INVESTIGATING NEAR-SURFACE WIND FIELDS AS INFLUENCED BY LOW-LEVEL JET OCCURRENCES IN MISSOURI

A Thesis presented to the Faculty of the Graduate School

University of Missouri-Columbia

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

---

by

MARC R. DAHMER

Dr. Patrick S. Market, Thesis Supervisor

MAY 2009

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

INVESTIGATING NEAR-SURFACE WIND FIELDS AS INFLUENCED BY LOW-LEVEL JET OCCURRENCES IN MISSOURI

Presented by Marc R. Dahmer,

A candidate for the degree of Master of Science,

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

Dr. Patrick S. Market

Dr. Neil I. Fox

Dr. Milon F. George

Dr. Jimmy O. Adegoke

……………………to Carrie: you are the sunshine of my life. i love you!

ACKNOWLEDGEMENTS

So, by a raising of hands…how many of y'all thought I would really get this thing done?? I am so glad that it is finished and I would like to take this time to thank those who have helped along the way.

First, I thank the Lord for blessing me with the opportunity and ability to do this work and for providing others to be an encouragement to me through it all. I would have accomplished nothing without Your steady, comforting hand guiding me when things were going well and when they were difficult. I would also like to show my appreciation to my bride, Carrie. You will never know how much I fully appreciate you and your sacrifice during this time. Your belief in me and my ability to complete this work kept me encouraged and sustained. Thank you! An overwhelming amount of thanks to the Dahmer/Haynes/Raymond families…I could not have done this without your continued prayers, faith, and love!

An abundance of thanks goes out to my advisor, Dr. Patrick Market, for your continued patience and helpful guidance as I worked on this project. I appreciate the time and energy you have invested in me over the years. It will not be forgotten. I would also like to thank my co-advisor, Dr. Neil Fox, for his continued support and for the opportunity to work on such a timely project. Thanks also to my other committee members, Dr. Milon George and Dr. Jimmy Adegoke, for their assistance in the improvement of this project. I would also like to thank Dr. Anthony Lupo who has also showed a strong faith in me…ever since I walked through his office door to change my major from Accounting to Atmospheric Science. Thank you all for making my experience in the Atmospheric Science department so fulfilling!

I would also like to thank Dr. Charles Graves, Dr. James Moore and Chad Gravelle from the Meteorology Department at Saint Louis University for providing data and the compositing program for this study. Thanks also goes out to the Atmospheric Radiation Measurement (ARM) program for also providing data utilized for this project.

There have been many past and present students within the Atmospheric Science department at MU that have assisted me in some way during my years as a Master's student. Many thanks go out to them…Willie Gilmore, Brian Pettegrew, Chris Melick, Steven Lack, Larry Smith, David and Amy Jankowski, Cody Fritz, Neville Miller, Chris Foltz, Daniel Hinch, and so many more. Thank you all! I would also like to take the time to acknowledge and appreciate Ali Koleiny for his support during the final stretch of this process. It was good to have someone going through the same issues with me…and good call on the Gates! Thanks also to my church families of Wabash Ave. Church of God and Christian Chapel. Thank you for your many prayers and support for me. The same applies to Robert Stewart. I appreciate your friendship and faith you showed in me. I would also like to thank everyone at the National Weather Service in Pleasant Hill…specifically Julie Adolphson, Suzanne Fortin, and Mark Mitchell. Thank you for your assistance and for allowing me the time to finish. I cannot thank you enough. Last, but not least, I would like to thank the Missouri Department of Natural Resources, the U.S. Department of Energy, Ameren, and Aquila for funding this project. Thank you for the commitment you have shown in this area of research.

COMMITTEE IN CHARGE OF CANDIDACY

Associate Professor Patrick S. Market
Chairperson and Advisor

Associate Professor Neil I. Fox

Associate Professor Milon F. George

Associate Professor Jimmy O. Adegoke

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table **Page**

INVESTIGATING NEAR-SURFACE WIND FIELDS AS INFLUENCED BY LOW-LEVEL JET OCCURRENCES IN MISSOURI

Marc R. Dahmer

Dr. Patrick S. Market, Thesis Supervisor

ABSTRACT

Renewable energy sources remain a topic of increasing importance in today's society. One possible source is the utilization of wind energy. As such, the objectives of this study were to investigate and classify the character of low-level jet (LLJ) in Missouri, based off certain criteria and determine whether near-surface (40, 60, 80, 100, 120 m AGL) wind fields are enhanced at times when the LLJ is active. Upper-air observations at Springfield, Missouri (SGF), from 01 May 2003 to 30 April 2004, were analyzed to determine the cases that satisfied our criteria. This analysis was also conducted to expand understanding of the monthly frequency, intensity, height, and direction of the LLJ maximums found in Missouri. A total of 75 preliminary events, out of a possible 732 cases, met the conditions of this study.

The 80-km model analysis version of the Rapid Update Cycle (RUC) was utilized in the determining of jet type classifications for each individual LLJ event, based on the jet types noted in the Walters and Winkler (2001) study. Out of the original 75 jet cases, 68 LLJ events were classified with seven (7) cases removed due to missing 80-km RUC data. Composite median wind speed analysis, based on each LLJ event, were generated at assumed turbine levels to determine whether wind speeds were enhanced on days when

the LLJ was active. This was assisted by the compositing of 42 non-LLJ events that were generated to compare to the LLJ composites. The data utilized in the generation of these composites was acquired using 20-km RUC model (RUC20) analysis. The RUC20 was thought to be the most applicable model to aid this study due to its fine horizontal and vertical resolution and its terrain-following sigma levels near the surface. The amount of timely observational data assimilated into the model was another major draw. A similar compositing process was undertaken to examine shear between the estimated top and bottom of wind-turbine blades for LLJ and non-LLJ events. Analyses of the median wind speed composites illustrate an approximate 1 to 8 ms^{-1} increase from non-LLJ to LLJ composites within the state of Missouri. A similar trend was noted with the shear composites as well.

Chapter 1

Introduction

Wind-generated energy is a process that is becoming ever more popular in today's environmentally-conscious society. Wind energy systems enable energy to be generated through a renewable source, as opposed to a non-renewable one, such as coal or natural gas. Some in our society believe that the use of fossil fuels to generate energy is an ethical issue, as burning these fuels produces waste products that may be harmful to our environment and to people. Then there are those who believe the amount of waste is so small, it is negligible. Thus, the climate debate begins. Others believe that renewable sources of energy are necessary in this day and age to wean ourselves off of dependency on foreign oil, which some see as a national security issue. There are others that advocate the use of renewable energy, such as wind and solar energy, to supplement and conserve fossil fuels on Earth. Wind-generated energy systems provide power from a source that is endless and does not require the burning of non-renewable sources that possibly adds pollutants into the air, such as coal. Some locales have even passed propositions aimed at making a higher percentage of the energy consumed, come from renewable energy sources (Moore 2004). In fact, in April of 2008, Rock Port, Missouri, became the first city in the country to be completely powered by wind power (Volkmann 2008). Using the wind as an energy source continues to be a relevant topic today, as so-called 'green jobs' are looked upon as production jobs of the future and are hoped to have a stimulating effect on the economy. While we have some sense of where the better sites for wind energy are located across Missouri and neighboring states, more work continues to be done to obtain an increasingly detailed assessment of how and where wind-generated energy sites would be best utilized.

The nature and location of the low-level jet (LLJ), has been studied and researched for many years (Blackadar 1957; Bonner 1968; Mitchell et al. 1995; Whiteman et al. 1997; Walters and Winkler 2001; Banta et al. 2002; Zhang et al. 2006). The *Glossary of Meteorology*, put forth by the American Meteorological Society, defines a LLJ as "a jet stream that is typically found in the lower 2-3 km of the troposphere" (Glickman 2000). However, the average height of the LLJ tends to vary by study. This is usually due to differences in the temporal frequency of sampling, in instrumentation used to collect data, or in differing sets of criteria used to determine what constitutes a LLJ. To illustrate that fact, some studies show the LLJ height around 1000 m above ground level (AGL) (Mitchell et al. 1995), while other studies situate the average height much lower (Banta et al. 2002). Most LLJ studies investigate jets that are synoptically-driven or generated by the nocturnal decoupling of flow, which permits the air just above the surface to move relatively free from surface friction and allows for acceleration of flow above the boundary layer. From these and other studies, many uses for LLJ data have been documented, especially when it pertains to convection. The formation and propagation of convection, and whether a storm could reach severe limits are, at many times, influenced by the LLJ. This study, however, will focus on the patterns and synoptic/mesoscale characteristics of LLJs in Missouri, as a way to locate areas that are best suited to take advantage of wind energy in Missouri.

1.1 Statement of Thesis

The purpose of this study is to develop a usable assessment to assist in predicting how near-surface winds in Missouri will react to the influence of a LLJ pattern above.

This particular study will investigate the lower-level wind pattern in the Midwest, particularly Missouri, to outline locations where wind-generated energy systems may be an economically-viable option. In order to execute this inquiry, model initial fields were interrogated to ascertain a number of characteristics of the LLJ and were also used to locate areas in Missouri where the wind speed, at turbine level, was enhanced by LLJ influence. The objectives of this study were to:

- Determine which types of LLJ patterns are more/less frequent in Missouri and what season is preferred for LLJ development.
- Determine whether turbine blade-level wind speeds will be influenced by a LLJ located higher in the atmosphere.

This study spans one full year, focusing on the state of Missouri, from May 2003 through April 2004. The particular LLJ cases selected for this study are based upon specific criterion applied to the upper air observations from Springfield, Missouri (SGF), during the specified period. Rapid Update Cycle (RUC) model analysis was utilized to illustrate each LLJ; allowing them to be classified into jet types.

This project has a distinct purpose and plan to denote locations where near-surface winds are positively (greater wind speed) influenced by the LLJ, which could provide locations where wind energy instruments can be most efficiently utilized. Wind-generated energy systems have grown in size and efficiency, with wind turbine hubs being placed on towers that are 80- to 100-m tall and turbine blades coming in at around 40 m long. However, the typical LLJ is usually located around the 500- to 1000-m mark, which underscores why it remains imperative that a better understanding of what occurs beneath the LLJ is provided to the wind energy community. Understanding the nature of this entity, the LLJ, and also what occurs beneath it will assist in delineating ways to utilize wind flow.

Chapter 2

Literature Review

2.1 Introduction

Means (1952) paper, ‘On Thunderstorm Forecasting in the Central United States’ was one of the first times the term low-level jet was used “to describe a zone of strong southerly flow below the 700-mb level in the south-central United States” (Bonner 1968). Since the coining of that term, a number of authors have conducted studies related to the LLJ and many of them reflect on some previous baseline studies that have helped to shape how the LLJ is considered. The current study is no exception. From the Blackadar (1957) study detailing his mechanism for LLJ development to the Bonner (1968) climatology study of the LLJ, there are a number of important studies that continue to remain relevant in the arena of LLJ research. A more pronounced influence on the current study was obtained from recent research that presented results with some possible wind energy application, such as the Banta et al. (2002) study.

2.2 Blackadar (1957)

This study on Blackadar's mechanism for LLJ development presented a different perspective on the process of LLJ generation. Blackadar (1957) suggested that the LLJ is not confined just to its appearance on the 850-mb surface and that examples of LLJs can be found during any season and almost everywhere in the United States. However, his benchmark study suggests the night-time hours over the Great Plains are the most favorable timeframe and location for LLJ development. This study discusses the relationship between the LLJ and nocturnal temperature inversions.

The criteria used to signify a LLJ event in this study are denoted as occurrences in which the maximum wind speed exceeds the wind speed at the next highest minimum by 5 knots or more. Blackadar (1957) believed that the period, from 8 p.m. to 8 a.m. local time, was the primary time when the height of the LLJ tended to coincide with the top of the nocturnal inversion. Because of this suggestion, he wanted to restrict the study to only nocturnal LLJ events, so the following conditions were determined.

1. Local time between 8 p.m. and 8 a.m.
2. Temperature increasing with height up to a single maximum within a distance of 1000 m of the surface (1396 m above sea level).
3. A significant wind speed maximum below 1000 m above the surface.

4. Temperature decreasing with height up to 2000 m above sea level at some time during the previous afternoon.

5. No obvious air mass changes during the night or during the previous afternoon (Blackadar 1957).

From these criteria, 88 cases were selected from a number of kite observations at Drexel, Nebraska, between 1916 and 1918. This data provided insight into the seasonal differences of nocturnal LLJs. During the summer, most overnight inversions satisfied these conditions. After comparing the height of the temperature inversion to the height of the wind maximum, the author noted that this association was ‘striking’ during the summer months; while during the winter months, that relationship becomes more relaxed. The strong association in Figure 2.1, Blackadar (1957) believed, is due to strong diurnal variations.

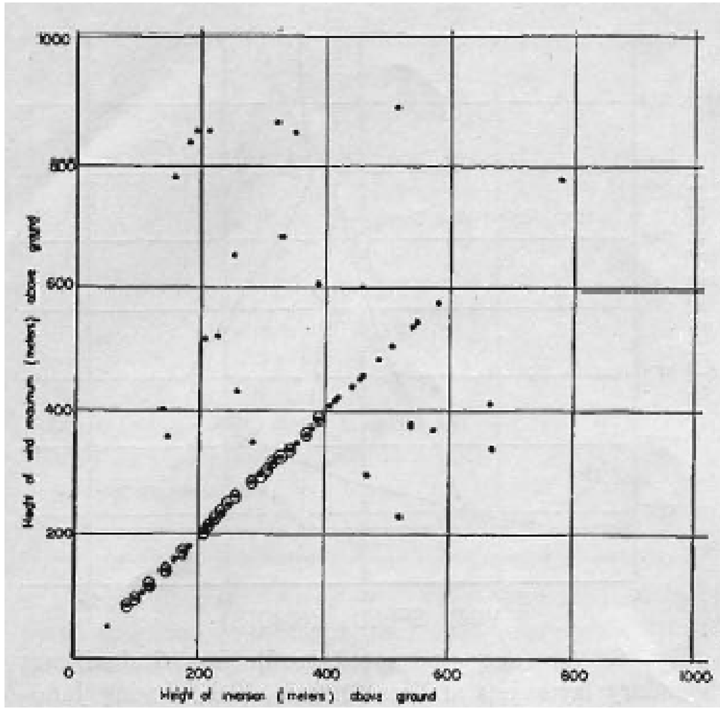


Figure 2.1: Comparison of the height of the wind maximum AGL (ordinate) and the height of the top of the nocturnal inversion AGL (abscissa). 88 cases selected from a series of kite observations at Drexel, Nebraska, between the years 1916 and 1918 (Reproduced from Blackadar 1957).

While assessing the reasons why the height of the LLJ and the nocturnal inversion were similar, the author hypothesized that turbulent transfer is the main influence on the rate of upward propagation of the nocturnal inversion. Large wind shear appears to be at the root of the production of turbulence. This wind shear is developed within the inversion and assists in overcoming stability by its ability to supply sufficient turbulent energy. The author states, “The character of the wind profile is important in determining whether the growth of the nocturnal inversion is orderly and controlled or whether it is chaotic or perhaps entirely absent” (Blackadar 1957). He goes into further detail by explaining that when a wind maximum is located at the top of an inversion, the production of turbulence within the inversion is automatically controlled and because of this, the upward growth tends to be gradual and orderly. However, turbulence will continue to be generated if other processes act to increase the wind shear or change the temperature distribution. According to the author, while a wind maximum at the top of an inversion illustrates a stable pattern, a wind maximum above the level of the inversion would possibly cause a chaotic breakdown.

Blackadar (1957) proposed that around sunset, the nocturnal inversion first begins to become established as rapid decreases in turbulent mixing in the layer above the inversion takes place, which ceases to have a significant effect on motion at that level. As was stated previously, the large wind shear associated with the wind maximum acts to maintain some turbulence within the nocturnal inversion. Heat is then transferred toward the surface, where it is dispersed through radiation. With no compensation in the upper layers, this loss of heat results in the upward expansion of the inversion at night. Not unlike how the heat is transferred, momentum is also carried downward by turbulence from the upper portion of the inversion. Once the momentum reaches the surface, it is effectively dissipated. As a pronounced LLJ profile emerges and becomes established, the negative wind shear above the jet maximum may be enough to produce turbulent mixing. Blackadar (1957) believed that this mixing would have a noteworthy effect on the evolution of the wind profile, but is probably not important during the formation of the wind maximum itself.

2.3 Walters and Winkler (2001)

The Walters and Winkler (2001) study investigated southerly LLJs during the warm seasons (Apr-Sep) of 1991 and 1992. The objectives of this study were four-fold. First, typical airflow patterns were identified for both, boundary layer-forced and synoptically-driven southerly LLJs. Then, the locating and analyzing of the spatial pattern of convergence, as it relates to the different airflow patterns, was undertaken. Determining the general pattern of moisture and temperature for each particular LLJ airflow configuration was done as well. Finally, the frequency and location of cloud-to-ground lightning strikes were illustrated, as it relates to the different LLJ types. It is mentioned that both types of LLJs (boundary layer-forced and synoptically-driven) previously mentioned, are an impetus for the initiation and enhancement of convection (Means 1952; Pitchford and London 1962; Bonner 1968).

Upper air observation data for eight rawinsonde stations were obtained from the National Climatic Data Center (NCDC). These eight locations, depicted in Figure 2.2, were all located in the central United States and included: Bismarck, North Dakota (BIS); St. Cloud, Minnesota (STC); Huron, South Dakota (HON); North Platte, Nebraska (LBF); North Omaha, Nebraska (OVN); Topeka, Kansas (TOP); Dodge City, Kansas (DDC); Norman, Oklahoma (OUN). To find events that satisfied the following criteria, wind speed and direction for each station was plotted at 00 and 12Z.

1. A wind speed greater than 8 ms^{-1} was observed at or below the 700-mb level.

2. The vertical wind shear between the level of strongest winds and the earth's surface equaled or exceeded 4 ms^{-1}.

3. The vertical shear between the level of strongest winds and either the next highest wind minimum or 550mb, whichever had the lower elevation, equaled or exceeded 4 ms^{-1} (Walters and Winkler 2001).

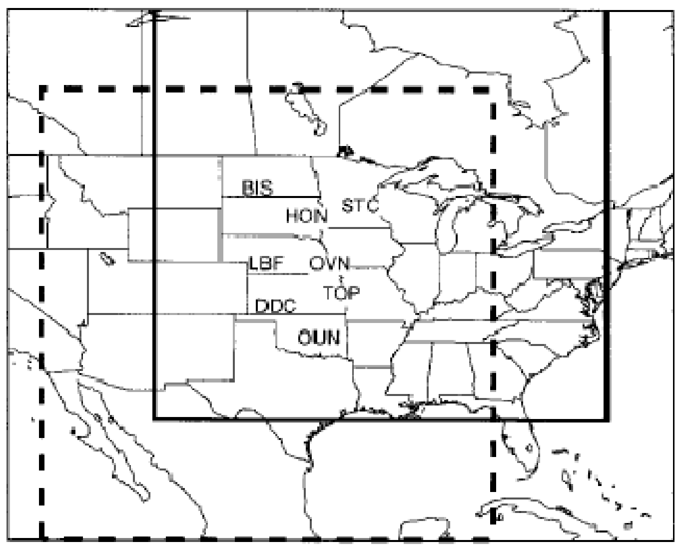


Figure 2.2: These eight rawinsonde stations in the central United States were used to identify vertical jet profile signatures and to analyze the airflow, temperature, and moisture patterns. The two smaller boxes (bold and dashed) illustrate the size of the sub-grid used to prepare the composite analysis (Reproduced from Walters and Winkler 2001).

As was stated earlier, only southerly LLJ profiles with a wind profile between 90° and 270° were retained. This condition was not important to the current study, as wind from any direction can generate energy. Streamlines and isotachs were then plotted for each profile on the pressure surface that corresponds to the elevation of the strongest wind speed. Walters and Winkler (2001) then decided it was important that one or more of the streamlines originated over the Gulf of Mexico. This criterion was added to emphasize the significance between convection and a southerly LLJ originating in the Gulf of Mexico, advecting warm, moist air into the plains. At this point, the authors subjectively-typed the plots of streamlines and isotachs on the closest pressure surface to the ground, based on the extent of the wind maximum, the orientation and curvature of the streamlines, as well as the orientation of any confluence, diffluence, and/or deformation zones. Of these events, only LLJ types that logged 10 or more events were kept, the others with below 10 events were considered unclassified. This left a total of 260 LLJ events, which were classified into 12 different jet types.

Walters and Winkler (2001) utilized a compositing approach to analyze the streamline, wind speed, divergence, temperature, and moisture fields for each LLJ type. This study also sought to depict the location of lightning activity relative to the LLJ for each event. Cloud-to-ground (CG) lightning data for the contiguous United States was acquired from the National Lightning Detection Network (NLDN). They described a lightning period as, "the occurrence of one or more cloud-to-ground lightning flashes in 1° latitude by 1° longitude grid cells during the 2-h period straddling the time of observation (0000 or 1200 UTC)" (Walters and Winkler 2001).

Walters and Winkler (2001) made it a point to discuss the spatial and temporal limitations of their study. Some of these are concerns that any researcher utilizing rawinsonde data as their main dataset may experience. Temporally, only receiving data twice a day, generally relegated to 0000 and 1200 UTC, inhibits the researcher from comparing data over a shorter span of time which may have allowed for the sampling of a LLJ event at the peak of the wind maxima. This snapshot at 0000/1200 UTC does not give an entirely accurate depiction of a LLJ event. Spatially, the authors investigated observations at stations that were located some 350 to 450 km away from the next station in closest proximity. This drawback would facilitate an underrepresentation of LLJs that are not as wide-ranging spatially. Thus, leading to the omission of some jet events altogether. Vertical interpolation of the original wind observations are another possible source for errors as it tends to act as a smoothing mechanism between levels where the original data existed. This will typically induce an unrealistic response in the data. Even with these limitations, Walters and Winkler (2001) believed that rawinsonde observations were still the best available dataset for their study.

For a number of the LLJ events, the airflow configurations changed with altitude. Of all the cases, 50% of the LLJ events had a different airflow pattern at higher elevations, with the jet maximum still at or lower than 700mb. Walters and Winkler (2001) noted that cyclonically curved LLJs generally had more multi-level jets than their anticyclonic counterparts and of those multiple levels, the airflow pattern became increasingly more anticyclonically curved with height. Unfortunately, due to the coarse horizontal and vertical resolution of the dataset, the authors were unable to determine whether these multi-level jets were composed of distinct, multiple airstreams separated in the vertical or if the multi-level jets were distinguished by a gradual change in airflow with height.

One of the most important findings of this study, in the estimation of the authors, involved the complexity of the spatial configuration of the LLJs. This is demonstrated by the expanse and different types of airflow configurations listed in Table 2.1 and Figure 2.3. Four of these LLJ types were anticyclonically curved (noted by an ‘A’ in the name of the jet type), another four were bifurcating (noted by a ‘B’), two of the 12 jet types were cyclonically curved (noted by a ‘C’), and the last two displayed a closed cyclonic circulation (noted by a ‘K’). Walters and Winkler (2001) noted that only 37% of their LLJ types were anticyclonically curved, which suggested to them that cyclonically curved and bifurcating jet types occurred at least as frequent as anticyclonically curved jets. This was an unexpected finding, as many previous studies centered on the anticyclonically curved jet type (Bonner 1968; Helfand and Schubert 1995).

Table 2.1: Acronyms used to denote jet types (Reproduced from Walters and Winkler 2001).

Acronym	*Characteristics of jet types*		*Acronym*	*Characteristics of jet types*
A	Anticyclonically curved		c	Confluence zone
B	Bifurcating flow		d	Deformation zone
C	Cyclonically curved		EW	East-west
K	Kurl*		SWNE	Southwest-northeast
L	Long		NWSE	Northwest-southeast

***The term kurl is used instead of closed cyclonic circulation to facilitate a distinction in the acronyms used for the different types. The letter C already stands for cyclonically curved in the notation employed (Walters and Winkler 2001).**

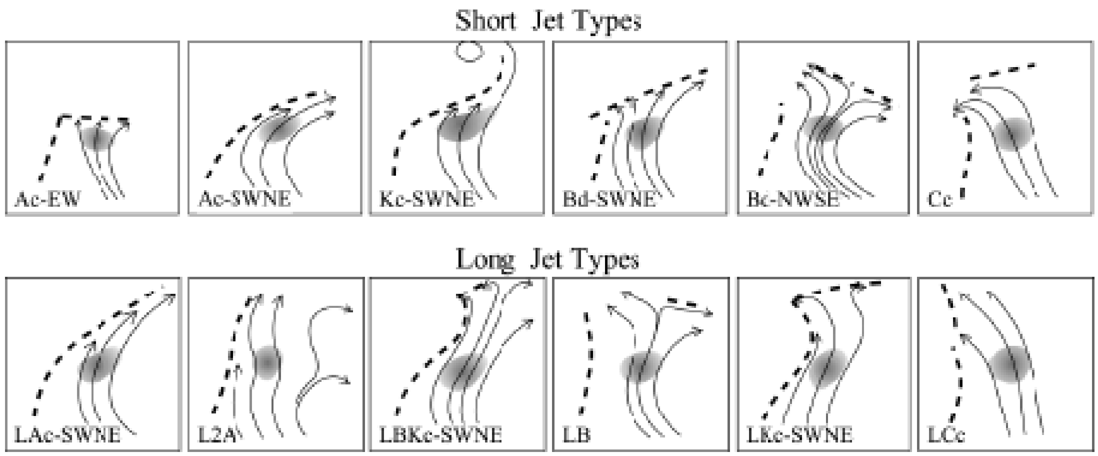


Figure 2.3: Schematic of the characteristic airflow of the 12 jet types. The solid lines represent streamlines, while the heavy dashed lines represent the location of significant confluence and/or deformation zones. The shaded areas are representative of the approximate location of jet cores (Reproduced from Walters and Winkler 2001).

The authors conveyed the operational applicability of this study when discussing the awareness forecasters should have when it comes to frequent occurring LLJs in the Great Plains. A high majority of LLJs, including some that are relatively weak, aid in supplying the necessary ingredients to produce or sustain convection. This idea is supported by the results gathered during this study, as 95% of the jet events were associated with cloud-to-ground lightning activity. This activity tended to be collocated with areas of strong convergence in the different airflow configurations. The strongest convergence is generally linked with an elongated region of confluence along the west (left) flank of the jet axis in the lower levels. At higher levels, the area of stronger convergence is usually located downstream of the jet axis, due to the effects from speed convergence. The temperature and moisture composites were also similar for the different LLJ patterns. It was hypothesized that this finding may be representative of the distinctive geography of the Great Plains, as the juxtaposition of a tongue of warm air and a strong moisture gradient tended to be located to the southwest of the LLJ axis. Despite all the information and results gathered, the authors also found it difficult to describe a LLJ event as “boundary layer” or “synoptically-driven” based solely on location, altitude, and temporal characteristics of the LLJs; as some jet characteristics suggest both to be a factor.

All in all, this study presents findings in a way that highlight the variability between the different LLJ configuration types, while also illustrating the similarities in lightning activity, general location of convergence, and composite temperature and moisture fields. The Walters and Winkler (2001) study also helped produce a baseline methodology for the research the current study is based on.

2.4 Banta et al. (2002)

The Banta et al. (2002) paper is a unique and significant case. The LLJ of interest in this case was nocturnal and has a role in generating shear and turbulence between the jet maximum and earth's surface. This study focuses heavily on the aforementioned Blackadar (1957) mechanism; especially focusing on the lowest wind maximum that occurs due to this process. The authors were seeking to determine the frequency of occurrence and evolution of this nighttime phenomenon, with one of the most significant discoveries being the elevation where a majority of the wind maximums were observed.

This 1999 Cooperative Surface-Atmosphere Exchange Study (CASES-99) was conducted in October of 1999 across the Walnut River watershed in southeast Kansas. The instrumentation used during this study included 915-MHz wind profilers with mini-sodars, a 60 m meteorological tower, and a High-Resolution Doppler Lidar (HRDL). A triangle of profiler/sodar sites surrounded the HRDL, which was located at the CASES-99 main site near the town of Leon, KS. The location of the profiler/sodar sites include: Beaumont (BEA), Whitewater (WHI), and Oxford (OXF), KS. BEA is located in the eastern portion of the watershed, while WHI and OXF are located in the northwestern and southern portions of the watershed, respectively. Also, at least 4 to more than 20 rawinsondes were launched from various sites within the CASES-99 instrument array every night during the study. However, 165 of 238 soundings did not provide winds in lowest 100 m due to a lost GPS satellite connection. Unfortunately, this partial lack of data precluded the usage of the rawinsonde soundings for this study.

At range resolution of 30 m and an approximate 0.1 ms^{-1} precision of velocity, HRDL maps out the Doppler-velocity field in the boundary layer. The HRDL produced profiles that were available at time intervals of less than 1 minute, with vertical resolutions of less than 10 m for a considerable portion of the nights investigated. Also, quality control procedures were performed to lessen the effects of poor data on the profiles, including hard target returns and occasional beams with poor signal quality.

Figure 2.4 illustrates the diverse jet profiles found during this study. Some profiles had a double and even a triple maximum. The authors hypothesized that the upper jet, which was out of the southwest, signified the Great Plains LLJ, while the lower jet represents acceleration after sunset due to the Blackadar (1957) mechanism. LLJs were initially identified by visual inspection of each profile of each scan. However, the study also adopted an objective definition based on the criterion in Andreas et al. (2000), which chose low-level wind speed maxima that displayed a decrease of at least 2 ms^{-1} above and below the level of the peak value Z_x. This criterion was chosen because criteria from other studies, i.e. Bonner (1968) and Whiteman et al. (1997), caused the exclusion of many jets the authors felt belonged in their sample. However, after visually inspecting the profiles, they noticed a large number of LLJs were being excluded due to the use of the Andreas et al. (2000) criteria. The main culprit of the exclusions seemed to be scans that were too shallow and not high enough to show the decrease needed in the wind speed aloft to be classified a LLJ. Due to the aforementioned precision of the HRDL and the fine vertical resolution in the profiles produced, the decrease threshold criteria used in this study for the HRDL analysis was 0.5 ms^{-1}, which illustrated the best agreement with visual inspections. However, confidence was low in using threshold criteria of 1.0 ms^{-1} or lower for the profiler/sodar analysis, due to measurement uncertainty. Thus, a decrease threshold of 1.5 ms^{-1} was used.

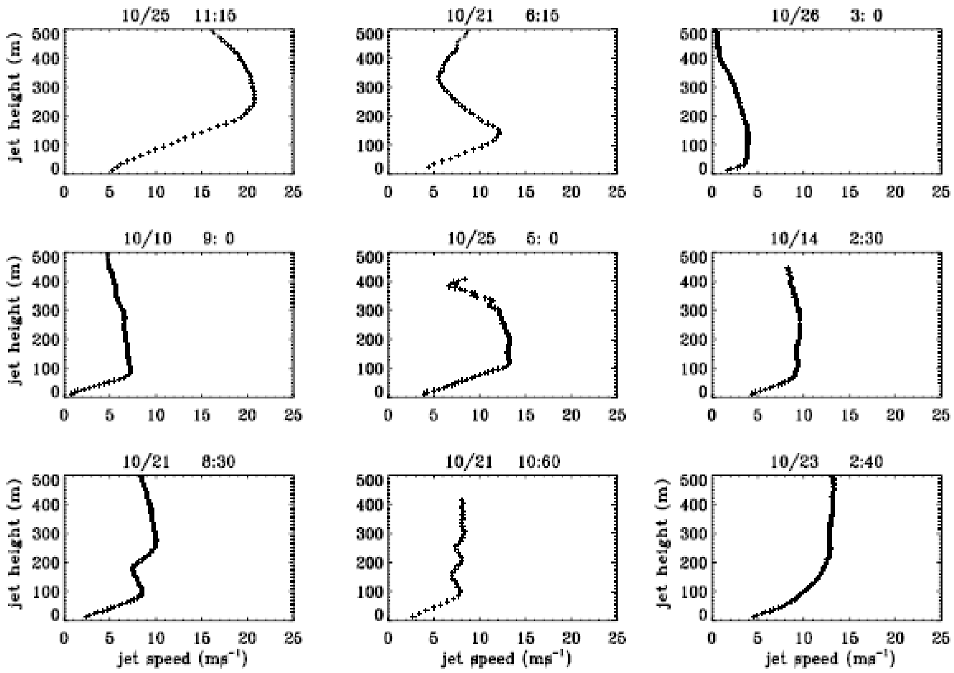


Figure 2.4: Sample LLJ profiles from either the HDRL vertical-slice scans or from VAD scans. The lowest wind speed maximum in each case, except the last one, was considered a LLJ. The last case (bottom-right) was not classified a LLJ (reproduced from Banta et al. 2002).

Boundary layer radar-wind profilers transmit a radar signal at 915 MHz and measure the Doppler-shifted frequency of the backscatter from one vertical beam and two or four offset beams to provide wind profiles. Six minutes are needed for one scan sequence. Subsequently, the averaging of multiple scans was utilized to create hourly averages of winds with precision within the ±1.0 ms^{-1} range. Winds usually became available at approximately 150 m AGL. The Doppler mini-sodars, which rely on the transmission of sound, were collocated with the three profilers to provide high-resolution wind profiles between 10 m AGL and the lowest level sampled by the profilers. The mini-sodars used for this study collect data from 10- to 200 m AGL. The data usually comes in 15-min averages, but were averaged into hourly profiles for compatibility with profiler data.

Histograms were produced based on the HRDL 15-min averages of speed (U_x), height (Z_x), and direction (D_x) of the LLJ (Figure 2.5). According to this dataset, most of the jet speeds (U_x) were between 7 and 10 ms^{-1}, with a mode at 8 to 9 ms^{-1} which encompassed nearly 19% of the occurrences. The data also illustrates jets originating from all directions. However, there is a noticeable peak in the southerly jets. One of the most significant findings had the majority of the jet heights (Z_x) around 100 m AGL. This is lower; if not significantly lower, than most other Great Plains studies. The authors believed this disparity demonstrates differences in study objectives and criteria for LLJ classification. They also noted that instrumentation could have been an issue, as the HRDL is perfectly suited to detect Z_x in the 30- to 150-m AGL range. With the use of other instrumentation, this height range represents a probable position of data unavailability or unreliability of the data sampled.

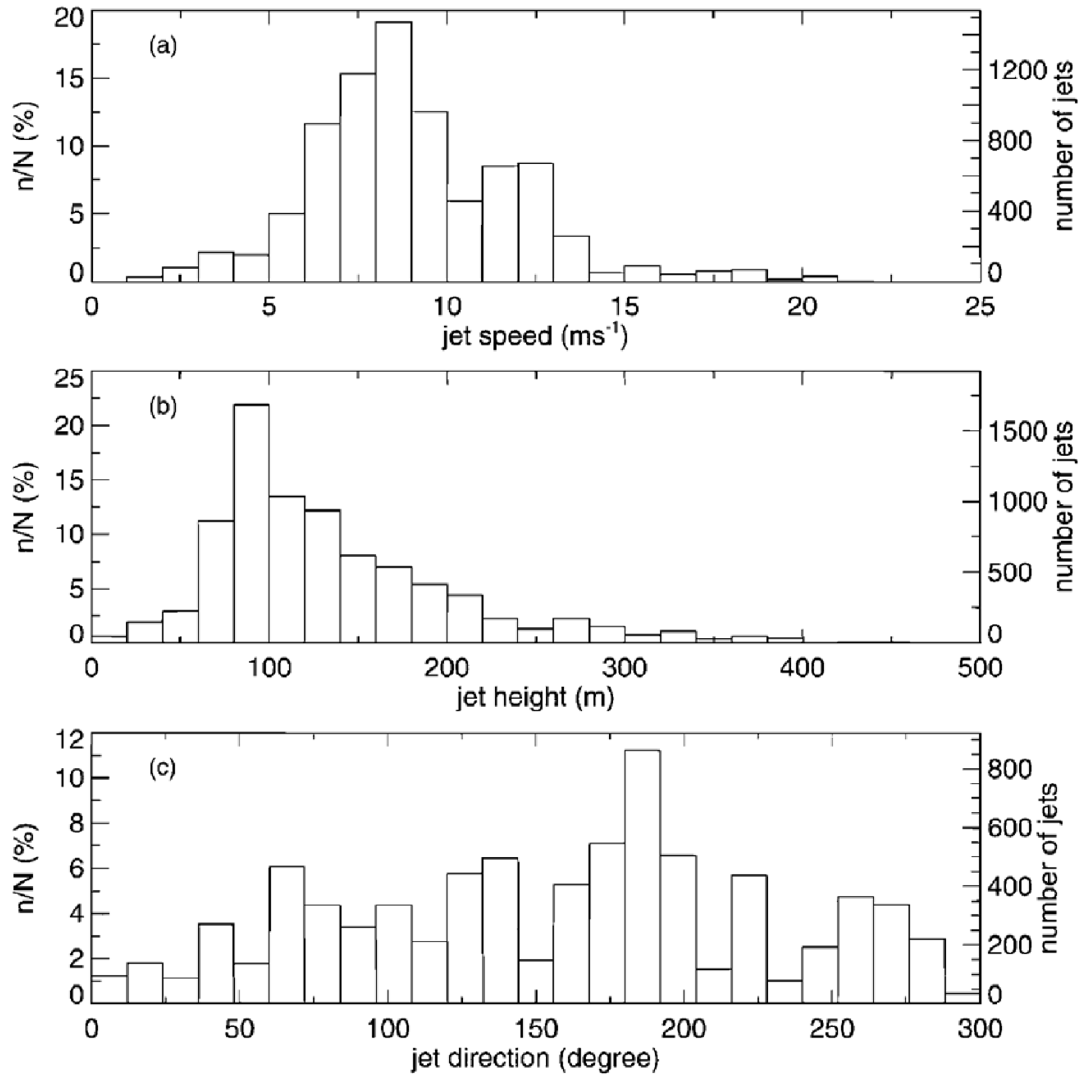


Figure 2.5: Presents histograms of the (a) jet speed U_x, the (b) height Z_x of maximum speed, and the (c) direction of the jet maximum D_x. Data were compiled from 15-min means of each quantity determined from HDRL vertical-slice and VAD-type scans. Percentages of occurrences are shown along the left vertical axis, while the total number of occurrences is indicated along the right vertical axis (Reproduced from Banta et al. 2002).

It is also worth noting that 46% of the jet maxima occurred below 100 m AGL and 69% occurred below 140 m AGL. While the majority of the jets occurred below 140 m AGL, notice the void left in the bottom right portion of Figure 2.6. This illustrates the lack of strong jets at lower heights.

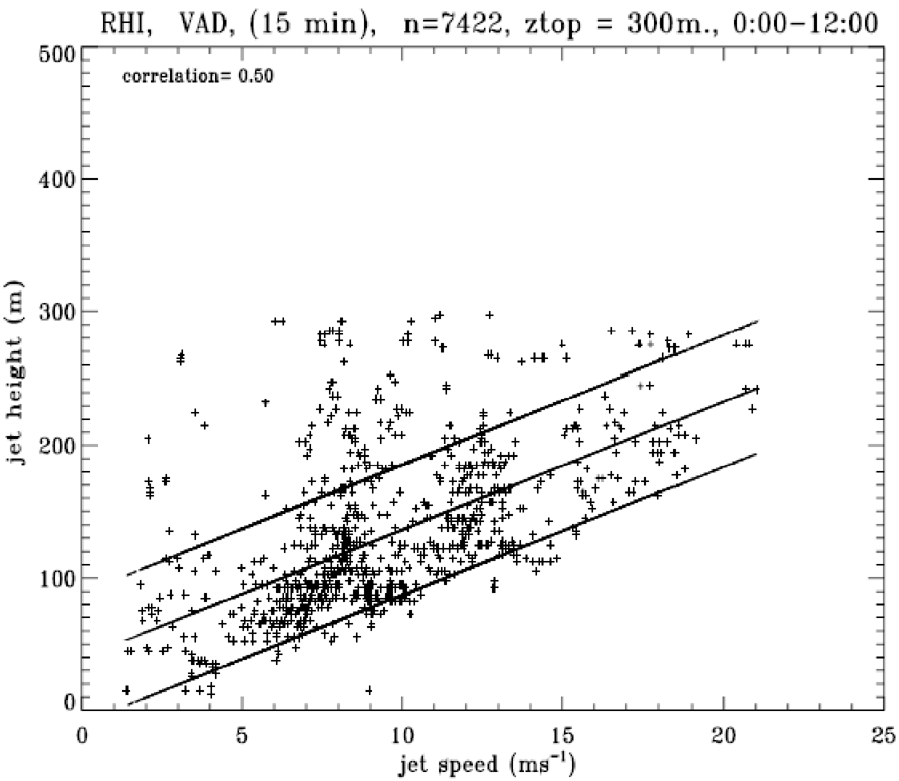


Figure 2.6: Scatter plot of Z_x versus U_x from the same data as in Figure 2.5, only utilizing those values where $Z_x < 300$m. The middle line represents a best-fit linear regression (R=0.50) and the upper and lower lines are for ±1 standard deviation (Reproduced from Banta et al. 2002).

While wind speeds generally in the 7 to 10 ms^{-1} range were noted in the HDRL data, the three profiler/sodar locations of BEA, WHI, and OXF show different jet speed distributions and jet speed peaks. BEA tended toward a wider range of jet speeds, with the majority falling between 4 and 20 ms^{-1}. The data from the BEA station also showed a peak in wind speeds from 10 to 12 ms^{-1} (Figure 2.7). The wind speed distribution at WHI tended toward lower wind speeds with most ranging from 4 to 12 ms^{-1}. The peak wind speed distribution fell to 4 to 6 ms^{-1} at WHI, which was the lowest out of all the profiler/sodar sites (Figure 2.8). The distribution at OXF was most notable from 6 to 14 ms^{-1}, with a peak in wind speeds between 6 and 8 ms^{-1} (Figure 2.9). Of a sample of 102 profiles, BEA continued to show the strongest jet 40.2% of the time, followed by WHI at 30.4%, then OXF at 29.4%.

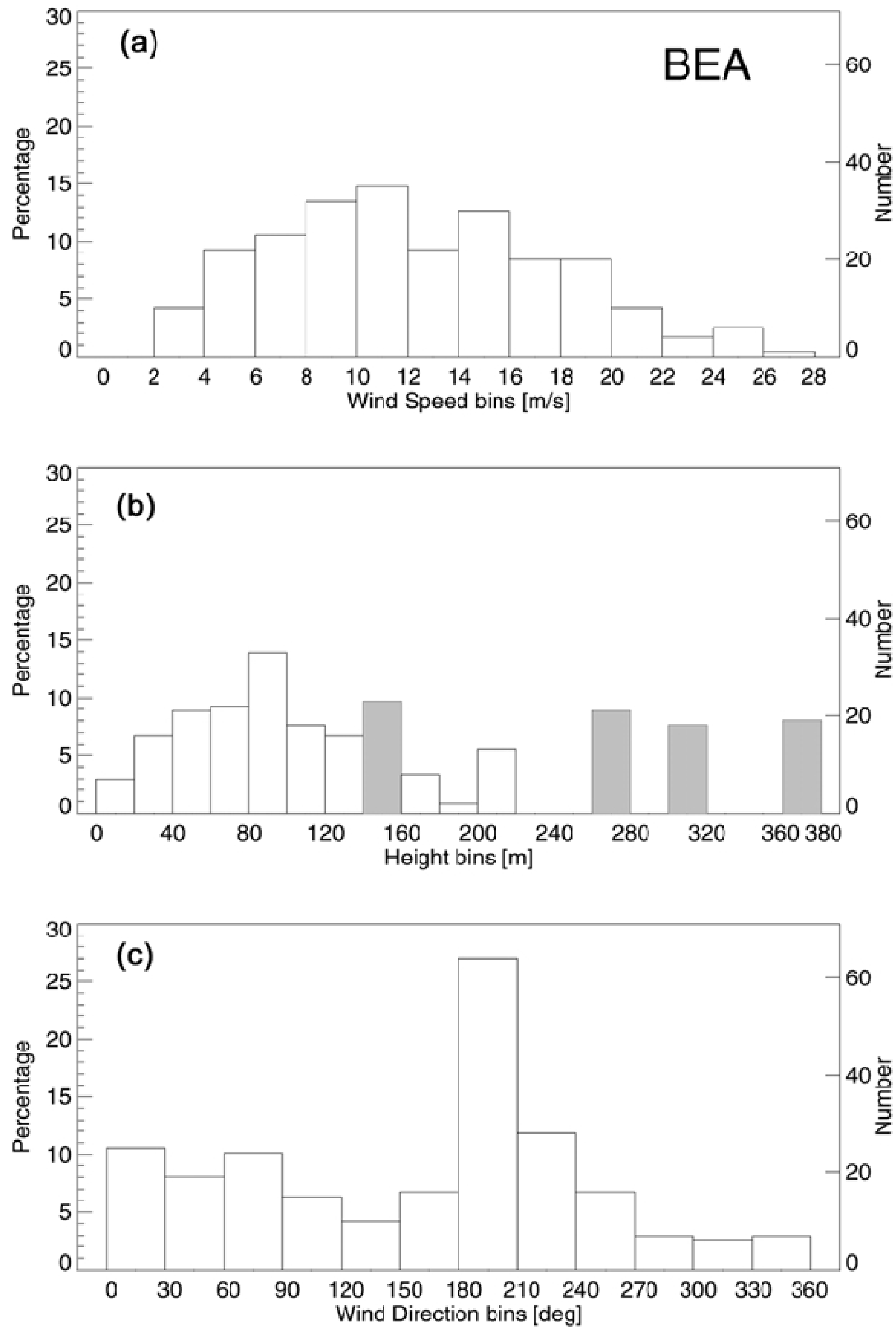


Figure 2.7: Distributions of the characteristics of LLJs identified in data from the Beaumont (BEA) sodar/profiler from 0000-1200 UTC, 3-31 October. (a) Depicts the distribution of wind speeds U_x at jet maximum. (b) Illustrates the distribution of the heights at which the jet was observed Z_x. Shaded bars indicate the levels of the profiler range gates, which are 60 m deep and lead to some quantization of jet heights. (c) Shows the distribution of wind directions D_x at jet maximum (0 degrees is from the north) (Reproduced from Banta et al. 2002).

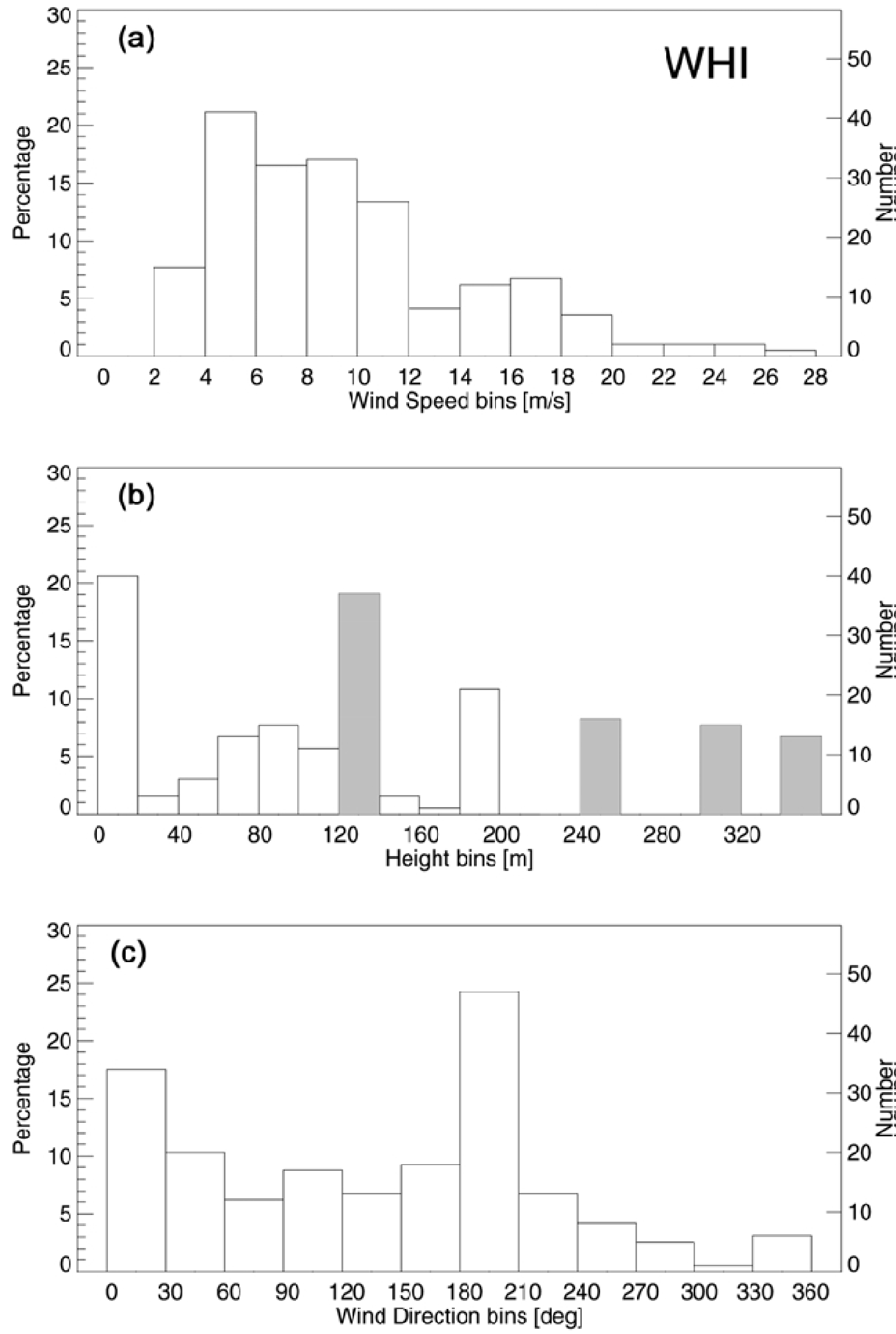


Figure 2.8: Same as Figure 2.7, but of data from the Whitewater (WHI) site (Reproduced from Banta et al. 2002).

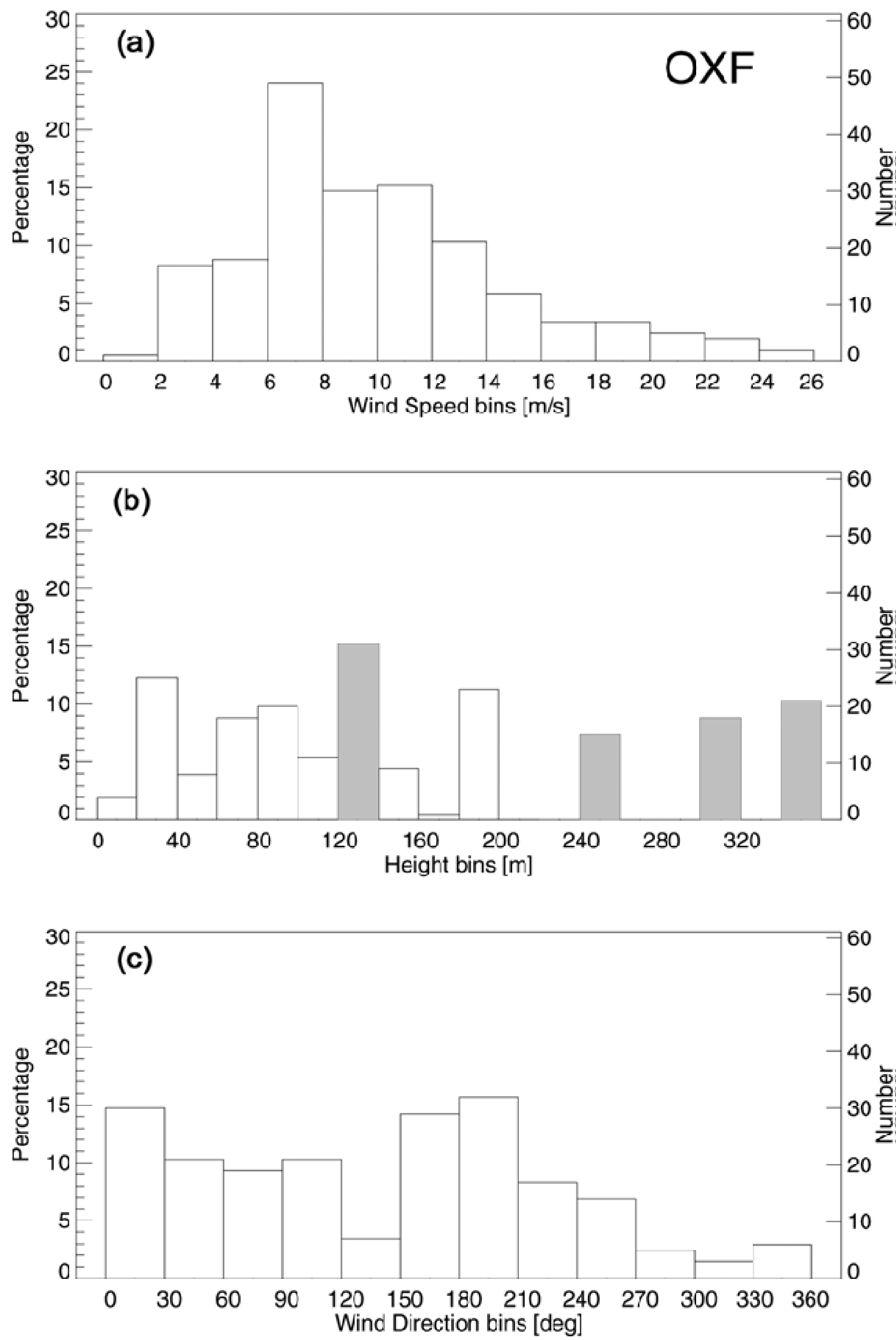


Figure 2.9: Same as Figure 2.7, but of data from the Oxford (OXF) site (Reproduced from Banta et al. 2002).

The Z_x at BEA was similar to the Z_x sampled by the HDRL with a peak of approximately 80 to 100 m AGL. The other two sites, WHI and OXF, had slightly higher peaks at 120 to 140 m AGL. This finding, above many of the others, is most significant to the wind energy community, as well as to the current study. Also, the authors noted that the highest station, BEA, usually had the lowest Z_x. Banta et al. (2002) hypothesized that the LLJ did not seem to be terrain following, but was more like "a sheet or extensive layer of high-momentum flow over the entire region" (Banta et al. 2002). The one commonality between all the profile sites and the HDRL is the southerly peak in LLJ direction.

Overall, this study brings to light the possibility that the nocturnal LLJ may be closer to the surface than most other studies have shown. Having the instrumentation to accurately sample at these heights was extremely beneficial to the gathering of data for this study. The HDRL, due to its fine resolution data, allowed the authors to focus on the initial wind speed maximum above the surface, theoretically produced by decoupling nocturnal flow. It was thought that this initial maximum is most likely responsible for the generation of shear and turbulence between the surface and LLJ. Data from the HDRL showed fluctuations of the LLJ speed and height over time periods of a matter of minutes. This, coupled with the number of LLJs with Z_x near or below 100 m AGL, was a significant finding for wind energy applications.

Chapter 3

Methodology

3.1 Study Focus

A number of LLJ studies have been conducted over the years. Some noted the effects or influence of LLJs on convection (Pitchford and London 1962; Bonner 1966; Walters and Winkler 2001), while others depicted the climatological characteristics of LLJs (Bonner 1968), and even some others looked at the role of nocturnal inversions in LLJ development (Blackadar 1957). Many of these have conflicting sets of criteria for what constitutes a LLJ, which can lead to differing values in the frequency, average level, and average speed of LLJs over a given area. The majority of these studies take place across the plains states, where LLJs tend to be more common (Bonner 1968; Blackadar 1957). This study primarily focuses on the lowest levels of the atmosphere, up to 150 m AGL. However, in order to choose the cases needed for this study, we developed our own LLJ criteria; partially adopted from Part I of the Walters and Winkler (2001) study.

3.2 LLJ Case Identification

For the year 01 May 2003 to 30 April 2004, we examined data from radiosondes launched by the National Weather Service (NWS) Weather Forecast Office (WFO) in Springfield, MO (SGF). SGF was chosen because it is the only site in the state of Missouri that launches radiosondes routinely and is also located in a more favorable area for LLJ development (Bonner 1966, 1968). Upper air observations at 00 and 12Z for each day were inspected and all instances of wind speeds at or greater than 15 knots at 850 and 925mb were chosen using the upper air archive maps from the Storm Prediction Center (SPC). Next, the events with winds stronger at 925mb than 850mb were set apart and reserved. With the focus of this study being wind energy generation in the lowest 150 m AGL, this step of keeping events with stronger winds at 925mb than at 850mb was a calculated choice aimed at examining the near-surface wind field based on LLJs that were lower than the typical, meteorologically significant 850mb level.

The following portion of our criteria was performed using upper air wind profiles of the radiosondes launched at SGF for the events reserved in the previous step. This information was obtained via a database of radiosonde data maintained by Global Systems Division of the Earth System Research Laboratory (ESRL), formerly Forecast Systems Laboratory (FSL) and plotted using the program RAOB. Utilizing an Excel spreadsheet, the following information on the retained cases was documented from this data: Date, Time (Z), Wind Maximum Level (mb), Wind Maximum Height (m AGL), Wind Maximum Direction (deg.), and Wind Maximum Speed (kts.). Now, the second half of our criteria was applied using the same dataset. The remaining criteria consisted of,

1) Vertical wind shear between the level of strongest winds and earth's surface equaled or exceeded 8 kts. (Walters and Winkler (2001) used 4 ms^{-1} or ≈7.78 kts.)

2) Vertical wind shear between the level of strongest winds and either the next highest wind minimum or 550mb, whichever is lower, equaled or exceeded 8 kts. (Walters and Winkler (2001) used 4 ms^{-1} or ≈7.78 kts.)

This left a total of 75 preliminary LLJ events, with 5 events occurring at 00Z and 70 events at 12Z. These events will be the focus of our study.

3.3 Jet Classification

One of our objectives with this study was to categorize each event into a particular form of LLJ type, which was adapted from Part I of the Walters and Winkler (2001) study (Table 2.1 and Figure 2.3). The purpose of this step was two-fold. First of all, it aided in producing the final number of LLJ events used for the study, as noted later in this section. Second, it allowed the author to obtain and document a small climatology of LLJ profiles across the state during a full year. This included noting the frequency of jet events found over SGF, the distribution of northerly and southerly jets, and the distribution of the southerly cases between the long and short jet types. 80-km RUC initialization data, obtained from the Meteorology Department at Saint Louis University

(SLU), was the source of information for this particular portion of the experiment. Unfortunately, seven of these cases were removed from the sample due to unavailable RUC data, leaving a total of 68 cases to be examined. Of this year long look at jet events, 63 of the 68 cases were noted at 12Z, leaving only 5 cases at the 00Z timeframe.

First, the author plotted RUC streamlines and isotachs (kts) at 850 mb for each jet event using the General Meteorology Package (GEMPAK) Analysis and Rendering Program (GARP); classifying each jet event as northerly or southerly. The final step for this procedure was to subjectively apply the Walters and Winkler (2001) jet types to each case and document.

3.4 Data

For the second half of this study, 20-km RUC data was obtained from the Atmospheric Radiation Measurement (ARM) program supported by the U.S. Department of Energy (DOE). Initial runs of the model for each hour during a one year time period from 01 May 2003 to 30 April 2004 were obtained. Each hour is represented by a grib file in the tarball. These grib files were then extracted for each individual hour's initial run. The grib files not needed for this study were deleted, leaving only the days and hours for each event. They were then converted to .gem format for use and interpretation in GEMPAK and GARP. These model grids were initially on hybrid (isentropic-sigma) levels and then converted to all isentropic (θ) levels utilizing a script created for this purpose. The final step before the compositing of the RUC analysis grids was to interpolate the grids to height above ground level (zagl) using the GEMPAK program, GDVINT, which performs interpolations between vertical coordinates.

The analysis fields of the RUC numerical model were employed during this study to assist in the classifying of jet types, as well as the compositing of LLJ and non-LLJ events. The 20-km RUC was the computer model of choice for the composites, due to a finer horizontal resolution (20-km grid spacing), the hybrid isentropic-sigma vertical coordinate system (50 computational levels) it employs, and the amount of recent observational weather data it assimilates. The 20-km grid spacing allows for better resolution of areas with small-scale terrain differences, producing better detail than its predecessors across the Ozark Plateau in southern Missouri. The RUC20 also utilizes slope envelope topography. In slope envelope topography, the terrain standard deviation is calculated with respect to a plane fit to the high-resolution topography in each grid box. This allows for more accurate terrain values, especially across sloping areas along the edge of high-terrain regions. Slope envelope topography also avoids the projecting of the edge of plateaus, such as the Ozark Plateau referred to in this study, too far laterally into lower-terrain regions (Benjamin et al. 2004). The hybrid vertical coordinate utilizes terrain-following sigma levels near the surface and isentropic surfaces aloft. In total, the RUC20 has 50 vertical levels with each of the levels having been assigned a reference virtual potential temperature (θ_v) that increases with height. The lowest atmospheric level (k=1) is assigned as the pressure at surface level or the model terrain elevation (Benjamin et al. 2002). A minimum pressure thickness is then assigned between each of the following 49 levels. For grid points with surface elevations near sea level, the minimum pressure thickness in the bottom four layers are 2.5, 5.0, 7.5, and 10mb. The tops of those layers correspond to approximately 21, 63, 127, and 212 m AGL, respectively. A minimum pressure thickness of 15mb is depicted for the layers above the bottom four, up to the 400-mb level (Dévényi and Benjamin 2003).

Wind data from a number of sources is assimilated into the RUC, including: rawinsonde observations, wind profiler data, VAD (Velocity Azimuth Display) winds from radar data (WSR-88Ds), ACARS (Aircraft Communications Addressing and Reporting System) aircraft flights, as well as surface METAR (Aviation Routine Weather Report) and mesonet observations (Benjamin et al. 2002). This, along with the terrain-following near-surface levels, was a major draw in the utilizing of RUC analysis data during this study.

Output from the RUC20 initial fields constitutes a majority of the data in this study. Due to this, we must acknowledge potential shortcomings in the analysis phase. Firstly and as stated earlier, the RUC files utilized in this study have a grid spacing of 20 km. Unfortunately, the existing observational data networks have station spacings far greater than 20 km. This includes data from most all observation networks noted previously in this section, which illustrates that the RUC analysis exists on a finer scale than that depicted by observational data. Secondly, the data with higher vertical resolution (rawinsondes) occur at relatively infrequent times compared to other datasets, while the higher temporal-frequency data (ACARS and wind profilers) have a diminished vertical resolution. However, this study happens to take place in an area where profiler data is in ample supply, allowing for better resolution instead of simply extrapolating surface data upward through some type of theoretical wind profile.

As the streams of observational data are assimilated into the RUC every hour, they are done so with the previous 1-h RUC forecast as a background used to produce a new 3D estimate of atmospheric fields. Observation innovations, which depict the difference between the observation and background data, are generated to produce an estimate of the 3D multivariate forecast error field, which is also referred to as the analysis increment. This analysis increment is then added to the 1-h forecast background to produce the new analysis (Benjamin et al. 2004). An optimal interpolation (OI) analysis was used previously within the RUC, with multivariate analysis of mass and momentum fields at all levels followed by a univariate analysis of the winds in the lowest 5 levels. The OI approach was replaced on 27 May 2003 by 3-D variational analysis, which has been detailed by Dévényi and Benjamin (2003) and Benjamin et al. (2004).

3.5 Non-LLJ Case Identification

Non-LLJ cases were chosen a bit differently because of how the criteria (i.e. 925>850mb wind) for choosing LLJ events were constructed. These cases could not be chosen arbitrarily or even with the pattern of choosing cases on days that surround our LLJ events. This would not present the intended result, as it could allow for the choosing of non-LLJ cases where the wind at 850mb was stronger than at 925mb and conceivably both greater than 15 knots. This would still be classified as a LLJ in other estimations, just not in this particular study. Thus, the results would perhaps not have as much significance, as would be possible by creating a separate set of criteria for identifying non-LLJ events. That idea gave birth to the following criteria:

- Using SPC upper air archives

  - Wind speed at 925/850mb < 15 knot barbs at SGF, Topeka, KS (TOP), and Omaha, NE (OAX).

  - Wind speed at 925/850mb ≤ 15 knot barbs at Lincoln, IL (ILX) and Davenport, IA (DVN).

These criteria provided a total of 42 cases, with 31 at 00Z and 11 at 12Z. The four additional sites (TOP/OAX/ILX/DVN) were chosen due to their proximity to Missouri, effectively lessening the chance a LLJ would be sampled in the identification of non-LLJ cases. A higher wind speed threshold was chosen on the eastern border of Missouri because most of the focus throughout this study has been on the western half of the state, where wind-generated energy potential is more viable (Silcock 2008). Also, if the threshold for ILX and DVN were set at < 15 knot barbs, as opposed to ≤ 15 knots, only 17 total cases would fit the criteria. The 20-km RUC data for these 42 non-LLJ cases then underwent the same data gathering, converting, and interpolating process as the previous 68 LLJ cases.

3.6 Composites

One of the final steps in analyzing the 20km RUC low-level wind fields, as it pertains to wind generated energy possibilities, comes from composites produced with a program provided by Dr. Charles Graves and Chad Gravelle of Saint Louis University (SLU). These composites were generated from the GEMPAK grids for each event, LLJ and non-LLJ. Composites of the total wind speed for both the LLJ and non-LLJ cases were generated in 20 m intervals from 40 m up to 120 m AGL. The composites were computed as percentiles, allowing us to gather information on what percentage of cases have a particular value or lower at any given grid point. These percentiles were calculated at the 90, 75, 50, 25, and 10th percentile levels, with 50 percent being the median. These median composites became the main results analyzed during this study. We also generated composite means of speed shear between the top and bottom of projected wind turbine blades. The equation used to calculate the speed shear between an upper bound (UB=140 or 120 m AGL) and a lower bound (LB=60 or 40 m AGL) for this step consisted of,

$$\frac{\partial V}{\partial z} = \left[\left(\frac{[mag\ wnd@UB - mag\ wnd@LB]}{80}\right)\right] \qquad (3.1)$$

Assuming the turbine hub is located at either 80 or 100 m AGL and that the diameter of the circle created by the turbine blades is 80 m, the two layers in which wind shear was composited are between 40 and 120 m and 60 and 140 m AGL.

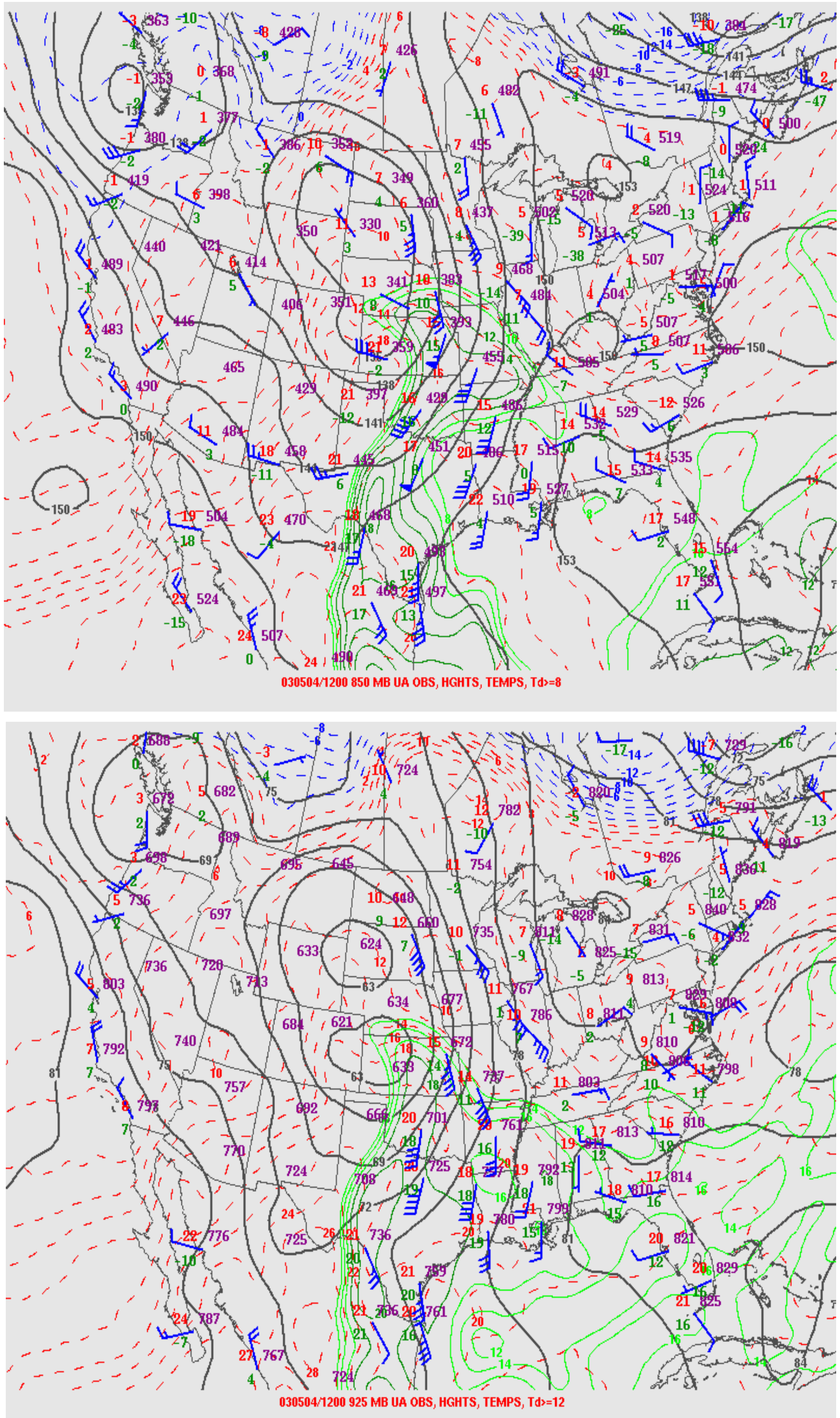
Chapter 4

Results

This study investigated events in the year-long period, 1 May 03 to 30 Apr 04, to define whether a LLJ was present across Missouri. Once identified, numerous characteristics and attributes of these LLJs were assessed for their seasonal variability and statistical significance. Upper air observations were also used to identify non-LLJ events using a separate set of criteria. RUC initial fields were then utilized to note the effect the LLJ or non-LLJ events have on the wind field at turbine levels. The name of this phenomenon, LLJ, distinguishes itself as a layer of increased wind speeds above the surface, but thought to be low enough to have some effect on near-surface wind speeds. These are the findings that were sought after. Any effect the LLJ would have on near-surface wind speed and shear would be of importance to the wind power community. This section will present results from the investigation of LLJ events in Missouri and the effect LLJ and non-LLJ events have on wind speeds and shear at turbine levels.

4.1 LLJ Cases

This particular study was not as concerned about whether the LLJ was generated via the planetary boundary layer (PBL) decoupling or whether it was synoptically-driven. Our main focus was to identify and classify those LLJs that met our criteria and possibly have a greater influence on near-surface wind speeds. As described in Chapter 3 and illustrated in Figure 4.1, the first step utilized SPC upper air archive maps, focusing on SGF, to find events at 00 or 12Z that had a wind speed of 15 knots or greater as well as a greater wind speed at 925mb than at 850mb.

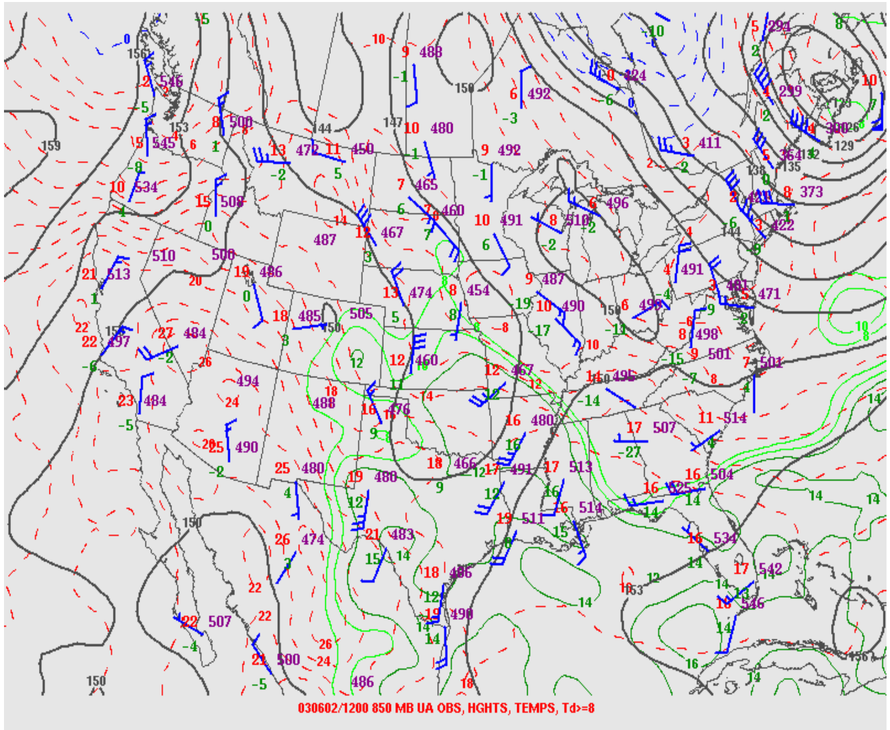


a)

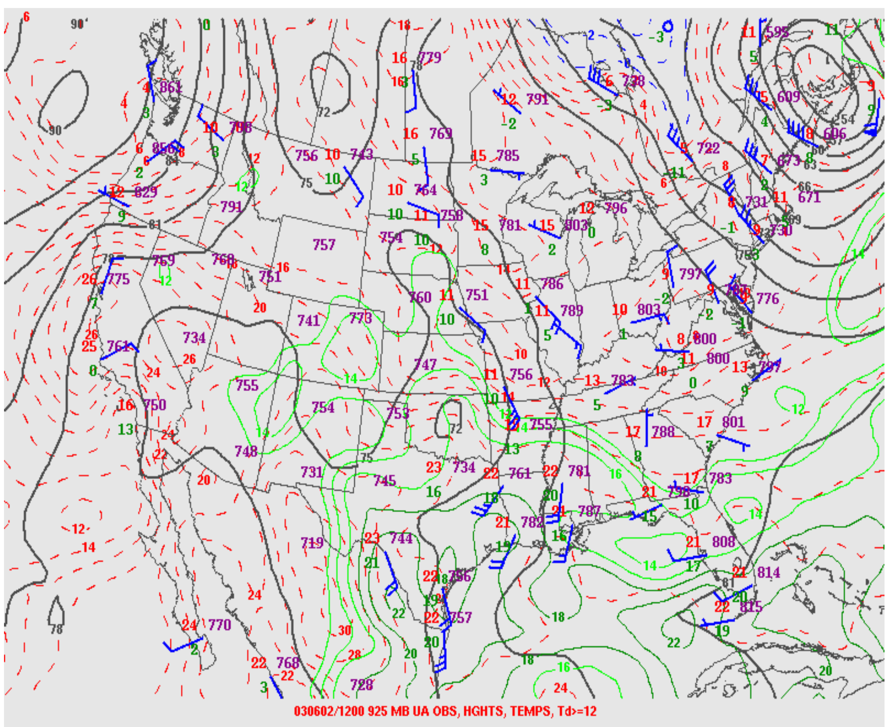
b)

Figure 4.1: Example of SPC upper air archive maps at a) 850 and b) 925mb that were utilized in the LLJ case identification process, looking across the entire year for events at 00/12Z in which the wind speed at 925mb was greater than 850mb in the SGF location. This example depicts wind barbs at SGF on the 850 and 925mb levels as 35 and 45 knots, respectively.

Out of all 366 days and a look at 732 individual cases, 135 events either had winds at 925mb greater than at 850mb or equal wind barbs at or above 15 knots that required more investigation, as in Figure 4.2, which was completed when the second portion of the criteria was applied. After diagnosing the vertical profiles and applying the remaining criteria, a total of 75 preliminary LLJ events were outstanding, with 5 events occurring at 00Z and 70 events at 12Z.



a)



b)

Figure 4.2: Example of a possible LLJ event that required more investigation, as the wind barbs at SGF on the a) 850 and b) 925mb levels were equal, at 25 knots.

After further analyzing the upper air sounding observations from SGF, the data provided good insight into the frequency, vertical positioning and strength of the 75 LLJ cases sampled. As was noted previously, one of the first details observed from these data is the number of jet events noted at 12Z, as opposed to 00Z. With just over 93 percent of all jet events sampled at 12Z, it could be hypothesized that the majority of these jet events were due to the nocturnal decoupling of the boundary layer. However, seven of the first ten days of May 2003 were noted by significant convective systems that may have induced a more synoptically-driven LLJ. That is just an example of the different mechanisms that play a role in LLJ development.

The data also confirmed the general direction from which a majority of the wind maxima occurred. Of the 75 cases examined, 69 events had a southerly (90°-270°) component and only 8% or six events were from a northerly (270°-90°) direction. These results help to illustrate that while northerly LLJs do occur, they are rare in nature. A more comprehensive look at the breakdown in the direction of the wind maxima is noted in Figure 4.3. The data show LLJs from all directions, except from the northwest (292.5°-337.5°). However, noticeable peaks in jet events are seen from the south (157.5°-202.5°) and southwest (202.5°-247.5°) directions. Note that the majority of the events were out of the southwest, with 40 cases registered, or just over half of the events. The southerly direction logged 20 of the 75 cases.

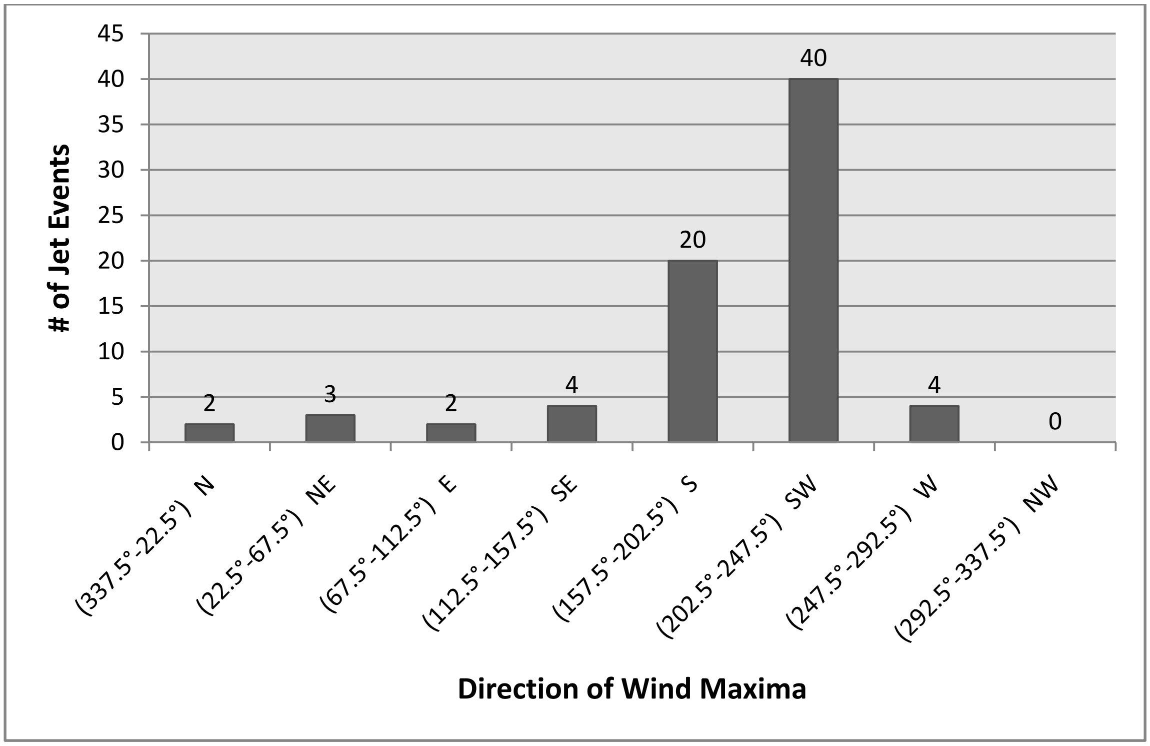


Figure 4.3: Histogram depicting the distribution of jet events by the wind direction of the jet maximum in all 75 cases within the sample. Data analyzed from upper air radiosonde observations at SGF.

The next SGF LLJ attribute discussed in this section is the monthly distribution of events, which is shown in Table 4.1. The two highest monthly counts of jet events occurred in December 2003 and July 2003, which produced 11 and 9 cases, respectively. Seasonally, the winter months logged the most LLJs with 21 events. However, the spread was rather small between the winter, summer, and fall months, with 20 and 19 LLJ events registered during the summer and fall, respectively. The least amount of events was registered during the spring months, comprised of May 2003 and March and April of 2004, where 15 LLJ cases were logged.

Table 4.1: Depicts the monthly distribution of LLJs events in this study. The number in the parentheses represents the number of jet events that were removed due to missing RUC data.

Month	*# of Jet Events*		*Month*	*# of Jet Events*
May 2003	4 (1)		November 2003	6
June 2003	7		December 2003	11 (2)
July 2003	9 (2)		January 2004	5
August 2003	4 (1)		February 2004	5
September 2003	7 (1)		March 2004	3
October 2003	6		April 2004	8

The height and millibar level of the low-level wind maxima over SGF, according to the criteria applied to the observations, was averaged at 375 m AGL and at 929mb, respectively. The lowest a jet was found, based on the data afforded, was 224 m AGL. All 75 cases fell between 200 and 900 meters, as depicted by Figure 4.4. Of those 75 total cases, a majority of the LLJ events, just over 86% (65), were noted in the 200 to 500 meter range with two distinct peaks in the number of jet events. These peaks occurred in the 200 to 300 m and 400 to 500 m AGL range, with 27 and 26 jet events respectively. This is significant because the typical LLJ height is generally defined as falling between 500 and 1500 m AGL (Bonner 1968; Mitchell et al. 1995; Zhang et al. 2005). Banta et al. (2002) found some LLJs to be at or below 100 m AGL, which is lower than what was found in the current study. Consequently, Banta et al. (2002) and the current study, both validate the need to investigate whether the LLJ has an effect on wind turbine-level wind fields.

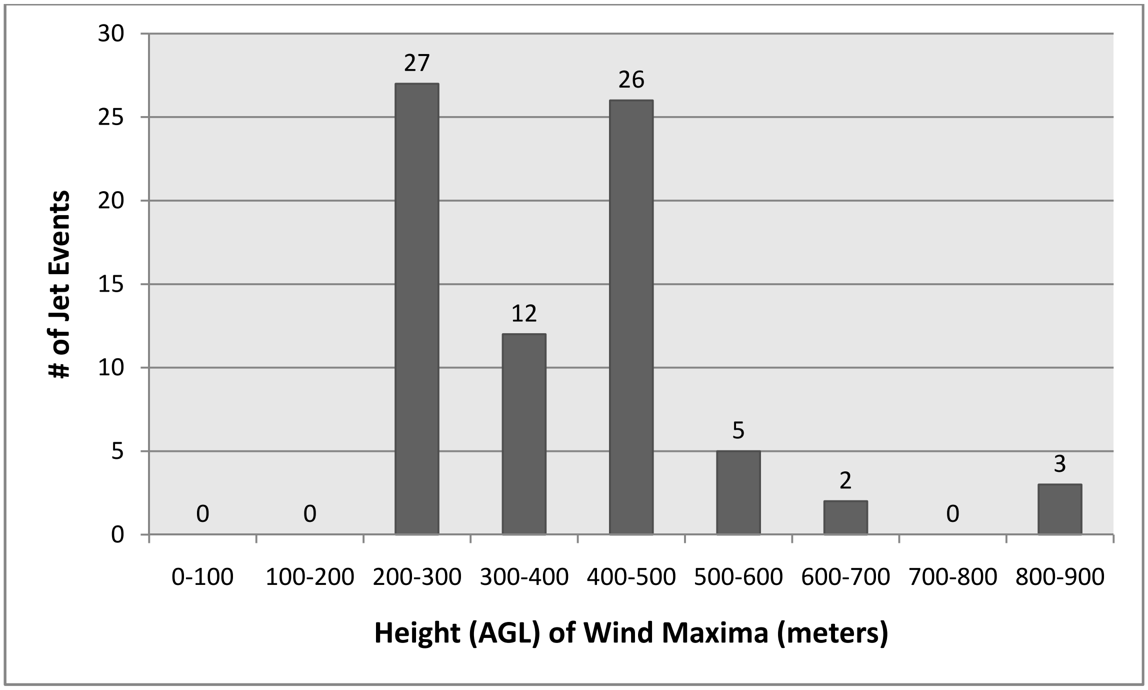


Figure 4.4: Histogram depicting the distribution of jet events by the height (AGL) of the jet maximum in all 75 cases within the sample. Data analyzed from upper air radiosonde observations at SGF.

Figure 4.5 illustrates a slightly more even distribution of the wind speed for the 75 LLJ cases. Nearly half of all the events had a jet maximum wind speed of between 25 and 35 knots, with a peak of 22 events located within the 25 to 30 knot range. There also appears to be a slight secondary peak in wind speed distributions between 40 and 50 knots. The average wind speed across all LLJ events was 32 knots, with two peak wind speed cases of 51 knots, both in the month of December 2003. Table 4.2 depicts the average monthly wind speeds for the jet maximums. Notice the higher averages were noted in the winter season, with January 2004 having the strongest average wind speed of 39 knots. The lowest averages were noted in the summer season, with the month of August 2003 having the weakest average LLJ wind speed of 24 knots.

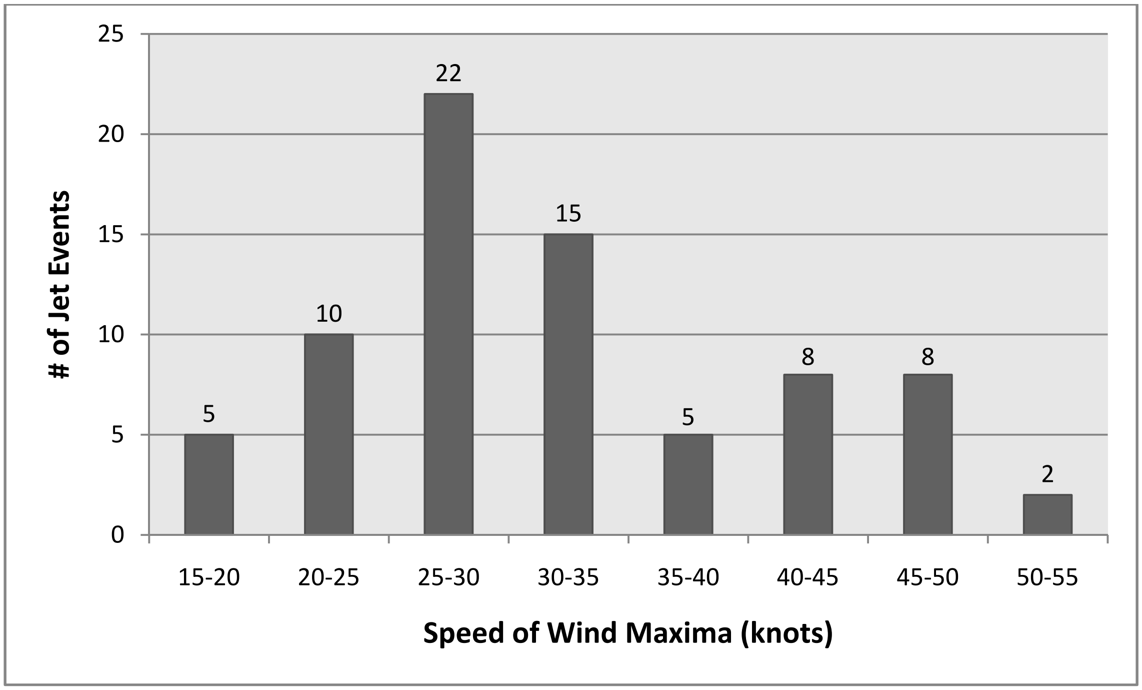


Figure 4.5: Histogram depicting the distribution of jet events by the speed of the jet maximum in all 75 cases within the sample. Data analyzed from upper air radiosonde observations at SGF.

Table 4.2: Depicts the average maximum wind speed of the LLJ events on a monthly basis. Data analyzed from upper air radiosonde observations at SGF.

Month	*Average Wind Speed of Jet Events (kts.)*		*Month*	*Average Wind Speed of Jet Events (kts.)*
May 2003	31		November 2003	32
June 2003	28		December 2003	37
July 2003	28		January 2004	39
August 2003	24		February 2004	38
September 2003	27		March 2004	38
October 2003	32		April 2004	34

Figure 4.6 is an illustration all 75 individual LLJ events, plotted for speed (knots) versus height (AGL). This plot is significantly affected by the vertical resolution of the data obtained from the SGF upper air observations. One example of the lack of vertical resolution within this data is the number of LLJ wind maximums located at 224 m (or 2,000 ft above mean sea level), which is the lowest a jet maxima was found. The linear trendline shows a gradual increase in the height of the LLJ maximums as the speed of the wind maximums increased. This illustrates a more shallow, yet similar trend to the Banta et al. (2002) results in Figure 2.6. However, there is one difference between the two studies: Banta et al. (2002) showed a pronounced lack of strong jets at lower heights which could be attributed to surface friction, while the current study demonstrates a decrease in the number of strong jets at relatively lower altitudes, but is not eliminated completely. This result could be a function of the Banta et al. (2002) study sampling much lower in the atmosphere than our instrumentation allowed. Figure 4.6 also conveys a lack of weaker jets at higher heights. However, this trend changes as a few jet maximums are noted at higher elevations as the LLJs become stronger.

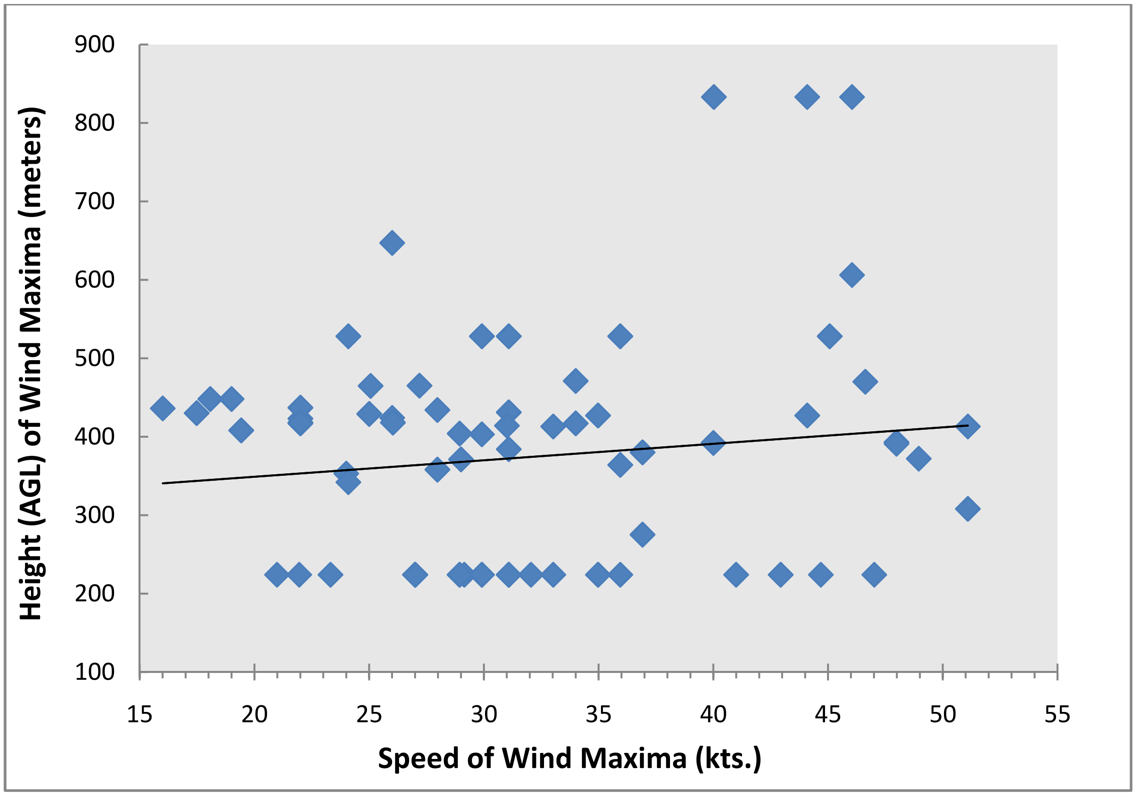


Figure 4.6: Scatter plot of speed (kts.) versus height (AGL) of all 75 jet maxima. The solid line represents a best-fit linear regression.

4.2 Jet Classification

A classification of LLJ profiles, based on jet profiles adopted from Walters and Winkler (2001), was undertaken as a way to gain a small climatology of jet types across Missouri and to finalize the number of jet cases used during this study. This was done utilizing 80-km RUC data analysis output for all 75 preliminary events. Due to missing RUC data, seven LLJ cases were removed. This left a final total of 68 cases to be classified and examined for influence on turbine-level winds. RUC streamlines and isotachs (kts) at 850 mb were plotted (Figure 4.7) for each event and the Walters and Winkler (2001) jet types, noted in Chapter 2 (Figure 2.3), were subjectively applied.

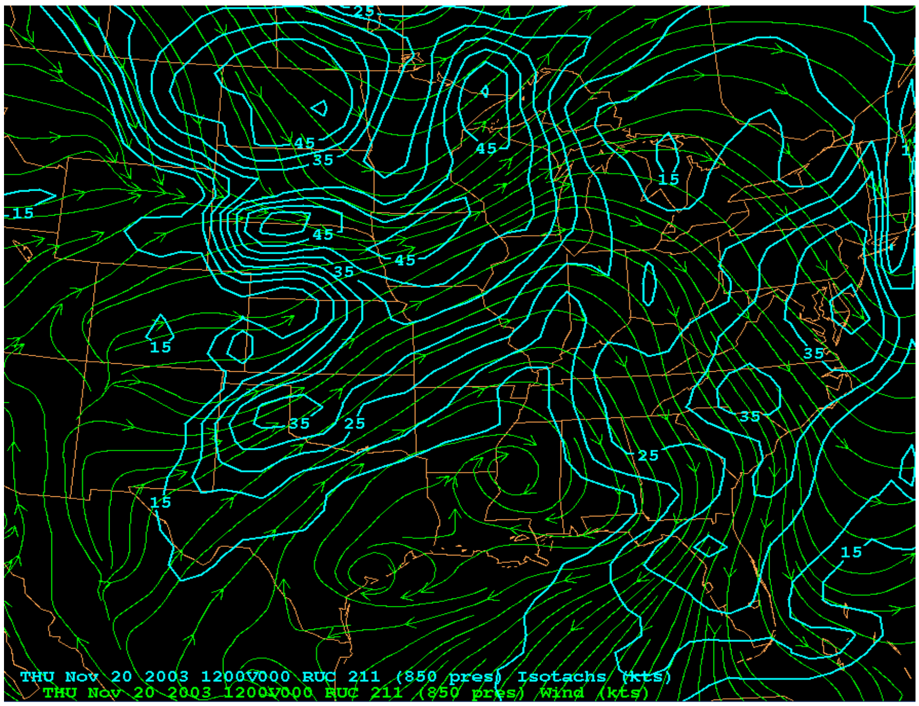


Figure 4.7: Example of 80km RUC initial fields for 850mb streamlines (green) and isotachs (kts-blue). These were the plots used for the subjective classification of jet types. This example was classified an Ac-SWNE jet.

Of these 68 jet cases, five of them illustrated a northerly component and of the 63 southerly cases, the distribution between long and short jet types were nearly equal, 32 and 31 cases respectively.

Table 4.3 depicts the distribution of jet events across all 10 of the Walters/Winkler jet types logged during this study. Just over 66%, or 42 of the southerly jet events in Table 4.3 have an anticyclonically-curved (denoted by an 'A' in Table 4.3) influence based on the subjective classification. Interestingly, the jet profiles with the highest amount of long and short LLJ events were the LAc-SWNE and Ac-SWNE, which are defined as the long and short versions of the 'Anticyclonically curved wind maximum with a confluence zone oriented southwest to northeast' (Walters and Winkler 2001). This finding also corresponds fairly well with Walters and Winkler (2001), as the jet profiles Ac-SWNE and LAc-SWNE logged the second and third-most first level jet events respectively, in their study. The jet type, Cc or 'Cyclonically curved wind maximum with confluence zone' (Walters and Winkler 2001), logged the highest amount of events in the Walters and Winkler (2001) study.

Table 4.3: The number of jet events classified into each jet type, based on subjective classification by the author.

Long Jet Types	***# of Jet Events***		***Short Jet Types***	***# of Jet Events***
LAc-SWNE	13		Ac-SWNE	20
L2A	4		Ac-EW	5
LKc-SWNE	5		Kc-SWNE	2
LBKc-SWNE	7		Bd-NWSE	4
LB	2			
LCc	1			

4.3 Non-LLJ Cases

A sample of non-LLJ cases was obtained to compare and contrast the turbine-level composites of LLJ and non-LLJ events. The acquisition of these non-jet cases required a separate set of criteria, tailored to finding non-LLJ days in Missouri. Initially, the thought was to utilize days surrounding the already chosen LLJ events and employ them as non-LLJ cases. This would not necessarily produce the intended results, as many of those days were still LLJ days, but did not meet our specific criteria. The criteria for this process are detailed in Section 3.5 of this document and the data was obtained from the upper air archives produced at the SPC. Analysis of this data produced a total of 42 cases chosen based on this set of conditions, with 31 cases at 00Z and 11 at 12Z. While not much in the way of results came from this process, these cases illustrate a necessary step in this study. The wind speed and shear composites depicted in the following section were generated for both LLJ and these non-LLJ cases. A comparison of the two composites assists in analyzing whether wind speeds at turbine level are positively (greater wind speed) influenced by a LLJ present above.

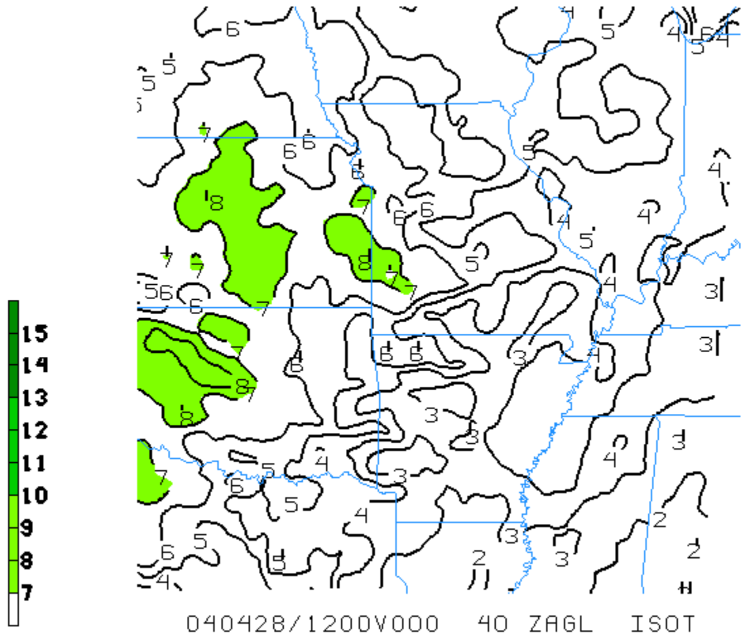
4.4 RUC Composites

The 20-km RUC initial fields were utilized to produce composite medians of the wind speeds in Missouri and across portions of neighboring states. The composites, comprised of all 68 final jet events, were generated at heights where wind turbines operate (40, 60, 80, 100, and 120 m AGL). These plots of LLJ-affected composites were then compared to composite medians of 42 events where no LLJ was observed. In the figures listed below, the green shading represents wind speeds exceeding 7 ms^{-1}.

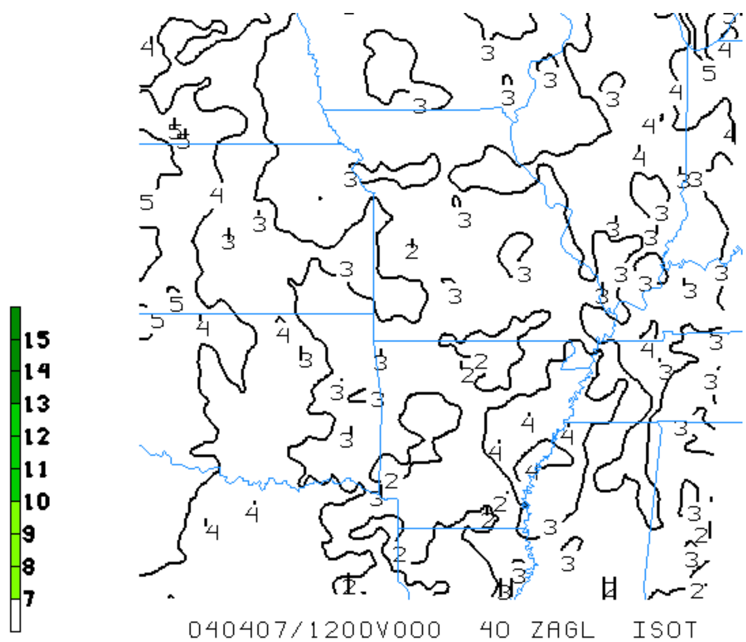
The composite figures below depict a comparison of the 20-km RUC analysis of median wind speeds at wind-turbine levels at times when the LLJ was active and when it was not. The composited output, for non-LLJ events, depicts wind speeds across the state of Missouri in the 1 to 5 ms^{-1} range with the wind speeds becoming only slightly higher with height, starting off in the 1 to 4 ms^{-1} range on the 40 m AGL surface to the 2 to 5 ms^{-1} range on the 120 m AGL surface. The output for the LLJ events depicts wind speeds ranging from 2 to 3 ms^{-1} in southeast Missouri to near 8 ms^{-1} across portions of west-central and southwest Missouri at 40 m AGL. Now, contrast that with wind speeds ranging from 5 to 6 ms^{-1} across southeast Missouri to near 11 ms^{-1} in far west-central to southwest Missouri, at 120 m AGL. The highest wind speeds, based on these composites, across all the turbine-level heights was portrayed as being across portions of west-central to southwest Missouri; more specifically, across Bates, Vernon, and Barton counties whose locations are depicted in Figure 4.8.

Figure 4.8: Depicts a county map of the state of Missouri with a green oval shape denoting Bates, Vernon and Barton counties, where higher median wind speeds on the LLJ-active composites were located (Reproduced from http://www.birding-minnesota.com/images/MO-N.gif).

At 40 m AGL (Figure 4.9), the highest median wind speeds, of 7 to 8 ms^{-1}, were noted in the west-central to southwest portion of Missouri at times when the LLJ was active. Additionally, amounts between 5 to 7 ms^{-1} were generally noted across the western third of Missouri. The lowest values, of 2 to 3 ms^{-1} were depicted across the southeastern portion of the state. A strong gradient of median wind speeds exists over southwest Missouri, more specifically, across the Ozark Plateau. A 3 to 4 ms^{-1} range is noted in south-central Missouri, where the elevation is lower compared to other nearby portions of the plateau (Figure 4.15b). Comparatively, 7 to 8 ms^{-1} is noted in west-central to southwest Missouri, where higher elevations exist across the Springfield Plateau portion of the Ozarks (Figure 4.15b). At times when the LLJ was not active, the wind field did not display as much variability as its LLJ-active counterpart. The median wind speeds range from 1 to 2 ms^{-1} across south-central Missouri to 3 to 4 ms^{-1} across the west-central to southwestern portion of the state. The highest wind speed increase between non-LLJ and LLJ composites at 40 m AGL was depicted, once again, across west-central to southwest Missouri, where a near 5 ms^{-1} increase was noted.



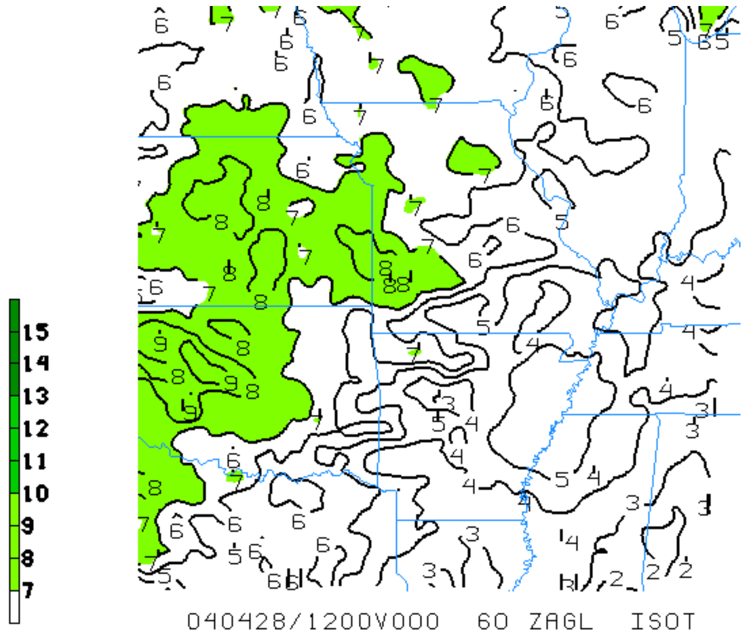
a)



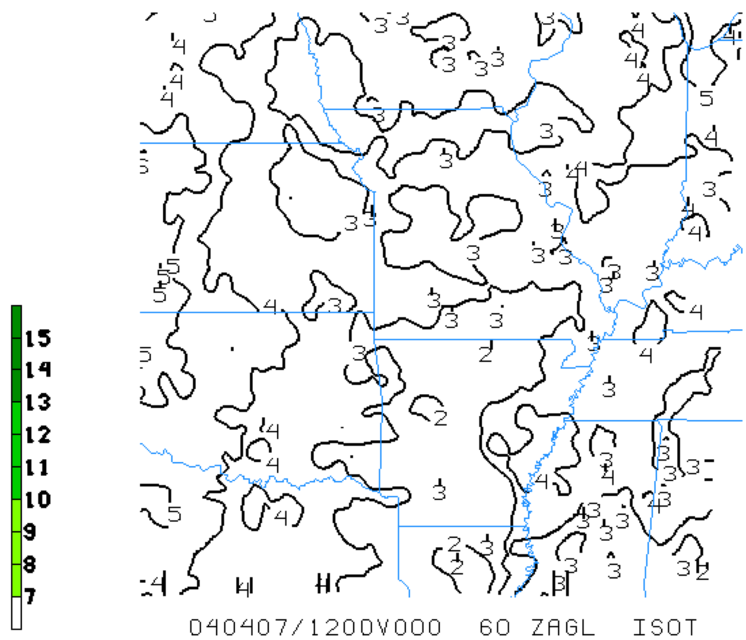
b)

Figure 4.9: Compares the median wind speed (ms^{-1}) plots at 40 m AGL, based on events where the a) LLJ or b) no LLJ was present.

At 60 m AGL (Figure 4.10), the highest median wind speeds, of 8 to 9 ms^{-1}, were noted in the west-central to southwest portion of Missouri at times when the LLJ was active. Additionally, wind speeds between 7 to 9 ms^{-1} were generally noted across the western fourth of Missouri. The lowest values, of 3 to 4 ms^{-1} were depicted across the southeastern portion of the state. Once again, a strong gradient of median wind speeds exists over southwest Missouri, more specifically, across the Ozark Plateau. In south-central Missouri, a 4 to 5 ms^{-1} range is noted, where the elevation is lower compared to other nearby portions of the plateau (Figure 4.15b). Comparatively, 7 to 9 ms^{-1} is noted in west-central to southwest Missouri, where higher elevations exist (Figure 4.15b). At times when the LLJ was not active, the wind field did not display as much variability from one side of the state to the other. The median wind speeds range from 2 to 4 ms^{-1} across the entire state of Missouri. The highest wind speed increase between non-LLJ and LLJ composites at 60 m AGL was depicted again across west-central to southwest Missouri, where a near 6 ms^{-1} increase was noted.



a)



b)

Figure 4.10: Compares the median wind speed (ms^{-1}) plots at 60 m AGL, based on events where the a) LLJ or b) no LLJ was present.

At 80 m AGL (Figure 4.11), the highest median wind speeds remained akin to the plot at 60 m AGL (Figure 4.10) as the highest speeds of 8 to 9 ms^{-1} were noted in the west-central to southwest portion of Missouri at times when the LLJ was active. Additionally, amounts between 7 to 9 ms^{-1} were generally noted across northern and western portions of Missouri. The lowest values, of 4 to 5 ms^{-1} were depicted, once again, across the southeastern portion of the state. A strong gradient of median wind speeds continues to persist at this level over southwest Missouri, more specifically, across the Ozark Plateau. In south-central Missouri, wind speeds of near 5 to 6 ms^{-1} are noted generally where the elevation is lower compared to other nearby portions of the plateau (Figure 4.15b). Speeds of 8 to 9 ms^{-1} are noted in west-central to southwest Missouri, where elevations are comparatively higher (Figure 4.15b). At times when the LLJ was not active, the wind field continued to not display as much variability as its LLJ-active counterpart. Median wind speeds of near 2 to 4 ms^{-1} were depicted across the state. As was the case with the 60 m AGL (Figure 4.10) plots, the highest wind speed increase between non-LLJ and LLJ composites at 80 m AGL located across west-central to southwest Missouri, where an increase of near 6 ms^{-1} was noted.

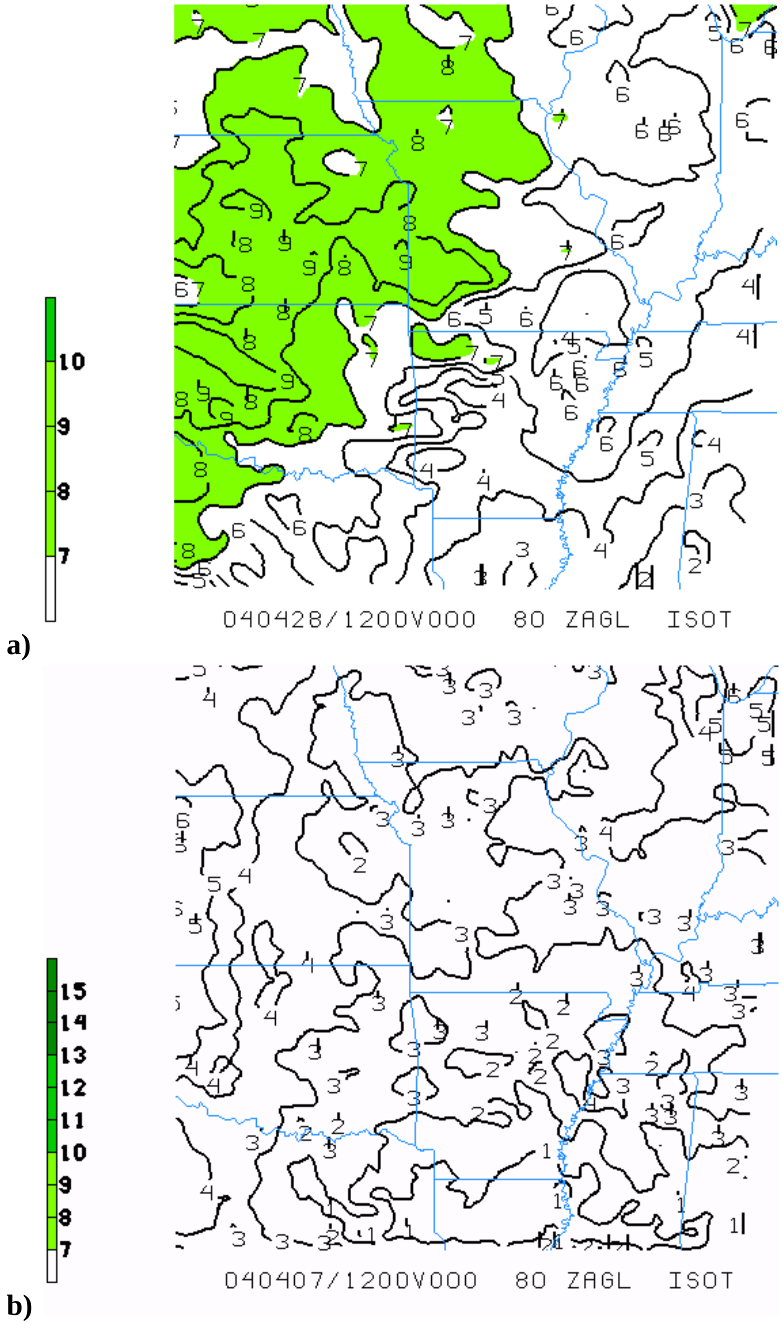
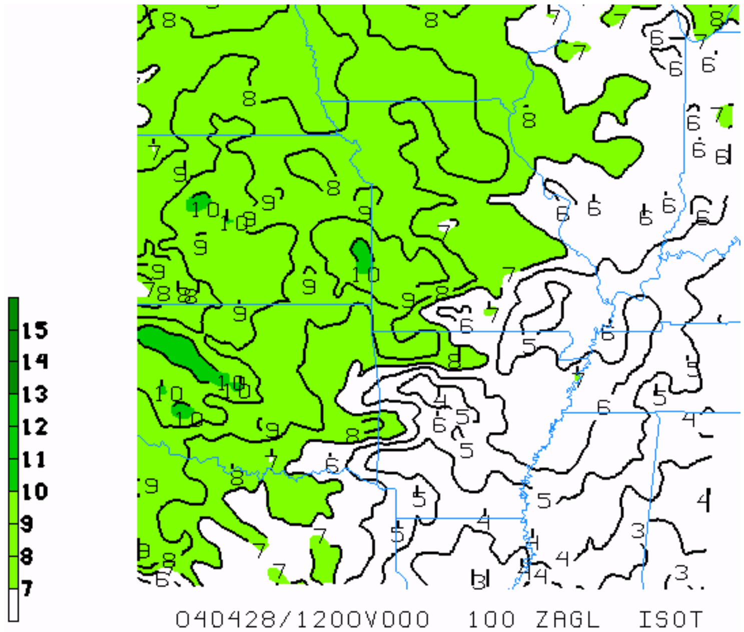
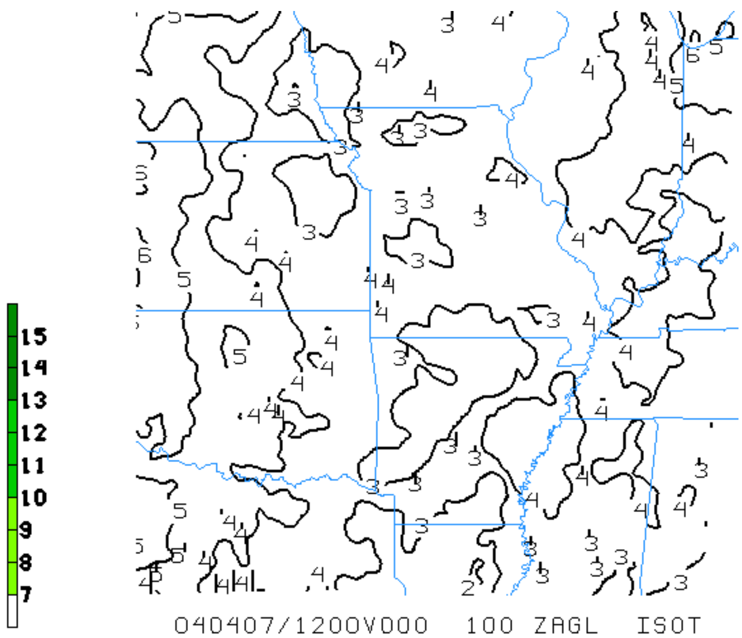


Figure 4.11: Compares the median wind speed (ms^{-1}) plots at 80 m AGL, based on events where the a) LLJ or b) no LLJ was present.

Continuing with the 100 m AGL (Figure 4.12) contours, the highest median wind speeds of near 10 ms^{-1} was depicted in extreme west-central to southwestern Missouri at times when the LLJ was active. That peak wind speed appears to reside in Vernon County, Missouri, on the border with the state of Kansas. Also, wind speeds between 8 to near 10 ms^{-1} were generally noted across the western half of Missouri. The lowest values, of 4 to 5 ms^{-1} were, once again, depicted across the southeastern portion of the state. The same strong gradient of median wind speeds, across the Ozark Plateau, continues to persist at this level as well. Winds speeds of 5 to 6 ms^{-1} were noted on the southeast side of the gradient, while stronger speeds of 9 to 10 ms^{-1} are depicted over the northwest side, where higher elevations exist (Figure 4.15b). The wind field did not display as much variability as its LLJ-active counterpart at times when the LLJ was not present. The non-LLJ median wind speed plot remained similar to the images from 60 (Figure 4.10b) and 80 m AGL (Figure 4.11b), with wind speeds ranging from 2 to 4 ms^{-1} across the state. Once again, the highest wind speed increase between non-LLJ and LLJ composites at 100 m AGL was depicted across west-central to southwest Missouri, where a near 7 ms^{-1} increase was analyzed.



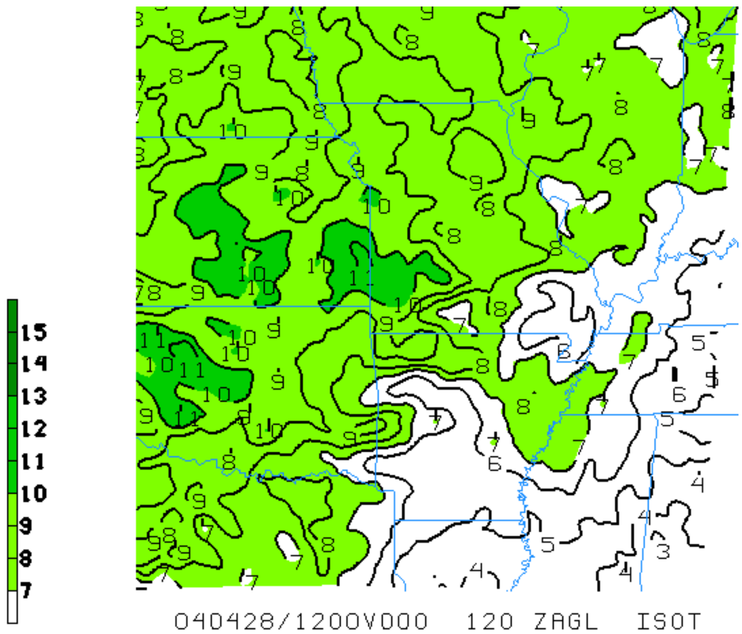
a)



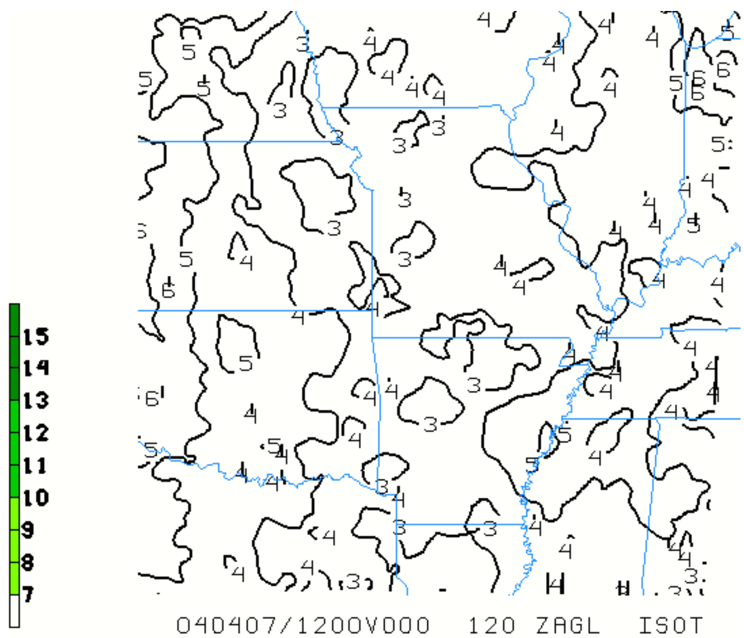
b)

Figure 4.12: Compares the median wind speed (ms^{-1}) plots at 100 m AGL, based on events where the a) LLJ or b) no LLJ was present.

Lastly, the highest median wind speeds at 120 m AGL (Figure 4.13), of 10 to near 11 ms^{-1}, were noted across the west-central to southwest portion of Missouri at times when the LLJ was active. Additionally, speeds between 9 to 11 ms^{-1} were generally noted across the western third of Missouri. The lowest values, of 5 to 6 ms^{-1} remain situated across the southeastern portion of the state. The strong gradient of median wind speeds persists over the Ozark Plateau in southwest Missouri at this level. A range between 6 to 7 ms^{-1} is noted in the lower elevations of south-central Missouri (Figure 4.15b). Comparatively, a 10 to 11 ms^{-1} range is depicted across west-central to southwest Missouri. The wind field did not display as much variability when the LLJ was not present. Median wind speeds ranged from 2 to 5 ms^{-1} across the state, with the higher amounts of 4 to 5 ms^{-1} depicted across portions of far eastern Missouri. The highest wind speed increase between non-LLJ and LLJ composites at this level was depicted across west-central to southwest Missouri, where a near 8 ms^{-1} increase was noted.



a)

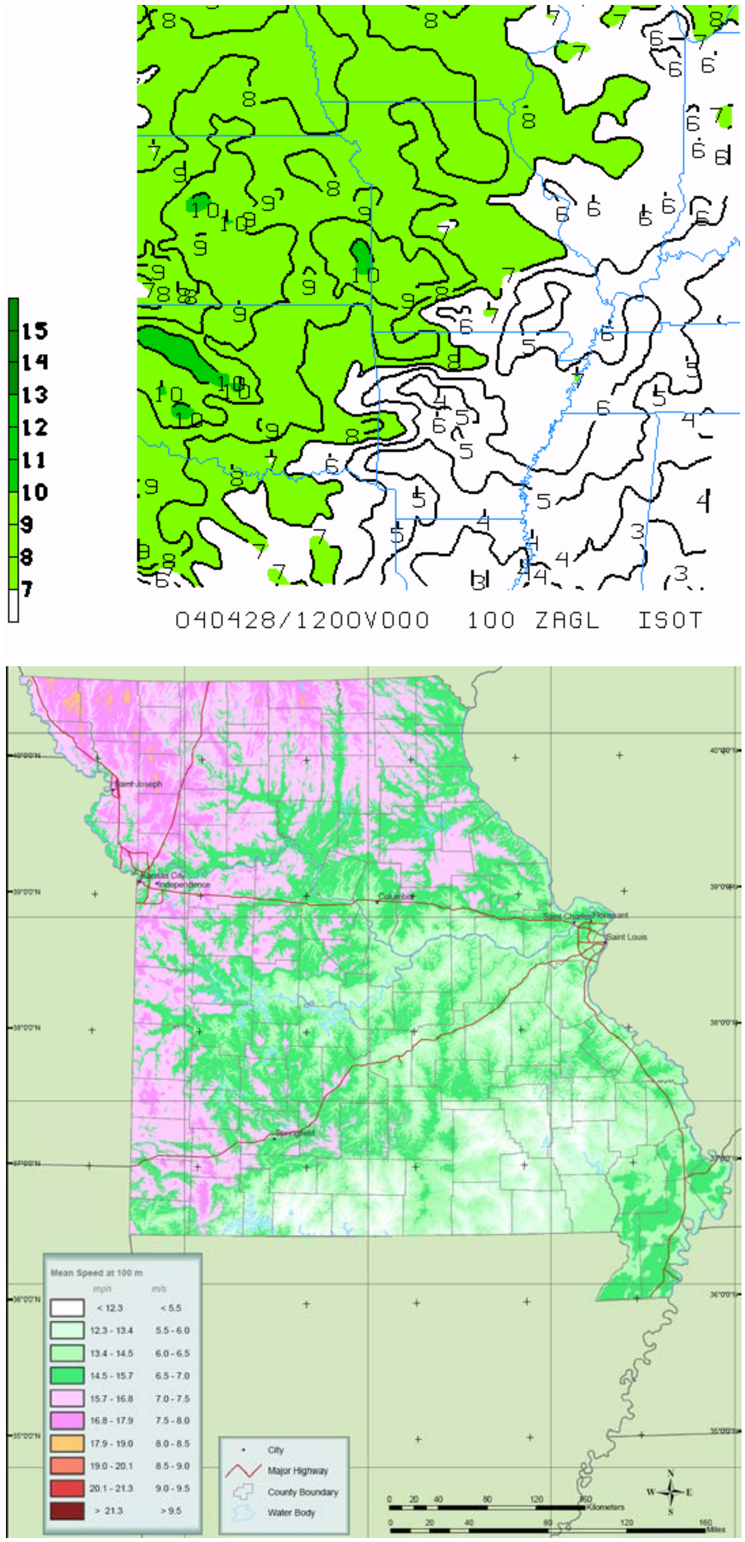


b)

Figure 4.13: Compares the median wind speed (ms^{-1}) plots at 120 m AGL, based on events where the a) LLJ or b) no LLJ was present.

Notice the clear disparity in wind speeds between the LLJ composites and the non-LLJ composites. This illustrates that the winds at turbine level, on occasions where the LLJ is active, are stronger than on days when there is no LLJ present. This pattern remains similar across all turbine-level heights. However, in these cases, the difference between the wind speeds of LLJ composites and non-LLJ composites tended to increase with height. Increases in wind speeds ranged from approximately 1 to 8 ms^{-1} from non-LLJ to LLJ composites in Missouri. The highest increases were generally noted in the west and southwest portions of Missouri, which may be partially influenced by the focus on SGF during the LLJ identification portion of this study. Wind speed increases of between 3 and 8 ms^{-1} were noted in this area across all turbine-level heights. This effect is also noted across portions of Kansas and Oklahoma, where the LLJ tends to be more active and occur more frequently. Based on these data, it would appear that on days when the LLJ is active over a certain area, the wind speed is increased at turbine level.

In Figure 4.14, the Arc GIS wind map, created by AWS Truewind Ltd., was made to assist in locating viable sites in Missouri where wind-generated energy would have a higher potential. This map was created using the MesoMap system. The MesoMap system is comprised of the Mesoscale Atmospheric Simulation System (MASS), a numerical weather model, and the program WindMap, which is a microscale wind flow model (Brower 2005). The AWS Truewind map depicts northwest Missouri as the preferred area for increased wind flow at 100 m AGL. The highest average wind speeds in that region came in between 8 and 8.5 ms^{-1}. Overall, most areas along northern Missouri, north of the Missouri River, and far western Missouri are depicted as producing average wind speeds above 7 ms^{-1}, which is approximately the level where wind-generated energy systems become profitable (Fox et al. 2008).

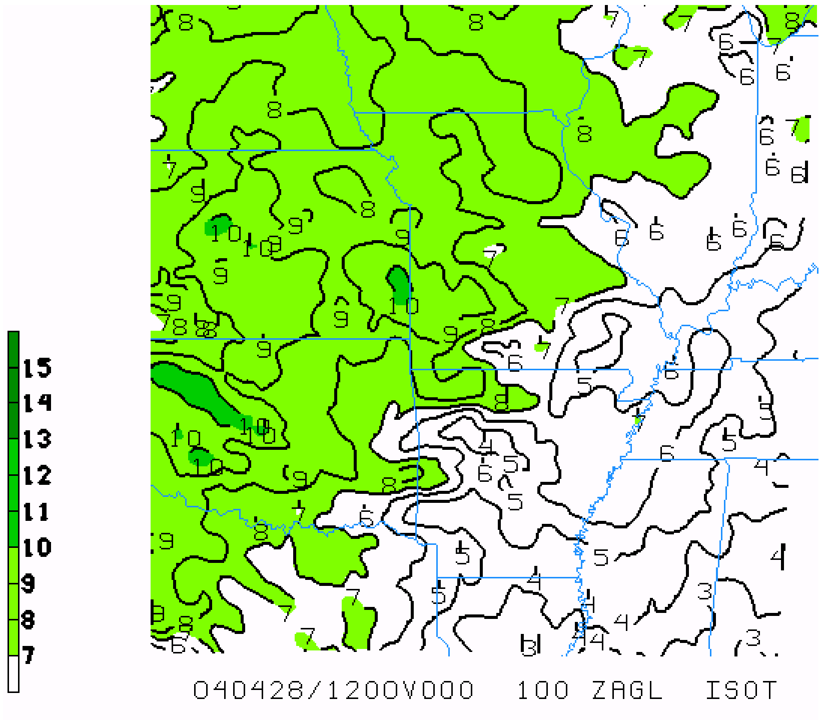


a)

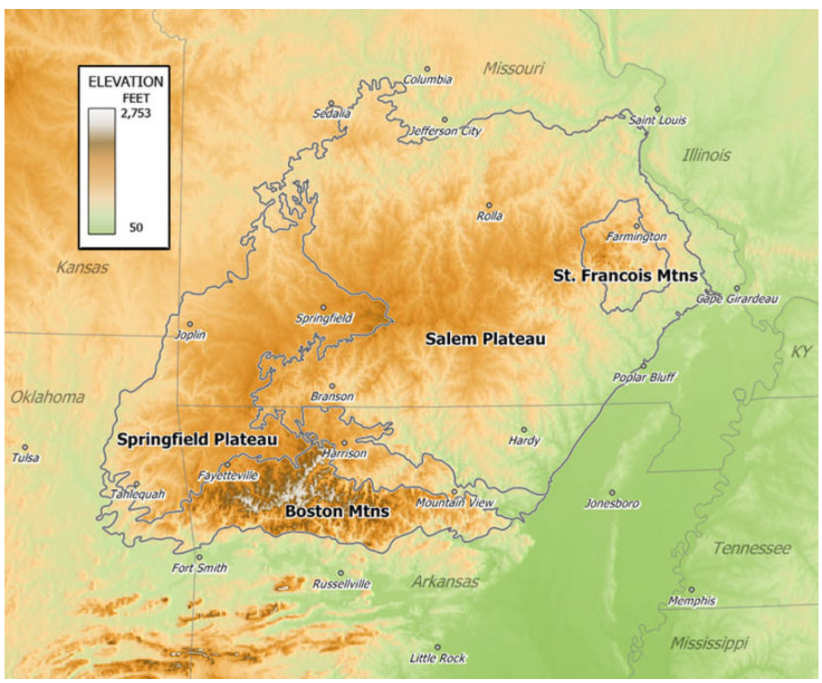
b)

Figure 4.14: Comparison of 100 m wind speed plots. The above image a) is the median wind speed (ms^{-1}) plot at 100 m AGL, based on composites of events when a LLJ was active in this study. The bottom image b) refers to the 100 m AGL wind speed based on the AWS Truewind map (Reproduced from Redburn 2007).

Figure 4.15 compares the different sections of the Ozark Plateau to the 100 m AGL RUC composite analysis of events where the LLJ was active. One item of note in the LLJ composite was the wind speed gradient (SW to NE) in southwest Missouri, where wind speeds range from 6 ms^{-1} on the southeast side of the gradient to 9 ms^{-1} on the northwest side, which seems to be a relatively short distance. This gradient seems to pattern after the delineation and relief differences between the Springfield and Salem Plateaus. While not exact, all the LLJ composited heights illustrate this same feature, as winds in the lower elevations across the southern Salem Plateau show relatively lighter winds than much of the Springfield and central Salem Plateaus.



a)



b)

Figure 4.15: Comparison of the 100 m median wind speed plot to an elevation map of the Ozark Plateau. The above image a) is the median wind speed (ms^{-1}) plot at 100 m AGL, based on composites of events when a LLJ was active in this study. The bottom image b) illustrates the elevation of the Ozark Plateau and delineates the different sections of the Plateau (Reproduced from http://www.ozarkcritters.net/img/OzarkRelief.jpg).

Similar to the wind speed composites, plots of mean wind shear were generated for events when a LLJ was present and when one was not. These shear plots were produced for two different layers, one between the 40 and 120 m AGL levels and the other between the 60 and 140 m AGL levels. These levels represent the location where the top and bottom of turbine blades may reside, with the turbine hub located at 80 m and 100 m AGL, respectively. Figure 4.16 and Figure 4.17 illustrate the difference in wind shear between the LLJ cases and non-LLJ cases. The wind shear depicted for both non-LLJ cases range from 0 to 0.02 s^{-1}, with the higher wind shear located over southeast Missouri. However, the variability compared to other portions of the state is not large. For the wind shear composites generated during times when LLJs were active, the state of Missouri saw values on the order of 0.03 s^{-1} and above. The highest values were noted in the south and southwest portion of Missouri, with peaks values of between 0.045 and 0.05 s^{-1} depicted. Once again, after comparing the LLJ to non-LLJ composites for both layers, it would appear that wind shear values do increase at times when a LLJ is active. Also, notice that the same portions of Kansas and Oklahoma that depicted similar results for the wind speed composites during LLJ events do not depict comparable results in wind shear composite plots. This leads to the idea that the higher wind shear values (green shading) are sensitive to the more abrupt changes in elevation of the Ozark Plateau and the Ouachita Mountains during days when the LLJ is active. It is thought that this wind shear can generate stress on the turbine blade hub, which would induce wear and cause increased maintenance costs. More work remains to be done concerning the effect that wind shear has on wind turbines.

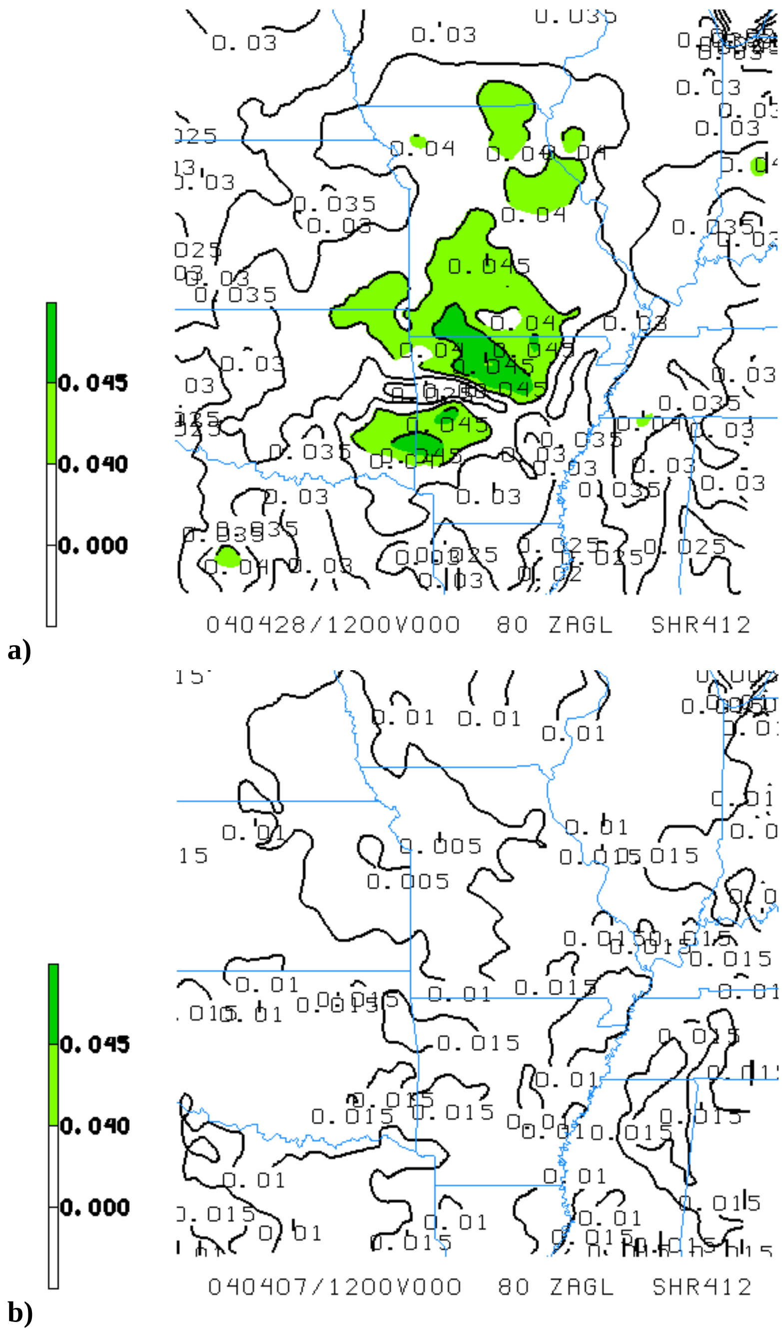
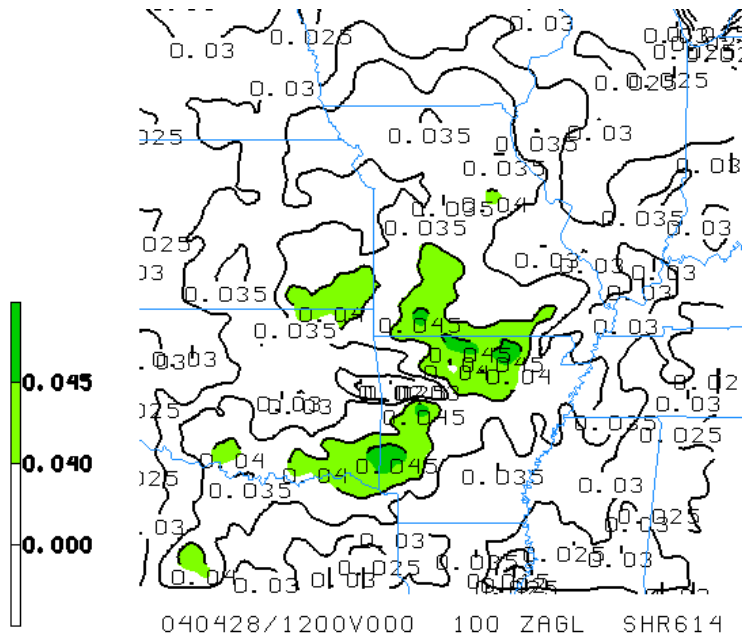
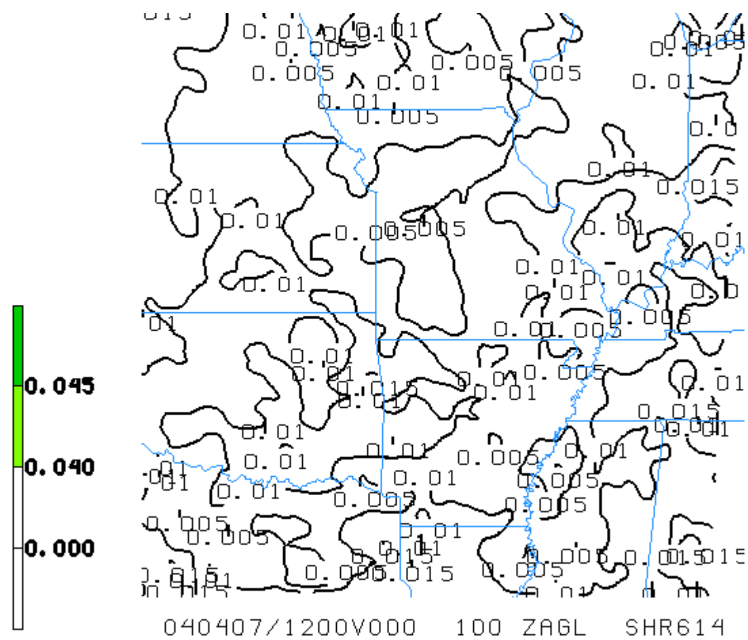


Figure 4.16: Compares the mean wind shear (s^{-1}) based on events where the a) LLJ or b) no LLJ was present. The wind shear between the 40 and 120 m AGL levels is depicted.



a)



b)

Figure 4.17: Compares the mean wind shear (s^{-1}) plots based on events where the a) LLJ or b) no LLJ was present. The wind shear between the 60 and 140 m AGL levels is depicted.

4.5 Errors and Limitations

There were a number of sources of limitations during this study, as well possible sources of errors. Many of these limitations were due to the use of radiosonde data, as well as RUC model analysis, as the main datasets for this study. There were also spatial and temporal limitations during the course of this study that may have allowed for the missing of some LLJ events. These inadequacies were taken into consideration for this study and should also be relayed for any future work that may be undertaken.

The preliminary work done for the identifying of LLJ cases was tedious work, encompassing the analyzing of SPC upper-air charts for an entire year (366 days), including four maps for each day. This could have led to simple errors that could cause the omission of a LLJ or inclusion of a non-LLJ event into the wrong sample because complete attention was not paid. These sort of possible tedious mistakes were, hopefully, mitigated by spreading this process over a number of days.

Many sources of limitations were due to the choice of radiosonde observational data at SGF as one of the main streams of data analyzed. SGF was chosen to identify LLJ events as it is the only site in Missouri that launches radiosondes routinely. This choice possibly restricted the actual amount of LLJs affecting Missouri, especially those that may protrude into the northwest portion of the state. Temporally, these upper air observations generally occurred at 00 and 12Z every day. While consistency matters, being able to sample the atmosphere more than just twice a day would possibly allow for the sampling of a LLJ at or closer to the peak of the wind maxima. This may also allow for the detecting of some LLJ events not initially included in the study. Also, the vertical distance between the radiosonde significant levels does not guarantee that the jet maximum is sampled. An effort was made to try to mitigate the effects from this limitation by analyzing all the wind data from these upper-air launches, including the fixed wind levels (PPBB). Of the limitations associated with the upper-air data, one was a chosen limitation. The keeping of LLJ events with stronger winds at 925mb than at 850mb was a deliberate choice made to examine those LLJs that were lower than the meteorologically significant 850mb level and that could possibly have a more influential effect on turbine-level wind fields. In the end, other data possibilities were considered. However, radiosonde data remained the most reliable option and was deemed the best dataset for this portion of the study, despite these limitations.

The RUC model data, utilized to classify jet types and generate composites of the turbine-level wind fields, provided another source of possible errors and limitations during this study. The 80-km RUC initial fields were employed as the dataset in the subjective classifying of each LLJ event. These RUC initial fields were the ‘best guess’, based on observational data provided to and assimilated into the computer model. This could allow for some minor perturbations within the wind flow, not sampled by the assimilated observational data, to be overlooked by the model output. As the classification was occurring, seven of the LLJ cases were removed from the sample due to unavailable RUC data. The subjective classification of jet types was another tedious process and could have also been a source for possible errors within the study. However, this process was completed over several days. Once again, the idea was to lessen concentration errors while trying to ensure that consistency was high during the jet typing process. Taking several days to complete this process may have aided produced inconsistency between work days. In the steps leading up to the composites, the 20-km RUC model grids were converted to all theta levels and were then interpolated to zagl. The interpolation of this data between the vertical levels where the original data existed can act to introduce inaccurate data into the sample. Interpolating between two levels tends to smooth out the values between the levels. This may have presented an unrealistic depiction of the turbine-level wind fields in the LLJ and non-LLJ scenario. The 20-km grid spacing in the RUC may have also been another source of limitations. When comparing the images in Figure 4.14 and Figure 4.15 above, the composite images may have shown greater detail and variability, especially across the Ozarks, if the RUC model utilized had a finer spatial resolution.

Chapter 5

Conclusions

5.1 Summary

The initial point of this study was to respond to a request for more data about the LLJ within the state of Missouri. However, a link between the LLJ and winds at turbine level was necessary to convey the influence the LLJ has as it passes through Missouri. Several characteristics of the LLJ were noted over this year-long analysis of data, including the monthly frequency of the LLJ and the distribution of the height, direction, and speed of the wind maximum. Then composites of the turbine-level wind fields were generated for times when the LLJ was active and times when it was not. This comparison makes clear the influence of the LLJ as it passes overhead.

Out of all 366 days and 732 individual cases analyzed for those LLJs, we found 75 that met our criteria. Five (5) of these cases occurred at 00Z, while 70 events were found at 12Z. One could speculate that the number of 12Z LLJ events could be higher due more to the PBL decoupling than synoptically-driven events. The monthly frequency of LLJ events varied much. However, the seasonal distribution saw little spread between the winter, summer and fall months. Interestingly, the spring months registered the least number of LLJ events. This may be due to the criteria used during this study, as some wind profiles illustrated winds increasing with height throughout the profile and others had winds stronger at 850mb than at 925mb. This occurred with some of the springtime convective events, especially during the beginning of May 2003.

After analyzing the upper-air observations from SGF for each individual jet event, a number of characteristics of the LLJ over Missouri were determined. The jet events illustrated significant peaks in the direction from which the jet maxima occurred. 60 out of the 75 total cases depicted a wind direction out of the south or southwest, with 20 and 40 cases noted respectively. This matches well with results from other LLJ studies. Next, the height of the wind maximum depicted two distinct peaks in LLJ events. The most jet events were noted in the 200- to 300-m range, while the second highest peak was seen in the 400- to 500-m range. This is significant because these peaks are located lower than where the typical LLJ is thought to reside. This may also be due to the criteria chosen for this study. The speed of the LLJ wind maximums demonstrated a peak in jet events in the 25- to 30-kt range. The average jet maxima wind speed across all 75 LLJ events was 32 knots. Not only did the winter months log the most LLJ events, higher averages in jet maxima wind speeds were noted in the winter as well. The height of the jet maximums increased gradually as the speed of the jet maximums became stronger. However, the gradual increase kept the trend within the 300- to 400-m range.

The classification of the LLJ events into the separate jet types from the Walters and Winkler (2001) study was done to build a small climatology of the type of LLJ that generally affects Missouri. The sample size of our study became reduced to 68 cases during this portion of the study, due to missing 80-km RUC data. After the 850-mb maps were analyzed, the highest numbers of jet types logged were the long and short Ac-SWNE, at 13 and 20 cases respectively. Of the 68 final cases, five (5) illustrated a northerly component, while the other 63 were southerly. 42 of those 63 southerly jet types were anticyclonically curved.

Composites of the wind field and wind shear at turbine level were then generated for the LLJ events and non-LLJ events. This was done to compare and contrast the two and illustrate whether the LLJ has an influence on turbine-level winds in Missouri. Walters and Winkler (2001) stated, "Composite analysis emphasizes commonly occurring features while smoothing more random fluctuations." The current study set out to accomplish this and while analyzing the composites when the LLJ was active, a number of effects were noted. Most of the work done previously on turbine-level wind fields in Missouri denotes the northwest portion of the state as the preferred area for wind energy development. Our composites (LLJ-active) still portray western Missouri as preferred with higher median wind speeds; however, the main focus becomes shifted to southwest Missouri as opposed to the northwestern portion of the state. There are several possible reasons for this, with the primary possibility being the focus on SGF during the LLJ identification process. The composite medians for the LLJ events illustrate stronger wind speeds across southeast Kansas and southwest Missouri at all turbine levels, ranging from 7 ms^{-1} at 40 m AGL to 12 ms^{-1} at 120 m AGL. Across the same area, the composite medians for the non-LLJ events range from 2 to 4 ms^{-1}. The difference between median wind speeds for the LLJ and non-LLJ events continued to grow with height. There is a clear difference in the median wind speeds between the LLJ-influenced and non-LLJ-influenced composites, which conveys the idea that the winds at turbine level are stronger at times when a LLJ is present above than when it is not. The same inference holds true when the plots of the mean wind shear were analyzed. While the wind shear remained greater at times when the LLJ was present, the same pattern was not replicated across Kansas and Oklahoma, as it was with the median wind speeds. It would appear that the higher wind shear values are located in areas with more abrupt changes in elevation.

Overall, this study set out to answer the question, "Does the LLJ have any influence, positive (greater wind speed) or negative (less wind speed), on turbine-level wind speeds?" The answer appears to be in the affirmative. Throughout each turbine level, the median wind speed was greater on days where the LLJ was active in Missouri. According to this study, the west-central to southwestern portion of the state appeared to present the most viable location for harnessing the wind and increasing the production in wind-generated energy at times when the LLJ is active.

5.2 Future Work

As the results in this study were analyzed and conclusions were made from the data, a number of new questions concerning the winds at turbine level arose. One of the initial questions concerned the criteria used in determining LLJ cases and whether the criteria used in this study was too stringent. Also, limiting LLJ cases to those with a stronger wind at 925mb than 850mb, while a calculated choice, was a restriction that hampered the number of LLJs sampled. Using a different criterion, maybe a more basic criterion of utilizing any jet maxima under 700mb and greater than or equal to 15 knots, would assist in gathering more LLJ cases, thus having a larger sample to analyze. Another limiting factor could also be the use of SGF as the only location for LLJ identification. The addition of the Topeka, Kansas (TOP) upper-air observation would be useful to compare to SGF and to also search for LLJs that may affect northwest Missouri, but not southwest Missouri. Additionally, is the RUC analysis output presenting a near-realistic depiction of actual conditions? To answer this question, a comparison to actual observations would need to be undertaken. This could provide another stream of data which could be of use operationally. Also, expanding the timeframe from one year to any number of years, whether the data is actual observations or model analysis, would assist in normalizing the yearly variability of the LLJ and would produce a more accurate climatology, instead of a one-year glance as in this study. The use of a finer resolution model, such as the 13-km RUC, would allow for greater detail in model output. This could possibly depict more variability within the composites across area where small-scale changes occur in elevation. Thus, allowing for greater detail across the Ozark Plateau.

As is stated above, there remains much to be assessed concerning the LLJs effect on wind generated energy systems. As more studies are conducted and more data is revealed, better efficiency and higher consumption of wind energy is believed to be attainable.

Appendix A: Date and Hour of LLJ Events at SGF

Date	Time (Z)
04 May 2003	12
13 May 2003	12
16 May 2003	12
(20 May 2003)	12
10 June 2003	12
20 June 2003	12
21 June 2003	12
22 June 2003	12
23 June 2003	12
24 June 2003	12
25 June 2003	12
07 July 2003	12
(09 July 2003)	12
15 July 2003	12
18 July 2003	12
(20 July 2003)	12
25 July 2003	12
26 July 2003	12
27 July 2003	12
28 July 2003	12
01 August 2003	12
21 August 2003	12
26 August 2003	12
(28 August 2003)	12
09 September 2003	12
10 September 2003	12
(11 September 2003)	12
17 September 2003	12
18 September 2003	12
24 September 2003	12
26 September 2003	12
03 October 2003	12
16 October 2003	12
20 October 2003	12
25 October 2003	12
27 October 2003	12
30 October 2003	12
03 November 2003	12

Date	Time (Z)
08 November 2003	12
20 November 2003	12
21 November 2003	12
26 November 2003	12
30 November 2003	12
03 December 2003	00
07 December 2003	12
08 December 2003	12
09 December 2003	12
15 December 2003	00
15 December 2003	12
(21 December 2003)	12
(26 December 2003)	12
27 December 2003	12
30 December 2003	12
31 December 2003	12
01 January 2004	12
08 January 2004	12
11 January 2004	12
17 January 2004	00
29 January 2004	12
04 February 2004	12
19 February 2004	12
20 February 2004	00
28 February 2004	12
29 February 2004	12
24 March 2004	12
26 March 2004	12
27 March 2004	12
08 April 2004	12
11 April 2004	00
12 April 2004	12
15 April 2004	12
16 April 2004	12
17 April 2004	12
20 April 2004	12
28 April 2004	12

( ) = Events removed due to missing RUC data.

Appendix B: Date and Hour of Non-LLJ Events

Date	Time (Z)
03 May 2003	00
03 May 2003	12
08 May 2003	00
22 May 2003	00
23 May 2003	00
24 May 2003	00
24 May 2003	12
26 May 2003	12
27 May 2003	00
14 June 2003	00
15 June 2003	12
16 June 2003	12
17 June 2003	00
18 June 2003	00
19 June 2003	00
13 July 2003	00
24 July 2003	00
28 July 2003	00
30 July 2003	00
31 July 2003	00
03 August 2003	00

Date	Time (Z)
05 August 2003	00
07 August 2003	12
08 August 2003	00
09 August 2003	00
11 August 2003	00
11 August 2003	12
12 August 2003	12
23 August 2003	00
03 September 2003	00
05 September 2003	00
07 September 2003	00
07 September 2003	12
20 September 2003	00
06 October 2003	00
24 October 2003	00
01 April 2004	00
01 April 2004	12
02 April 2004	00
03 April 2004	00
05 April 2004	00
07 April 2004	12

Appendix C: RUC20 Average Wind Speed Profiles in Select Cities across Missouri

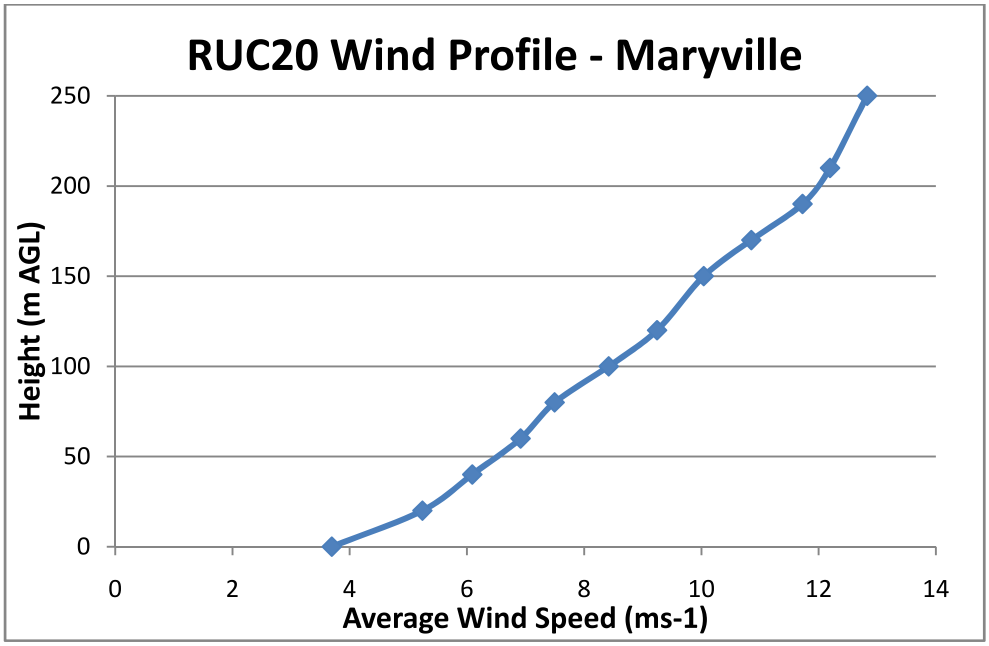


Figure C.1: Depicts the wind profile of wind speeds averaged at the 0, 20, 40, 60, 80, 100, 120, 150, 170, 190, 210, and 250-m AGL level for all 68 LLJ-active cases at Maryville, MO (40.38, -94.86).

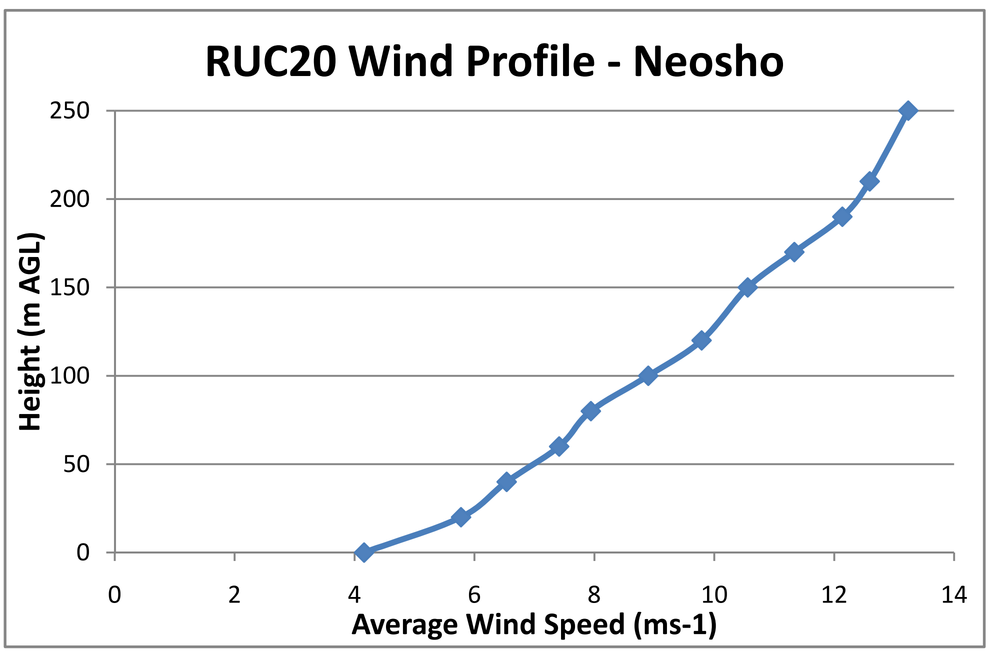


Figure C.2: Depicts the wind profile of wind speeds averaged at the 0, 20, 40, 60, 80, 100, 120, 150, 170, 190, 210, and 250-m AGL level for all 68 LLJ-active cases at Neosho, MO (36.88, -94.43).

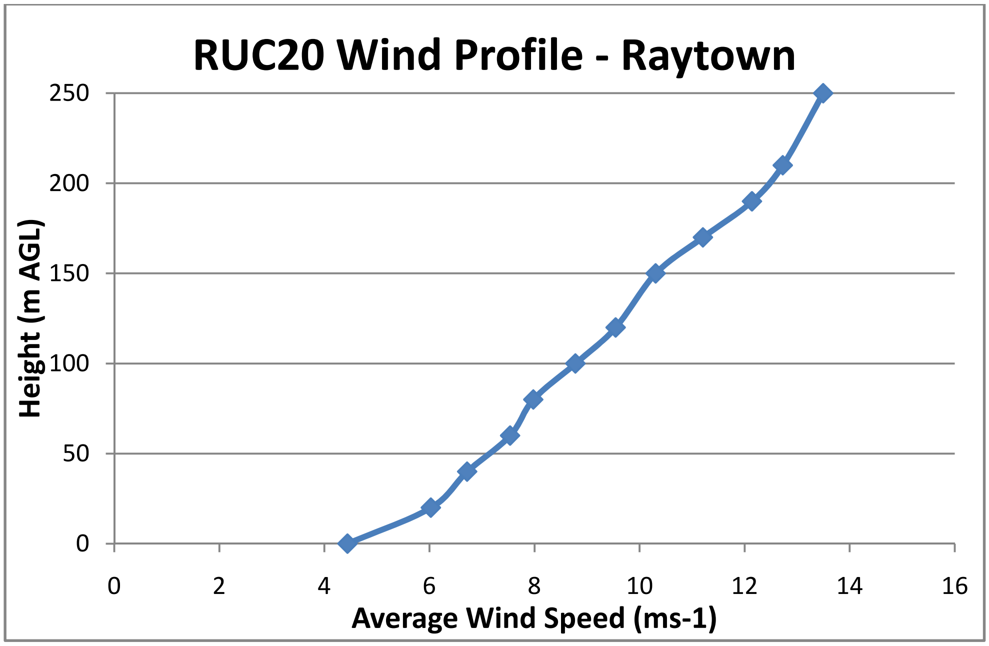


Figure C.3: Depicts the wind profile of wind speeds averaged at the 0, 20, 40, 60, 80, 100, 120, 150, 170, 190, 210, and 250-m AGL level for all 68 LLJ-active cases at Raytown, MO (39.04, -94.49).

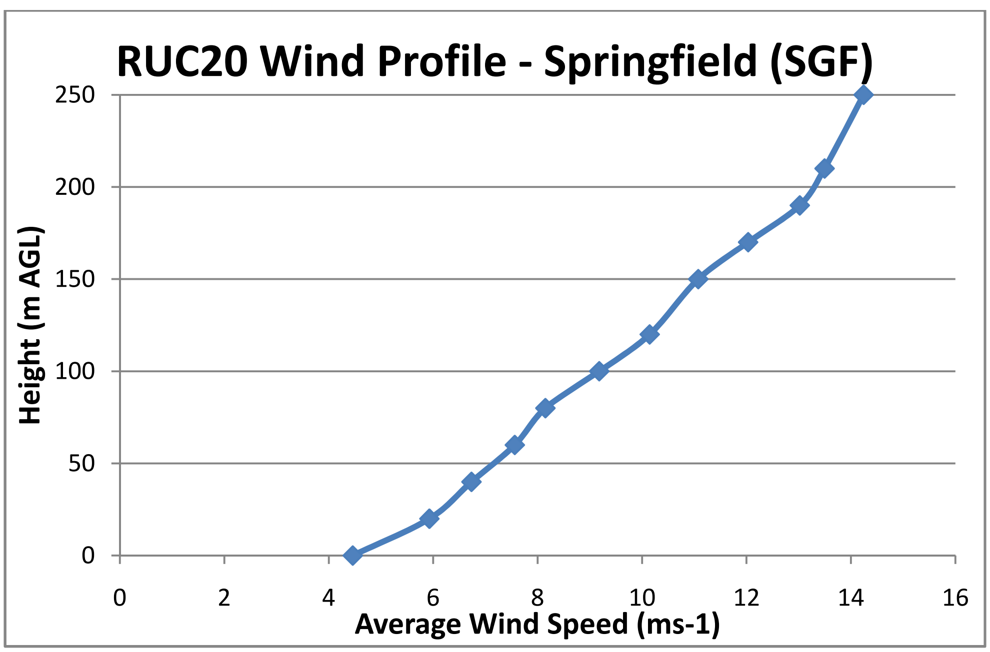


Figure C.4: Depicts the wind profile of wind speeds averaged at the 0, 20, 40, 60, 80, 100, 120, 150, 170, 190, 210, and 250-m AGL level for all 68 LLJ-active cases at Springfield, MO (SGF).

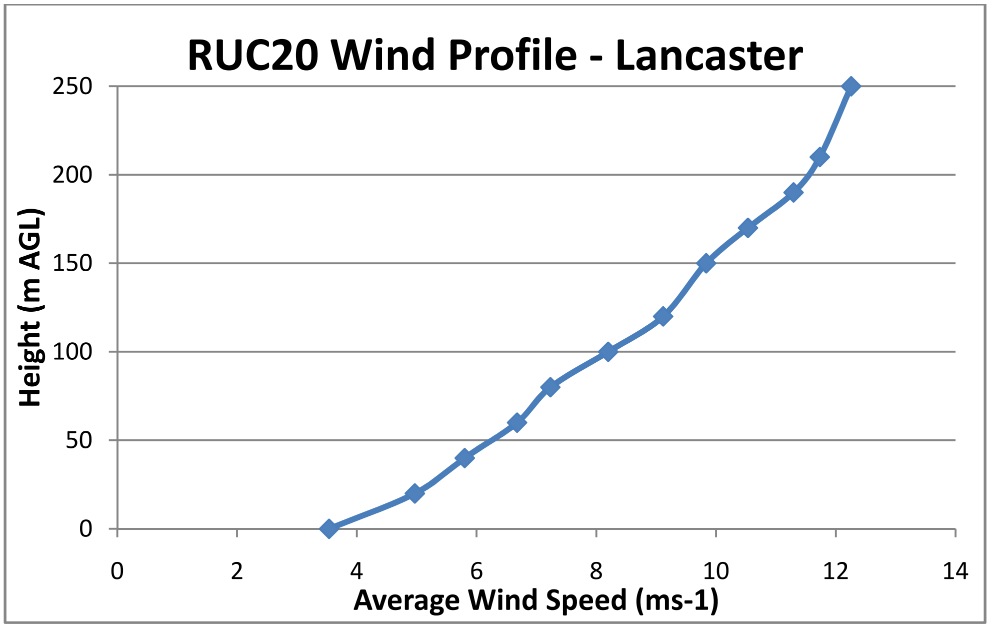


Figure C.5: Depicts the wind profile of wind speeds averaged at the 0, 20, 40, 60, 80, 100, 120, 150, 170, 190, 210, and 250-m AGL level for all 68 LLJ-active cases at Lancaster, MO (40.53, -92.44).

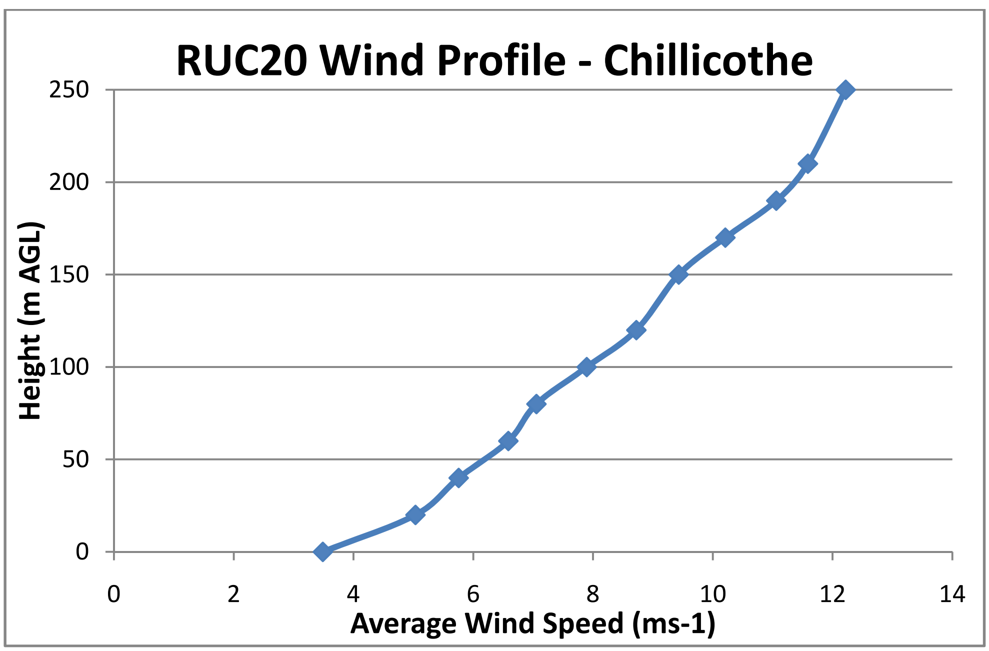


Figure C.6: Depicts the wind profile of wind speeds averaged at the 0, 20, 40, 60, 80, 100, 120, 150, 170, 190, 210, and 250-m AGL level for all 68 LLJ-active cases at Chillicothe, MO (39.81, -93.59).

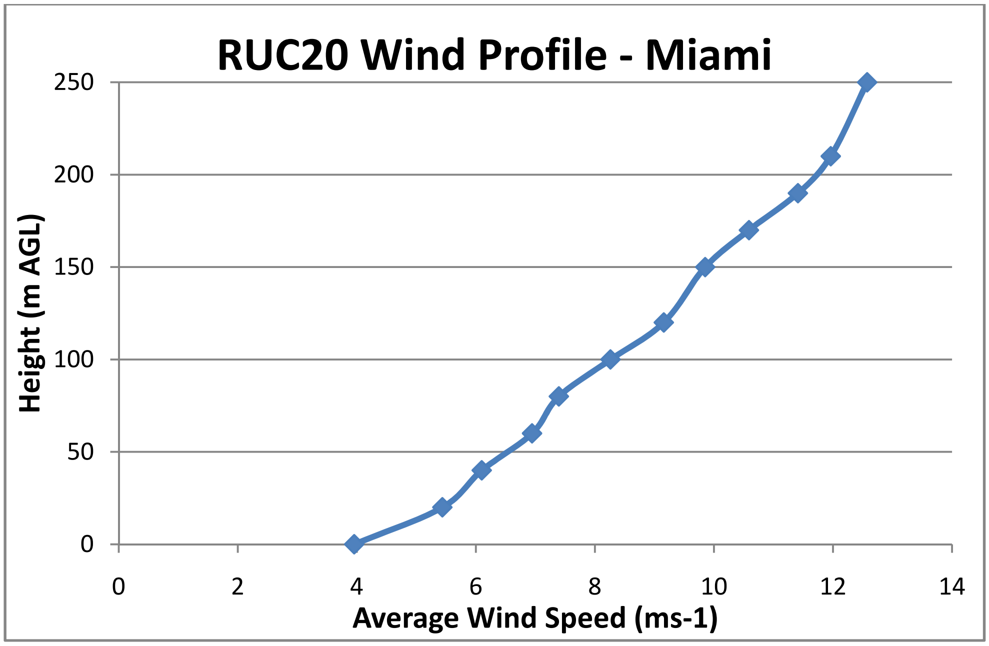


Figure C.7: Depicts the wind profile of wind speeds averaged at the 0, 20, 40, 60, 80, 100, 120, 150, 170, 190, 210, and 250-m AGL level for all 68 LLJ-active cases at Miami, MO (39.28, -93.23).

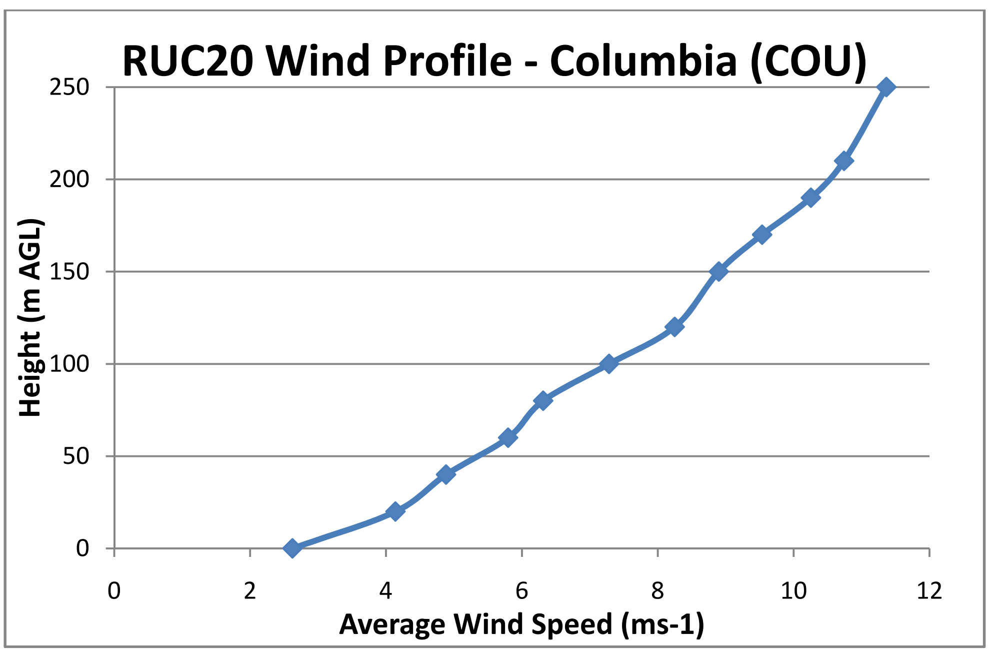


Figure C.8: Depicts the wind profile of wind speeds averaged at the 0, 20, 40, 60, 80, 100, 120, 150, 170, 190, 210, and 250-m AGL level for all 68 LLJ-active cases at Columbia, MO (COU).

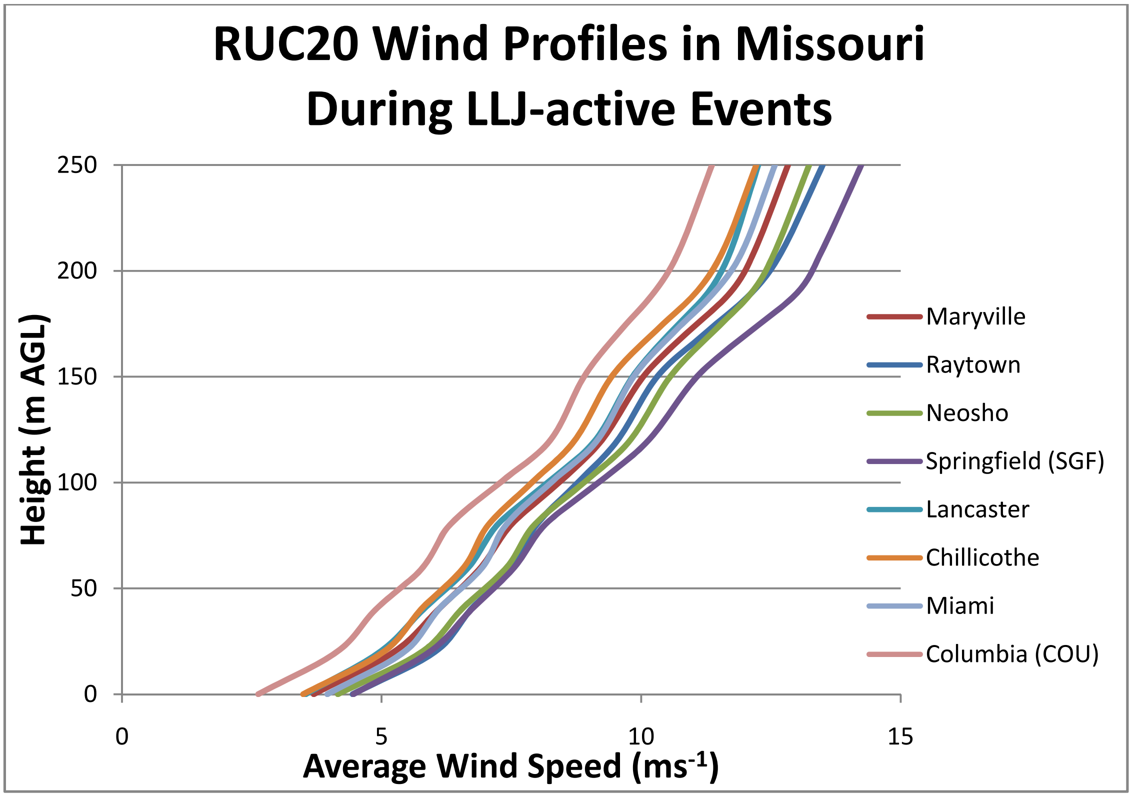


Figure C.9: Illustrates all eight (8) wind profiles together. This image depicts Springfield (SGF) as having the stronger average wind speeds, while Columbia has the weakest average wind speeds during the LLJ-active events.

References

Andreas, E. L., Claffey, K. J., and Makshtas, A. P., 2000: Low-level atmospheric jets and inversions over the western Weddell Sea. *Bound.-Layer Meteor.*, **97**, 459-486.

Banta, R. M., R. K. Newsom, J. K. Lundquist, Y. L. Pichugina, R. L. Coulter, and L. Mahrt, 2002: Nocturnal low-level jet characteristics over Kansas during CASES-99. *Bound.-Layer Meteor.,* **105,** 221–252.

Benjamin, S. G., J. M. Brown, K. J. Brundage, D. Dévényi, G. A. Grell, D. Kim, B. E. Schwartz, T. G. Smirnova, T. L. Smith, S. S. Weygandt, and G. S. Manikin, 2002: RUC20 – The 20-km version of the Rapid Update Cycle. NWS Tech. Procedures Bulletin No. 490, 30 pp.

——, D. Dévényi, S.S. Weygandt, K.J. Brundage, J.M. Brown, G.A. Grell, D. Kim, B.E. Schwartz, T.G. Smirnova, T.L. Smith, and G.S. Manikin, 2004: An Hourly Assimilation–Forecast Cycle: The RUC. *Mon. Wea. Rev.*, **132**, 495–518.

Birding-Minnesota Home Page: Missouri state map with county outlines. [Available online at http://www.birding-minnesota.com/images/MO-N.gif.]

Blackadar, A. K., 1957: Boundary layer wind maxima and their significance for the growth of nocturnal inversions. *Bull. Amer. Meteor. Soc.,* **38,** 283–290.

Bonner, W. D., 1966: Case study of thunderstorm activity in relation to the low-level jet. *Mon. Wea. Rev.*, **94**, 167–178.

——, W. D., 1968: Climatology of the low level jet. *Mon. Wea. Rev.*, **96**, 833–850.

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

Dévényi, D. and S. G. Benjamin, 2003: A variational assimilation technique in a hybrid isentropic-sigma coordinate. *Meteorology and Atmospheric Physics*, **82**, 245–257.

Fox, N. I., A. R. Lupo, P. S. Market, A. Koleiny, M. R. Dahmer, and J. Miller, 2008: Tall tower studies of Missouri wind: Final report. Report to Missouri Department of Natural Resources, Aquila Incorporated, Ameren Services Company, and the U.S. Department of Energy, 88 pp.

Glickman, T., Ed., 2000: *Glossary of Meteorology*. 2nd ed. Amer. Meteor. Soc., 855pp.

Helfand, H. M., and S. D. Schubert, 1995: Climatology of the Great Plains low-level jet and its contribution to the continental moisture budget of the United States. *J. Climate*, **8,** 784–806.

Means, L. L., 1952: On thunderstorm forecasting in the central United States. *Mon. Wea. Rev.*, **80**, 165–189.

Mitchell, M. J., R. W. Arritt, and K. Labas, 1995: A climatology of the warm season Great Plains low-level jet using wind profiler observations. *Wea. Forecasting*, **10**, 576–591.

Moore, D., 2004: Energy proposal favored by a landslide margin. *Columbia Daily Tribune*, 3 November.

Ozark Critters, cited 2007-2009: Ozark area relief map. [Available online at http://www.ozarkcritters.net/img/OzarkRelief.jpg.]

Pitchford, K. L., and J. London, 1962: The low-level jet as related to nocturnal thunderstorms over midwest United States. *J. Appl. Meteor.,* **1,** 43–47.

Redburn, R., 2007: A tall tower wind investigation of northwest Missouri. M.S. thesis, Dept. of Soil, Environmental, and Atmospheric Sciences, University of Missouri at Columbia, 109 pp.

Silcock, J., cited 14 July 2008: Wind farms generate power, revenue, say MU Extension specialists. [Available online at http://cafnr.missouri.edu/news/wind-farms.php.]

Volkmann, K., 2008: University of Missouri experts help Mo. town become first in nation to run on wind energy. *St. Louis Business Journal*, 15 July.

Walters, C. K., and J. A. Winkler, 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.

Whiteman, C. D., X. Bian, and S. Zhong, 1997: Low-Level Jet Climatology from Enhanced Rawinsonde Observations at a Site in the Southern Great Plains. *J. Appl. Meteor.*, **36**, 1363–1376.

Zhang, D. L., S. Zhang, and S. J. Weaver, 2006: Low-level jets over the Mid-Atlantic States: Warm-season climatology and a case study. *J. Appl. Meteor. Climatol.*, **45**, 194–209.