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WRF-Simulated Springtime Low-Level Jets over Iowa: Implications for Wind Energy

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Abstract. High-resolution simulations with the Weather Research and Forecasting (WRF) model are analyzed to characterize the frequency, intensity, height, and duration of springtime low-level jets (LLJ) and their implications for wind energy resource assessment and planning in Iowa. The time evolution of short-duration LLJ is analyzed to understand wind behavior around LLJ events and to illustrate their importance for high-frequency (few hours) variability in wind speeds and rotor plane turbulent kinetic energy (TKE). During spring, the LLJ core height has a spatiotemporal mean value of 217 m, but the LLJ depth means it frequently intersects typical wind turbine rotor planes. Nearly one-quarter of LLJ exhibit a maximum within the height interval 50-150 m AGL. LLJ profiles are found to have higher mean wind speeds across typical wind turbine rotor planes than non-LLJ profiles and to exhibit lower values of TKE. LLJ occur under stable stratification (i.e. positive Richardson numbers) and are associated with low TKE and the occurrence of high vertical wind shear. The frequency and duration of LLJ exhibit geospatial variability across Iowa with highest values in the northeast of the state. Analyses of daytime and night-time LLJ indicate topographic variability is an important factor in the development of LLJ.

1. Introduction

Low-level jet (LLJ) is a generic term for wind speed maxima that occur in the lower troposphere. Generally, LLJ formation is attributed to diurnal variability in surface forcing and atmospheric stability and can be influenced by terrain effects [1, 2]. LLJ frequency and duration vary seasonally, as various areas across the U.S. experience greater LLJ magnitude and formation frequency in the spring season [3]. The most widely studied LLJ is the US Great Plains LLJ, which is generally seen at higher elevations than those that are considered in this study, with the Great Plains LLJ wind speed maximum occurring between 500-1000 m [4]. Offshore and onshore LLJ occurring at or near heights that intersect the rotor plane may have relevance for the wind energy industry via their impact on: the resource, short-term forecasting, and fatigue loading via wind shear and turbulent kinetic energy [5, 6].

Previous studies have investigated and validated simulations with the Weather Research and Forecasting (WRF) model in terms of the near-surface wind climate [7] and features of LLJ [8]. Other studies have explored the impact of LLJ on regional wind resources and indicate that negative shear from the LLJ can reduce loading on the rotor plane [9]. However, there is still a need for further investigation of various LLJ characteristics in the context of wind resource planning, such as: the
relationship between terrain elevation and variability and LLJ duration, wind speed and duration of daytime and nighttime LLJ, and how LLJ of different speeds affect loading on the rotor plane. Due to Iowa’s high installed wind energy capacity (>10 GW) and varying regional terrain, the state is an ideal region for LLJ analysis [10]. For greater insight into wind resource assessment and planning, this study utilizes WRF simulations to examine the characteristics and frequency of LLJ over Iowa during spring, when wind speeds and wind turbine power production in Iowa reach their peak [11].

Although the LLJ is a widely studied and globally occurring atmospheric phenomenon, an objective and generalizable methodology for identifying LLJ events is lacking. Much of the existing identification methods are subjective and highly dependent on data resolution, geographic location, and data retrieval methods [12, 13]. Consequently, derived LLJ characteristics in a given region vary by study. Common methods of identifying LLJ events involve quantifying the strength of the LLJ speed maximum and the difference in wind speed around it, and defining the presence of a LLJ if these values meet pre-defined criteria [12, 14]. Other methods identify the presence of a LLJ through setting a minimum difference in wind speed (wind threshold) around the profile maximum [15], and counting the profile as a LLJ if that difference is met or exceeded. The value of the wind threshold criteria varies by study, and is typically adjusted based on temporal and spatial resolution [16].

Although LLJ have been characterized in a wind energy context, the wind behavior before and after these LLJ events that is relevant to understanding the wind resource for a region has not yet been examined. Studying LLJ evolution (wind behavior before, during, and after a LLJ event) presents an opportunity to examine the mechanisms by which LLJ build and decline, while gaining insight into the effects of varying wind threshold criteria. Thus, in addition to defining regional LLJ characteristics, this study aims to characterize the wind behavior around a LLJ event in a wind energy context, while also presenting a preliminary analysis showing the evolution of a rapidly forming LLJ at heights relevant to wind energy.

2. Methodology

2.1. WRF Simulation Overview

Due to the ability to consider a large domain at a high resolution, WRF simulations offer a great advantage in defining LLJ effects on the wind resource. High-resolution simulations were conducted with WRF (v3.8.1) over a 9-month period for a nested domain wherein the outer domain comprises 150 by 150 12-km grid cells and encompasses much of the US Midwest, and the inner domain, centered over Iowa, comprises 247 by 205 4-km grid cells [11] (Figure 1). A sub-grid of 147 by 100 grid cells covering the state of Iowa is the focus of analyses presented here.

Figure 1. WRF multi-grid simulation domain. White markers indicate wind turbine locations as of the end of 2014.
2.2 LLJ Profile Identification

An objective algorithm is used to isolate and identify LLJ in wind speed profiles in all domain grid cells. First, any wind speed maximum in a wind speed profile within the lowest 560 m of the atmosphere is identified as a potential LLJ. Then, if the wind speed above and below this height decreases by at least 2 m s\(^{-1}\) (the wind threshold method), the case is selected for analysis.

This LLJ identification method is chosen to ensure a wide range of LLJ behavior for analysis. Other studies that use this method have chosen wind threshold criteria as low as 0.5 m s\(^{-1}\), depending on data resolution and manual analysis of identified LLJ profiles [16]. The algorithm wind speed threshold criterion of 2 m s\(^{-1}\) is chosen based on analysis of turbulent kinetic energy (TKE) and mean wind speed profiles at the rotor plane when compared to lower thresholds. Using a wind threshold method to identify LLJ profiles is generally more robust than other methods, such as combining maximum LLJ speed criteria with wind threshold criteria [12, 13]. The profile identification method used in this study allows for analysis of LLJ characteristics under a wide range of wind speeds, which is important for wind resource characterization.

3. Results

3.1. LLJ Characteristics

LLJ occurred in at least one grid cell over Iowa on all simulated nights, except for a single night in April (a night is defined based on sunset and sunrise times for Iowa in April, 8pm-6am local time, respectively). Furthermore, approximately 74% of LLJ occur during this night-time interval. For the domain-wide spatiotemporal mean, the LLJ speed maximum is 12.7 m s\(^{-1}\) and the height of the LLJ maximum is 217 m (Figure 2). 24.4% of LLJ exhibit maxima within ± 50m of the nominal turbine hub height of 100 m.

![Figure 2. (a) – TKE as a function of height above ground level (m AGL) for LLJ and non-LLJ profiles. Each quantity is plotted against the mean height per vertical level (♦), which is averaged over space and time for the domain, since the sigma height AGL is time dependent due to base state and perturbation geopotentials; (b) – Normalized mean wind speed-LLJ profiles (→) v. non-LLJ (←) profiles. All wind speed profiles were normalized by the maximum wind speeds in each profile.](image)
These results are consistent with past research that has indicated mean LLJ wind speed maxima of 10-14 ms\(^{-1}\) and heights of LLJ wind speed maxima of 100-400 m (both quantities depending on the vertical resolution of the model or observations [9, 13]). As shown in Figure 2, the mean LLJ wind speed profile is clearly differentiable from the non-LLJ profile as is the TKE profile, with much lower values of TKE during LLJ periods. Furthermore, the LLJ occurs with higher wind speeds at the rotor plane overall when compared to non-LLJ occurrences.

The average duration of LLJ periods varies by geographical location with the longest mean duration of up to 5 hours, and highest frequency of occurrence of LLJ (up to 0.21 or 21\%) in the northeast of the state of Iowa (Figure 3). The calculated mean LLJ duration is consistent with wind profiler studies of the Great Plains LLJ [17]. The frequency of occurrence is defined throughout the entire time interval, and thus represents the frequency of LLJ appearance over time for each grid cell. Certain regions of high LLJ frequency are coincident with locations of wind turbine deployments (Figure 3). The locations of high frequency and duration suggest that terrain effects contribute to LLJ formation and duration in Iowa.

It is notable that the regions of highest terrain elevation, located in the west of the state, do not exhibit the highest LLJ frequency and duration. Similarly, regions of lowest elevation, located in the southeast of the state, also exhibit low LLJ frequency and duration. LLJ events occur more often during easterly flow and have 5\% higher mean wind speeds at the nominal turbine hub height of 100 m when compared to non-LLJ events (Figure 4).

**Figure 3.** (a) – Regional elevation (m) and contours of the highest 30\% of LLJ frequency (≥ 0.17); (b) – Regional mean LLJ duration. Black markers indicate wind turbine locations as of the end of 2014.

**Figure 4.** (a) – Wind rose for LLJ at nominal turbine hub height (100 m) for entire springtime domain; (b) – Wind rose for non-LLJ profiles at nominal turbine hub height (100 m) for entire springtime domain.
High LLJ frequency and duration in the northeast of the state, along with high LLJ frequency during easterly flow, suggest that the regions of locally complex terrain elevation are important regional mechanisms in LLJ formation. This is potentially due to the influence of topographic variability in the formation of gravity waves, which have been found to contribute to LLJ formation [18, 19].

3.2. LLJ Maximum Speed and Rotor Plane Effects
LLJ events for the domain exhibited a wide range of maximum wind speed values, with nearly 40% of maximum LLJ wind speed values falling within the range of 5 m s\(^{-1}\) to 11 m s\(^{-1}\). Approximately 45% of LLJ with maximum wind speed values in this range also had wind speed maxima located in the nominal rotor plane height range of 50-150 m. These maximum wind speed values fall within the cut-in and rated wind speed ranges for most commercial wind turbines. However, LLJ events with higher altitude wind speed maxima still affect turbine operating conditions via modification of the vertical profile of TKE and shear. To examine these effects more closely and to understand the rotor plane effects of LLJ with maxima of varying speeds, LLJ are sorted into four bins based on the magnitude of their wind speed maxima (Figure 5). LLJ with wind speed maxima at any height are considered. This allows for evaluation of rotor plane effects for any LLJ that occur below 560 m AGL. Stability is estimated by using a calculation of the Bulk Richardson number around the rotor, \(R_i_{Rotor}\), as defined in (1) [20]:

\[
R_i_{Rotor} = \frac{2(Z_2-Z_1)g}{\theta_{Z_2}\theta_{Z_1}} \left[ \frac{\theta_{Z_2}-\theta_{Z_1}}{(u_{Z_2}-u_{Z_1})^2+(v_{Z_2}-v_{Z_1})^2} \right]
\]

The shear exponent, \(\alpha\), is calculated across the rotor plane using the wind shear power law:

\[
\left( \frac{U_{Z_2}}{U_{Z_1}} \right) = \left( \frac{Z_2}{Z_1} \right)^{\alpha}
\]

Where: \(U, u, v, \) and \(\theta\) represent wind speed, wind speed components \(u\) and \(v\), and virtual potential temperature, respectively, at height \(Z\) above ground level.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** (a) – Median \(R_i_{Rotor}\), grouped by LLJ wind speed maxima (–5-11 m s\(^{-1}\), –12-16 m s\(^{-1}\), –17-21 m s\(^{-1}\), –22 m s\(^{-1}\) – max speed); (b) – Mean shear exponent (\(\alpha\)); (c) – Mean TKE (m\(^2\) s\(^{-2}\))

Conditional sampling of the Richardson number by the LLJ maximum wind speed indicates that less stable conditions are associated with higher LLJ wind speeds (stronger LLJ) and higher TKE. This finding is consistent with studies that have linked higher LLJ speeds to increased turbulent mixing and less stable conditions [21, 22]. Furthermore, conditions become more stable with increasing height AGL for LLJ of all strengths. This is consistent with findings that relate peaks in stability to locations of the
LLJ wind speed maximum (jet core) [21]. Around the LLJ speed maximum, shear is nearly zero and TKE is lessened [21]. Thus, as the height increases and approaches the height of the LLJ wind speed maximum, shear and TKE decrease while stability increases.

For the weakest LLJ, shear decreases rapidly with height AGL, reaching a near zero value around 150 m AGL. This trend is unique when compared to the other LLJ speed bins, and can potentially be attributed to the location of the LLJ wind speed maximum: for the weakest LLJ (wind speed maximum of 5-11 ms⁻¹), the average height of the wind speed maximum is 179.7 m AGL. For all other LLJ, the average height of the wind speed maximum is 243.4 m AGL.

3.3. Daytime and Nighttime LLJ Characteristics

Traditionally, LLJ studies over land have focused on the nocturnal LLJ, which is observed much more frequently than daytime LLJ. However, 26% of LLJ events occur during daytime hours, and daytime events are found throughout the majority of the state. Overall, daytime LLJ form and decline more rapidly than nighttime LLJ, with a mean daytime LLJ duration of 1.9 hours and a mean nighttime duration of 3.0 hours. Mean wind speeds at a nominal wind turbine hub height of approximately 100-m AGL are lower for daytime LLJ than nighttime LLJ (Figure 6 - a, b).

![Figure 6](image-url)

**Figure 6.** (a) – Daytime mean LLJ wind speed (W.S.) at a nominal wind turbine hub height (100 m) shown with the coloured shading and contours of highest mean regional LLJ duration (hours); (b) – Nighttime mean LLJ wind speed (W.S.) at a nominal wind turbine hub height and contours of longest regional LLJ duration (hours); (c) – Daytime mean non-LLJ wind speed at a nominal wind turbine hub height; (d) – Nighttime mean non-LLJ wind speed at a nominal wind turbine hub height. Black markers indicate wind turbine locations as of the end of 2014.

To gain a greater understanding of regional hub height LLJ wind speed, daytime and nighttime temporal mean non-LLJ wind speeds at nominal turbine hub height are also computed. As expected, mean daytime hub height wind speeds are lower than nighttime speeds (Figure 6 – c, d). However, daytime LLJ wind speeds are higher than daytime non-LLJ wind speeds, and exhibit more spatial variability than non-LLJ wind speeds, particularly in areas of high terrain elevation. Both nighttime and daytime non-LLJ wind speeds show similar amounts of variability in areas of high terrain elevation. In
contrast, nighttime LLJ events show higher speed variability in areas of high terrain elevation when compared to daytime LLJ events, possibly indicating that nighttime LLJ speeds are more influenced by terrain elevation effects than speeds of daytime LLJ.

### 3.4 Evolution and Frequency of Rapidly Evolving LLJ

LLJ are identified with high frequency. The LLJ criteria is reached, at least once, in any domain-wide grid cell, on 98% of nights, and up to 21% of the total time in certain areas of the state. Although LLJ frequency is high, the evolution of wind conditions prior to and after a LLJ has not been widely studied or considered in a wind energy context. These periods of formation and dissipation are characterized by pronounced differences in wind behavior, particularly in wind speed and TKE (Figure 7).

![Figure 7](image_url)

**Figure 7.** Mean TKE and wind speed 50-550 m AGL for non-LLJ profiles (—) 2 hours before (a, b) and after (d, e) a rapidly evolving LLJ event (c) (—)

If the LLJ occurs in the rotor plane, the LLJ may be associated with high mechanical loadings and high frequency variations in power production if they are of short duration. Single hour LLJ events are common - approximately 40% of simulated LLJ over Iowa are identified in output from a single hour only. These one-hour events are referred to herein as rapidly evolving LLJ. Of these events,
approximately 20% have a wind speed maximum within the rotor plane. To characterize LLJ evolution, wind speed and TKE profiles are analyzed for two hours before and after these events (Figure 7). The LLJ wind speed profile has a clear LLJ speed maximum, while the profiles prior to and after the LLJ more closely approximate a stability-corrected logarithmic wind speed profile. There is a slight decrease in wind speed magnitude for the hour immediately preceding the LLJ event. After the LLJ event, mean wind speed is increased over the entire profile. Mean TKE for all hours is lower than during non-LLJ periods (Figure 2). During the hours preceding these rapidly-evolving (short-lived) LLJ, TKE decreases and there is a marked minimum across the rotor plane. The LLJ event also exhibits the highest mean TKE at heights above the rotor plane, which is consistent with literature indicating that LLJ generally increase TKE [23]. TKE remains low after a LLJ event, but increases during the second hour after the event.

The mean wind speed profiles in the hours before and after the LLJ event provide evidence that the wind threshold criterion of 2 ms\(^{-1}\) correctly captures the presence of LLJ. The LLJ profile is the only one of the five profiles that displays a clear wind speed maximum. The lower mean value of TKE for the five intervals, when compared to average non-LLJ TKE (Figure 2), indicates that TKE behavior around a LLJ is extremely similar to the behavior during a LLJ event. Use of a wind speed threshold criteria of 1.5 ms\(^{-1}\) to identify the presence of a LLJ increases the frequency of occurrence and leads to 15% of profiles in each interval before and after the LLJ event being classified as LLJ.

Rapidly evolving LLJ do not exhibit a strong spatial bias in terms of frequency of occurrence (Figure 8). While the formation of these rapidly evolving LLJ may also be affected by terrain variability, in contrast to LLJ frequency over the domain for nighttime and daytime intervals (Figure 6), areas of high frequency are observed in areas of low elevation. It is possible that the appearance of rapidly evolving LLJ is more strongly influenced by thermal gradients arising from variations in land use or land cover.

![Figure 8. Fraction of all LLJ events that are identified as rapidly evolving. Black markers indicate wind turbine locations as of the end of 2014.](image)

### 4. Conclusions

WRF simulations conducted with a spatial resolution of 4 km are analyzed to determine the frequency and characteristics of LLJ over Iowa in spring. The detection algorithm with an objective LLJ wind threshold criterion of 2 ms\(^{-1}\) successfully identifies low-level jet profiles. The vertical profile of wind speeds under LLJ exhibits a clear maximum at a mean height of around 220 m. Identified profiles exhibit characteristics consistent with previous studies. LLJs are found to occur at least once in the entire domain on approximately 98% of nights, and during conditions of relatively low TKE indicating stable atmosphere conditions. The highest LLJ frequency and mean duration are found in the northeast of the state. Daytime LLJ have a shorter mean duration (1.9 hours) than nighttime LLJ (3 hours). Mean wind speeds at the rotor plane for daytime LLJ are lower than those of nighttime LLJ.

Rapidly evolving LLJ (LLJ identified only in a single hour) that have a jet core within a nominal wind turbine rotor plane of 50 to 150 m, may have implications for rapid changes in power production and hence are of particular interest. Conditions during two hours before and after each one-hour LLJ event
are analyzed. The time interval before a LLJ event is associated with a slight decrease in rotor plane wind speed and a pronounced decrease in TKE. After the LLJ period there is evidence of higher wind speeds and increasing TKE. Rotor plane TKE in all intervals is lower than mean non-LLJ TKE. Adjusting the wind threshold criterion to 1.5 ms\(^{-1}\) causes nearly 15\% of wind speed profiles in each interval before and after the LLJ event to be identified as LLJ. This implies a high sensitivity of event identification and characterization to the precise wind threshold criteria employed. Rapidly evolving LLJ are identified for the entire state of Iowa, but are most frequent in areas of lowest terrain elevation. This is a unique characteristic of rapidly evolving LLJ, as other LLJ are biased towards the north of the state in areas with high topographic variability.

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