevant. Therefore, each of the towers was instrumented with 2 anemometers and a singular wind vane at 3 different heights: close to 70 m, close to 100 m, and then anywhere above 100 m, with the exception of the two towers in southwest MO. More specifically, each anemometer was mounted on a boom approximately 2.87 m long and weighing approximately 7.84 kg. Each set of two booms was placed at 180˚ to one another, either extending on the north and south sides of the tower or the northwest and southeast sides. This configuration was chosen to reduce the error that occurs with anemometers involving the effects of the tower, boom and other mounting arrangements on the wind flow. Since there were three instruments at each height, three cables needed to be run down the tower from each height to a data logger mounted at ground level. However, the structure of the tower also affected the exact height where the instruments were placed. For example, the cables that were supplied for the lower two heights are both 70 m and 100 m in length. This resulted in the instruments being placed slightly lower than these heights to properly attach the cables. Table 3.2 shows the heights at which instrumentation, supplied by NRG Systems Ltd. was placed on each tower.

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
Chillicothe	152	61	97	137
Santa Rosa	124	63	93	121
Lancaster	336	67	95	140
Miami	122	67	93	114
Raytown	152	67	93	142
Monett	77.4	50	60	70
Neosho	97.5	50	70	90

Table 3.2 Tall-tower information specific to tower and instrumentation heights.

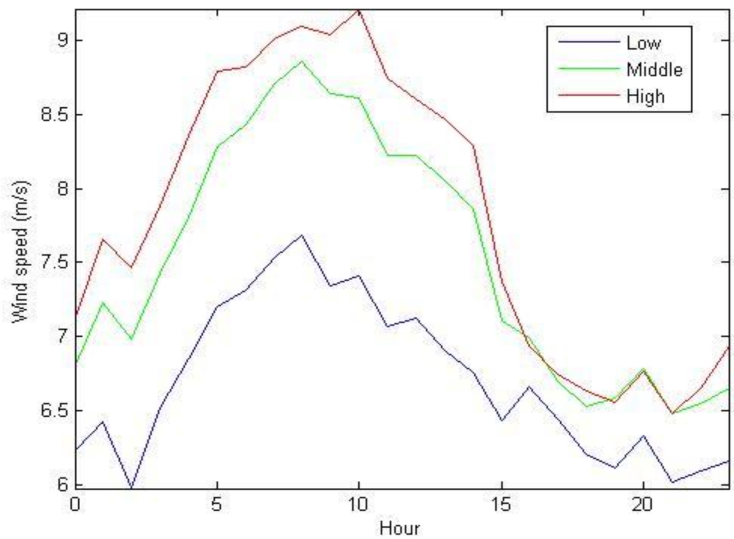
3.3 Data Collection and Processing

All of the observational data from this study 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 scaled text files could either show 10-minute averages or 60-minute averages of the wind data. However, due to time constraints and with such a large dataset, it was only possible to examine the hourly averages of wind speeds for each month.

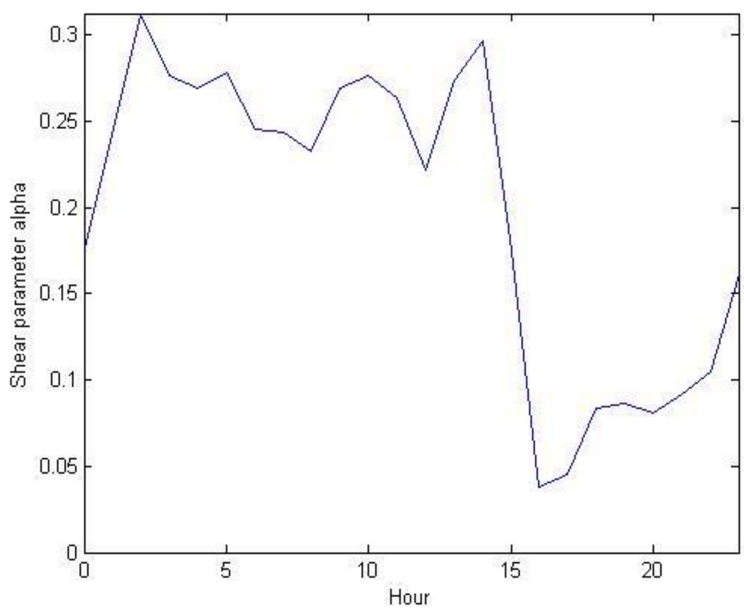
These files were then imported into Microsoft Excel. To ensure that bad data is not incorporated into the final analysis of the wind observations, the hourly averages underwent a quality control process. The logger system actually does not record wind speeds of 0 m s^{-1} when instrumentation is iced over or is not working properly; bad data is indicated by the default zero value of 0.4 m s^{-1}. This effectively addressed issues and concerns of ice which can cause the instruments to freeze. Much of the instrumentation on each of the towers has a life span of typically 2 years. Towards the end of 2008 some of the original instrumentation had been in place for 2 years or more. After 2 years in operation, the quality of the data being recorded may be considered questionable. For example, the logger began recording bad data towards the end of December in 2008 at the Raytown tower. Specifically channels 4 and 6 which measure the wind speed at the middle and lower elevations began recording values of 0.4 m/s. As no icing event occurs at this time, it is suspected that the instrumentation at the tower is becoming faulty. Most of the data used in this work is restricted to the first year of operation.

3.4 Observational Wind Data Analysis and MATLAB

After undergoing quality-control, these monthly processed files can then be read into a program written for MATLAB to produce graphical summaries of the wind observations. MATLAB is the program of choice to preview data graphics due to the amount of data that needs to be analyzed. Such graphics can show diurnal variations in wind speeds and shear (α) characteristics at different heights, as indicated by Figure 3.2.



a)



b)

Figure 3.2 Examples of graphics produced using MATLAB that show **a)** diurnal wind speeds at 3 heights, and **b)** diurnal variation in alpha, at the Blanchard site in February 2007 where hour is in UTC.

As indicated by the strong diurnal variations at the towers such as in Figure 3.2, the maximum mean wind speed is observed overnight. This is believed to be due to the contribution of the low-level jet, or at least some sort of increased stability during the nighttime hours. To investigate the behavior and activity of the LLJ, a new MATLAB program will be used to calculate and analyze average monthly wind speeds during the times of the identified low-level jet cases over this observational period. Results of these mean wind speeds, given in m s^{-1}, will be presented in Chapter 4.

This same MATLAB program will be used for wind shear analysis at each of the tower locations. Equation 2.10 in Chapter 2 will be used to solve for the dimensionless wind shear alpha values. The mean friction velocity (u_*), also given in m s^{-1}, will be calculated using hourly averages of wind data to accompany these alpha calculations. It is questioned whether the alpha parameter provides the best measurement and insight in the presence of wind shear, as alpha proves very sensitive to height. Equation 3.1 is an alternative equation for friction velocity that will be used to obtain results and is solved from the logarithmic wind profile.

$$u_* = \frac{k(u_2 - u_1)}{\ln\left(\frac{z_2}{z_1}\right)} \qquad \textbf{(3.1)}$$

This equation is slightly different from Equation 2.2, but still provides a good alternative calculation to compare with the alpha parameter.

Three different calculations for alpha and friction velocity will initially be made using MATLAB for each month: between the lower and upper level anemometers (α_1 and u_{*1}), the lower and middle level anemometers (α_2 and u_{*2}), and the middle and upper level anemometers (α_3 and u_{*3}). However, due to some uncertainty in data quality at a couple of the towers, only mean α values and friction velocities between the lower and upper anemometers will be presented in Chapter 4.

Each hourly averaged wind speed represents the mean magnitude of the wind speed recorded by both anemometers at the respective heights. To ensure a more accurate measurement of alpha, winds must be strong enough (> 3 m s^{-1}) to be included in the results and final analysis. Any mean wind speed less than this will be removed from the analysis by the MATLAB program.

Since two anemometers are recording wind speeds at the same level for each of the three heights, the MATLAB program was written to discard the weaker wind speed observation. The weaker wind speed observation usually coincides with the anemometer that is sheltered by the tower. This renders a more accurate measurement of the real wind, and therefore keeps the weaker winds from figuring into the analysis. As the study will be based on hourly averages of the data, a few advantages and disadvantages exist at certain times. Using hourly averages of the wind data gives a reasonable picture of the diurnal variations in wind speed and wind shear. On the other hand, in situations where the observed winds can change within a matter of minutes, hourly averages will not suffice. These situations occur or result in the presence of synoptic or mesoscale weather patterns such as strong northerly winds behind an arctic cold front or outflow boundaries created from dying thunderstorms. These ramp-up and ramp-down periods in wind speeds can occur on timescales less than an hour.

3.5 Selection and Verification of LLJ Events

Since most of the towers began collecting data in the second half of 2006, initial selection and analysis of LLJ events will be restricted to September of 2006 through August of 2007. With the exception of a couple major icing events at the beginning of

December 2006 and the middle of January 2007, most of the data collected is believed to be of valuable quality. Only two of the ten towers (Lancaster and Neosho) did not begin collecting wind data until the last half of 2007 and therefore results and analysis of data from these towers will not be presented in the following chapter. The Santa Rosa tower will also be excluded from results and analysis as a result of bad data for channels 2 and 4 at the low and mid-levels, as well as bad data recorded from both anemometers at the higher level. Therefore, results and analysis of only 7 of the 10 towers will be presented and discussed in the following chapters.

3.5.1 LLJ Identification Process

For this study, LLJ events were identified from upper-air observational winds using reanalysis data from the National Centers for Environmental Prediction (NCEP) office. This data is assimilated by NCEP's North American Regional Reanalysis (NARR). NARR provides consistent climate data on a regional scale over the domain of North America and gives an improved long-term reanalysis of basic meteorological quantities on a high resolution grid (32 km), either as a daily or monthly dataset. For this research, the daily datasets provided useful graphical products of the atmospheric wind field. These graphical plots of the analyzed wind fields, although less detailed than the RUC model initialization fields analyzed by Dahmer (2009), are available at increments every 25 mb, ranging from 1000 mb near the surface aloft to 100 mb. It is important to realize that these graphical plots do not provide an exact measure of wind speeds, but they do reveal the presence of existing jets.

The selection of LLJ events during this year is similar to the approach of Walters and Winkler (2001). They used a set of three criteria, all of which had to be met, to define the LLJ profile signature:

1. A wind speed greater than 8 m s^{-1} was observed at or below 700 mb,
2. The vertical wind shear between the level of strongest winds and the earth's surface equaled or exceeded 4 m s^{-1},
3. The vertical shear between the level of strongest winds and either the next highest wind minimum or 550 mb (whichever had the lower elevation) was greater than or equal to 4 m s^{-1}.

During the selection process however, many days had observed wind speeds greater than this criteria according to the graphical reanalyses products. As a result, the first criterion was modified so that LLJ events were more pronounced and did not occur every day. Any event having wind speeds below 16 m s^{-1} will not be considered a LLJ event and will be excluded from this study. Identified LLJ events were classified as either being weak or strong; weak events exhibited wind speeds between 16-20 m/s and strong events had wind speeds anywhere above this range. Each identified LLJ event easily met the second criterion, according to the modification of the first one. However, the last criteria was largely ignored for this study, as most of the observed tall-tower wind data is located near the level of maximum wind speed or lower.

In some instances when identifying LLJ events using the regional reanalysis, a wind speed maximum would occur at two different heights (i.e. 875 mb and 825 mb). In this case, the lowest level (875 mb) would be chosen as the height at which the wind speed maximum exists. Below are two examples of graphical plots which are available through the regional reanalysis. Figure 3.3 shows a strong jet event which occurred on 11 January 2007 in which all the towers appeared to be affected. The height of the jet speed maxima for this event is 875 mb (not displayed by the graphical plot) and the corresponding time was approximately 06Z, half-way in between the observational time period. The units for wind speeds in the color scale to the right of the domain are given in m s^{-1}.

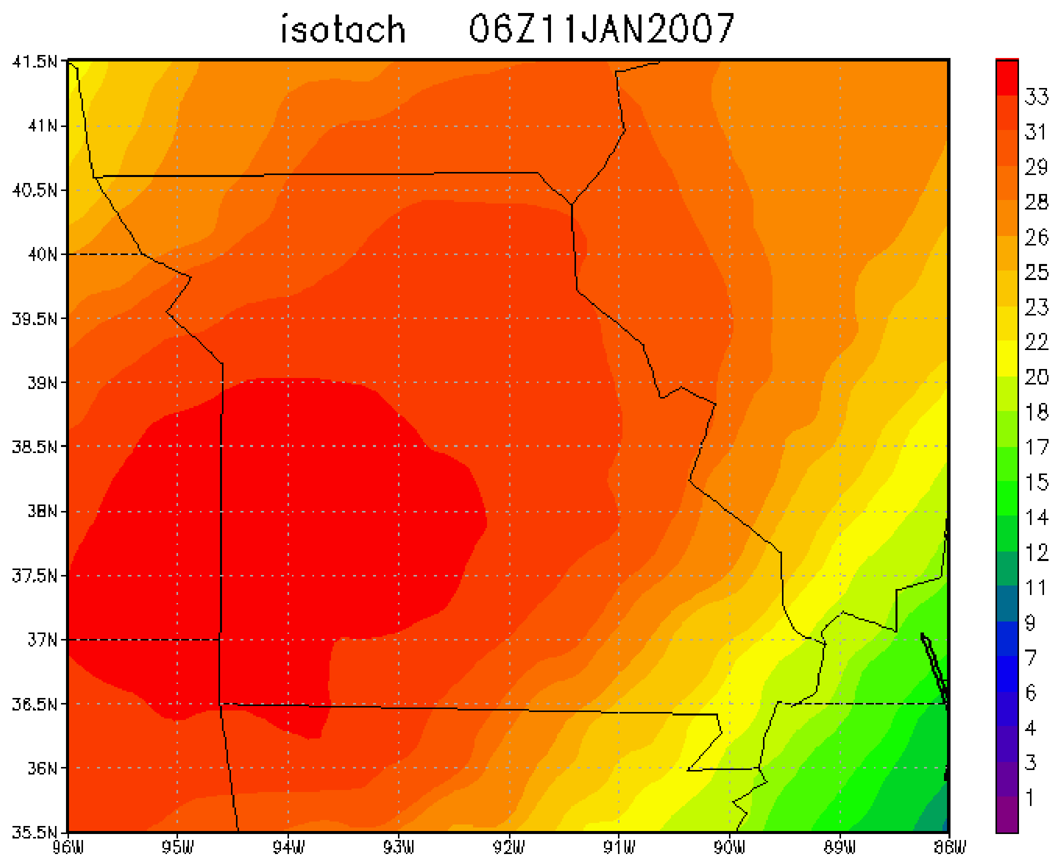


Figure 3.3 An example of a strong jet event day affecting all tower locations at 06Z on 11 January 2007.

Figure 3.4 shows an example where no jet event was detected on 17 January 2007. The same time and pressure level are presented to show how a non-jet day compares to a jet day during the same month.

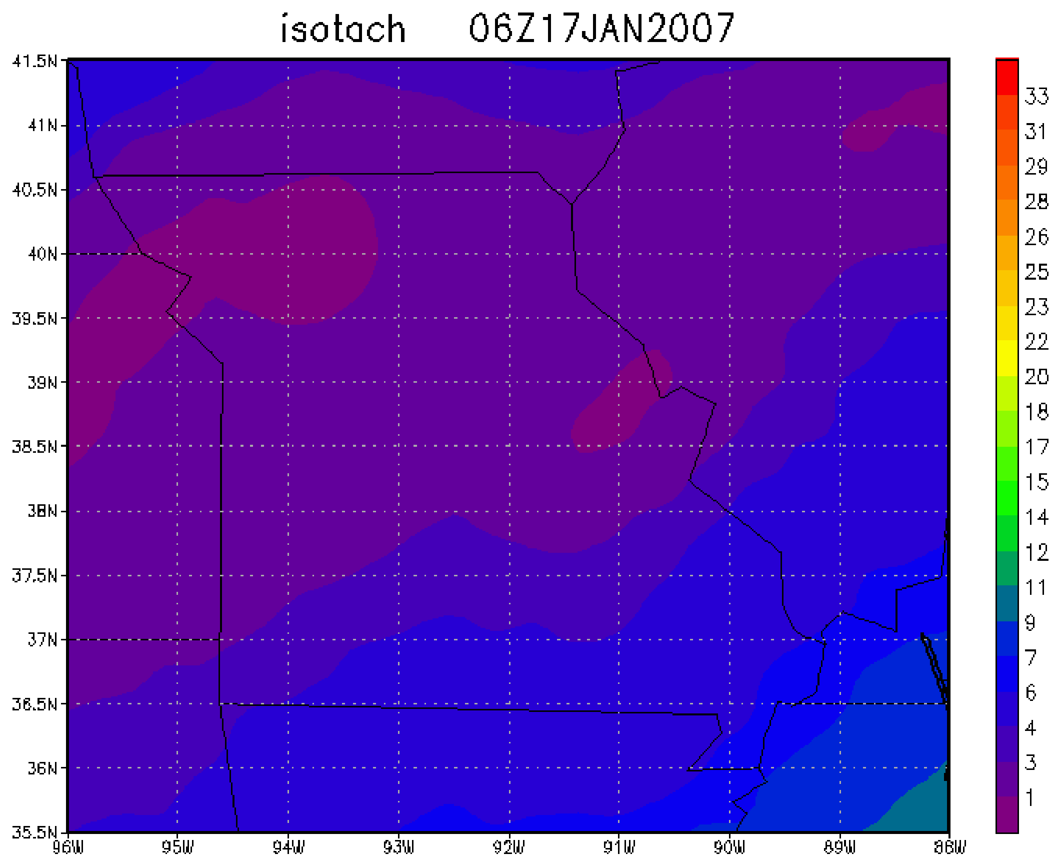


Figure 3.4 An example of a non-jet event day in which none of the towers seem to be affected at 06Z on 17 January 2007.

3.5.2 Identified Low-Level Jet Event Summary

The identified number of LLJ events/days indicates that the LLJ is most active during the late fall and winter months from November stretching through March. The majority of strong events also occurred during the same time where the LLJ appears most active. Another interesting artifact of the identification process revealed that out of the

206 low-level jet cases, 37 (18%) of them were predominantly from a northerly direction. These northerly jets occurred primarily during the months of November and December, indicating that these northerly jets coincide with strong cold fronts while very few northerly jets are observed in late spring and during the summer. In contrast to the the previous study using RUC model output and upper air soundings from Springfield, Dahmer (2009) revealed that only 5 (7%) of the 68 identified jet cases were associated with these northerly jets.

Observational Period	Total # of Jet Events	Northerly Jet Events	Strong	Weak
September2006	16	2	9	7
October2006	20	3	17	3
November2006	22	8	18	4
December2006	29	9	20	9
January2007	23	3	13	10
February2007	22	3	18	4
March2007	25	4	16	9
April2007	15	2	9	6
May2007	15	3	8	7
June2007	4	0	2	2
July2007	3	0	2	1
August2007	12	0	5	7

Table 3.3 Identified LLJ events throughout observational period.

Additionally, however not shown in the table, the height of the maximum wind speed tends to be located closer to the surface during this same time, often below 800 mb. LLJ events that occurred in the warm season (June, July, and August) tended to have a jet wind speed maximum located below 850 mb. Throughout much of the time period, the maximum observed winds occurred primarily between 9Z and 12Z (also not shown in Table 3.3) which is in general agreement with the 68 events identified using the RUC analyses fields. LLJ events occurring outside the warm season months exhibited more variability with respect to the height of the jet speed maximum. The identification process shows that the months of September and December in 2006, along with March in 2007, had wind speed maximums located above 800 mb.

Something else not mentioned in Table 3.3 is which towers are affected by each identified jet event. For example, one jet event may only affect the towers in northwest Missouri, without affecting the towers in the southwestern part of the state. The results presented in the following chapter will compare all the towers for each month, even if a portion of the towers was not apparently affected by the LLJ in a single or group of jet events during a particular month.

Chapter 4 Results and Discussion

4.1 Initial Investigation

The MATLAB program discussed in the previous chapter was used to investigate wind speed and shear characteristics at the low, middle, and upper anemometer levels at each tower between 00Z and 12Z for the year starting September 2006 ending through August 2007. Out of this time period, dates were selected when the LLJ maximum wind speed was found at or below 850 mb. This results in a reduction of the 206 originally identified jet cases down to approximately 158 jet cases. The data from these particular days of each month were then compared to an equal amount of days when the LLJ is not believed to be present. Frequencies of jet event and non-jet event days are listed by month in Table 4.1. The number in parentheses indicates the total number of event days that were included within the presented results.

Observational Period	LLJ Events (at or below 850 mb)	Non-Jet Days Only
September 2006	9	14 (9)
October 2006	14 (11)	11
November 2006	18 (8)	8
December 2006	20 (2)	2
January 2007	20 (8)	8
February 2007	18 (6)	6
March 2007	18 (7)	7
April 2007	8	15 (8)
May 2007	15	16 (15)
June 2007	4	26 (4)
July 2007	3	28 (3)
August 2007	11	19 (11)

Table 4.1. Frequencies of jet and non-jet event days listed by month.

Oftentimes during the winter, a particular month had more days where the LLJ (with max winds at or below 850 mb) was present, and maybe only a few days when it was not. Therefore, to obtain an objective analysis of the data for that particular month, the number of LLJ days would be limited so that it would equal the number of non-LLJ days. On the other hand, some months like June and July only had a few days when the LLJ was present at or below 850 mb, leaving an abundance of non-LLJ days in the same month. Therefore, the number of non-LLJ days was limited in the analysis to equal the number of LLJ days for a more objective analysis and comparison of wind speeds and shears during the appropriate times.

4.2 Monthly Tall-Tower Wind Speeds

Calculated average monthly wind speed tables for the period of interest will be included in this section to show their respective wind speeds between jet and non-jet events. The same average monthly wind speeds will also be plotted graphically to show whether each tower follows the same trend from season to season. For this graph, the low-level wind averages for the towers in northwestern Missouri will be compared with the upper-level wind averages for the Monett tower, as most of these averages are located around a height of 70 m.

4.2.1. Maryville

The mean monthly wind speeds observed during jet events at the Maryville tower are shown in Table 4.2. The number shown in parentheses is the number of jet days used in the analysis. The strongest winds tend to occur in the months of December 2006 and January 2007. However, it should be noted that the strongest mean wind speeds in December come from a relatively small sample size of 2 days. The months of November

2006 and January 2007 do use a similar sample size in their averages. Therefore, it appears that the mean wind speeds are reasonable. Average wind speeds are also near a maximum in the summer months of June and July. During these months, the sample size used in the analysis is smaller relative to months such as April or May. This may therefore influence the average wind speeds to be slightly higher during these two months. Most of the other towers experienced higher wind speeds during the summer months as well.

Month	Low (61 m)	Middle (93 m)	High (117 m)
September 2006 (9)	8.39	9.80	10.49
October 2006 (11)	7.66	8.97	9.64
November 2006 (8)	8.55	9.48	9.87
December 2006 (2)	9.13	11.08	12.07
January 2007 (8)	8.85	10.21	10.88
February 2007 (6)	7.83	8.78	9.16
March 2007 (7)	7.86	9.14	9.70
April 2007 (8)	8.05	9.17	9.69
May 2007 (15)	7.57	8.72	9.27
June 2007 (4)	8.86	10.16	10.77
July 2007 (3)	6.86	8.21	9.08
August 2007 (11)	6.45	7.62	8.28

Table 4.2 Observed mean wind speeds (m s^{-1}) for jet events at Maryville.

The mean monthly wind speeds observed during non-jet events at the Maryville tower are shown in Table 4.3. The maximum observed winds during the non-jet events tend to occur twice during the period: October 2006 and April 2007. These numbers appear reasonable as both months sample a reasonable amount of days respectively.

Month	Low (61 m)	Middle (93 m)	High (117 m)
September 2006 (9)	5.41	6.34	6.72
October 2006 (11)	6.25	7.52	8.12
November 2006 (8)	5.65	6.76	7.20
December 2006 (2)	4.46	5.21	5.53
January 2007 (8)	5.48	6.43	6.82
February 2007 (6)	5.48	6.38	6.71
March 2007 (7)	5.84	6.82	7.25
April 2007 (8)	7.07	8.23	8.72
May 2007 (15)	5.57	6.57	7.00
June 2007 (4)	5.37	6.50	7.13
July 2007 (3)	5.38	6.76	7.47
August 2007 (11)	5.01	5.93	6.41

Table 4.3 Observed mean wind speeds (m s^{-1}) for non-jet events at Maryville.

Figure 4.1 shows the difference in jet and non-jet mid-level wind speeds at Maryville. This plot is a graphical display of the mean monthly mid-level winds recorded in Table 4.2 and Table 4.3. A larger spread exists between the two curves, particularly towards the last couple months in 2006. However, the spread between the jet curve and non-jet curve decreases as the mean monthly winds are more similar as the springtime approaches.

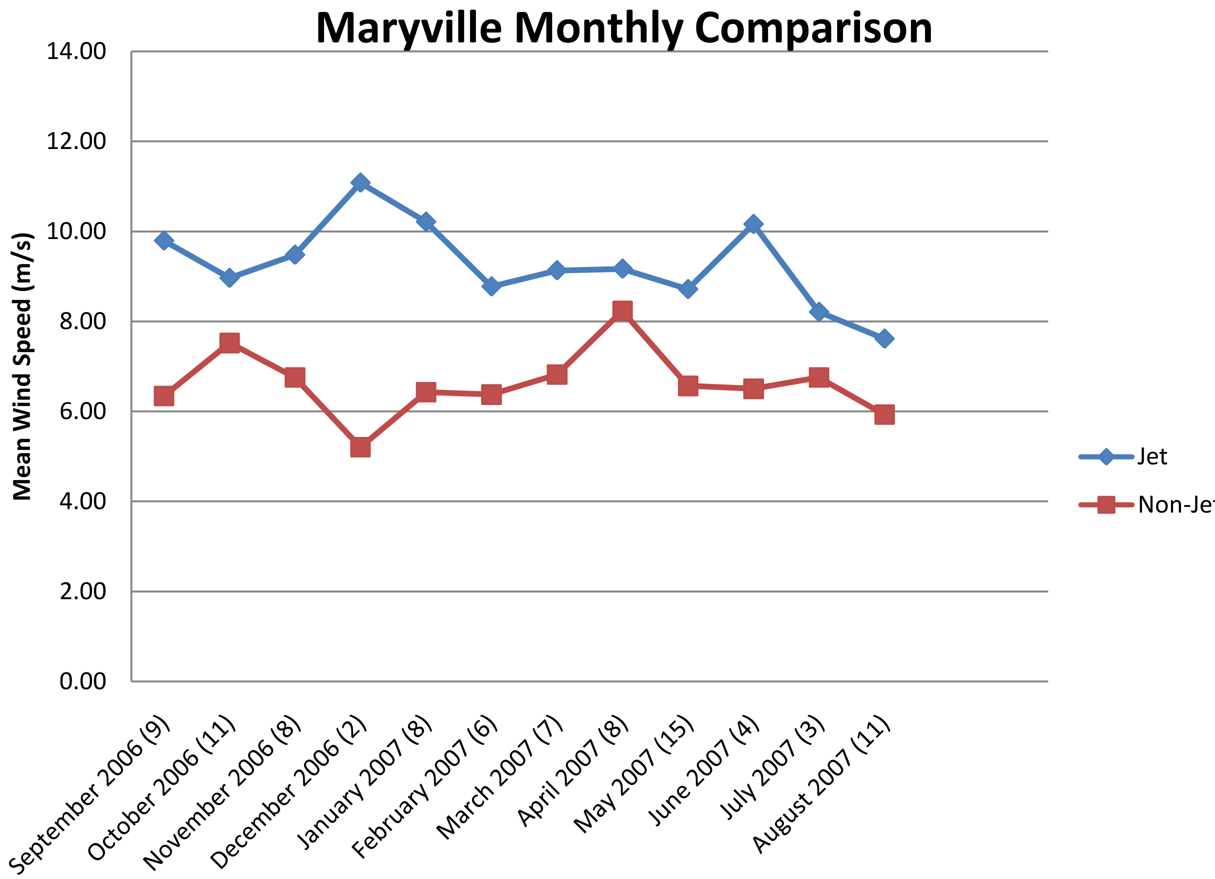


Figure 4.1 A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Maryville.

4.2.2. Blanchard

The mean monthly wind speeds during jet events for the Blanchard tower are given in Table 4.4. The Blanchard tower exhibits the strongest wind speeds throughout the observed period since Blanchard is the most exposed site compared to the other towers. Halfway through the month of January 2007, the logger records bad data for a single anemometer at each of the three heights. This coincides with an ice storm that occurred at roughly the same time, and this bad data continued to record until the end of

March of that same year. However, this icing effect does not impact the observed mean wind speeds too much, as quality data still is recorded by the sheltered anemometers at all three levels.

Month	Low (61 m)	Middle (97 m)	High (137 m)
September 2006 (9)	8.92	10.28	11.42
October 2006 (11)	8.32	9.64	10.68
November 2006 (8)	8.82	10.08	10.84
December 2006 (2)	8.12	9.75	11.21
January 2007 (8)	8.42	9.72	10.49
February 2007 (6)	7.41	8.52	8.97
March 2007 (7)	7.86	9.18	10.27
April 2007 (8)	8.95	10.12	10.94
May 2007 (15)	8.31	9.45	10.27
June 2007 (4)	10.43	11.45	12.16
July 2007 (3)	7.31	8.66	9.73
August 2007 (11)	7.33	8.51	9.39

Table 4.4 Observed mean wind speeds ($m\ s^{-1}$) during jet events at Blanchard.

The mean monthly wind speeds during non-jet events for the Blanchard tower are given in Table 4.5. During non-jet events at the upper-level heights, the mean winds often reach wind speeds close to 8 $m\ s^{-1}$. This indicates that good wind resource is still available during this period.

Month	Low (61 m)	Middle (97 m)	High (137 m)
September 2006 (9)	5.64	6.84	7.43
October 2006 (11)	6.55	7.66	8.54
November 2006 (8)	6.31	7.30	7.74
December 2006 (2)	4.88	5.59	5.92
January 2007 (8)	5.49	6.28	6.52
February 2007 (6)	5.24	6.18	6.35
March 2007 (7)	5.41	6.20	6.67
April 2007 (8)	7.69	8.66	9.42
May 2007 (15)	6.03	7.07	7.78
June 2007 (4)	5.92	7.19	7.93
July 2007 (3)	6.63	7.81	8.76
August 2007 (11)	5.83	6.62	7.18

Table 4.5 Observed mean wind speeds (m s^{-1}) during non-jet events at Blanchard.

Figure 4.2 shows the difference in jet and non-jet mid-level wind speeds at Blanchard. A larger spread exists at the beginning of the observational period. Towards the beginning of 2007, the overall spread tends towards a smaller difference in the two trends.

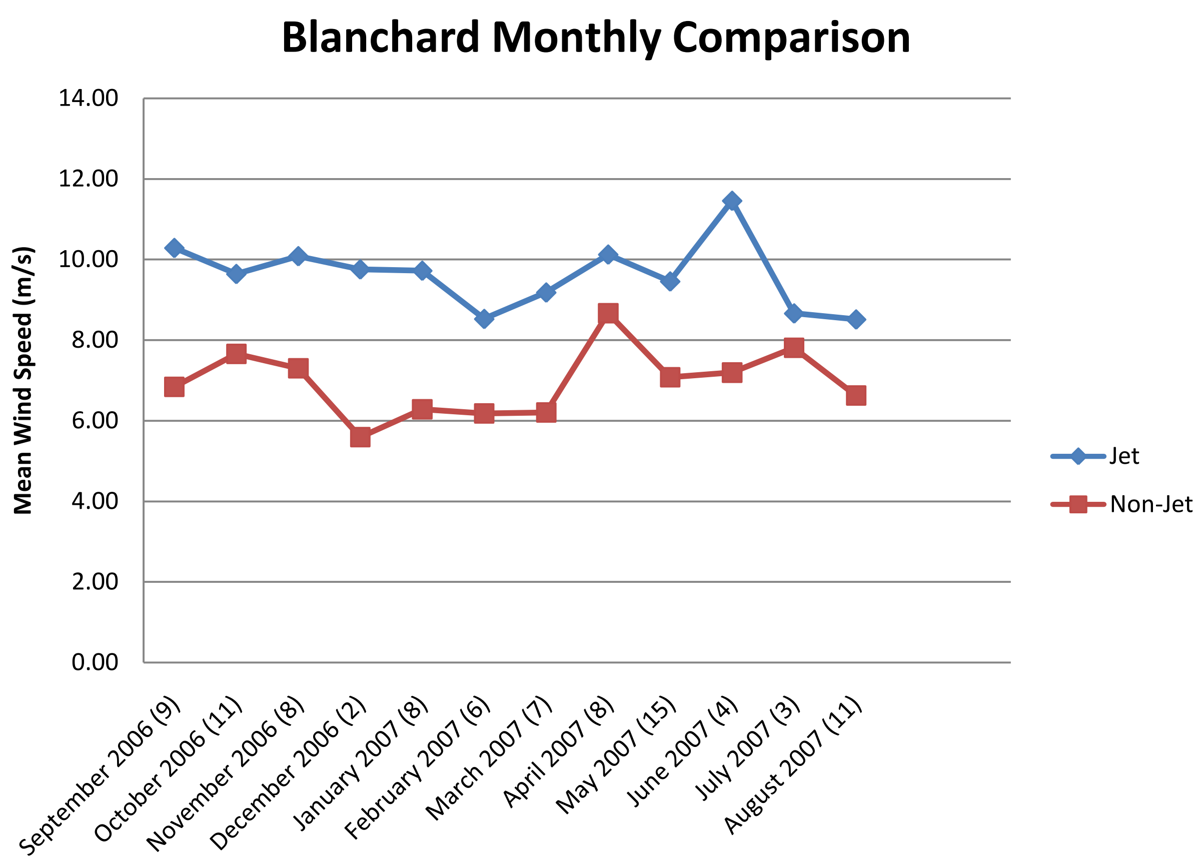


Figure 4.2 A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Blanchard.

4.2.3. Mound City

Beginning in the last half of September 2006, both anemometers at the low-level and one at the mid-level began recording bad data. This continued through mid-December until one of the low-level anemometers came back online. The logger was re-wired at this time, in order to get a recording of somewhat reliable data at each level. The logger was eventually replaced by January 2007 so that reliable data would be recorded by each of the anemometers at each height. Table 4.6 shows that the monthly averaged wind speeds at the lower level appear to be somewhat weak during the month of

September, as a result of bad readings starting around the 23rd. Days were used after the 23rd in the analysis, which appear to influence the low value for that month. The monthly averaged wind speeds peak somewhat towards the end of 2006 and the beginning of 2007. However, the magnitude of the peak wind speeds during jet events is comparably less than observed averages at the Blanchard and Maryville towers. Less variability in the mean winds at all three levels is apparent when plotting them throughout the 12-month period.

Month	Low (61 m)	Middle (97 m)	High (117 m)
September 2006 (9)	5.60	8.77	9.96
October 2006 (11)	N/A	7.03	8.69
November 2006 (8)	N/A	7.18	8.97
December 2006 (2)	8.50	8.85	10.38
January 2007 (8)	8.47	9.04	10.02
February 2007 (6)	7.21	7.88	8.56
March 2007 (7)	7.28	8.10	8.76
April 2007 (8)	7.26	7.96	8.51
May 2007 (15)	6.96	7.79	8.36
June 2007 (4)	8.86	9.79	10.40
July 2007 (3)	6.73	7.73	8.54
August 2007 (11)	6.28	7.18	7.86

Table 4.6 Observed mean wind speeds (m s^{-1}) during jet events at Mound City.

When plotting the mean wind speeds during non-jet events throughout the year period, a little bit more variability exists between the maximum and minimum averages at each level. Table 4.7 shows that the maximum average wind speeds for non-jet events tends to occur during the spring months, particularly March and April 2007. The strongest wind speeds at the upper levels seldomly approach a value of 8 m/s compared to the Blanchard data, indicating less available wind resource during non-jet events.

Also of interest is the particularly small value in the month of December. Only 2 non-jet days occurred during this month, and on one of those days both lower channels recorded bad data. This should account for the abnormally low value for the month period.

Month	Low (61 m)	Middle (97 m)	High (117 m)
September 2006 (9)	4.15	5.33	5.98
October 2006 (11)	N/A	6.31	7.27
November 2006 (8)	N/A	4.66	6.27
December 2006 (2)	1.10	4.69	4.70
January 2007 (8)	5.04	5.54	6.16
February 2007 (6)	4.87	5.33	5.77
March 2007 (7)	5.35	5.96	6.52
April 2007 (8)	6.54	7.29	8.01
May 2007 (15)	4.93	5.57	6.06
June 2007 (4)	5.25	6.10	6.72
July 2007 (3)	5.66	6.63	7.30
August 2007 (11)	5.05	5.91	6.37

Table 4.7 Observed mean wind speeds (m s^{-1}) during non-jet events at Mound City.

Figure 4.3 shows the difference in jet and non-jet mid-level wind speeds at Blanchard. A similar trend exists in the spread between the jet and non-jet curves. However the jet curve shows a dip in the winds right before taking on a larger spread, which is a result of some of the bad data observed during the months of October and November.

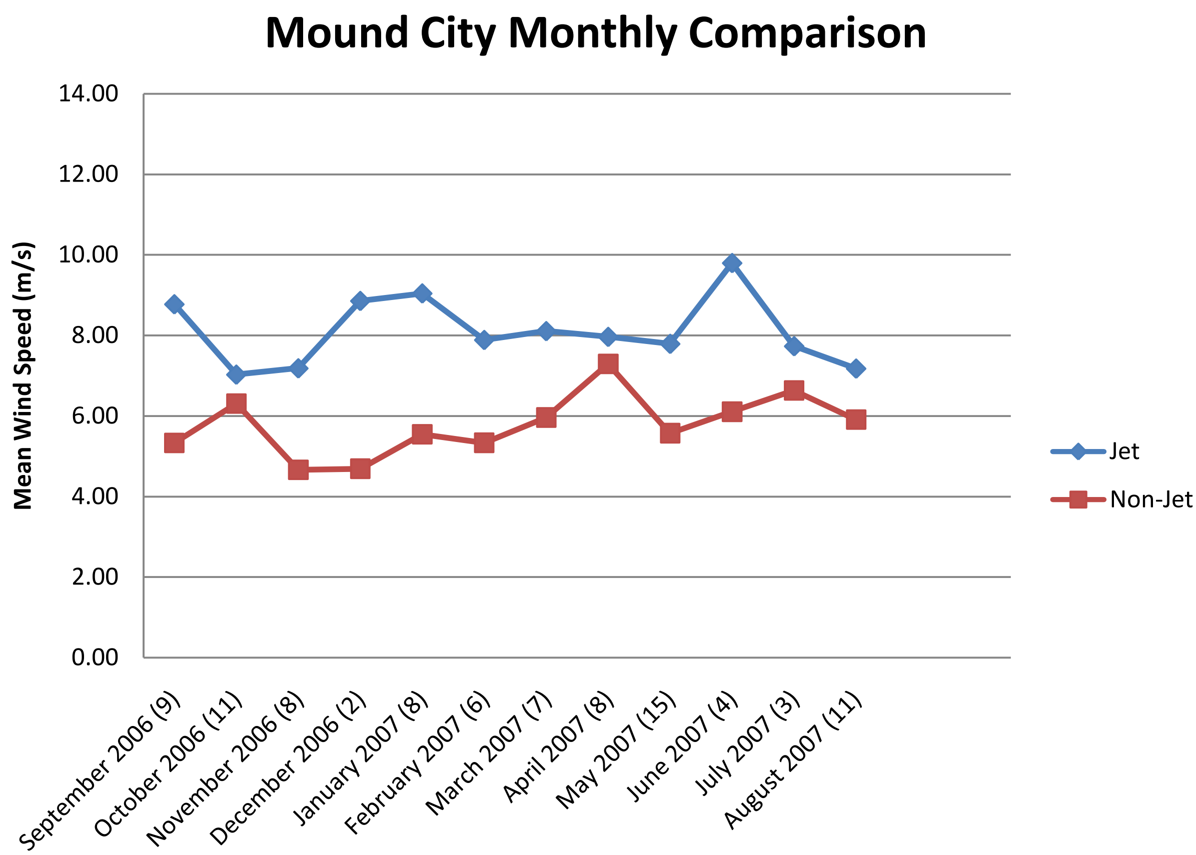


Figure 4.3 A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Mound City.

4.2.4. Chillicothe

The average winds at the lower-level anemometers are usually on the order of 6-7 m s^{-1}, while the mid-level anemometers recorded an average wind between 7-8 m s^{-1}, and the upper level anemometers recorded average wind speeds typically above 8 m s^{-1}. The strongest winds actually peak in the spring months, particularly April 2007. However, the maximum average winds are weaker (< 10 m s^{-1}) which may be due to the presence of a forested area to the south and significant farm buildings to the north of the tower.

Month	Low (61 m)	Middle (97 m)	High (137 m)
October 2006 (11)	6.46	7.53	8.85
November 2006 (8)	6.99	8.01	9.02
December 2006 (2)	6.33	7.54	8.86
January 2007 (8)	7.06	7.89	8.97
February 2007 (6)	6.18	6.99	7.82
March 2007 (7)	6.70	7.74	8.82
April 2007 (8)	7.25	8.31	9.48
May 2007 (15)	6.33	7.30	8.42
June 2007 (4)	7.28	8.18	9.12
July 2007 (3)	5.94	7.11	8.43
August 2007 (11)	5.84	6.89	8.02

Table 4.8 Observed mean wind speeds (m s^{-1}) during jet events at Chillicothe.

Average wind speeds during non-jet events followed the same pattern of average wind speeds during jet events. The primary difference is the magnitude of the averages at each height. At the lower level, average wind speeds rarely exceeded 5 m s^{-1}. The middle level winds and upper level winds rarely exceeded 6 m s^{-1} and 7 m s^{-1} respectively as indicated in Table 4.9.

Month	Low (61 m)	Middle (97 m)	High (137 m)
October 2006 (11)	5.30	6.10	6.90
November 2006 (8)	4.84	5.81	6.72
December 2006 (2)	4.23	5.02	5.56
January 2007 (8)	4.55	5.13	5.79
February 2007 (6)	4.18	4.70	5.11
March 2007 (7)	4.97	5.92	6.89
April 2007 (8)	5.75	6.69	7.63
May 2007 (15)	4.80	5.60	6.40
June 2007 (4)	4.48	5.42	6.22
July 2007 (3)	4.97	6.14	7.22
August 2007 (11)	4.55	5.45	6.36

Table 4.9 Observed mean wind speeds (m s^{-1}) during non-jet events at Chillicothe.

Figure 4.4 shows the difference in jet and non-jet mid-level wind speeds at Chillicothe. There appears to be a smaller spread between the jet and non-jet curves throughout much of the period, unlike some of the towers in northwest MO (see Figure 4.2, 4.3).

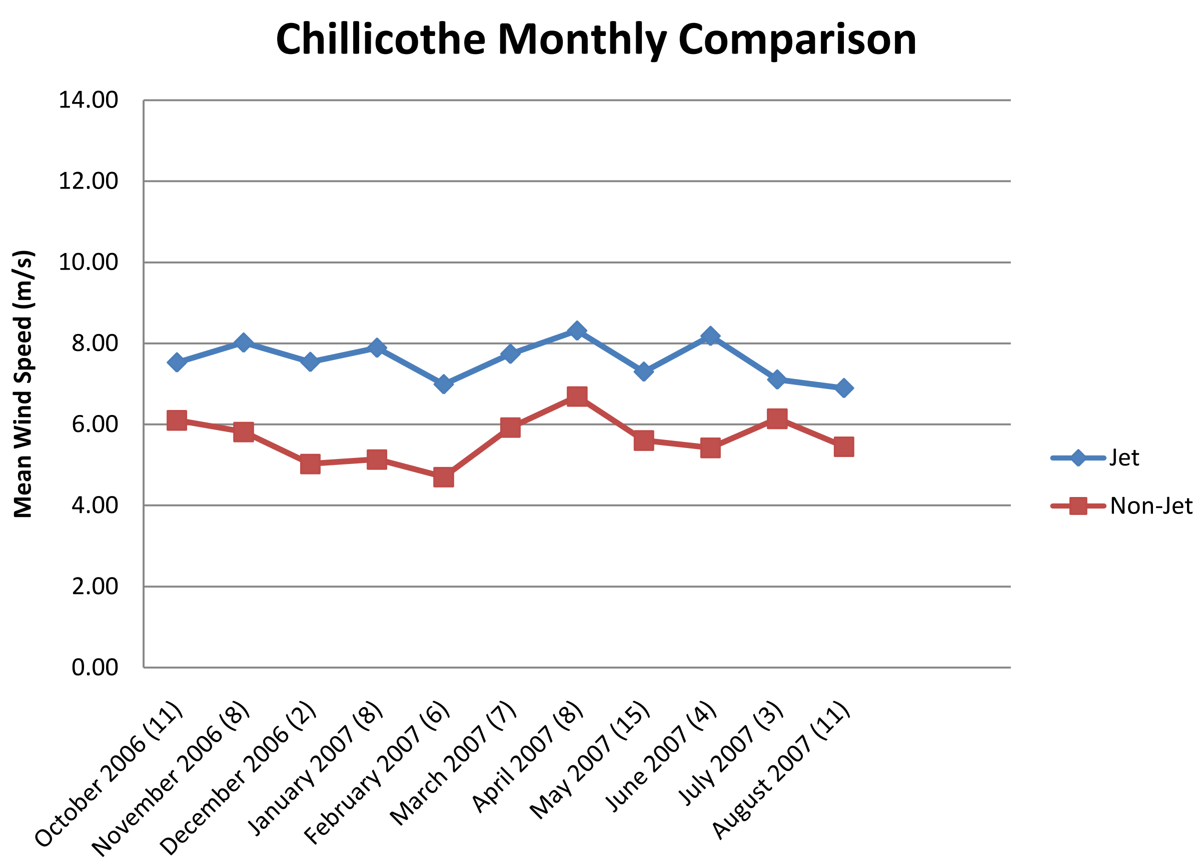


Figure 4.4 A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Chillicothe.

4.2.5. Miami

The strongest average wind speeds during the jet events for the Miami tower tended to occur towards the end of 2006 and ended through April 2007. Most of the average wind speeds recorded at each level were on the order of at least 8 m s^{-1}. The weakest wind speeds were rarely less than 7 m s $^{-1}$ at each level during jet periods. The months of November, January, and April all use the same sample size to use for the analysis; each month appears to have reasonable average values at all three levels. Towards the end of the period, the mean winds at the 93 m level drops a bit under the mean winds at the 67 m level, which coincides with a period of bad data.

Month	Low (67 m)	Middle (93 m)	High (114 m)
September 2006 (9)	6.70	7.70	8.38
October 2006 (11)	7.66	8.97	10.04
November 2006 (8)	8.35	9.44	10.00
December 2006 (2)	7.50	8.55	9.97
January 2007 (8)	8.50	9.52	10.40
February 2007 (6)	6.99	7.58	8.33
March 2007 (7)	7.72	8.24	9.68
April 2007 (8)	8.63	8.73	10.92
May 2007 (15)	6.92	6.51	8.86
June 2007 (4)	7.77	7.73	9.28
July 2007 (3)	7.34	8.73	10.57
August 2007 (11)	6.90	7.41	9.45

Table 4.10 Observed mean wind speeds (m s $^{-1}$) during jet events at Miami.

During non-jet events, similar to other towers, the Miami tower had weaker average wind speeds as shown in Table 4.11. Low-level average wind speeds hovered around 5 m s $^{-1}$. Only a couple months in the springtime had wind speeds at the middle and upper-level heights which exceeded 8 m s $^{-1}$.

Month	Low (67 m)	Middle (93 m)	High (114 m)
September 2006 (9)	5.00	5.54	5.93
October 2006 (11)	6.11	6.94	7.65
November 2006 (8)	5.54	6.43	7.09
December 2006 (2)	5.63	6.22	6.55
January 2007 (8)	4.27	4.70	5.02
February 2007 (6)	4.63	4.75	5.10
March 2007 (7)	6.83	7.08	8.60
April 2007 (8)	7.18	8.00	9.23
May 2007 (15)	5.11	5.56	6.56
June 2007 (4)	5.39	5.79	6.69
July 2007 (3)	5.49	6.34	7.56
August 2007 (11)	5.15	5.78	6.66

Table 4.11 Observed mean wind speeds (m s^{-1}) during non-jet events at Miami.

Figure 4.5 shows the difference in jet and non-jet mid-level wind speeds at Miami throughout the period. The spread for the Miami tower between the jet and non-jet curves resembles the pattern in spreads for the other towers as well.

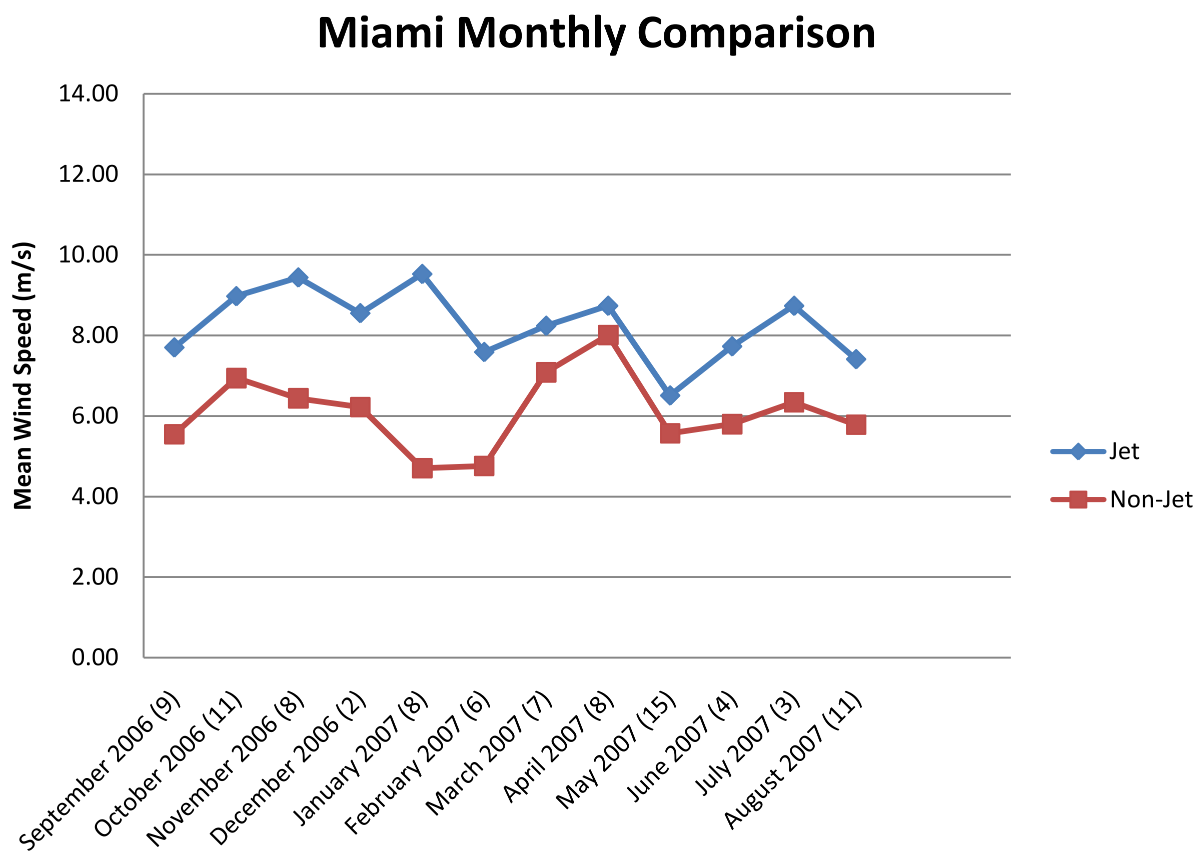


Figure 4.5 A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Miami.

4.2.6. Raytown

Low-level average winds range between 5.5 m s^{-1} and 7 m s^{-1} during jet events, while average winds at the mid-level are typically somewhere between 7 m s^{-1} and 8 m s^{-1}, and the upper-level average winds are commonly above 8 m s^{-1}. However, during this period wind speeds struggle to get to or exceed 10 m s^{-1}. This could be a result of the Raytown tower being located in a more urban-type setting, as prison building surrounds its southern border along with a mixed forest surrounding the tower itself. The increase in frictional effects around the tower act to retard the wind flow a bit more compared to the other towers being investigated.

Month	Low (67 m)	Middle (93 m)	High (142 m)
September 2006 (9)	6.42	7.75	9.21
October 2006 (11)	5.72	7.20	8.93
November 2006 (8)	6.58	7.98	9.52
December 2006 (2)	6.03	7.73	9.75
January 2007 (8)	7.15	8.03	8.66
February 2007 (6)	5.61	6.31	6.98
March 2007 (7)	5.95	7.07	8.21
April 2007 (8)	6.13	7.40	8.73
May 2007 (15)	5.30	6.61	7.98
June 2007 (4)	7.03	8.22	9.16
July 2007 (3)	5.41	6.91	8.35
August 2007 (11)	5.52	6.83	8.13

Table 4.12 Observed mean wind speeds ($m\ s^{-1}$) during jet events at Raytown.

During non-jet events, the average wind speeds were weaker due to the increased frictional effects near the tower. Typically, the low-level winds in Table 4.13 ranged between 3.5 $m\ s^{-1}$ and 5 $m\ s^{-1}$. At the mid-levels, the average wind rarely exceeded 6 $m\ s^{-1}$; only in the case of April 2007 did this occur. Table 4.13 shows that the upper-level wind speed only exceeded 7 $m\ s^{-1}$ once, during this same month.

Month	Low (67 m)	Middle (93 m)	High (142 m)
September 2006 (9)	3.91	4.90	5.92
October 2006 (11)	4.55	5.61	6.62
November 2006 (8)	3.63	5.04	6.64
December 2006 (2)	3.51	4.73	6.26
January 2007 (8)	3.57	4.24	4.61
February 2007 (6)	3.94	4.30	4.53
March 2007 (7)	4.15	5.18	6.20
April 2007 (8)	5.71	6.84	7.95
May 2007 (15)	3.78	4.94	6.00
June 2007 (4)	4.29	5.43	6.58
July 2007 (3)	3.66	4.74	6.10
August 2007 (11)	4.13	5.27	6.10

Table 4.13 Observed mean wind speeds (m s $^{-1}$) during non-jet events at Raytown.

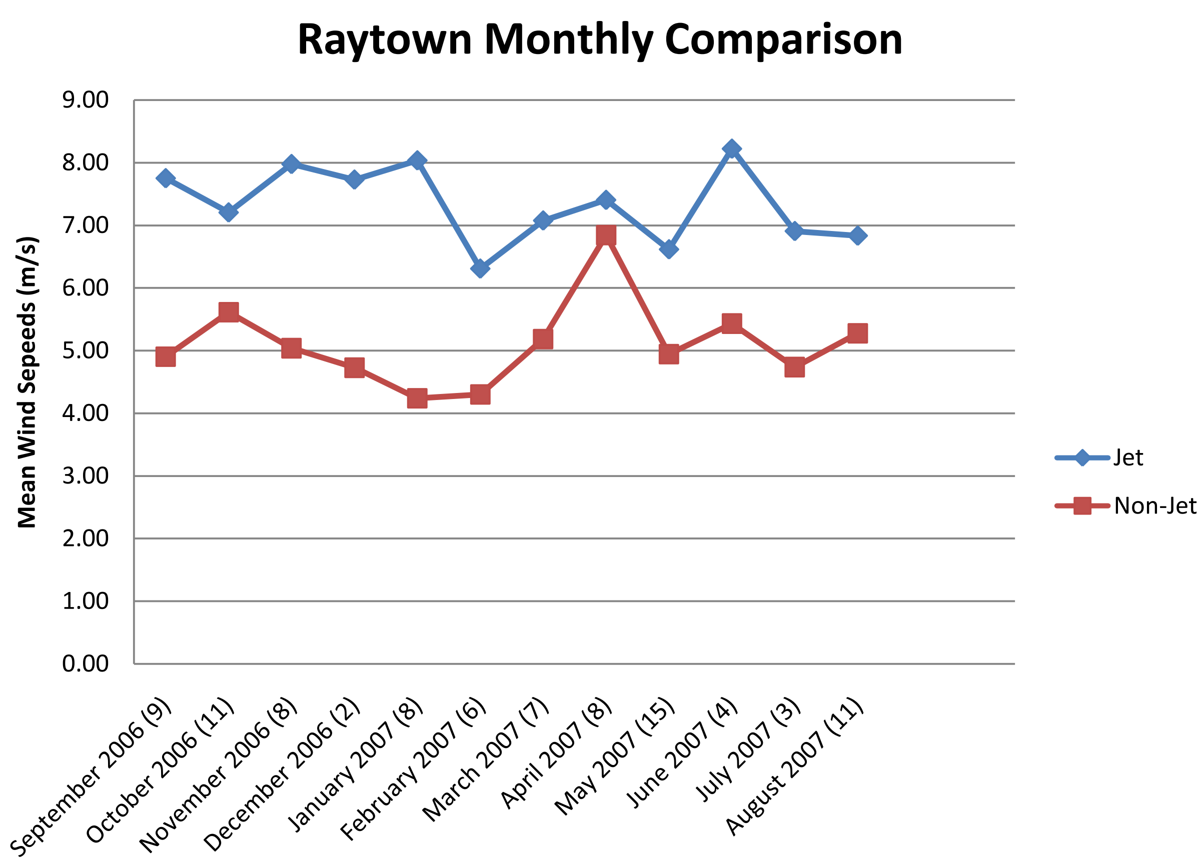


Figure 4.6 A graphical comparison of the mean mid-level winds (m s $^{-1}$) between jet and non-jet event cases at Raytown.

4.2.7. Monett

The major difference between the Monett tower and the other towers that one has to consider is the different heights at which the mean winds are observed. The low-level anemometers at Monett are about 10 m lower compared to the low-level anemometers at the other towers. Meanwhile, the mid-level anemometers at Monett, at approximately 60 m, are about 30 m lower compared to the mid-level anemometers at the rest of the towers. The upper-level anemometers at Monett, at approximately 70 m, are typically measuring wind speeds 50 m, and sometimes depending upon the tower up to 70 m, lower than the other towers. It is also important to note that the Monett tower and the Neosho tower in southwest MO sit at slightly higher elevations compared to the other towers. Despite a higher elevation, the presence of the Ozark Mountains to the south may affect wind speeds, depending on the orientation of the jet/wind direction.

Mean wind speeds during jet events at the lower-level anemometers tend to range between 6 m s^{-1} and 7 m s^{-1}. The mean wind speeds at the mid-level height is generally between 7 m s^{-1} and 8 m s^{-1}. The mean wind speeds at the upper-level height manage to only exceed 9 m s^{-1} during November 2006. Data collection began on the tower on November 14th; therefore, the results for this month (Table 4.14) were calculated such that the analysis did not include days prior to the 14th of the month.

Month	Low (50 m)	Middle (60 m)	High (70 m)
November 2006 (8)	7.86	8.28	9.12
December 2006 (2)	6.60	7.15	8.02
January 2007 (8)	6.89	7.36	8.06
February 2007 (6)	6.67	7.07	7.82
March 2007 (7)	6.35	6.86	7.68
April 2007 (8)	7.54	7.98	8.79
May 2007 (15)	6.46	6.95	7.73
June 2007 (4)	7.71	8.11	8.90
July 2007 (3)	5.95	6.38	7.01
August 2007 (11)	6.38	6.81	7.53

Table 4.14 Observed mean wind speeds ($m\ s^{-1}$) during jet events at Monett.

The magnitude of the mean low-level wind speeds during non-jet events is roughly a couple meters per second less than its jet counterpart, with winds typically being between 4 $m\ s^{-1}$ and 5 $m\ s^{-1}$. The mid-level winds experience a slightly bigger range, averaging between 4 $m\ s^{-1}$ and 6 $m\ s^{-1}$. The upper-level winds average anywhere between 4.5 $m\ s^{-1}$ and 7 $m\ s^{-1}$.

Month	Low (50 m)	Middle (60 m)	High (70 m)
November 2006 (8)	5.65	6.27	7.21
December 2006 (2)	3.97	4.11	4.53
January 2007 (8)	4.01	4.22	4.54
February 2007 (6)	4.13	4.34	4.62
March 2007 (7)	5.71	6.10	6.83
April 2007 (8)	5.83	6.20	6.81
May 2007 (15)	4.54	4.91	5.44
June 2007 (4)	5.02	5.48	6.11
July 2007 (3)	4.88	5.23	5.84
August 2007 (11)	3.77	4.00	4.31

Table 4.15 Observed mean wind speeds ($m\ s^{-1}$) during non-jet events at Monett.

Figure 4.7 shows the difference in jet and non-jet mid-level wind speeds at Monett. The pattern in both curves resembles the patterns of other towers (i.e. Chillicothe) fairly well, despite taking measurements at lower elevations AGL.

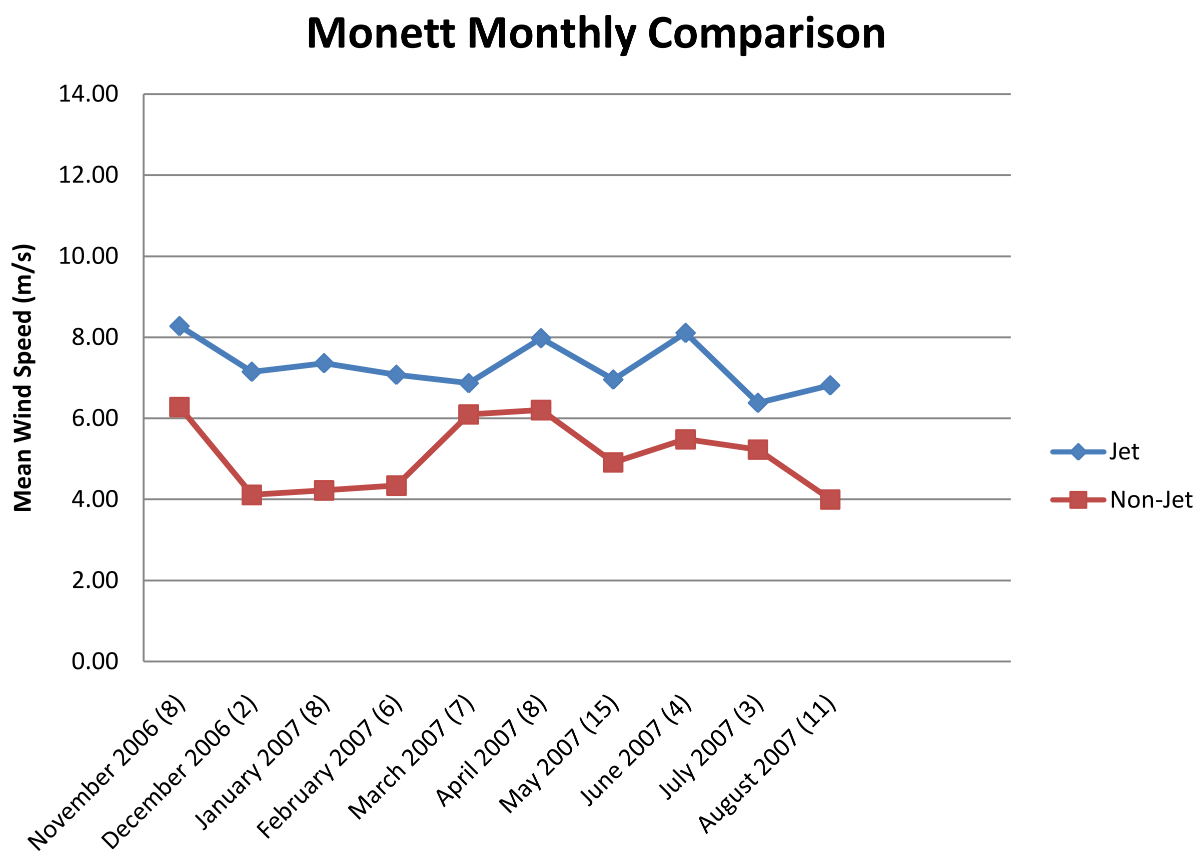


Figure 4.7 A graphical comparison of the mean mid-level winds (m s^{-1}) between jet and non-jet event cases at Monett.

4.2.8. Tower Comparison

Since the heights of the anemometers at Monett are different from the anemometer heights at the other tower locations, two comparisons will be used to include the Monett data. The first comparison involves the upper heights on the Monett tower

(70 m) being plotted against the lower heights at the Miami and Raytown towers (approximately 67 m) in Figure 4.8.

Throughout the period, all three towers tend to follow the same wind pattern for this comparison during jet events. However, the Miami and Monett towers are more similar in their mean wind speeds. Meanwhile, the low-level winds at the Raytown tower appear to lag a bit as a result possibly of increased friction in an urban setting.

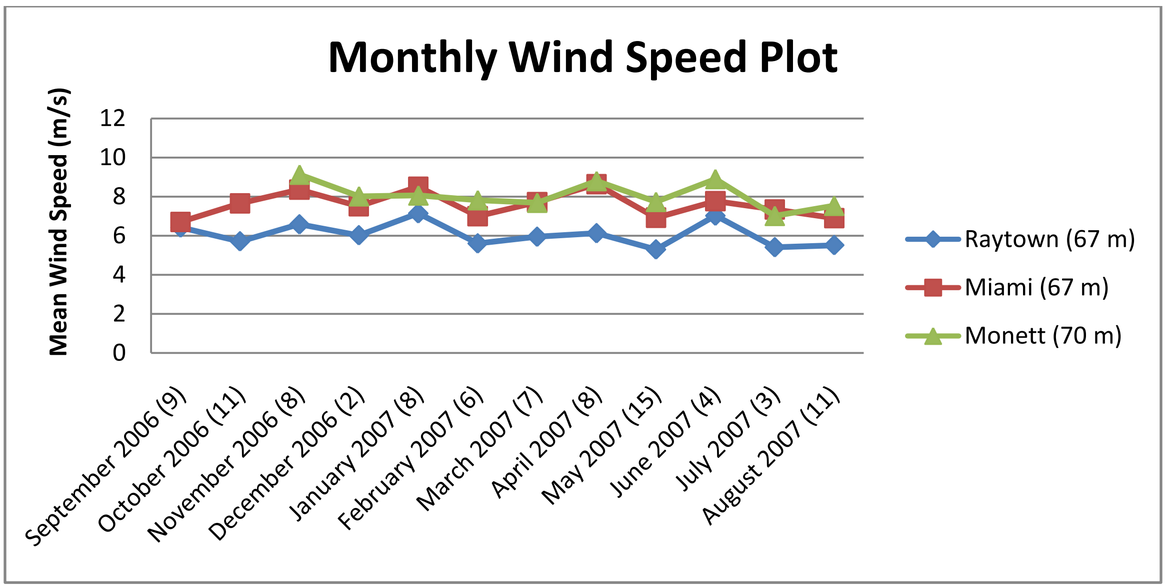


Figure 4.8 A comparison of the mean winds (m s^{-1}) between the low-level winds at Raytown and Miami compared to the high-level winds at Monett during jet events.

The second comparison then involves the middle height averages on the Monett tower (60 m) being plotted against the averages of the lower heights at the other four towers in Figure 4.9 below. Throughout the same time period, the remaining towers compared fairly well to each other. The Monett tower wind speed trend line lies in between the Blanchard and Chillicothe trend lines, so this data appears in reasonable agreement. Despite missing a couple months of data, the Mound City tower gets back in line with the other tower patterns starting at the end of 2006.

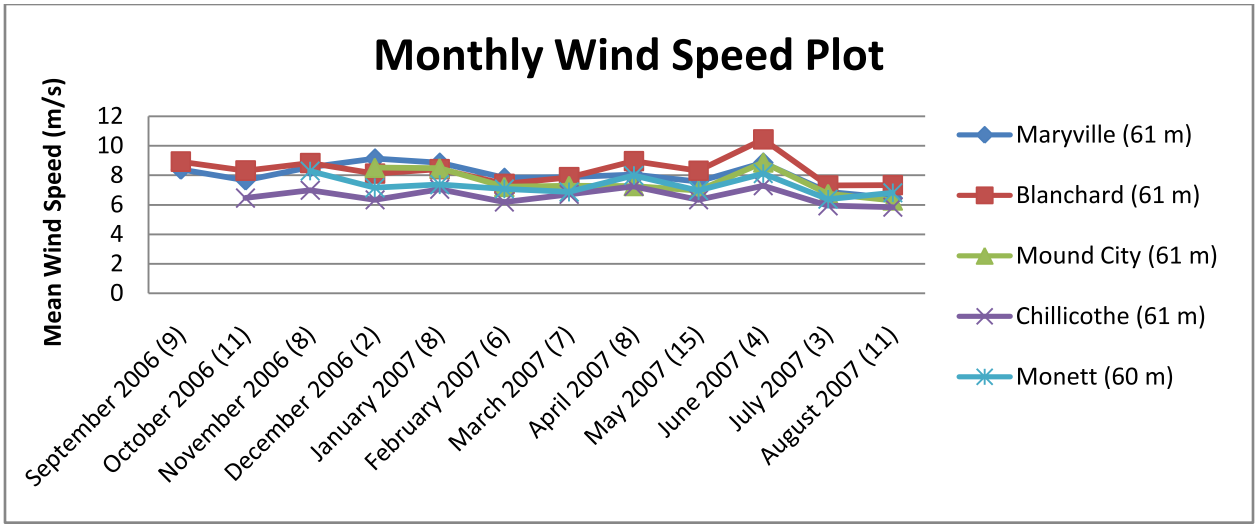


Figure 4.9 A comparison of the mean winds (m s^{-1}) between the low-level winds at Maryville, Blanchard, Mound City, and Chillicothe compared to the mid-level winds at Monett during jet events.

Figures 4.10 and 4.11 shown below are similar to Figures 4.8 and 4.9, but with respect to non-jet event cases. Figure 4.10 shows that, despite showing average winds during non-jet cases, the towers all follow a similar pattern to what is observed in the jet event cases (see Figure 4.8). The only real difference appears to be the magnitude of the mean wind speeds. This is also quite true for the observed mean wind pattern in Figure 4.11 compared to Figure 4.9.

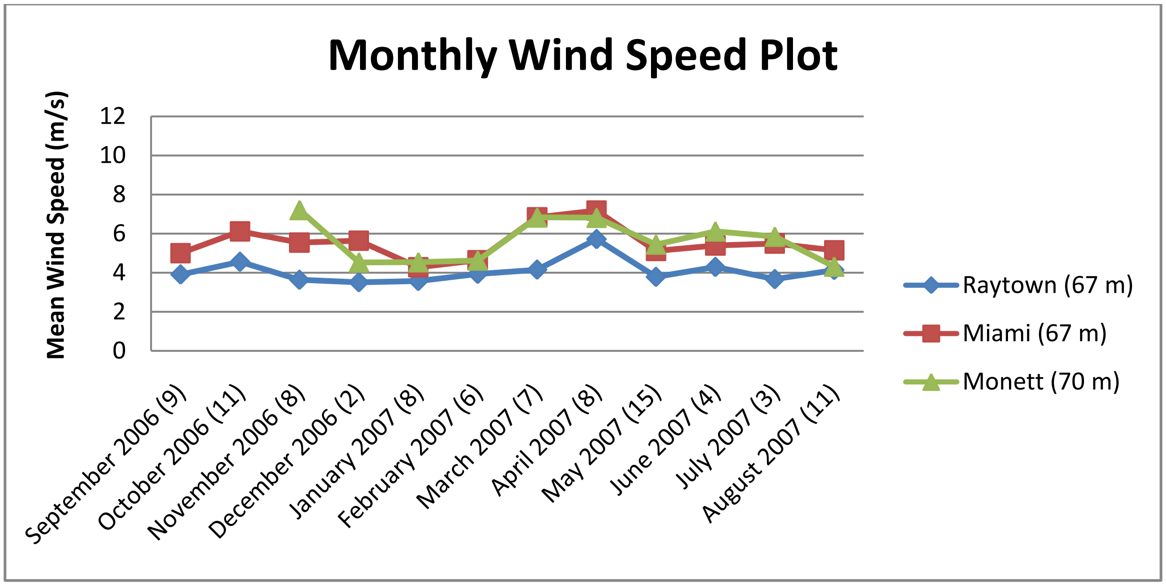


Figure 4.10 A comparison of the mean winds (m s $^{-1}$) between the low-level winds at Raytown and Miami compared to the high-level winds at Monett during non-jet events.

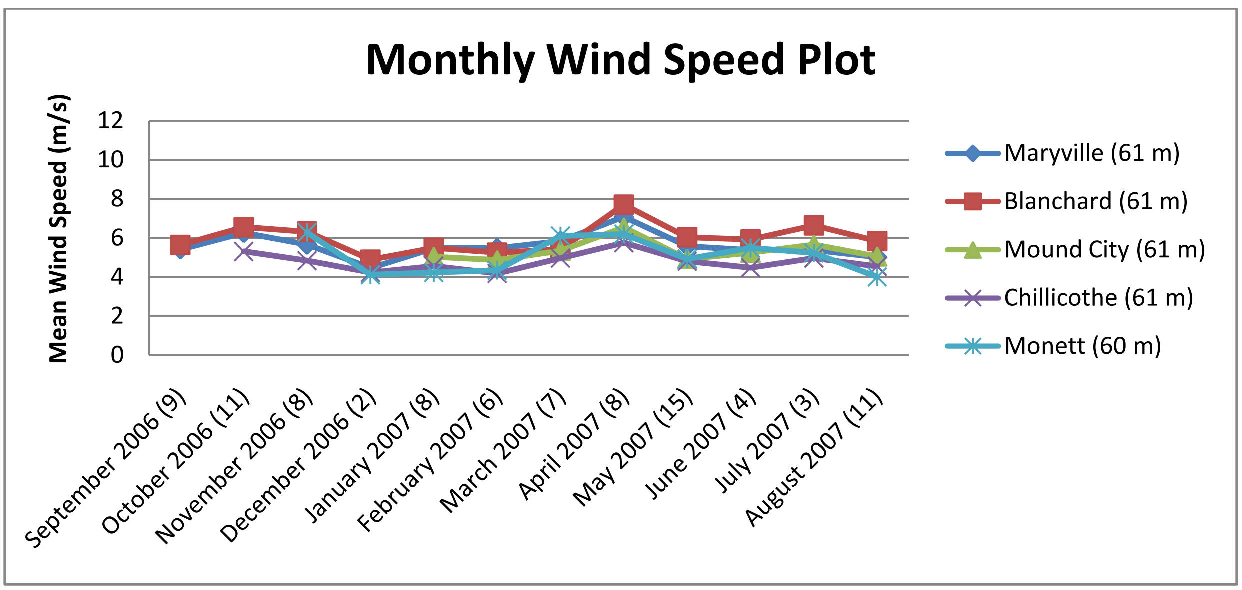


Figure 4.11 A comparison of the mean winds (m s $^{-1}$) between the low-level winds at Maryville, Blanchard, Mound City, and Chillicothe compared to the mid-level winds at Monett during non-jet events.

4.3 Monthly Tall-Tower Wind Shear

Wind shear values (alpha) are presented in this subsection. These alpha values will describe the entire shear that exists between the low-level anemometers and the upper-level anemometers. Separate alpha values were calculated between the low-level anemometers and mid-level anemometers, and between the mid-level anemometers and the upper-level anemometers. However, due to uncertainty in some of the calculated alpha values between the lower and middle heights along with a few months of bad data for the Mound City and Miami towers, alpha values seemed more reasonable to investigate between the lower and upper-level anemometers.

4.3.1 Mound City, Maryville, and Miami Comparison

When investigating differences in wind shear between the seven towers, the towers were organized and split up into three groups, depending on the height at which the anemometers were originally placed. The first group consists of the Maryville, Miami, and Mound City towers since the anemometers are all placed at relatively similar heights. Calculated alpha values during jet event cases for these towers and trends in alpha values by month can be seen in Table 4.16 and Figure 4.12 respectively. Values for the Mound City tower are not plotted for the months of October and November that correspond to bad data. The Mound City tower also appears to have less alpha variation throughout the 2007 time period, while the Miami tower has a greater variation in alpha during the jet events.

Values for the entire period, highlighted in blue, represent the mean alpha for each tower throughout the entire observational period. Essentially, the values in the last row of Table 4.16, 4.17, etc. are a mean of all the monthly means combined together for each of the respective towers.

Month	Mound City	Maryville	Miami
September 2006 (9)	0.31	0.38	0.41
October 2006 (11)	N/A	0.39	0.51
November 2006 (8)	N/A	0.25	0.32
December 2006 (2)	0.33	0.43	0.50
January 2007 (8)	0.29	0.35	0.38
February 2007 (6)	0.29	0.25	0.31
March 2007 (7)	0.32	0.36	0.42
April 2007 (8)	0.27	0.32	0.45
May 2007 (15)	0.31	0.35	0.47
June 2007 (4)	0.30	0.36	0.34
July 2007 (3)	0.41	0.46	0.68
August 2007 (11)	0.38	0.42	0.58
Entire Period	0.32	0.36	0.45

Table 4.16 Monthly calculated average alpha values at Mound City, Maryville, and Miami during jet events.

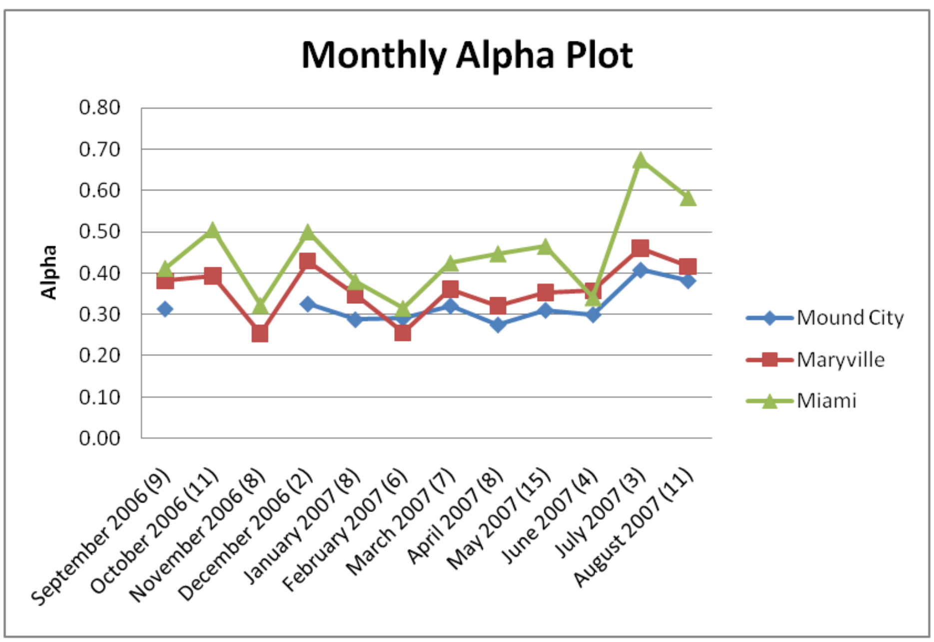


Figure 4.12 A graphical display of alpha values for the entire period at Mound City, Maryville, and Miami during jet events.

Non-jet event case results of alpha can be seen in Table 4.17 and graphically in Figure 4.13. For some unknown reason, the December 2006 alpha value calculated by MATLAB for the non-jet events was originally negative and appeared questionable as the mean wind speed did increase between the lower and upper anemometers on the tower according to MATLAB analysis (refer back to Table 4.7). Therefore, this alpha value (highlighted in yellow) was corrected such that it would not factor into the analysis, and is not included in Figure 4.13.

Month	Mound City	Maryville	Miami
September 2006 (9)	0.44	0.33	0.26
October 2006 (11)	N/A	0.43	0.39
November 2006 (8)	N/A	0.37	0.43
December 2006 (2)	N/A	0.31	0.26
January 2007 (8)	0.32	0.30	0.24
February 2007 (6)	0.25	0.32	0.20
March 2007 (7)	0.34	0.38	0.41
April 2007 (8)	0.33	0.33	0.43
May 2007 (15)	0.35	0.37	0.46
June 2007 (4)	0.42	0.47	0.37
July 2007 (3)	0.44	0.55	0.63
August 2007 (11)	0.41	0.40	0.46
Entire Period	0.37	0.38	0.38

Table 4.17 Monthly calculated average alpha values at Mound City, Maryville, and Miami during non-jet events.

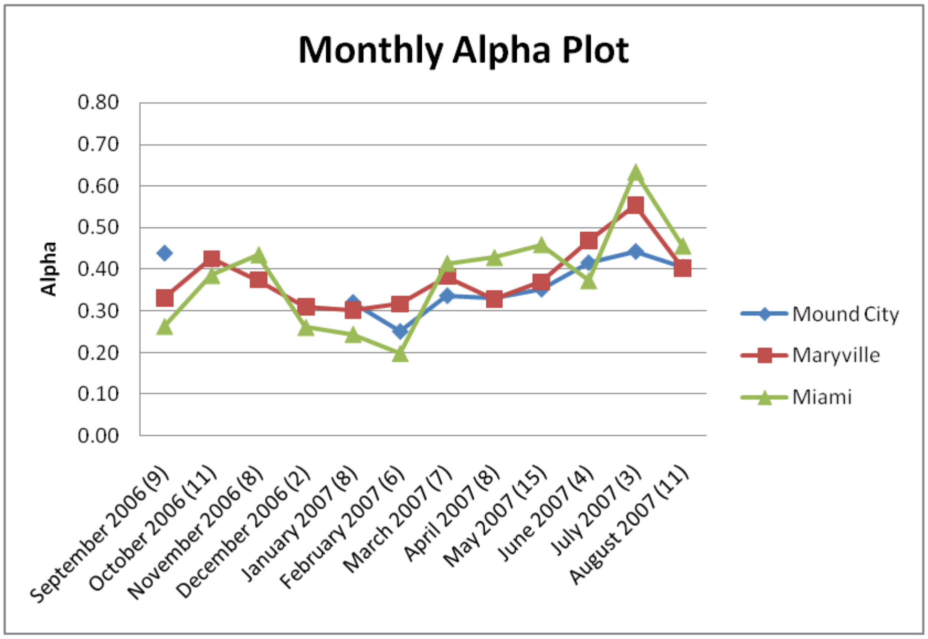


Figure 4.13 A graphical display of alpha values for the entire period at Mound City, Maryville, and Miami during non-jet events.

Both Figures 4.12 and 4.13 show similar trends in alpha for the Mound City, Maryville and Miami towers during jet and non-jet events. However, when each average monthly alpha in Tables 4.16 and 4.17 is averaged again over the whole period, both the Mound City and Maryville towers have higher average alpha values during non-jet events versus jet events. This is likely due to higher monthly alphas during the months of June and July for the non-jet event cases. The Miami tower is the only one that has a much higher overall alpha average in the jet events compared to the non-jet events.

4.3.2 Blanchard, Raytown, and Chillicothe Comparison

The second group then consists of the Blanchard, Raytown, and Chillicothe towers. Calculated alpha values during jet event cases for these towers and trends in alpha values by month can be seen in Table 4.18 and Figure 4.14 respectively. Non-jet event case values of alpha can be seen in Table 4.19 and graphically in Figure 4.15.

Month	Blanchard	Raytown	Chillicothe
September 2006 (9)	0.33	0.47	N/A
October 2006 (11)	0.32	0.61	0.43
November 2006 (8)	0.28	0.49	0.33
December 2006 (2)	0.43	0.63	0.45
January 2007 (8)	0.30	0.27	0.32
February 2007 (6)	0.25	0.28	0.31
March 2007 (7)	0.35	0.43	0.37
April 2007 (8)	0.26	0.47	0.35
May 2007 (15)	0.29	0.55	0.39
June 2007 (4)	0.23	0.36	0.30
July 2007 (3)	0.37	0.57	0.46
August 2007 (11)	0.31	0.52	0.41
Entire Period	0.31	0.47	0.38

Table 4.18 Monthly calculated average alpha values at Blanchard, Raytown, and Chillicothe during jet events.

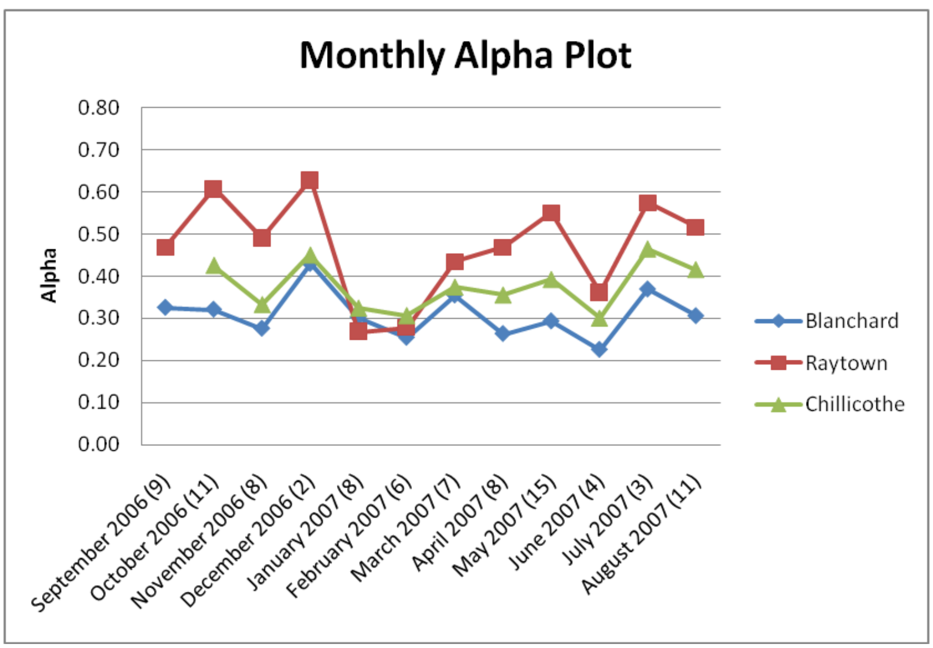


Figure 4.14 A graphical display of alpha values for the entire period at Blanchard, Raytown, and Chillicothe during jet events.

Month	Blanchard	Raytown	Chillicothe
September 2006 (9)	0.34	0.50	N/A
October 2006 (11)	0.35	0.49	0.34
November 2006 (8)	0.25	0.76	0.42
December 2006 (2)	0.29	0.62	0.34
January 2007 (8)	0.20	0.31	0.29
February 2007 (6)	0.26	0.18	0.27
March 2007 (7)	0.29	0.52	0.44
April 2007 (8)	0.26	0.44	0.36
May 2007 (15)	0.32	0.55	0.40
June 2007 (4)	0.37	0.58	0.41
July 2007 (3)	0.36	0.70	0.50
August 2007 (11)	0.27	0.49	0.44
Entire Period	0.30	0.51	0.38

Table 4.19 Monthly calculated average alpha values at Blanchard, Raytown, and Chillicothe during non-jet events.

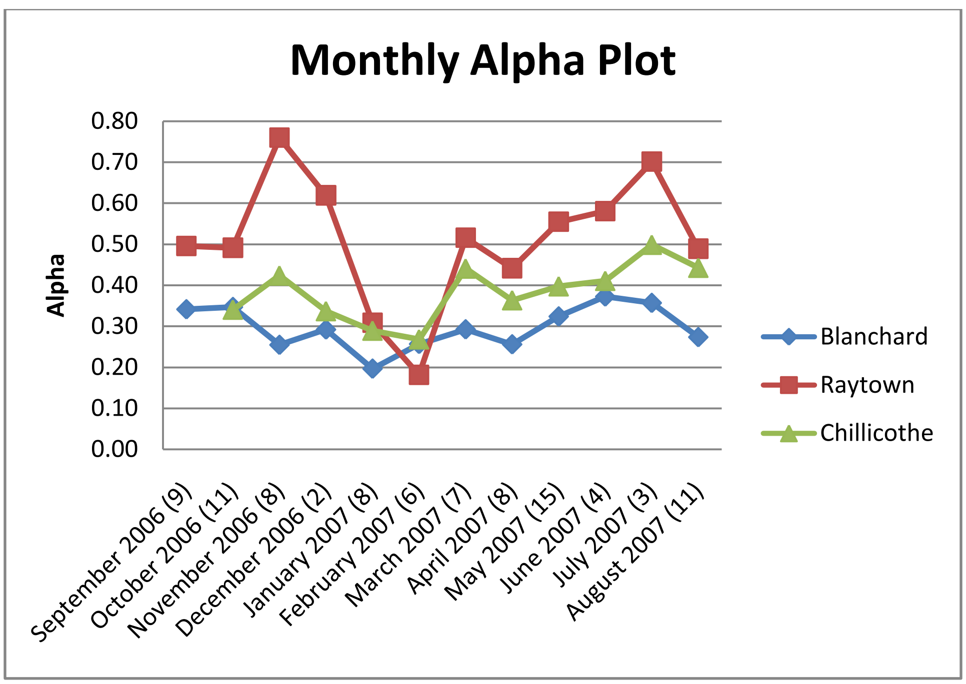


Figure 4.15 A graphical display of alpha values for the entire period at Blanchard, Raytown, and Chillicothe during non-jet events.

According to Figures 4.14 and 4.15, Raytown has higher mean monthly alphas compared to Blanchard and Chillicothe. When each monthly alpha value in table 4.18

and 4.19 is averaged over the whole period, the Raytown tower is the only one that has a significantly higher mean alpha in the non-jet event cases. Meanwhile, the Blanchard and Chillicothe towers result in roughly the same mean alpha during both the jet and non-jet event cases.

4.3.3 Monett

Unfortunately, the heights of the Monett anemometers do not match up very well with the instrument heights of any of the other towers. To better investigate the Monett wind shear data, the values of calculated alpha will be compared between jet event days and non-jet event days only without being directly compared to any other tower. These results can be seen in Table 4.20 and graphically displayed in Figure 4.16.

With the exception of the very beginning and ending of the time period, alpha values were greater in jet event cases. When each of the monthly alpha values was averaged together, the overall mean value of alpha was slightly higher in the jet event cases.

Month	Jet Event	Non-Jet Event
November 2006 (8)	0.44	0.72
December 2006 (2)	0.58	0.43
January 2007 (8)	0.49	0.36
February 2007 (6)	0.50	0.31
March 2007 (7)	0.56	0.51
April 2007 (8)	0.46	0.45
May 2007 (15)	0.53	0.53
June 2007 (4)	0.44	0.58
July 2007 (3)	0.48	0.53
August 2007 (11)	0.49	0.40
Entire Period	0.50	0.48

Table 4.20 Monthly calculated average alpha values at Monett during both jet and non-jet events.

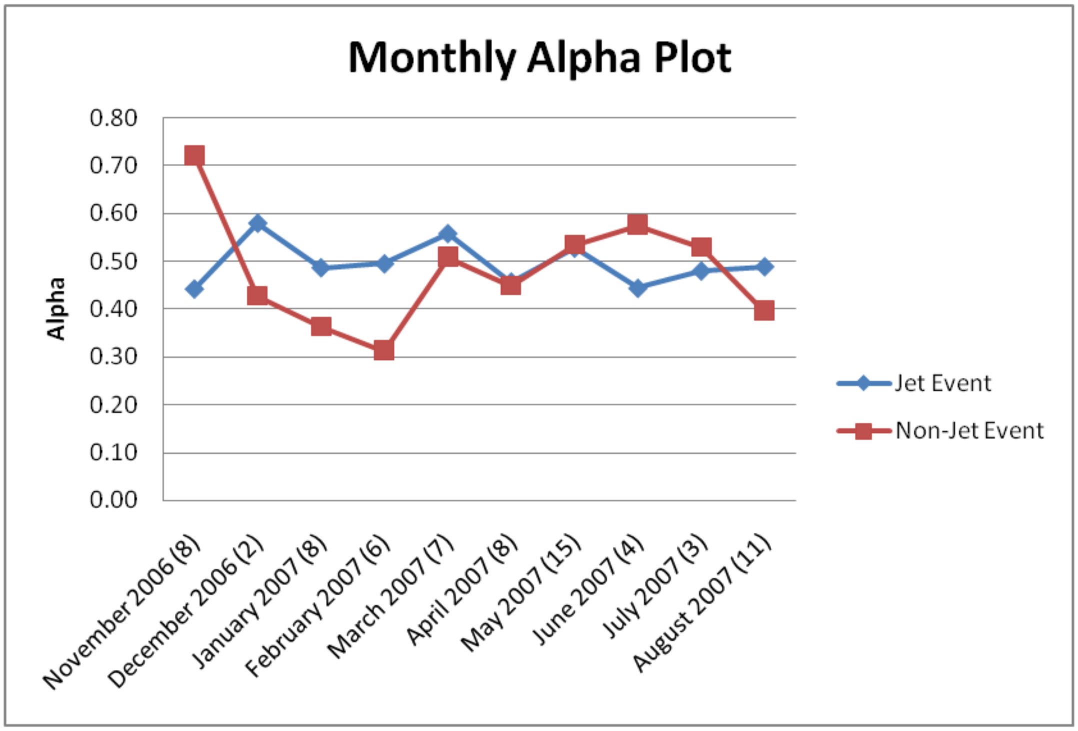


Figure 4.16 A graphical display of alpha values for the entire period at Monett during both jet and non-jet events.

4.4 Friction Velocity Comparisons

Friction velocity (m s^{-1}) calculated results will be presented on the following pages to supplement the alpha calculations presented in the previous section. Higher values of u_* should coincide with higher values of alpha, and one would expect therefore to see similar results as seen in Figures 4.5, 4.6, etc. at each of the towers. It is also of interest to calculate the mean friction velocity over the entire observational period to determine whether higher values are more predominant in jet cases or non-jet cases.

4.4.1 Mound City, Maryville, and Miami Comparison

During the jet events, Miami consistently has higher friction velocities compared to the Maryville and Mound City towers throughout the period as seen in Figure 4.17. With respect to the non-jet events shown in Figure 4.18, the same is fairly true particularly during the last half of the observational period. These trends in friction velocities mirror the trends in mean monthly alphas for each tower. Again, the friction velocity at Mound City in December (highlighted in yellow) was excluded from this analysis.

Month	Mound City	Maryville	Miami
September 2006 (9)	1.15	1.46	1.27
October 2006 (11)	N/A	1.36	1.86
November 2006 (8)	N/A	0.94	1.32
December 2006 (2)	1.28	2.00	2.31
January 2007 (8)	1.05	1.38	1.43
February 2007 (6)	0.93	0.92	1.00
March 2007 (7)	1.01	1.25	1.48
April 2007 (8)	0.88	1.16	1.75
May 2007 (15)	0.98	1.20	1.56
June 2007 (4)	1.05	1.30	1.22
July 2007 (3)	1.23	1.60	2.44
August 2007 (11)	1.13	1.30	1.96
Entire Period	1.07	1.32	1.63

Table 4.21 Monthly calculated average friction (m s^{-1}) velocity values at Mound City, Maryville, and Miami during jet events.

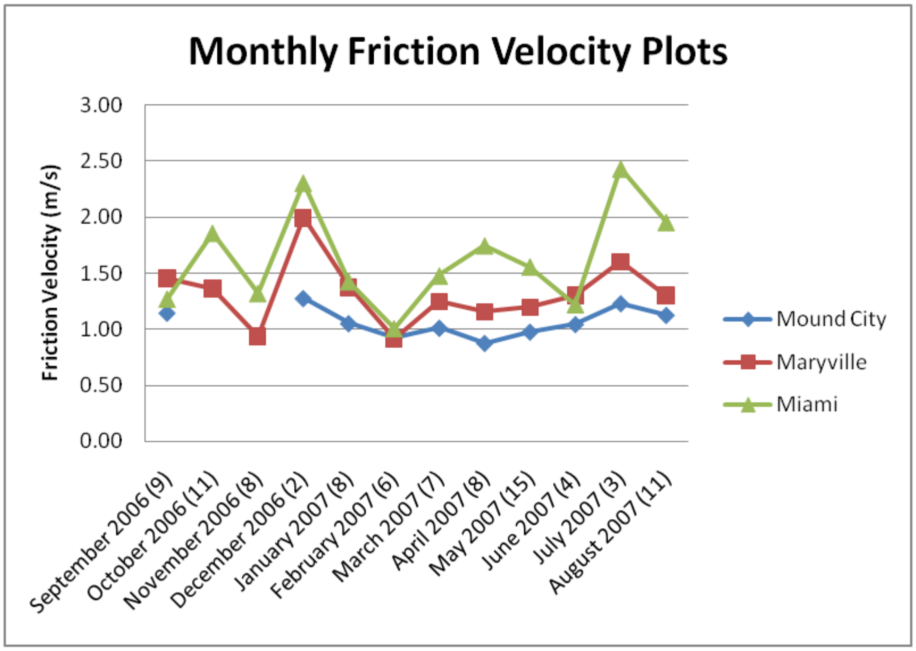


Figure 4.17 A graphical display of friction velocity (m s^{-1}) values for the entire period at Mound City, Maryville, and Miami during jet events.

Again, as with the Mound City alpha value for December during the non-jet events, the mean friction velocity value comes out negative using the MATLAB program. Therefore, the mean value of this month (highlighted in yellow) in Table 4.22 was left out, such that it does not figure into the overall analysis.

The values of the mean friction velocities over the entire periods indicate higher mean values during jet events versus non-jet events, as indicated by the last rows in Tables 4.21 and 4.22. This comes into better agreement with expected results of shear in the jet events to the non-jet event time periods.

Month	Mound City	Maryville	Miami
September 2006 (9)	1.09	0.96	0.82
October 2006 (11)	N/A	1.32	1.22
November 2006 (8)	N/A	1.06	1.33
December 2006 (2)	N/A	1.05	0.75
January 2007 (8)	0.90	1.01	0.55
February 2007 (6)	0.64	0.89	0.44
March 2007 (7)	0.87	1.06	1.33
April 2007 (8)	1.08	1.16	1.59
May 2007 (15)	0.88	1.09	1.27
June 2007 (4)	1.00	1.20	1.00
July 2007 (3)	1.12	1.45	2.06
August 2007 (11)	1.02	1.03	1.37
Entire Period	0.96	1.11	1.14

Table 4.22 Monthly calculated average friction velocity (m s $^{-1}$) values at Mound City, Maryville, and Miami during non-jet events.

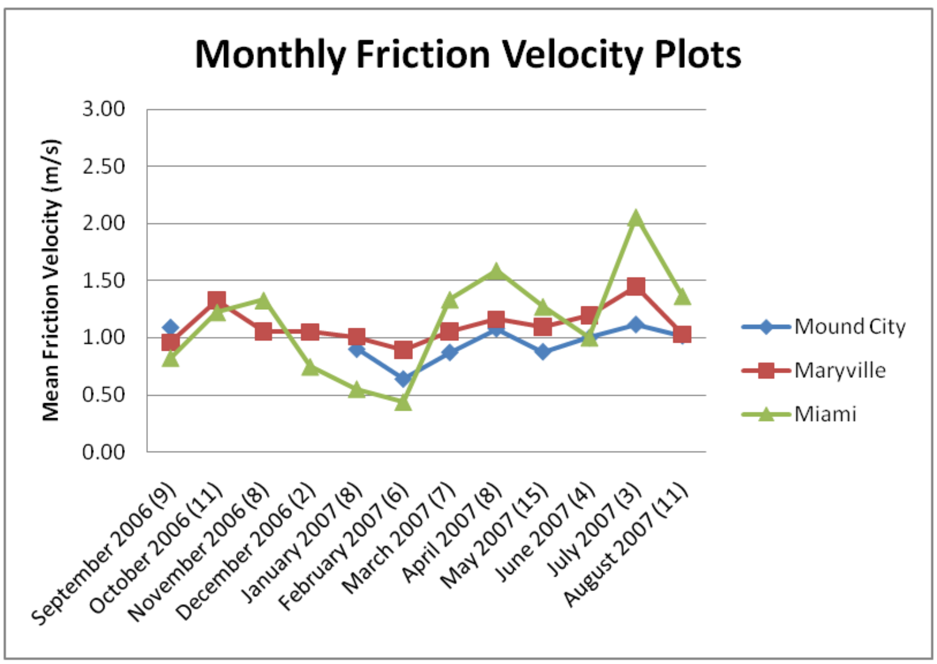


Figure 4.18 A graphical display of friction velocity (m s $^{-1}$) values for the entire period at Mound City, Maryville, and Miami at during non-jet events.

4.4.2 Blanchard, Raytown, and Chillicothe Comparison

During jet events, the Raytown tower had consistently higher friction velocities compared to the other two towers during much of the period. The trends in friction velocity at the Blanchard and Chillicothe towers often mirrored each other throughout the same time period as well.

When investigating non-jet events, the Raytown tower again had much higher friction velocities compared Blanchard and Chillicothe towers. However, during this time period Figure 4.20 shows that the Blanchard and Chillicothe towers were in less agreement compared to the jet event cases shown in Figure 4.19.

Month	Blanchard	Raytown	Chillicothe
September 2006 (9)	1.33	1.52	N/A
October 2006 (11)	1.29	1.78	1.32
November 2006 (8)	1.09	1.60	1.12
December 2006 (2)	1.66	2.21	1.52
January 2007 (8)	1.11	0.80	1.03
February 2007 (6)	0.86	0.75	0.88
March 2007 (7)	1.29	1.20	1.14
April 2007 (8)	1.11	1.44	1.20
May 2007 (15)	1.12	1.56	1.16
June 2007 (4)	1.02	1.17	1.01
July 2007 (3)	1.30	1.57	1.33
August 2007 (11)	1.15	1.43	1.19
Entire Period	1.19	1.42	1.17

Table 4.23 Monthly calculated average friction velocity (m s^{-1}) values at Blanchard, Raytown, and Chillicothe during jet events.

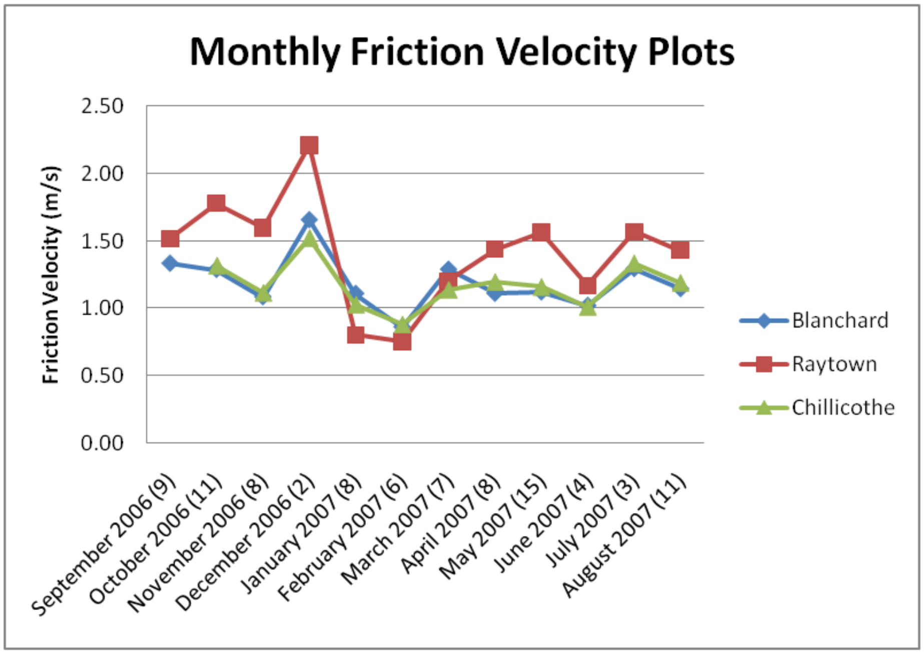


Figure 4.19 A graphical display of friction velocity (m s^{-1}) values for the entire period at Blanchard, Raytown, and Chillicothe during jet events.

Comparisons of the mean values over the entire time period indicate that the Blanchard tower experienced a greater spread in values between the jet event and non-jet event cases. However, Raytown did have a higher mean frictional velocity for the entire period compared to the Blanchard and Chillicothe towers.

Month	Blanchard	Raytown	Chillicothe
September 2006 (9)	1.09	1.26	N/A
October 2006 (11)	1.10	1.22	0.95
November 2006 (8)	0.82	1.87	1.10
December 2006 (2)	1.08	1.56	0.87
January 2007 (8)	0.60	0.69	0.68
February 2007 (6)	0.61	0.36	0.58
March 2007 (7)	0.84	1.12	1.06
April 2007 (8)	0.97	1.31	1.10
May 2007 (15)	1.06	1.35	0.98
June 2007 (4)	1.08	1.39	0.96
July 2007 (3)	1.14	1.63	1.33
August 2007 (11)	0.79	1.18	1.07
Entire Period	0.93	1.24	0.97

Table 4.24 Monthly calculated average friction velocity (m s^{-1}) values at Blanchard, Raytown, and Chillicothe during non-jet events.

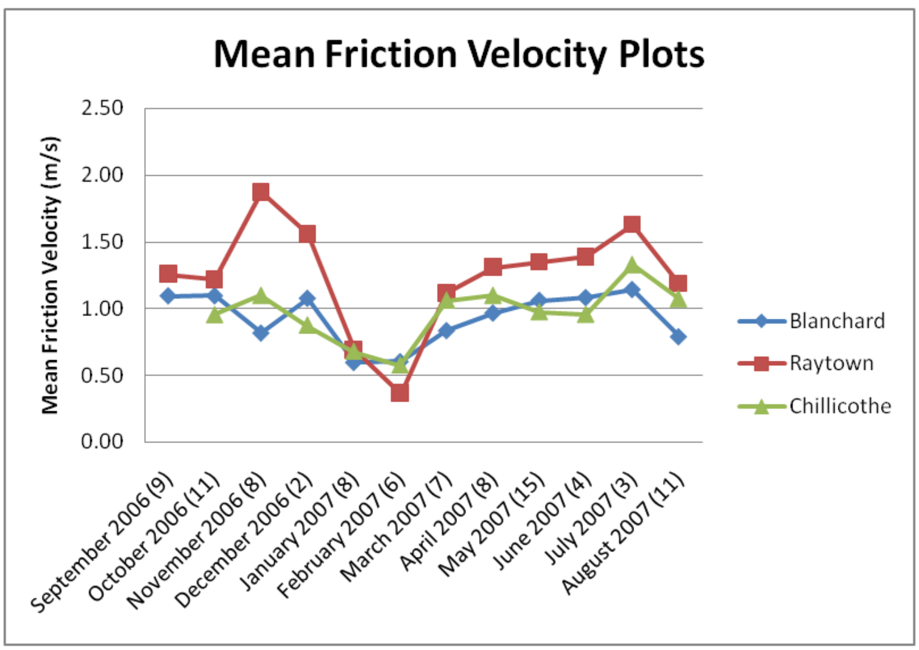


Figure 4.20 A graphical display of friction velocity (m s^{-1}) values for the entire period at Blanchard, Raytown, and Chillicothe during non-jet events.

4.4.3 Monett

Friction velocities during the jet events are much higher than they are for the non-jet events as indicated by Table 4.23 and Figure 4.21. The weaker velocities during the jet events occur mainly during the summer while the ones in the non-jet events occur primarily in the winter months.

Month	Jet Event	Non-Jet Event
November 2006 (8)	1.56	1.84
December 2006 (2)	1.69	0.83
January 2007 (8)	1.43	0.76
February 2007 (6)	1.46	0.62
March 2007 (7)	1.66	1.39
April 2007 (8)	1.49	1.25
May 2007 (15)	1.54	1.32
June 2007 (4)	1.42	1.31
July 2007 (3)	1.26	1.18
August 2007 (11)	1.37	0.79
Entire Period	1.49	1.13

Table 4.25 Monthly calculated average friction velocity (m s^{-1}) values at Monett during both jet and non-jet events.

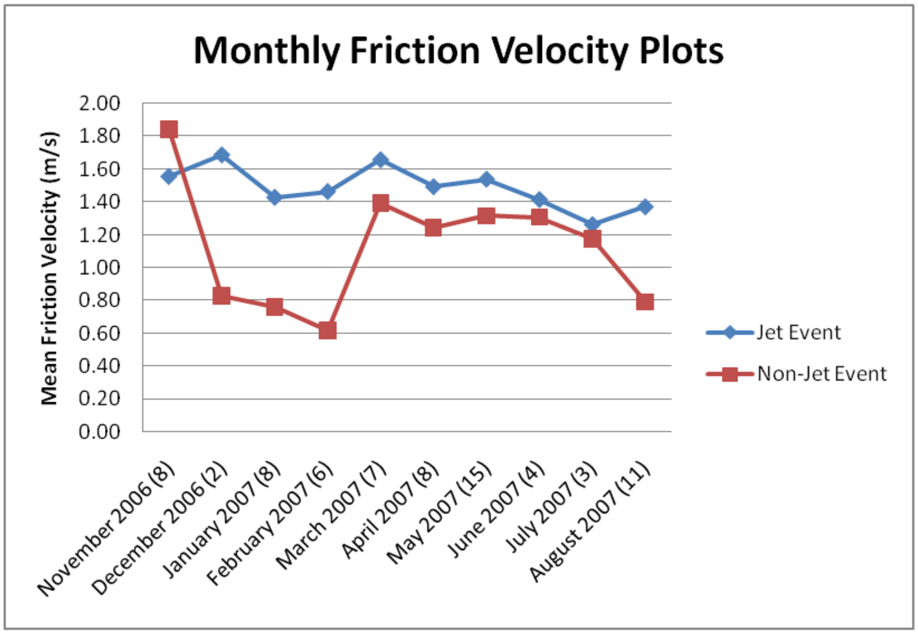


Figure 4.21 A graphical display of friction velocity (m s^{-1}) values for the entire period at Monett during both jet and non-jet events.

4.4 Strong Jet Cases vs Weak Jet Cases

Another interesting analysis will involve comparing data between strong jet events (>20 m s^{-1}) and weak jet events (between 16 m s^{-1} and 20 m s^{-1}). It is a goal then to obtain results for both strong and weak jet events which appear to have an effect on all 7 towers in this study. According to the regional reanalysis used to originally identify possible jet events, 66 out of the 110 strong jet events appeared to affect all 7 towers in the study. Meanwhile, a smaller portion of weak events appeared to affect all 7 towers (13 out of 48 weak events).

A majority of the strong events also occurred in the late fall and winter months, which makes sense as this is the time when the majority of jet events was originally found to occur. This is also the same time period when more of the weak jet events occur. July 2007 was the only month of the period not to have a single strong event.

Meanwhile, 3 months over the same period failed to have a single weak event: September 2006, November 2006, and May 2007.

A downside to this part of the research is that a smaller dataset is available to draw reasonable conclusions from. The amount of strong jet days analyzed is much greater to the amount of weak jet days. Therefore, drawing conclusions from this may prove difficult since it is like comparing a larger group of apples to a smaller group.

Another thing to remember is that the analysis between strong and weak events samples a different size of data that was originally used in the first part of the results section. For example, the original analysis in December 2006 used only 2 days to figure into that analysis. However, when looking at the amount of strong jets that affected all the towers in the same month, a larger number of days (11) was used in this part of the analysis. Careful consideration also went in to ensuring that the same days used in the original analysis between jet and non-jet events were also used in the strong versus weak jet event analysis. Again, due to working with such a smaller sample size made this impossible to do in most situations.

Since a much smaller dataset will be used to draw results upon, it may be easier to visualize the results during strong and weak jet cases by plotting charts of the monthly mean winds for each tower instead of just looking at tables of just numbers. The frequency of strong and weak events during each month will also be located on the chart, such that conclusions of results may be made a bit easier.

4.4.1. Maryville

During the strong jet events, mean wind speeds remained fairly constant at all three heights. These winds ranged predominantly between 8 m s^{-1} and 12 m s^{-1} throughout most of the period, as indicated by Figure 4.22. Figure 4.23 shows that during the weak jet events, the mean wind speeds were a bit higher in months that only had 1 weak event at the beginning of the period. When more weak events occurred in the winter months, the mean wind speed for all three heights decreased. Wind speeds for weak events tended to drop off a bit during the summer time as well, coinciding with few weak events. The difference in wind speed magnitudes between jet and non-jet events likely has to do with the number of events that figure into the averages for each respective month.

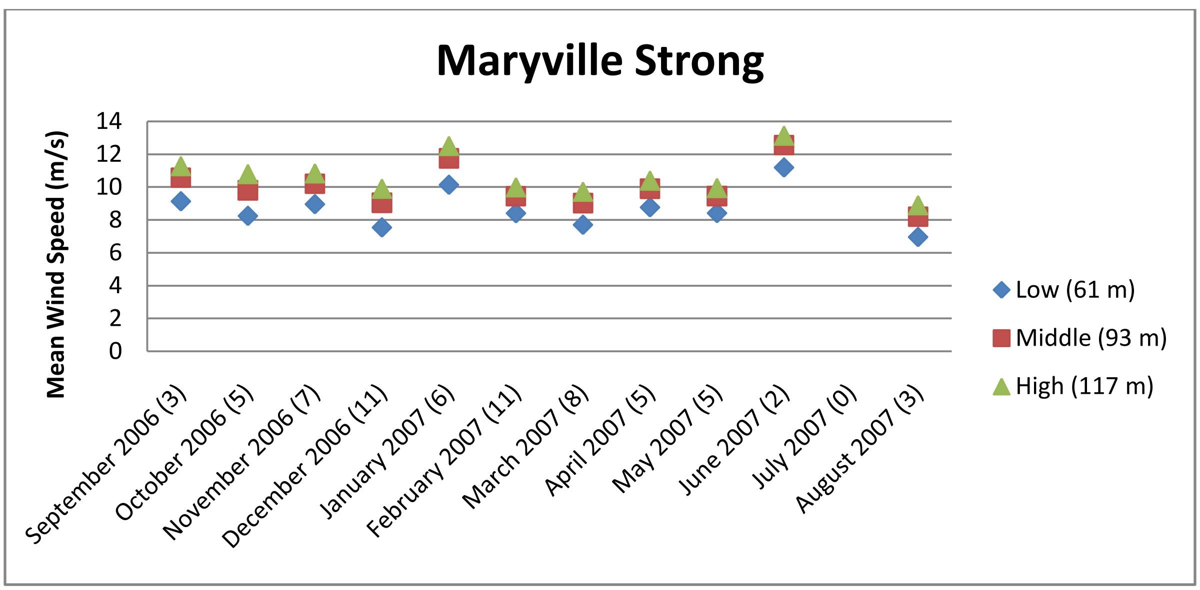


Figure 4.22 Mean monthly wind speeds (m s^{-1}) at Maryville during strong jets.

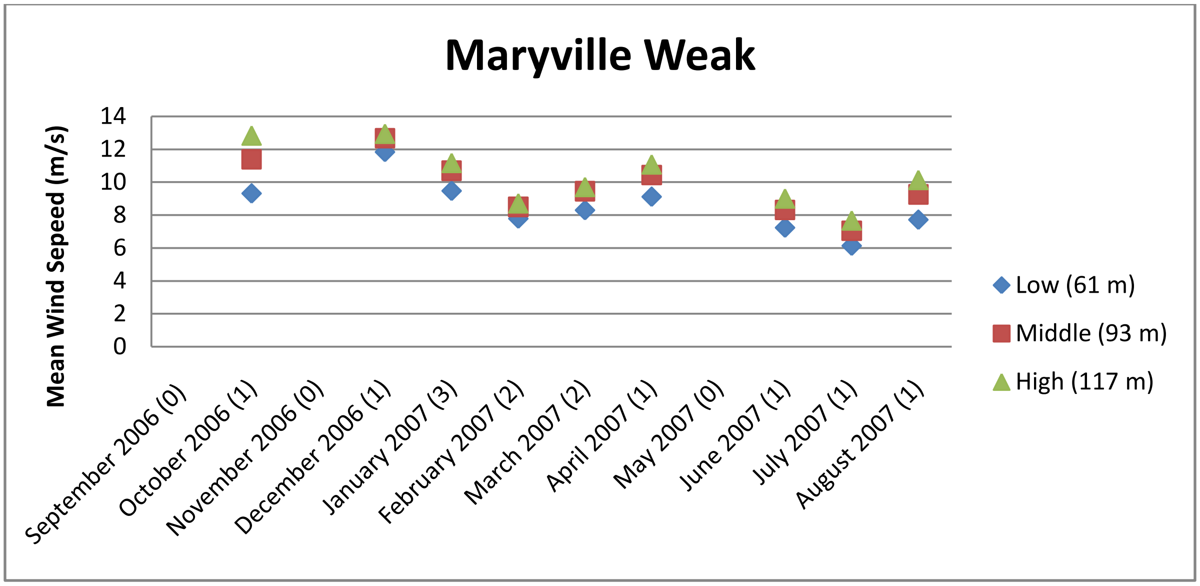


Figure 4.23 Mean monthly wind speeds (m s^{-1}) at Maryville during weak jets.

4.4.2 Blanchard

Just like the Maryville location, the monthly mean wind speeds remained fairly constant throughout much of the period. However, the monthly wind speeds shown in Figure 4.24 indicate that most of them fell between a range between 10 m s^{-1} and 12 m s^{-1}, particularly at the 97 m and 137 m anemometers. Like the Maryville tower as well during weak jet events, the maximums in wind speed magnitude occurred in months that only observed one weak event such as October 2006 and April 2007.

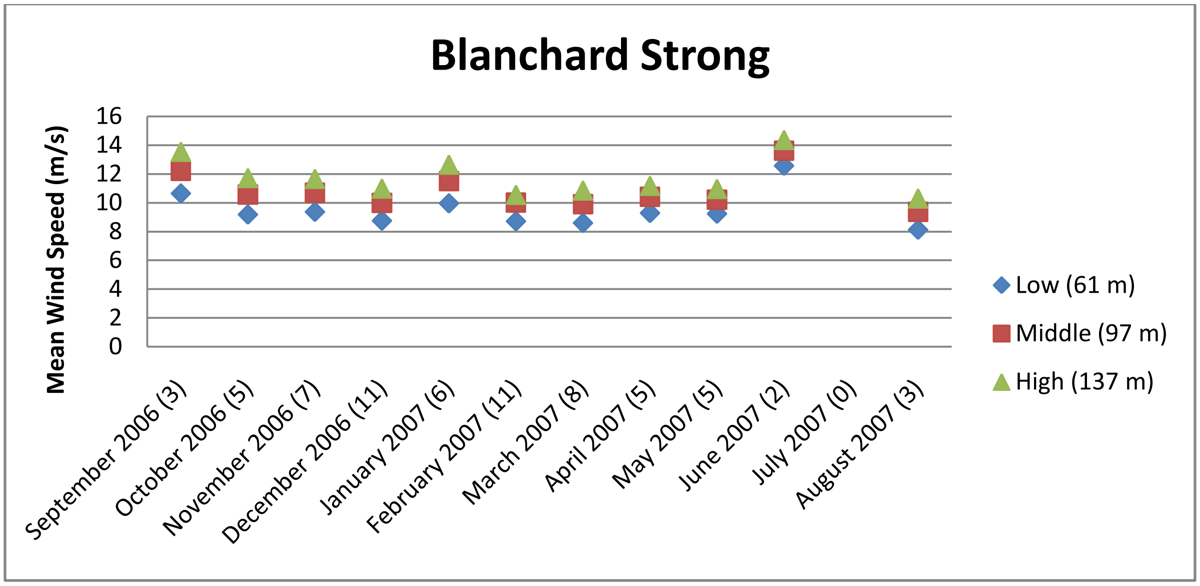


Figure 4.24 Mean monthly wind speeds ($m\ s^{-1}$) at Blanchard during strong jets.

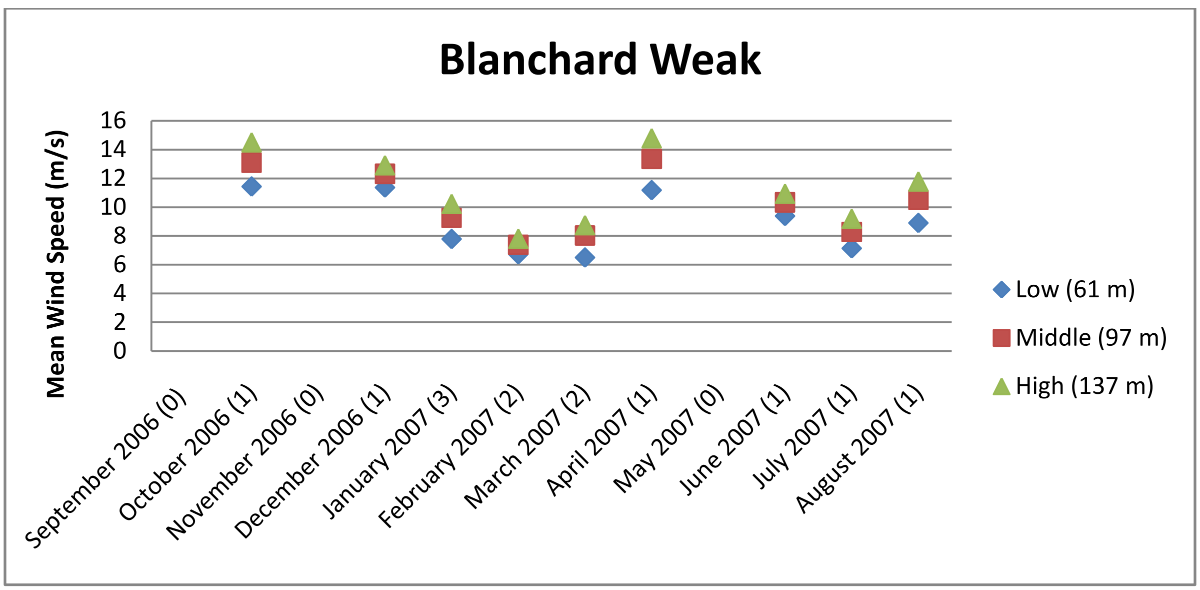


Figure 4.25 Mean monthly wind speeds ($m\ s^{-1}$) at Blanchard during weak jets.

4.4.3 Mound City

Minus the period of data missing for the 61 m anemometers at the end of 2006, the winds manage to remain fairly consistent throughout the period according to Figure 4.26. Most of the data at the 97 m and 117 m anemometer heights ranges between 8 m s^{-1} and 10 m s^{-1} throughout much of this period with respect to the strong jet events. With respect to the weak jet events, the results for Mound City mirrored those of the other towers. When more than one weak event occurred in a month (i.e. February 2007), the average wind speeds hovered around 8 m s^{-1}. Figure 4.26 shows that the same magnitude of wind speeds is experienced in the summer months as well. This makes some sense, given the expected weaker winds during the summer.

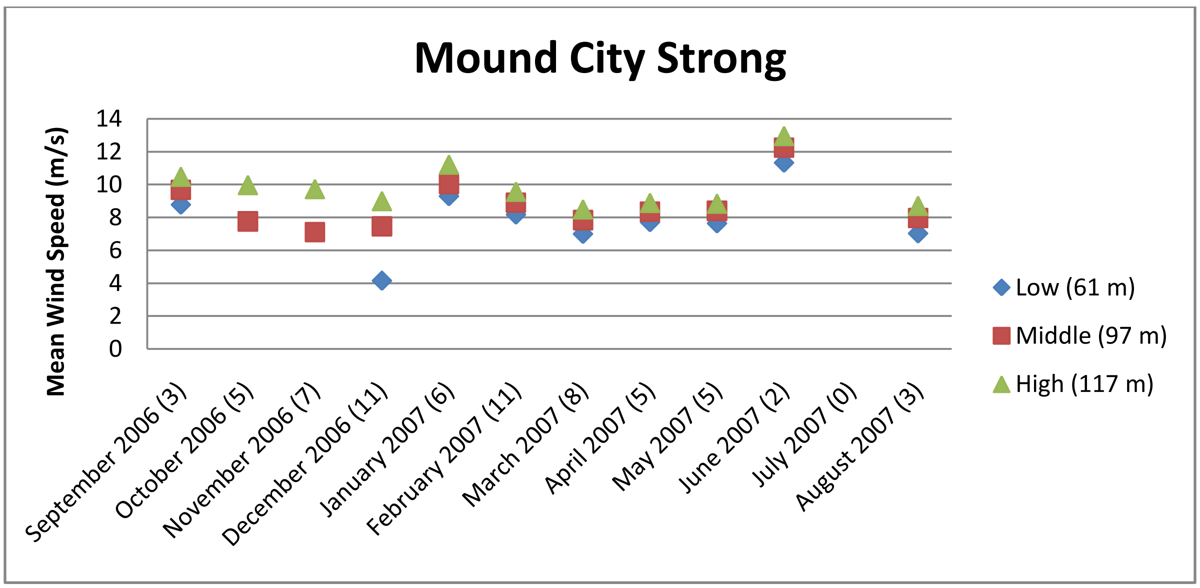


Figure 4.26 Mean monthly wind speeds (m s^{-1}) at Mound City during strong jets.

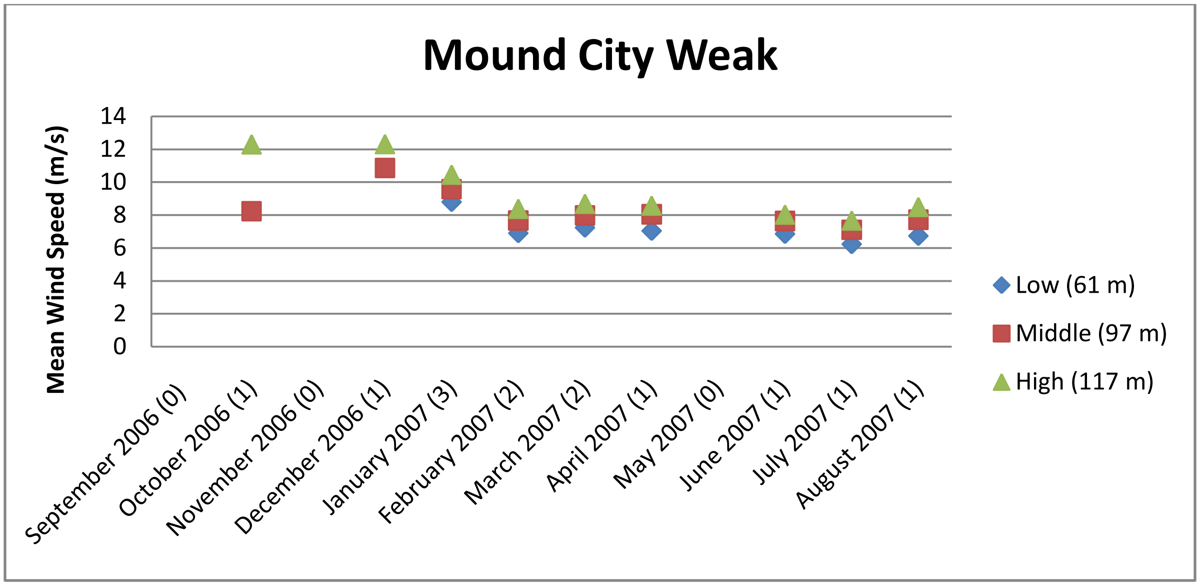


Figure 4.27 Mean monthly wind speeds (m s $^{-1}$) at Mound City during weak jets.

4.4.4 Chillicothe

Aside from no strong jets occurring in July 2007, the mean wind speed pattern remains fairly consistent throughout the period. The wind speed ranges between 7 m s $^{-1}$ and 10 m s $^{-1}$ from the bottom anemometer height to the top anemometer height. During the weak jet events, most of the mean wind speeds hovered around 8 m s $^{-1}$ during the months that have more than one weak event (January, February, and March).

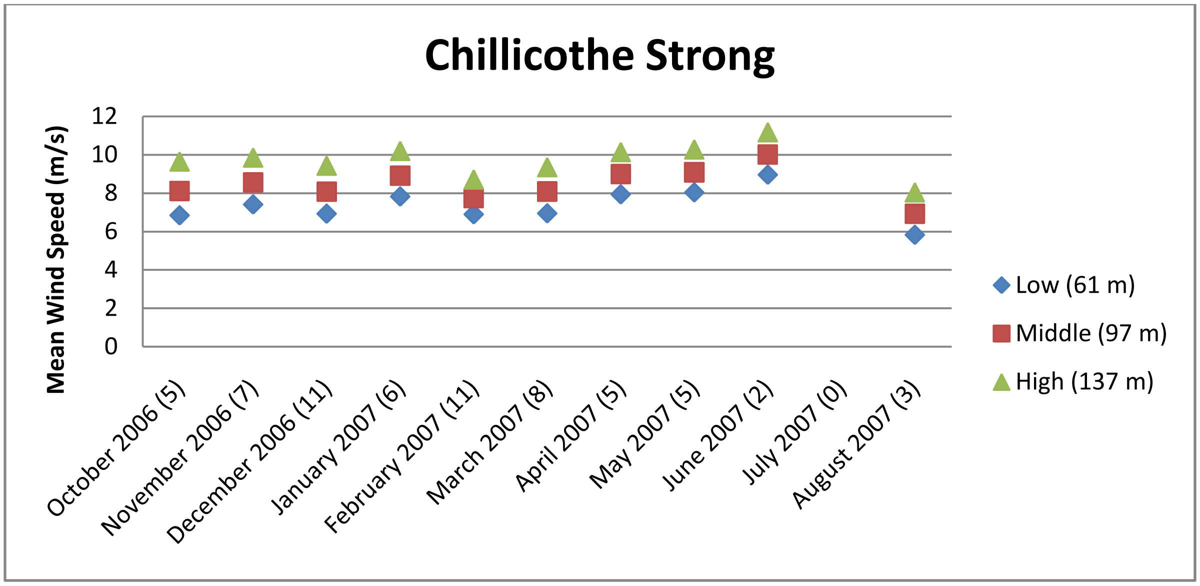


Figure 4.28 Mean monthly wind speeds (m s $^{-1}$) at Chillicothe during strong jets.

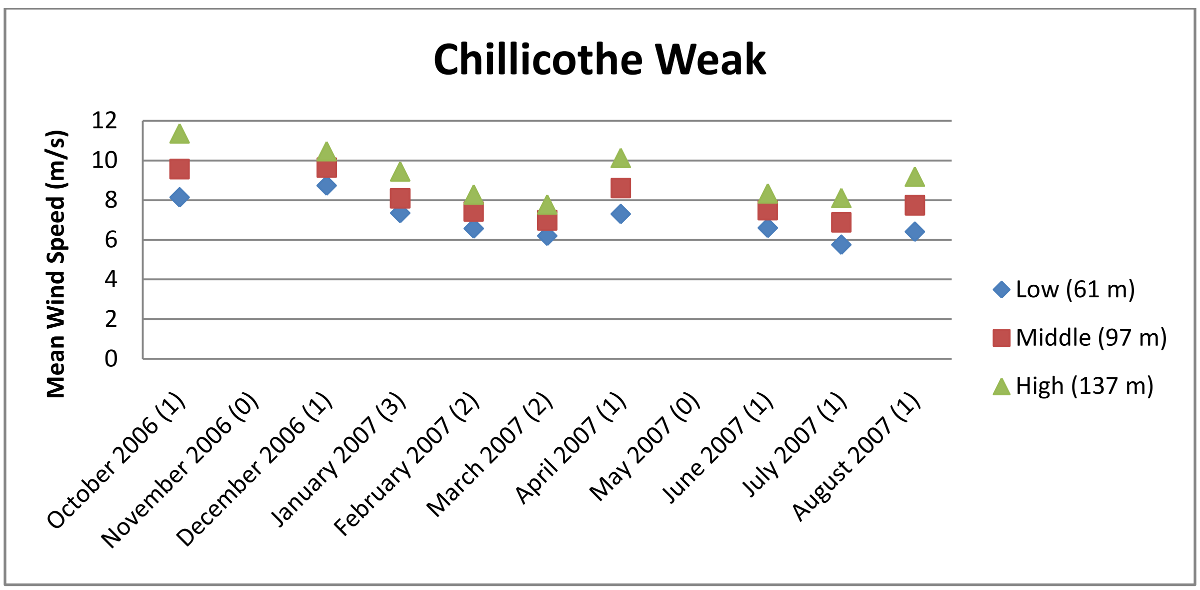


Figure 4.29 Mean monthly wind speeds (m s $^{-1}$) at Chillicothe during weak jets.

4.4.5 Miami

With the exception of bad data at the 93 m anemometer height towards the late spring and early summer months, most of the wind speeds during the strong jet events appear reasonable. The mean winds range between 8 m s^{-1} and 12 m s^{-1} roughly for the observed period. In the case of weak jet events, the mean wind is commonly between 8 m s^{-1} and 10 m s^{-1}, with 8 m s^{-1} winds being more prevalent at the 67 m height and the 10 m s^{-1} winds at the 137 m heights.

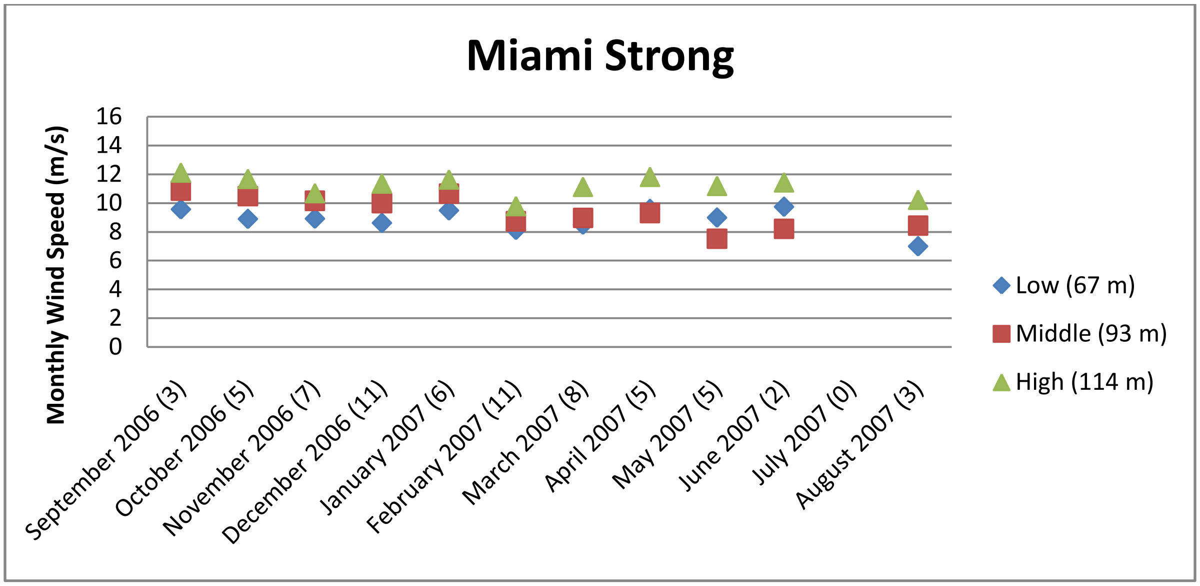


Figure 4.30 Mean monthly wind speeds (m s^{-1}) at Miami during strong jets.

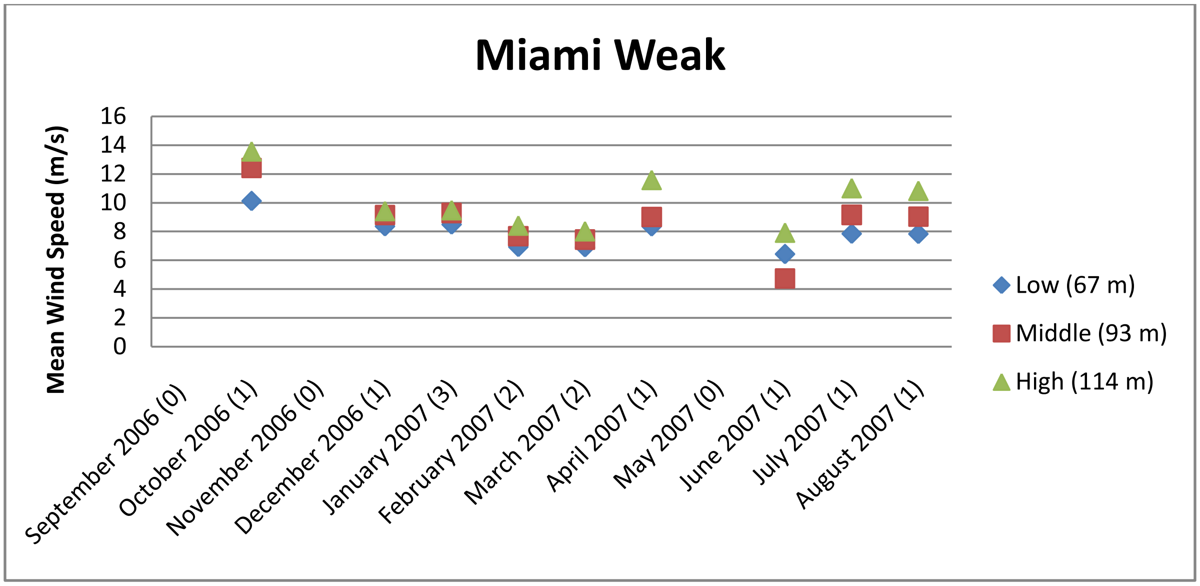


Figure 4.31 Mean monthly wind speeds (m s $^{-1}$) at Miami during weak jets.

4.4.6 Raytown

The magnitude of the mean winds during strong jet periods remained fairly consistent and fell between approximately 6 m s $^{-1}$ (close to 67 m) and 10 m s $^{-1}$ (close to 142 m). During the months that had more than one identified weak jet event, average mean winds were typically between 6 m s $^{-1}$ and 8 m s $^{-1}$. These lower ranges during both strong and weak jet event periods seem to make sense, given the urban setting surrounding the Raytown tower.

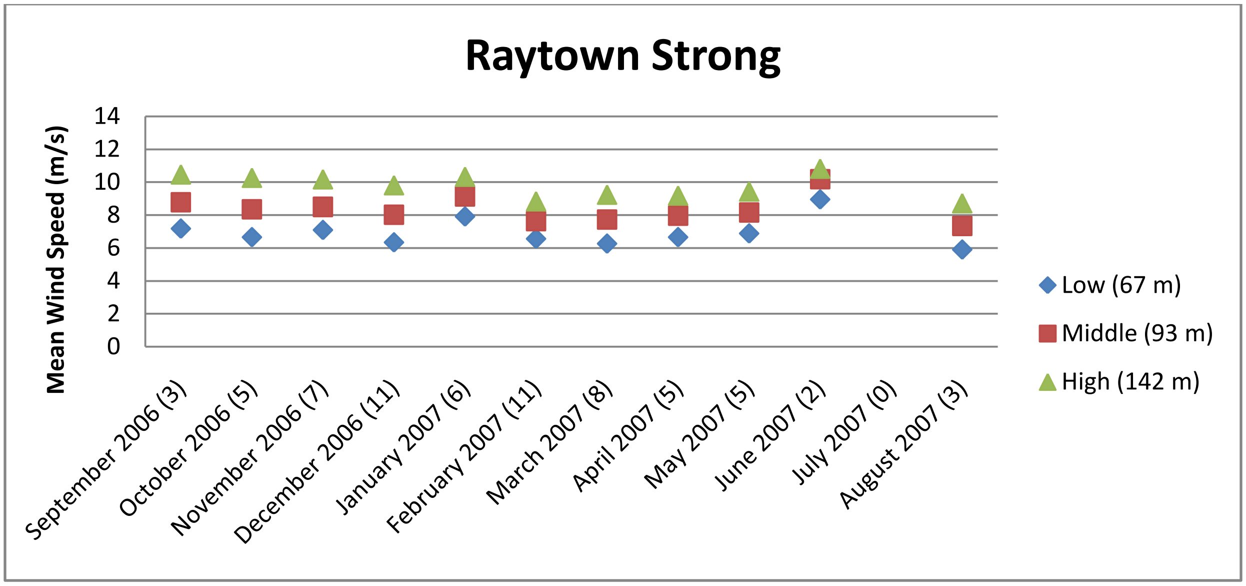


Figure 4.32 Mean monthly wind speeds (m s^{-1}) at Raytown during strong jets.

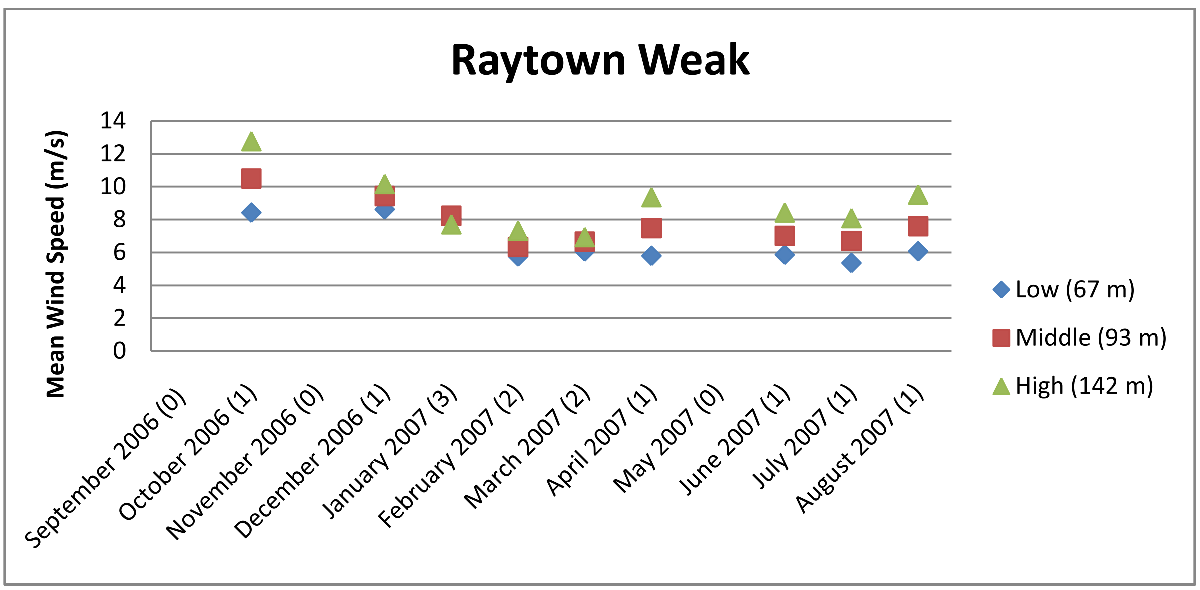


Figure 4.33 Mean monthly wind speeds (m s^{-1}) at Raytown during weak jets.

4.4.7 Monett

The mean monthly winds during the strong jet events ranged between 8 m s^{-1} and 10 m s^{-1}. Figure 4.34 shows the spread of the lower, middle, and upper-level mean trendlines to be closer than most of the other towers during these strong events. With respect to the weak events, the range in the magnitude of the mean winds is between 6 m s^{-1} and 8 m s^{-1} in January, February, and March. This indicates that winds are on the order of a couple meters per second less during weak jet events (Figure 4.35).

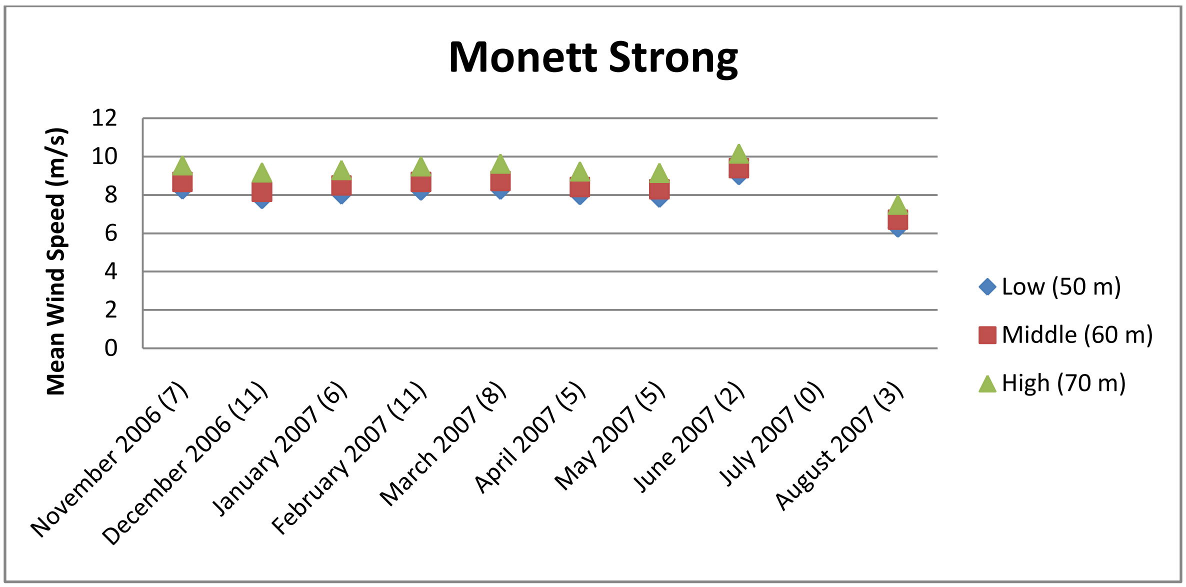


Figure 4.34 Mean monthly wind speeds (m s^{-1}) at Monett during strong jets.

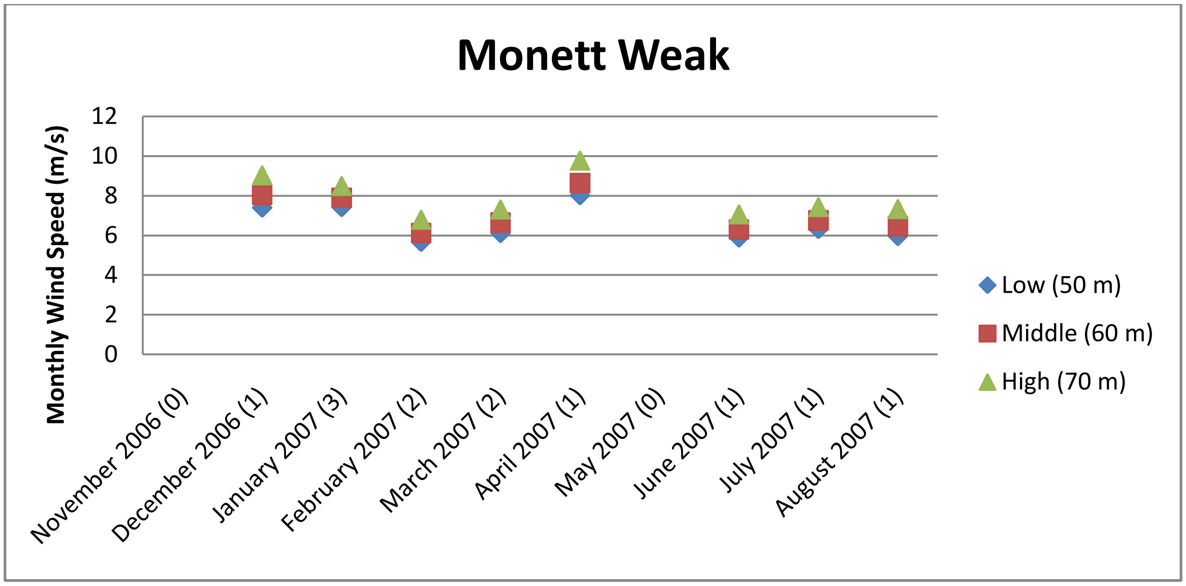


Figure 4.35 Mean monthly wind speeds (m s^{-1}) at Monett during weak jets.

Chapter 5 Conclusions and Future Work

This investigation of LLJ behavior for a 12-month period (September 2006 through August 2007) in Missouri has revealed some key insights into the available wind resource within the state.

- Analysis of hourly averaged wind speeds for 158 jet event days
- Wind speeds higher in jet events on the order of 2-3 m s^{-1}, depending on exact tower location
- Alpha values during non-jet events typically higher at most locations, with the exception of Miami, Blanchard, and Monett
- Friction velocity values consistently higher in jet events over non-jet events at all locations

Hopefully knowledge of these insights will prove useful to the future state of alternative energy within Missouri.

5.1 Jet Events Versus Non-Jet Events

The nocturnal LLJ appears to strongly influence the wind resource at the site locations here in Missouri. Table 5.1 shows the contribution of the LLJ to the wind observations at each of the towers and also each tower's ranking with respect to each level. Each of the wind speeds presented in the following tables are means of the entire observational period of each tower listed in Chapter 4 Section 2. Table 5.2 shows how each tower ranks in observed mean wind speeds during non-jet events. The Monett site ranks last at the middle and high elevations in both tables. If the middle and high elevations at the Monett tower were more similar to the heights at the other towers, it would seem reasonable that it would rank higher than the Raytown tower, and perhaps the Chillicothe tower as well.

Tower Ranking and Location	Low	Middle	High
Blanchard	8.35 (1)	9.62 (1)	10.53 (1)
Maryville	8.01 (2)	9.28 (2)	9.91 (2)
Miami	7.58 (3)	8.26 (3)	9.66 (3)
Mound City	6.10 (6)	8.11 (4)	9.08 (4)
Chillicothe	6.58 (5)	7.59 (5)	8.71 (5)
Raytown	6.07 (7)	7.34 (6)	8.63 (6)
Monett	6.84 (4)	7.29 (7)	8.07 (7)

Table 5.1 Tower location rankings for the mean wind speed (m s^{-1}) at all three heights during low-level jet periods.

Tower Ranking and Location	Low	Middle	High
Blanchard	5.97 (1)	6.95 (1)	7.52 (1)
Maryville	5.58 (2)	6.62 (2)	7.09 (2)
Miami	5.53 (3)	6.09 (3)	6.89 (3)
Mound City	4.00 (7)	5.78 (4)	6.43 (5)
Chillicothe	4.78 (4)	5.64 (5)	6.44 (4)
Raytown	4.07 (6)	5.10 (6)	6.13 (6)
Monett	4.75 (5)	5.09 (7)	5.62 (7)

Table 5.2 Tower location rankings for the mean wind speed (m s^{-1}) at all three heights when the LLJ is not present.

The Blanchard, Maryville, and Miami towers consistently rank at the top with respect to mean wind speed magnitudes during both times when the LLJ is present and also when it is not. This is reasonable given the fact that these tower locations are more exposed compared to the other 4 towers. From Tables 5.1 and 5.2, it appears that the presence of the LLJ increases the wind speed commonly by 2-3 m s^{-1}, depending on tower location.

5.2 Alpha versus Friction Velocity

Unfortunately it appears harder to draw solid conclusions from the shear parameter alpha. One is led to believe from the power law relationship discussed in Chapter 2 that a higher alpha value would indicate a greater presence of shear in a layer. This contradicts the findings of this study which show higher mean alpha values over the entire period during the non-jet events at Mound City, Maryville, and Raytown. Furthermore, the Chillicothe and Monett towers had just a slightly higher mean alpha during the jet periods compared to the non-jet periods. These mean alpha results were briefly discussed in section 4.3.

Physically this makes little sense, as the LLJ is believed to enhance the shear and turbulence between the level of the jet max and the surface. However, it does come into agreement with conclusions made by Kelley et al. (2004) during their one year statistical study of wind characteristics for the Lamar Low-Level Jet Project.

Mathematically, these unexpected observations can be explained in the power law relationship originally used to solve for alpha. For example, during a non-jet time period the wind speeds at the lower (61 m) and upper height (137 m) can be weaker at 4 m s^{-1} and 9 m s^{-1} respectively. During a time when the low-level jet is present however, the wind speeds at the lower and upper heights can be stronger, at 6 m s^{-1} and 12 m s^{-1} respectively. In the latter case, the wind speed doubles by a factor of 2. In the case of the former, the wind speed doubles by more than a factor of 2. The increase of a factor like this in the numerator of the equation for alpha would then act to increase the shear exponent.

An illustration of this difference can be seen in the following example calculation with a non-jet case on the left and a jet case on the right:

$$\alpha = \frac{\ln\left(\frac{9}{4}\right)}{\ln\left(\frac{137}{61}\right)} \approx 1.0 \qquad \alpha = \frac{\ln\left(\frac{12}{6}\right)}{\ln\left(\frac{137}{61}\right)} \approx 0.85$$

Even though the amount of shear is increasing between the surface and the 61 m height physically due to the presence of the jet, the calculation still results in a lower alpha value.

Even though the shear exponent alpha is commonly used in the wind power industry, questions must be raised as to whether it truly is the best indicator of and provides the best measurement of shear within a particular layer. One then has to wonder, based on results in this study and among others, whether the alpha calculations are merely just an artifact of the power law relationship or whether there is some physical explanation that can account for stronger mean alphas during the non-jet event periods.

The use of friction velocity as a measure of shear may actually prove to be more quantitative. Every tower location tended to have higher frictional velocities in the jet event cases versus the non-jet event cases. This is especially true when all of the monthly mean frictional velocity values are averaged over the entire observational period.

5.3 Strong Jet Events versus Weak Jet Events

The rankings do not change all that much in contrasting between strong jet events (Table 5.3) and weak jet events (Table 5.4) shown below. Table 5.3 and Table 5.4 show the average wind speeds at each height for the entire observational period, and come from data pertaining to Section 4.4. The difference in mean wind speeds between the strong and weak jet events appears to be less than 1 m s^{-1}. The one contradiction appears to be the Monett tower which exhibits a slightly larger difference with respect to the mean wind speed magnitudes at each height.

Tower Ranking and Location	Low	Middle	High
Blanchard	9.50 (1)	10.76 (1)	11.70 (1)
Maryville	8.67 (3)	9.99 (2)	10.67 (3)
Miami	8.85 (2)	9.39 (3)	11.20 (2)
Mound City	6.46 (7)	8.69 (4)	9.80 (4)
Chillicothe	7.35 (5)	8.44 (5)	9.69 (6)
Raytown	6.94 (6)	8.34 (7)	9.75 (5)
Monett	7.96 (4)	8.39 (6)	9.24 (7)

Table 5.3 Tower location rankings for the mean wind speed (m s^{-1}) at all three heights during strong jet events.

Tower Ranking and Location	Low	Middle	High
Blanchard	8.93 (1)	10.28 (1)	11.22 (1)
Maryville	8.54 (2)	9.75 (2)	10.36 (2)
Miami	7.91 (3)	8.65 (3)	10.03 (3)
Mound City	5.53 (7)	8.31 (4)	9.43 (4)
Chillicothe	7.01 (4)	8.04 (5)	9.23 (5)
Raytown	6.66 (5)	7.76 (6)	8.92 (6)
Monett	6.60 (6)	7.11 (7)	7.91 (7)

Table 5.4 Tower location rankings for the mean wind speed (m s^{-1}) at all three heights during weak jet events.

When looking at strong and weak jet events, peaks in the wind speeds during the strong jet events tended to be bi-modal at most of the towers. This was usually evident around December 2006 and January 2007, and then once more around summer of 2007. Of interest is the peak in wind speeds in the summer. This peak may indicate strong jets occurring in the warmer months. However, this peak also coincides with a smaller portion of the dataset as well, leaving it hard to draw any solid conclusions.

When investigating wind speeds during weak jet events, a couple of peaks occur throughout the period. However these peaks coincided with months in which only one day was available for analysis. The second peak in December 2006 is followed by a couple months that have a few more days available for analysis. Those months result in weaker wind speeds, probably as a result of more days averaging into the results. This type of pattern in the wind speed results is typical at most of the towers. Therefore, these results appear to be a bit more reasonable for the months of January, February, and March 2007. Still, with such a limited dataset, even these results must not be weighted too heavily.

5.4 Future Work

The lack of more qualitative data proves to be the major hindrance in drawing sound conclusions. This is particularly when comparing strong and weak jet events, as even fewer sample days were used in this part of the analysis. It would then make sense to continue investigation of wind data beyond the initial year of observed data. With a more substantial dataset available, one could then draw more solid conclusions about wind speeds during weak jet events. A larger dataset should also allow better insight into the shear parameter alpha and its reliability in measuring the amount of shear in a layer.

Another interesting analysis could be performed to determine the differences in wind speed and shear between two different time intervals. Of the original set of LLJ cases Dahmer (2009) identified, a majority of them (~63) occurred in the morning towards 12Z, while only 5 were identified around 00Z. Since the analysis in this study only focused on the 00Z through 12Z time period daily, it would be of interest to split up this 12 hour interval. The wind observations between 00Z and 06Z could then be compared to the results of the wind observations between 06Z and 12Z. Hopefully results of this future study can then confirm what Dahmer (2009) found to be true about the original set of cases.

The investigation into strong and weak jet events could also be expanded upon further. In this study, only strong and weak jet events which affected all the towers were studied. Since some of the jet events only affected a few of the towers locally, it would be of interest to compare those towers with towers which were not believed to be directly impacted by the LLJ.

Despite the fact that only observed wind speeds were used in the analysis, one could also begin investigating wind directional data that correlated with observed wind speeds at turbine heights. This study did not focus necessarily on the types of jets which were believed to be affecting the tower locations. By investigating the wind directions at times of possible nocturnal LLJ events, this could lend insight into the type of jet that is occurring (i.e. southerly nocturnal jet or a northerly jet possibly associated with a cold front). The classification of jet events could make research such as this more widely applicable and relevant.

References

Ahrens C. D., 2000: Meteorology Today. 6th ed. Brooks/Cole, 528 pp.

Arya, S. Pal, 1998. Introduction to Micrometeorology. San Diego, CA: Academic Press, 420.

Blackadar, A.K., 1957: Boundary Layer Wind Maxima and their Significance for the Growth of Nocturnal Inversions. *Bulletin of the American Meteorological Society,* ***38***, 283-290.

Brower, M., 2005. AWS Truewind- Wind Energy Resource Maps of Missouri.Available from Missouri Department of Natural Resources, CD-ROM.

Dahmer, M., 2009: Investigated Near Surface Wind Fields Influenced by Low-Level Jet Occurrences in Missouri. M.S. thesis, Dept. of Soils, Environmental, and Atmospheric Science, The University of Missouri-Columbia, 93 pp.

Holton, J. R., 1967: The diurnal boundary layer wind oscillation above sloping terrain. *Tellus*, **19,** 199-205.

Jacobsen, M., Z., 1999: *Fundamentals of Atmospheric Modeling.* Cambridge University Press, 656 pp.

Kelley, N., Shirazi, M., Jager, D., Wilde, S., Adams, J., Buhl, M., Sullivan, P. and Patton, E., 2004: Lamar Low-Level Jet Project Interim Report. National Renewable Energy Laboratory and the National Center for AtmosphericResearch. Available on-line at http://www.osti.gov/bridge/product.biblio.jsp?osti_id=15006544.

Pichugina, Y.L., Banta, R.M., Kelley, N.D., Sandberg, S.P., Machol, J.L. and Brewer, W.A., 2004: Nocturnal Low-Level Jet Characteristics Over Southern Colorado. Preprints, 16th Symp. On Boundary Layers and Turbulence, Portland, ME, American Meteorological Society, CD-ROM,4.11.

Redburn, R., 2007: A Tall Tower Wind Investigation of Northwest Missouri. M.S. thesis, Dept. of Soils, Environmental, and Atmospheric Science, The University of Missouri-Columbia, 109 pp.

Rochette, S.M., and Market, P.S., 2006: A primer on the ageostrophic wind. *Nat. Wea. Dig*., **30**, 17-28.

Schwartz, M., and Elliot, D., 2005: Towards a Wind Energy Climatology at Advanced Turbine Hub-Heights. Preprint, 15th Conference on Applied Climatology, Savannah, GA, American Meteorological Society.

Schwartz, M., and Elliot, D., 2006: Wind Shear Characteristics at Central Plains Tall Towers. Preprint, Wind Power 2006 Conference, Pittsburgh, PA, American Wind Energy Association.

Stull, R. B., 1988: An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, 666 pp.

Walters, C. K., and Winkler, J. A., 2001: Airflow configurations of warm season southerly low-level wind maxima in the Great Plains. Part I: Spatial and temporal characteristics and relationship to convection. *Wea. Forecasting*, **16,** 513–530.