Identification of Low-Level Jets from AWAKEN Lidar Data

C. Alexander Hirsta

a University of Colorado Boulder, Boulder, Colorado, U.S.A

*Corresponding author*: C. Alexander Hirst, camron.hirst@colorado.edu

1. Introduction

The AWAKEN program is a landmark international campaign to collect measurements of wake interactions within wind power plants, spearheaded by the National Renewable Energy Lab (Moriarty et al., 2020). The motivation for this campaign is the poorly understood effect that wake interactions have within wind plants, which leads to significant and unpredictable power and financial losses. High-fidelity, long duration data is being gathered in north-central Oklahoma, an area important and relevant for near-term wind energy developments in the U.S. Great Plains. This data is critical for the development and validation of models which will in turn inform wind development projects and ultimately reduce the cost of wind energy.

This project uses doppler lidar data from the AWAKEN project to find and classify low-level jets (LLJs) in the region. LLJs are an important phenomenon to understand and quantify, as they can have a significant effect on wind farm operations. LLJs induce elevated windspeeds across the rotor layer, which increased the overall wind resource. However, increased shear and veer within a LLJ places additional stresses on turbine structures, which can increase operational costs and decrease service life (Kelley, 2011).

We analyze data from a doppler lidar located at site H (Figure 1), which is in the immediate vicinity of turbines in the King Plains wind farm. Utilizing the methodology developed in (Vanderwende et al., 2015), three LLJ events are identified between Nov. 9 – Nov. 17 2022. Both northerly and southerly LLJs have been observed, exhibiting characteristics typical for winter months in the area (Whiteman et al., 1997).

Map

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Figure 1: The AWAKEN field experiment layout. In this work, doppler lidar data from site H is used to identify LLJs in the region. Figure adapted from (Debnath et al., 2022)

2. Related Works

While wind farm technology has seen rapid growth and improvement, there still exist problems to overcome over several scales of space and time. Improved understanding of the physics of atmospheric flow and interaction with wind turbines has been identified as a grand challenge in wind energy research (Veers et al., 2019). Improved understanding of atmospheric flows will inform techniques to maximize the efficiency and therefore cost effectiveness of wind plants.

LLJs are an impactful weather event found around the world, driving the transportation of moisture, pollutants, dust, and other airborne substances for thousands of kilometers, all within the atmospheric boundary layer (Rife et al., 2010). Nocturnal migratory birds have been shown to take advantage of LLJs, with southerly winds providing substantial tail winds during the spring migration (Wainwright et al., 2016). These phenomena also impact wind farms, as modern turbines reach heights where LLJs commonly occur. LLJs can increase power output but can also cause damage to wind turbines. The Great Plains region of the United States experiences strong nocturnal LLJs during the warm season, which can be hundreds of kilometers wide and thousands of kilometers long. As this region is also home to much of our wind power resources, understanding LLJs is of great importance.

One of the first studies of LLJs in the U.S. Great Plains was conducted and presented in (Bonner, 1968). The author used two years of radiosonde data from 46 weather stations to identify hundreds of cases of nocturnal LLJs using a criterion developed therein. The diurnal variation and oscillation of the LLJ was observed throughout the year, although most often in spring and late summer. This landmark study provided substantial proof of the prominence and massive scales of LLJs in the region which significantly impact the local climate.

A more recent climatology of LLJs in the Great Plains of the United States provided more detail on general trends in the region (Walters et al., 2008). This study combined forty years of twice-daily radiosonde observations from 36 weather stations across the Great Plains. The authors were able to identify several characteristics of LLJs which vary based on seasonality and location. While this paper helped provide a broad description of LLJs in the region, the authors conclude that much remains to be documented and understood.

Other works have studied LLJs in the U.S. Great Plains using lidar measurements. In 2013, researchers deployed profiling and scanning lidars to collect data which was used to detect LLJs in central Iowa as part of the CWEX-13 field campaign (Vanderwende et al., 2015). The authors detailed a systematic procedure for computing wind profiles from the scanning lidar and using these profiles to detect and classify LLJs. LLJs were consistently identified, with peak windspeeds around 250-500m at the observation site, heights relevant to modern wind turbines. The authors also investigated the ability of various numerical weather models (and ensembles of said models) to predict LLJs in the area, demonstrating good performance. The LLJ classification procedure will be used in the proposed project to detect LLJs during the AWAKEN experiment.

Prior work has studied LLJ climatology in the north-central Oklahoma region (Whiteman et al., 1997), just tens of miles from where the data used in this project was collected. Both southerly and northerly LLJs were observed in the region, the former being much more frequent during the warm season (April – September). Southerly LLJs tend to be lower (300-600m AGL), occur more often at night and exhibit a diurnal clockwise rotation in wind direction and oscillations in speed. Northerly jets were found to be associated with south-bound cold air fronts. They are less dependent on time of day, do not exhibit rotations, and have nose heights that are correlated to distance behind cold fronts. Many of these characteristics were observed in this project.

2. Methods

To identify LLJs, this work implements a slightly modified version of the procedure developed in prior work (Vanderwende et al., 2015). The identification of LLJs from lidar measurements is done in three steps:

1. Initial quality assurance of wind speed and direction measurements at each bin.
2. Calculation of wind speed and direction profiles from Lidar radial velocity measurements.
3. Identification and classification of LLJs using wind speed profiles.

Wind speed and direction profiles at each altitude were found using a commonly used technique known as velocity azimuth display (VAD). VAD assumes a homogenous flow over the course of a 360-degree azimuth scan. As the Lidar is sweeping the azimuth angles, the radial velocity measurement axis will move in and out of alignment with the horizontal wind vector, resulting in a sinusoidal velocity profile. Using nonlinear least squares, the following function was fit to data at each available altitude bin:

Where is the radial wind speed, is the azimuth angle of the measurement, and are all parameters to be fit. The fitted parameters are then used to derive the horizontal wind speed and direction using:

Where is the beam elevation angle from horizontal. To filter out wind speed and direction datapoint which are poorly fit to the sinusoidal model, we calculate the commonly used value as:

Where is the sum of squares of the residuals, while is the total sum of squares. A threshold of 0.7 was place on this metric, as described in (Vanderwende et al., 2015). If a lower value was found, then the wind speed and direction measurement for that altitude was rejected. See Figures 10-12 in the Appendix for examples of valid/invalid VAD fits and their corresponding values.

This procedure can be run for each radial range bin from the Lidar profile. As we know the range and elevation angle of the lidar beam (in this work, 60 [deg]), we can derive the AGL altitude via:

The final step is to classify LLJs based on criteria originally proposed in (Bonner, 1968), then modified by (Whiteman et al., 1997) and (Song et al., 2005). There are two criteria that a wind profile must fulfill to be classified as a LLJ. First, the profile must contain a maximum windspeed above a windspeed threshold, and this maximum windspeed must occur below a height threshold. While Song/Vanderwende impose a 2km threshold, we observed consistently valid data only below 1km in the data available. We therefore placed a height threshold at 1km, and only considered profiles below that threshold. Maximum LLJ nose height observed occurred at 688m, justifying this choice.

The second criteria involves a threshold on the reduction of wind speed above the LLJ nose. This shear value must meet a certain threshold for LLJ classification. In (Whiteman et al., 1997), four jet intensity levels (0-3) are specified as a function of maximum windspeed and shear, with thresholds provided in the following table:

|  |  |  |
| --- | --- | --- |
| LLJ Category | Max windspeed [m/s] | Upper shear [m/s] |
| LLJ-0 |  |  |
| LLJ-1 |  |  |
| LLJ-2 |  |  |
| LLJ-3 |  |  |

3. Results and Discussion

Data used in this project was acquired through the DOE’s Atmosphere to Electron website (Shi et al.), and can be found at <https://a2e.energy.gov/ds/awaken/arm.lidar.sgp_s6.ppi.b1> . Unfortunately, only a limited amount of data was able to be acquired from the A2E site via the link above. Therefore, this project examines a dataset composed of measurements taken between Nov 9, 2022, and Nov 17, 2022. Lidar measurements are available at approximately 30-minute intervals throughout this period. Measurement azimuth angles ranged from 0 – 360 degrees, at 30-degree intervals. Measurement elevation angles were 20 and 60 degrees (Figure 2). In this work, only measurements at 60-degree elevation were used, however the code could be easily modified to incorporate measurements at 20 degrees elevation.

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Figure 2: Elevation and azimuth angles at which measurements are taken by the AWAKEN Site H Doppler Lidar.

In all, three LLJ events were classified within the data between Nov. 9 – Nov. 17 2022. These events occurred on the 10th, 13th, and 14th and are discussed below.

Nov. 10 2022 Event:

Around 4 pm CST on Nov. 10 2022, a LLJ was detected by the doppler radar. Initially a class 1, the LLJ continued to develop until reading class 3 around 11pm CST. The development of this LLJ corresponded to a strong south-bound cold front moving through the area (Figure 3). Peak windspeeds reached over 23 m/s. As the LLJ developed, it rose from an initial height of 454m to 668m (Figure 4), which aligns with prior observations of LLJ height growing as a function of distance behind cold front (Whiteman et al., 1997). Winds were approximately southerly during the entire event, exhibiting little turning. See Figure 13 in the Appendix for an example windspeed profile during this event. Little wind direction rotation of the LLJ nose was observed (Figure 5) , which is also consistent with previous northern LLJ observations in the area. Complete time series data for this event can be found in Table 2 in the Appendix.

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Figure 3: Screenshot of weather map on Nov. 10, 2022. A south-bound cold front can be seen moving across north-centrol Oklahoma, corresponding to the formation of a northerly LLJ. Adapted from: <http://www.wpc.ncep.noaa.gov/dailywxmap/index_20221110.html>

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Figure 4: Evolution of windspeed during the Nov. 10 2022 LLJ event. Increasing nose height was observed as the south-bound cold front moved away from the observation site.

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Figure 5: Evolution of wind direction during the Nov. 10 2022 LLJ event. Relatively little change in LLJ nose wind direction was observed. Strong wind veer was found aloft (near 1000m)

Nov. 13, 2022 Event:

A weaker LLJ was detected on Nov. 13, 2022. This LLJ originated around 1:30 am CST and persisted sporadically until 6 am CST. Maximum windspeeds reached just under 12 m/s, with winds originating from the southeast. The reason for sporadic classification was profiles were on the cusp of being classified as LLJ-0 (Table 2; Figures 14 and 15 in Appendix). Oscillatory windspeeds in southerly LLJs have been observed in prior observations, but have longer periods as part of the diurnal cycle (Whiteman et al., 1997). This event also occurred at a very low altitude of just 168m AGL maximum (Figure 6), which indicates potential impact on wind turbines. The data also indicated significant wind shear below 200m AGL, which could cause increased wear on local wind turbines. Little wind direction rotation was observed over the event, although significant wind veer was found from ground level to 1000m AGL (Figure 7). Complete time series data for this event can be found in Table 3 in the Appendix.

Chart

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Figure 6: Evolution of windspeed during the Nov. 13 2022 LLJ event. Oscillation around the 10 m/s threshold was observed over ~5 hours.

Chart

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Figure 7: Evolution of wind direction during the Nov. 13 2022 LLJ event. Nose height is observed to increase as the south-bound cold front moves away.

Nov. 14 2022 Event:

The final LLJ event was detected on Nov. 13, 2022. This LLJ originated around 7:00 am CST, and persisted just an hour until 8:00 am CST. Maximum windspeeds reached just under 14 m/s, with nose height around 500m AGL and winds originating from the south. Once again, fast oscillations in windspeeds were observed (Figure 8). Little change in nose wind direction was observed (Figure 9), likely due to the short time span of the event. Significant wind veer was observed from 400m to 1000m AGL. Complete time series data for this event can be found in Table 4 in the Appendix.

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Figure 8: Evolution of windspeed during the Nov. 14 2022 LLJ event. Oscillation around the 10 m/s threshold was observed over ~5 hours.

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Figure 9: Evolution of wind direction during the Nov. 13 2022 LLJ event. Nose height is observed to increase as the south-bound cold front moves away.

4. Conclusion and Future Work

This work used doppler lidar data to detect and classify low-level jets using the methods presented in (Vanderwende et al., 2015) and prior works. In total, 3 LLJ events were identified at site H of the AWAKEN experiment between Nov. 9 – 17, 2022. The LLJs observed exhibited characteristics that were largely consistent with prior observations (Whiteman et al., 1997). The LLJs were found within and around wind farms, thus may have distinct impacts on wind farm performance.

This project was limited in scope. There are several notable extensions that could readily be investigated. First, a study investigating the dependence of LLJ formation and severity as a function of atmospheric stability should be done. This project did not have temperature profile data available, making atmospheric stability calculations difficult. Second, it may be interesting to see how well an NWP model could predict the observed LLJs in the area. This could validate whether NWP models can be used for predictive control of wind farms. Third, an investigation into LLJ occurrence over a longer period would be interesting and informative. Is LLJ climatology changing over time? The code developed in this project could be readily used to analyze a larger dataset, when it becomes available. Finally, the lidar measurements in this study were taken near the King Plains wind farm (Figure 1). An investigation into the effect of the wind farm on local LLJ formation should be conducted, as the wind farm likely influences our ability to detect local low-altitude LLJs when taking measurements down wind.

Acknowledgements

The author acknowledges the code contributions from Daphne Quint and Prof. Julie Lundquist, which helped kick-start the project. All code to recreate the results can be found on GitHub at: <https://github.com/CamronAlexanderHirst/ATOC5770_LLJ> .

APPENDIX

LLJ Figures

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Figure 10: VAD Fit of Lidar scan on Nov. 11 2022 at 12m AGL. R-squared value does not meet the 0.7 threshold, therefore the windspeed and wind direction measurement was rejected.

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Figure 11: VAD Fit of Lidar scan on Nov. 11 2022 at 2325m AGL. R-squared value meets the 0.7 threshold, therefore the windspeed and wind direction measurement was accepted.

Chart, line chart

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Figure 12: VAD Fit of Lidar scan on Nov. 11 2022 at 142m AGL. R-squared value meets the 0.7 threshold, therefore the windspeed and wind direction measurement was accepted.

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Figure 13: A windspeed profile taken on Nov 10 2022. This profile is a distinct example of LLJ formation, with maximum windspeed exceeding 22 m/s. This profile was classified as LLJ-3.

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Figure 14: A windspeed profile taken at 8:00am UTC on Nov 13, 2022. This profile met the windspeed threshold of 10 m/s to be classified as LLJ-0. Similar profiles resulted during the Nov 13 event, leading to sporadic LLJ identification.

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Figure 15: A windspeed profile taken at 8:30am UTC on Nov 13, 2022. This profile did not meet the windspeed threshold of 10 m/s to be classified as an LLJ. Similar profiles resulted during the Nov 13 event, leading to sporadic LLJ identification.

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Figure 16: A windspeed profile taken on Nov. 14 2022. This profile did not meet the shear criteria to be classified as an LLJ.

**Table 2: Nov. 10 2022 Low-Level Jet Event**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Time [UTC]** | **LLJ Class** | **Nose Height [m]** | **Upper Shear [m/s]** | **Max. WS [m/s]** | **Wind Direction [deg]** |
| **2022-11-10 22:00:21** | 1 | 454.66 | 10.55 | 12.95 | -3.24 |
| **2022-11-10 22:30:03** | 1 | 532.61 | 12.08 | 15.42 | 0.71 |
| **2022-11-10 23:00:21** | 2 | 558.59 | 16.35 | 18.07 | 16.57 |
| **2022-11-10 23:30:03** | 2 | 558.59 | 15.89 | 18.58 | 14.13 |
| **2022-11-11 00:00:21** | 2 | 584.57 | 13.43 | 19.03 | 23.69 |
| **2022-11-11 00:30:04** | 2 | 636.53 | 13.16 | 19.12 | 19.98 |
| **2022-11-11 01:00:21** | 2 | 558.59 | 10.26 | 19.73 | 20.96 |
| **2022-11-11 01:30:04** | 3 | 610.55 | 10.57 | 20.89 | 19.80 |
| **2022-11-11 02:00:21** | 3 | 636.53 | 12.42 | 23.05 | 25.92 |
| **2022-11-11 02:30:03** | 3 | 662.51 | 10.72 | 22.29 | 23.65 |
| **2022-11-11 03:00:21** | 3 | 688.49 | 10.69 | 21.76 | 22.91 |

**Table 3: Nov. 13 2022 Low-Level Jet Event**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Time [UTC]** | **LLJ Class** | **Nose Height [m]** | **Upper Shear [m/s]** | **Max. WS [m/s]** | **Wind Direction [deg]** |
| **2022-11-13 07:30:03** | 0 | 142.89 | 7.38 | 10.59 | 106.56 |
| **2022-11-13 08:00:21** | 0 | 168.87 | 6.29 | 10.15 | 116.64 |
| **2022-11-13 08:30:03** |  |  | 5.52 | 9.93 |  |
| **2022-11-13 09:00:21** | 0 | 168.87 | 5.55 | 10.27 | 120.19 |
| **2022-11-13 09:30:03** | 0 | 168.87 | 5.21 | 10.25 | 123.61 |
| **2022-11-13 10:00:20** |  |  | 4.63 | 9.84 |  |
| **2022-11-13 10:30:04** |  |  | 4.38 | 10.28 |  |
| **2022-11-13 11:00:21** |  |  | 4.93 | 11.02 |  |
| **2022-11-13 11:30:03** |  |  | 4.71 | 11.43 |  |
| **2022-11-13 12:00:21** | 0 | 168.87 | 5.32 | 11.95 | 128.43 |

**Table 4: Nov. 13 2022 Low-Level Jet Event**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Time [UTC]** | **LLJ Class** | **Nose Height [m]** | **Upper Shear [m/s]** | **Max. WS [m/s]** | **Wind Direction** |
| **2022-11-14 13:00:21** | 0 | 532.61 | 5.54 | 13.85 | 180.74 |
| **2022-11-14 13:30:03** | 1 | 480.64 | 6.53 | 12.49 | 168.52 |
| **2022-11-14 14:00:21** | 1 | 532.61 | 6.38 | 13.42 | 175.31 |

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