Influence of Low-Level Jet intensity on aerodynamic loads of horizontal axis wind turbine rotor

Xuyao Zhang\textsuperscript{a}, Congxin Yang\textsuperscript{a,b,c} and Shoutu Li\textsuperscript{a,b,c}

\textsuperscript{a}School of Energy and Power Engineering, Lanzhou University of Technology, Lanzhou, People’s Republic of China; \textsuperscript{b}Gansu Provincial Technology Centre for Wind Turbines, Lanzhou, People’s Republic of China; \textsuperscript{c}Key Laboratory of Fluid Machinery and Systems, Lanzhou, People’s Republic of China

ABSTRACT

High wind speeds associated with Low-Level Jet (LLJ) make wind resources more favorable for wind energy production. However, the aerodynamic loads of large-scale horizontal axis wind turbine (HAWT) rotor under different LLJ inflow conditions have not been thoroughly studied. To gain insight into the aerodynamic loads of rotor under LLJ inflow conditions with different LLJ intensities, a method to establish an engineering LLJ inflow model was proposed according to the plane wall jet theory and Von Karman spectra model with user-defined scaling. The parameters in the engineering LLJ inflow model were determined by comparing the wind speed distribution obtained from the GP_LLJ spectral model, which was summarized from field measurements in the real atmosphere. The LLJ fluctuating wind fields with different intensities generated by the engineering LLJ inflow model were used as the inflow conditions of Fatigue, Aerodynamics, Structures, and Turbulence (FAST) open source code to calculate and analyze the aerodynamic loads of the HAWT. It was found that the engineering LLJ inflow model can be used to establish the LLJ inflow condition of HAWT. When the LLJ height is located at the hub height and LLJ intensity increases from 8 to 16 m/s, the RMS rotor unbalanced aerodynamic load coefficients, including ones of lateral force, longitudinal force, tilt moment and yaw moment are increased by 2.2, 2.13, 1.02 and 0.95 times, respectively.

1. Introduction

Low-Level Jets (LLJs), which are defined as relative maxima in the profiles of the wind speed within the atmospheric boundary layer, have been widely concerned due to their close connection with the climate formation process and wind energy utilization. Previous studies have shown that the dominant mechanism of forming a LLJ is inertial oscillations (Blackadar, 1957; Van de Wiel et al., 2010). Besides, some other mechanisms, such as baroclinity associated with the sloping terrain and the thermal wind connected with land-sea heating contrast (Bonner & Paegle, 1970; McNider & Pielke Sr, 1981; Parish, 2000), are associated with the development of LLJ. The definition and classification of LLJ in the references are ambiguous due to the differences of observations at different regions (Baas, Bosveld, Klein Baltink, & Holtslag, 2009; Banta et al., 2002; David Whiteman, Bian, & Zhong, 1997; Song, Liao, Coulter, & Lesht, 2005), but the basic structural characteristics of LLJ can be described by the LLJ intensity (LLJ wind speed maximum), LLJ height (height of the wind speed maximum) and the wind shear coefficient (Emeis, 2014; Shu, Li, He, & Chan, 2018).

As for wind energy utilization, the flow characteristics of the boundary layer have direct impact on the operation of the wind turbine (Porté-Agel, Wu, & Lu, 2012; Zheng et al., 2018). LLJ plays an important role in the generation of the shear and turbulence within the atmospheric layer that occupied by the large-scale HAWTs (Kelley et al., 2004; Pichugina et al., 2017; Storm, Dudhia, Basu, Swift, & Giammanco, 2009). Therefore, the appearance of LLJ will change the normal inflow conditions of large-scale HAWTs. The most obvious feature of LLJ vertical wind speed profile is the presence of the maximum wind speed, the negative and positive wind shear that above and below the height of the maximum wind speed. In order to get more energy, the tower height and rotor diameter of the large-scale HAWT increase gradually, and the turbine develops toward the multi-MW level. Therefore, large-scale HAWTs are more likely to be affected by the LLJ.

When the LLJ height is located at the heights of the wind turbine rotor, the increase of the LLJ intensity can enhance the inflow wind power (Storm et al., 2009). Further study has shown that the wind power
density increases more than 15 times at the heights of the rotor in LLJ conditions (Gutierrez et al., 2016). Obviously, it is good for delivering substantially more electric power. However, the strong wind speed and intense wind shear of the LLJ may cause unbalanced aerodynamic loads on the rotor. The results indicated that the LLJ impose mechanical loads and fatigue cycles over the wind turbines (Gutierrez et al., 2016). Nowadays, numerical simulation methods have been widely accepted in various fields (Akbarian et al., 2018; Faizollahzadeh Ardabili et al., 2018; Ramezanizadeh, Alhuyi Nazari, Ahmadi, & Chau, 2019) owing to the progress of computer capabilities and the advances in numerical model.

In this paper, to elucidate the influence of LLJ intensity on aerodynamic loads of HWAT rotor, a method to establish an engineering LLJ inflow model was proposed according to the theory of plane wall jet and Von Karman spectra model with user-defined scaling. The rotor aerodynamic loads were studied under LLJ fluctuating wind fields with different intensities generated by the engineering LLJ inflow model.

The paper is organized as follows. Section 2 describes the wind turbine model and FAST open source code. Section 3 validates the calculation model and method in FAST. Section 4 presents a method to establish an engineering LLJ inflow model, which is used to generate the LLJ fluctuating wind fields with different intensities. Section 5 validates the reasonableness of the method to establish the engineering LLJ inflow model by comparing the results of the GP_LLJ spectral model. In addition, the influence of LLJ intensity on rotor aerodynamic loads was studied. Section 6 presents the major conclusions of this study. Results of this study can provide a method to establish the LLJ inflow conditions of HAWTs and clarify the aerodynamic loads of the large-scale HAWTs under LLJ inflow conditions with different LLJ intensities.

### 2. Wind turbine model and FAST

The wind turbine used in this work is the National Renewable Energy Laboratory (NREL) 5 MW reference turbine. It is a three-blade upwind variable-speed variable-blade pitch-to-feather-controlled turbine. To meet the typical hub height of the current low-wind speed turbines, the hub height of the wind turbine is assumed to be 150 m. The parameters of the rotor are shown in Table 1. Additional details of the wind turbine can be found in Jonkman, Butterfield, Musial, and Scott (2009).

| Parameters                      | Value   |
|--------------------------------|---------|
| Rotor, Hub diameter (m)        | 126.3   |
| Shaft Tilt, Precone (°)        | 5, 2.5  |
| Airfoil distribution           | NACA series airfoils, DU series airfoils |
| Blade number                   | 3       |
| Cut-in, Rated, Cut-out wind    | 3, 11, 4, 25 |
| Speed (m/s)                    |         |
| Cut-in, Rated rotor speed (r/min) | 6.9, 12.1 |

The data in the table is from Jonkman et al. (2009).

![Figure 1. Rotor speed and pitch angle at different wind speeds.](image)

In this study, the wind turbine blades were modeled by actuator line model coupled with FAST open source code developed by the NREL. The code can model the response of both three-blade and two-blade, conventional, HAWTs (Jonkman & Buhl, 2005). Within FAST, each blade is represented by a series of discrete elements along the spanwise direction. The aerodynamic properties of the airfoils at blade element were used to compute the aerodynamic forces. The Leishman and Beddoes model (Leishman & Beddoes, 1989) is applied to capture the dynamic stall characteristics. The aerodynamic loads of the blade are computed by integrating the distributed forces along the analysis nodes on the blade.

### 3. Validation of calculation model and method in FAST

To verify the accuracy of the calculation model and method in FAST, the rotor power was obtained by using the FAST code under the uniform inflow conditions with different wind speeds. As shown in Figure 2, the calculated results were compared with those from the reference (Jonkman et al., 2009). It can be seen that the current results are in good agreement with the calculated results.
by Jonkman et al. (2009). The maximum relative error is 1.23% at the wind speed of 25 m/s. Therefore, it can be considered that the calculation model and method used in FAST are reasonably accurate.

4. LLJ inflow wind fields

Understanding the LLJ structural characteristics in real atmospheric boundary layer is the basis for studying the influences of LLJ on large-scale HAWTs. Although scholars have observed and analyzed LLJ structural characteristics in different regions (Banta, 2008; Eméis, 2014; Shu et al., 2018), most results lack a summary. To predict the characteristics of atmosphere, the Weather Research and Forecasting (WRF) model was developed by research institutions (Skamarock et al., 2005). Study indicated that the WRF model can capture some characteristics of LLJ, but the core of LLJ obtained from the WRF model is higher than the observed results (Storm et al., 2009). By comparison, the GP_LLJ spectral model (Jonkman & Buhl, 2006) based on the Lamar Low-Level Jet Program (LLJP) (Kelley et al., 2004) that developed by the NREL, U.S. Department of Energy (DOE) and General Electric Wind Energy was developed to describe the LLJ structural characteristics by the researchers of the NREL. The meteorological parameters of the GP_LLJ spectral model were obtained from a tower with a height of 120 m and an acoustic wind profiler (sonic detection and ranging, SODAR). The spectra and spatial coherence parameters defined in the GP_LLJ spectral model were based on the time-series data with a frequency of 20 Hz. The wind turbine response under LLJ conditions was studied by means of the GP_LLJ spectral model (Kelley, Scott, & Jonkman, 2006). However, the GP_LLJ spectral model can only be used to simulate the LLJ characteristics of the Great Plains. Therefore, it is necessary to provide a method to establish an LLJ model that is also applicable to other regions.

An engineering LLJ inflow model was established in this paper. The method of establishing the LLJ inflow wind fields was to superimpose the fluctuating wind on the average wind field. Therefore, the model established in this paper consists of two parts: the average wind field and fluctuating wind field.

4.1. Average wind field

In the engineering LLJ inflow model, the average wind field was established based on the theory of plane wall jet in fluid mechanics. According to the knowledge of fluid mechanics, the relationship between the horizontal velocity component $v(x, H)$ and jet maximum velocity $v_m(x)$ of the planar free jet is given as follows (Tiqian, 2007):

$$\frac{v(x, H)}{v_m(x)} = 1 - \tanh^2 \left( k \frac{H}{x} \right),$$

where $H$ represents the height, $x$ represents the streamwise distance and $k$ is a parameter related to the shape of the jet.

Assuming that the horizontal velocity distribution in streamwise is uniform, Equation (1) can be written as

$$\frac{v(H)}{v_m} = 1 - \tanh^2 \left( C_s \frac{H - H_s}{H_s} \right),$$

where $H_s$ is the height of maximum velocity of the free jet, $C_s$ is the free jet shape factor, which is related to the shape of the free jet velocity profile.

The average LLJ velocity distribution was obtained by superimposing the velocity profile of the free jet and the wind shear. The power-law profile was used to describe the change of wind speed with height in wind shear condition (Mou, He, Zhao, & Chau, 2017). The expression of the average LLJ velocity profile is given as follows:

$$v_{LLJ}(H) = v_{ref} \left( \frac{H}{H_{ref}} \right)^\alpha + v_m \left[ 1 - \tan h^2 \left( C_s \frac{H - H_s}{H_s} \right) \right],$$

where $H_{ref}$ is the reference height, $v_{ref}$ is the wind speed at the reference height and $\alpha$ is the wind shear exponent. The meanings of the parameters in Equation (3) are shown in Figure 3. The $v_{LLJ}$ indicates the LLJ intensity, which is defined as the maximum value of the LLJ velocity.

However, the free jet term in Equation (3) does not satisfy the no-slip condition at $H = 0$. Therefore, the free jet term was modified by multiplying the boundary layer
shape function \((H/H_{ref})^\alpha\) to satisfy the no-slip condition. The final expression of the average LLJ velocity profile is shown in Equation (4).

\[
v_{LLJ}(H) = \left\{ v_{ref} + v_m \left[ 1 - \tanh^2 \left( C_s \frac{H - H_s}{H_s} \right) \right] \right\} \left( \frac{H}{H_{ref}} \right)^\alpha.
\]

(4)

For the convenience of description, the engineering LLJ inflow model established in this paper is named Jet_Shear model. In order to establish the LLJ average wind fields with different intensities, the parameters in the Jet_Shear model must be determined. Considering that the GP_LLJ spectral model is based on the high-frequency data of the real atmospheric boundary layer, the parameters were determined by comparing the average wind speed profiles obtained from the GP_LLJ spectral model. Observations in some regions show that the jet speed maximum is different in LLJ condition. As shown in the literature, the maximum frequency of occurrence of jet speed is in the range 9–11 m/s (R D & Ernest Raj, 2015), and the average jet speed maximum for LLJ observations is 14.5 m/s (Shu et al., 2018). Therefore, the LLJ inflow conditions in this study are as follows: the average LLJ intensities of the wind fields are 8, 10, 11.4, 12, 14 and 16 m/s, respectively. The average LLJ heights are 150 m for all wind fields, which correspond to the hub height. It is found that when the parameters in the Jet_Shear model are assigned (Table 2), the wind speed profiles similar to the GP_LLJ spectral model can be obtained. The average wind speed profiles with different LLJ intensities obtained by the two models are shown in Figure 4. The horizontal dotted lines indicate the positions of the top-tip and bottom-tip of the wind turbine rotor. Figure 4 shows that, at the heights occupied by the wind turbine rotor, the average wind speed profiles obtained by the Jet_Shear model are in good agreement with the profiles obtained by the GP_LLJ spectral model, and the maximum relative error is 4.4%. Therefore, the Jet_Shear model can be used to establish LLJ average wind fields with different intensities.

### 4.2. Fluctuating wind field

In order to meet the actual flow conditions of the atmospheric boundary layer, the Von Karman spectrum with user-defined scaling was used to establish the fluctuating wind fields.

The velocity spectrum for the streamwise wind component \((u)\) is (Jonkman & Buhl, 2006)

\[
S_u(f) = \frac{4(StdScale_u, \sigma(H))^2 \cdot L(H)}{\left(1 + 71(f \cdot L(H)/v_{LLJ}(H))^2 \right)^{5/6}}.
\]

(5)

The velocity spectrum for the transverse wind component \((k = v)\) and vertical wind component \((k = w)\) is (Jonkman & Buhl, 2006)

\[
S_k(f) = \frac{2(StdScale_k, \sigma(H))^2 \cdot L(H)/v_{LLJ}(H)}{(1 + 71(f \cdot L(H)/v_{LLJ}(H))^2)^{11/6}}.
\]

(6)
where \( f \) represents the frequency, \( L(H) \) and \( \sigma(H) \) are the integral length scale and standard deviation at the height of \( H \), and \( \text{StdScale} \) is the coefficient of standard deviation.

Although the measurement results indicated that the turbulence parameters change with the height in the LLJ conditions (Emeis, 2014), there is no clear expression to describe the relationship. Considering the difficulty of measuring and the simplicity of the model, it is assumed that the length scale and standard deviation do not change with the height. According to the IEC standard, \( L(H) = 3.5 \Lambda_U \) and \( \Lambda_U = 42 \text{ m} \), where \( \Lambda_U \) is turbulence scale parameter. The different measurement results indicated that the ratio of the standard deviation to the LLJ intensity ranges from 0.025 to 0.064 (Banta, Pichugina, & Brewer, 2006). It means that the standard deviation is related to the LLJ intensity, and the ratios in different regions are not the same. In the Von Karman spectrum model, the parameters related to the standard deviation are defined as follow: \( \text{StdScale}_u = \text{StdScale}_v = \text{StdScale}_w = 0.06v_{\text{LLJ}} \) and \( \sigma(H) = 1 \). The turbulence intensity \( TI(H) \) is defined by the turbulence deviation \( \sigma(H) \), and the relationship between turbulence intensity and turbulent standard deviation is: \( TI = 100\sigma(H)/v_{\text{LLJ}}(H) \). The values of \( v_{\text{LLJ}}(H) \) are given by Section 4.1.

According to the Jet_Shear model and the given values for parameters, the LLJ fluctuating wind fields with different intensities were established. In order to verify the accuracy of the simulated wind speed, the calculation power spectrum and target power spectrum of the fluctuating wind fields with the LLJ intensities of 11.4 m/s were compared. Figure 5 shows the time history of the hub height fluctuating wind components obtained from the Jet_shear model. The comparison results of the power spectrum are shown in Figure 6. As can be seen from Figure 6, for the three wind components, the calculated spectrum agrees well with target spectrum over the entire frequency range. In summary, it can be considered that the fluctuating characteristics of the simulated LLJ fluctuating wind fields accord with the target spectrum.

5. Results and discussion

5.1. RMS of aerodynamic loads

Under LLJ inflow conditions, the rotor aerodynamic force coefficients and moment coefficients are defined as follows:

\[
C_{F_i} = \frac{F_i}{(1/2) \rho V^2 A},
\]

\[
C_{M_i} = \frac{M_i}{(1/2) \rho V^2 AR^2},
\]

where \( F_i \) and \( M_i \) represent the rotor aerodynamic forces and aerodynamic moments subjected in the \( i \) direction (\( i = x, y, z \)), \( \rho \) is the air density, \( A \) is the rotor swept area and \( V \) is the rated wind speed of wind turbine. The schematic of the aerodynamic loads and reference coordinate system is shown in Figure 7.

The LLJ fluctuating wind fields with different intensities generated by the two LLJ inflow models were used as the inflow condition of the wind turbine to calculate the rotor aerodynamic loads. Since the GP_LLJ spectral model is established based on the actual measurement data, the results under the LLJ wind field generated by GP_LLJ spectral model can be used to verify the results of the Jet_Shear model. The RMS aerodynamic load...
coefficients, including ones of thrust \(F_x\), lateral force \(F_y\), longitudinal force \(F_z\), torque \(M_x\), tilt moment \(M_y\) and yaw moment \(M_z\), were compared to verify the reasonableness of method of establishing the Jet_Shear model. In addition, the influence of the LLJ intensity on rotor aerodynamic loads was studied.

The results under different LLJ fluctuating wind fields are shown in Figure 8. It can be seen that the RMS rotor aerodynamic force coefficients and moment coefficients calculated by the Jet_Shear model are consistent with the results obtained from the GP_LLJ spectrum model. The relative errors of the two models are shown in Table 3, where the maximum relative error is \(-6.82\%\). The difference of the results obtained from two models may relate to the assumptions in the Jet_Shear model. For example, the length scale and standard deviation in the Jet_Shear model are considered not to vary with height. Considering the simplification and calculation accuracy of the model, the LLJ wind fields generated by the Jet_Shear model can be used as the inflow conditions of large-scale HAWTs to forecast the average aerodynamic loads.

The influence of the LLJ intensity on rotor aerodynamic forces and moments was studied. As can be seen from the calculation results of the Jet_Shear model in Figure 8, when the LLJ intensity is below the rated wind speed, the rotor torque coefficient and thrust coefficient increase with the increment of the LLJ intensity. When the LLJ intensity is above the rated wind speed, the rotor thrust coefficient has a tendency to decrease, and the torque coefficient remains basically unchanged. This can be explained by the variation of the pitch angle at high wind speeds. In terms of the unbalanced aerodynamic loads exerting on the rotor, when LLJ intensity increases from 8 to 16 m/s, the RMS rotor aerodynamic load coefficients, including ones of lateral force, longitudinal force, tilt moment and yaw moment, are increased by 2.2, 2.13, 1.02 and 0.95 times, respectively. This can be explained by the increase of wind shear with the enhancement of LLJ intensity, resulting in an increase in the unbalanced aerodynamic loads.

**Figure 7.** Schematic of the aerodynamic loads and reference coordinate system.

**Figure 8.** The variation of the rotor force coefficient and moment coefficient with LLJ intensity: (a) rotor force coefficient; (b) rotor moment coefficient.

**Table 3.** The relative error of the rotor aerodynamic load coefficients for different LLJ intensities.

| \(v_{LLJ}\) (m/s) | \(F_x\) (%) | \(F_y\) (%) | \(F_z\) (%) | \(M_x\) (%) | \(M_y\) (%) | \(M_z\) (%) |
|-----------------|--------------|--------------|--------------|-------------|-------------|-------------|
| 8               | -2.20        | -4.84        | -4.11        | -3.05       | 1.91        | 3.84        |
| 10              | 0.21         | -1.94        | -4.04        | 0.54        | 3.80        | 2.37        |
| 11.4            | 1.18         | -6.68        | -6.82        | 2.29        | -3.31       | -4.90       |
| 12              | 1.57         | -3.58        | -4.10        | 2.41        | -2.76       | -5.37       |
| 14              | 2.17         | -1.48        | -2.08        | 2.68        | -2.86       | -1.57       |
| 16              | 3.27         | 5.51         | 5.16         | 3.44        | 2.43        | 4.30        |
5.2. Fluctuating characteristics of rotor thrust and torque

Apart from the average characteristics of aerodynamic loads, the fluctuating characteristics are also the key to the normal operation of wind turbine. To verify the capability of forecasting the fluctuating characteristics of rotor aerodynamic loads under LLJ inflow conditions generated by the Jet Shear model, the power spectrum characteristics of the rotor thrust and torque were compared under LLJ inflow condition generated by the GP_LLJ model and the Jet_Shear model. Figure 9 shows the comparison results under LLJ inflow condition with LLJ intensity of 11.4 m/s (rated wind speed). It can be seen that the power spectrum characteristics of rotor thrust and torque calculated by the Jet_Shear model are similar to the results obtained from the GP_LLJ spectrum model. It is also observed that the curves of power spectrum have distinct peaks, and the amplitudes decrease with the increase of frequency. Under LLJ inflow condition with LLJ intensity of 11.4 m/s, the rotor speed is 12.1 r/min, so the passing frequency ($f$) of the blade is 0.605 Hz for three-blade rotor. Further analysis shows that the peaks are observed at the frequencies of 0.605, 1.215, 1.81 and 2.425 Hz, which correspond to the harmonics of the passing frequency of the blade ($1f$, $2f$, $3f$, $4f$). This finding is in agreement with the previous studies shown in Churchfield, Lee, Michalakes, and Moriarty (2012).

In summary, the LLJ wind fields generated by the Jet Shear model can be used as the inflow conditions of large-scale HAWTs to forecast the rotor aerodynamic loads. Compared with the GP_LLJ spectrum model, the Jet_Shear model has more advantages. In the Jet_Shear model, the characteristic parameters describing the LLJ are more intuitive and understandable, while there are many parameters related to meteorological condition in the GP_LLJ spectrum model. In addition, the GP_LLJ model needs several iterations to get the desired results. But the Jet_Shear model established in this paper can obtain the required LLJ velocity profile quickly, and can improve the calculation efficiency. Therefore, the Jet_Shear model is more convenient for engineering applications.

6. Conclusion

This paper provides a method to establish an LLJ inflow model named Jet_Shear according to the plane wall jet theory and Von Karman spectra model with user-defined scaling. The reasonableness of the method was verified by comparing with the results of the GP_LLJ spectral model. The LLJ fluctuating wind fields with different intensities generated by the Jet_Shear model were used as the inflow condition of the wind turbine to study the aerodynamic loads. The following conclusions are drawn from this study.

The Jet_Shear model established in this paper can simulate the LLJ inflow wind fields of wind turbine. The RMS rotor aerodynamic load coefficients and power spectrum characteristics calculated by the Jet_Shear model are similar to the results obtained from the GP_LLJ spectrum model. Although the parameters determined in model cannot be applicable for any arbitrary sites, the method of establishing the LLJ inflow model can provide advice for other regions. Compared with the GP_LLJ spectrum model, the characteristic parameters describing the LLJ in the Jet_Shear model are more intuitive and understandable. In addition, the Jet_Shear model can establish the required LLJ inflow wind fields quickly. Therefore, the Jet_Shear model is more convenient for engineering applications.

In terms of the unbalanced aerodynamic loads exerting on rotor under LLJ inflow conditions, when the LLJ...
height is located at the hub height and LLJ intensity increases from 8 to 16 m/s, the RMS rotor aerodynamic load coefficients, including ones of lateral force, longitudinal force, tilt moment and yaw moment, are increased by 2.2, 2.13, 1.02 and 0.95 times, respectively.

The values of the parameters in Jet_Shear model may not be applicable to any other regions. Future studies should focus on determining universal parameters in Jet_Shear model by comparing with other models. In addition, the influence of other LLJ structural characteristics, such as LLJ height and turbulence distribution, on aerodynamic characteristics of HAWT will be studied.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This research was funded by the National Basic Research Program of China (No. 2014CB046201).

References
Akbarian, E., Najafi, B., Jafari, M., Faizollahzadeh Ardabili, S., Shamshirband, S., & Chau, K. (2018). Experimental and computational fluid dynamics-based numerical simulation of using natural gas in a dual-fueled diesel engine. Engineering Applications of Computational Fluid Mechanics, 12(1), 517–534. doi:10.1080/19942060.2018.1472670
Baas, P., Bosveld, F. C., Klein Baltink, H., & Holtslag, B. (2009). A Climatology of Nocturnal Low-Level Jets at Cabauw. Journal of Applied Meteorology and Climatology, 48(8), 1627–1642. doi:10.1175/2009JAMC1965.1
Banta, R. M. (2008). Stable-boundary-layer regimes from the perspective of the low-level jet. Acta Geophysica, 56(1), 58–87. doi:10.2478/s11600-007-0049-8
Banta, R. M., Newsom, R., Lundquist, J., Pichugina, Y., Coulter, R. L., & Mahrt, L. (2002). Nocturnal low-level jet characteristics over Kansas during CASES-99. Boundary-Layer Meteorology, 105, 221–252. doi:10.1023/A:1019992330866
Banta, R. M., Pichugina, Y. L., & Brewer, W. A. (2006). Turbulent velocity-variance profiles in the stable boundary layer generated by a nocturnal low-level jet. Journal of the Atmospheric Sciences, 63(11), 2700–2719. doi:10.1175/JAS3776.1
Blackadar, A. K. (1957). Boundary layer wind maxima and their significance for the growth of nocturnal inversions. Bulletin of the American Meteorological Society, 38(5), 283–290. doi:10.1175/1520-0475-38.5.283
Bonner, D., & Paege, J. (1970). Diurnal variations in boundary layer winds over the South-Central United States in Summer. Monthly Weather Review, 98(10), 735–744. doi:10.1175/1520-0493(1970)098<0735:DVBLW>2.0.CO;2
Churchfield, M. J., Lee, S., Michalakes, J., & Moriarty, P. J. (2012). A numerical study of the effects of atmospheric and wake turbulence on wind turbine dynamics. Journal of Turbulence, 13, N14. doi:10.1080/14685248.2012.668191
David Whiteman, C., Bian, X., & Zhong, S. (1997). Low-level jet climatology from enhanced rawinsonde observations at a site in the Southern Great Plains. Journal of Applied Meteorology, 36, 1363–1376. doi:10.1175/1520-0450(1997)036<1363:LLJCFE>2.0.CO;2
Eimeis, S. (2014). Wind speed and shear associated with low-level jets over Northern Germany. Meteorologische Zeitschrift, 23(3), 295–304. doi:10.1127/0941-2948/2014/0551
Faizollahzadeh Ardabili, S., Najafi, B., Shamshirband, S., Minaei Bidgoli, B., Deo, R. C., & Chau, K. (2018). Computational intelligence approach for modeling hydrogen production: A review. Engineering Applications of Computational Fluid Mechanics, 12(1), 438–458. doi:10.1080/19942060.2018.1452296
Gutierrez, W., Araya, G., Kiliyanpilakkil, V. P., Ruiz-Columbie, A., Tutkun, M., & Castillo, L. (2016). Structural impact assessment of low level jets over wind turbines. Journal of Renewable and Sustainable Energy, 8, 23308. doi:10.1063/1.4945359
Jonkman, B. J., & Buhl, M. L. J. (2006). Turbsim user’s guide. United States. doi:10.2172/891594
Jonkman, J., & Buhl, M. L. J. (2005). FAST user’s guide. doi:10.2172/15020796.
Jonkman, J., Butterfield, S., Musial, W., & Scott, G. (2009). Definition of a 5-MW reference wind turbine for offshore system development. doi:10.2172/947422.
Kelley, N. D. D., Scott, G. N. N., & Jonkman, B. J. J. (2006). The Great Plains turbulence environment: Its origins, impact and simulation. 2006 American Wind Energy Association WINDPOWER conference & exhibition.
Kelley, N., Shirazi, M., Jager, D., Wilde, S., Patton, E. G., & Sullivan, P. (2004). Lamar Low-Level Jet Project Interim Report. Golden: National Renewable Energy Laboratory.
Leishman, J. G., & Beddoes, T. S. (1989). A semi-empirical model for dynamic stall. Journal of the American Helicopter Society, 34(3), 3–17.
McNider, R. T., & Pielke Sr, R. (1981). Diurnal boundary-layer development over sloping terrain. Journal of Atmospheric Sciences, 38(10), 2198–2212. doi:10.1175/1520-0469(1981)038<2198:DBLDOS>2.0.CO;2
Mou, B., He, B.-J., Zhao, D.-X., & Chau, K. (2017). Numerical simulation of the effects of building dimensional variation on wind pressure distribution. Engineering Applications of Computational Fluid Mechanics, 11(1), 293–309. doi:10.1080/19942060.2017.1281845
Parish, T. R. (2000). Forcing of the summertime low-level jet along the California Coast. Journal of Applied Meteorology, 39(12), 2421–2433. doi:10.1175/1520-0450(2000)039<2421:FOTSLJ>2.0.CO;2
Pichugina, Y., Brewer, W. A., Banta, R. M., Choukulkar, A., Clack, C., Marquis, M., . . . Hardesty, R. M. (2017). Properties of the offshore low level jet and rotor layer wind shear as measured by scanning Doppler Lidar. Wind Energy, 20, 987–1002. doi:10.1002/we.2075
Porté-Agel, F., Wu, Y.-T., & Lu, H. (2012). Interaction between large wind farms and the atmospheric boundary layer. Procedia IUTAM, 10, 11101. doi:10.1016/j.piutam.2014.01.026
R D, & Ernest Raj, P. (2015). Features of nocturnal low level jet (NLLJ) observed over a tropical Indian station using high resolution Doppler wind lidar. Journal of Atmospheric and Solar-Terrestrial Physics, 123(2015), 113–123. doi:10.1016/j.jastp.2015.01.001
Ramezanizadeh, M., Alhuyi Nazari, M., Ahmadi, M. H., & Chau, K. (2019). Experimental and numerical analysis of a nanofluidic thermosyphon heat exchanger. *Engineering Applications of Computational Fluid Mechanics, 13*(1), 40–47. doi:10.1080/19942060.2018.1518272

Shu, Z. R., Li, Q. S., He, Y. C., & Chan, P. W. (2018). Investigation of low-level jet characteristics based on wind profiler observations. *Journal of Wind Engineering and Industrial Aerodynamics, 174*, 369–381. doi:10.1016/j.jweia.2018.01.035

Skamarock, C., Klemp, W., Dudhia, J., O, J., Gill, D., Barker, D., ... Powers, J. G. (2005). A Description of the Advanced Research WRF Version 2. Tech. Note TN-475 + STR (Vol. NCAR/TN-46). doi:10.5065/D68S4MVH.

Song, J., Liao, K., Coulter, R. L., & Lesht, B. M. (2005). Climatology of the low-level jet at the Southern Great Plains atmospheric boundary layer experiments site. *Journal of Applied Meteorology, 44*(10), 1593–1606. doi:10.1175/JAM2294.1

Storm, B., Dudhia, J., Basu, S., Swift, A., & Giammanco, I. (2009). Evaluation of the weather research and forecasting model on forecasting low-level jets: Implications for wind energy. *Wind Energy, 12*(1), 81–90. doi:10.1002/we.288

Tiqian, L. (2007). *Fluid mechanics (3rd ed.).* Beijing: Mechanical Industry Press.

Van de Wiel, B., Moene, A. F., Steeneveld, G.-J., Baas, P., Bosveld, F. C., & Holtslag, B. (2010). A conceptual view on inertial oscillations and nocturnal low-level jets. *Journal of the Atmospheric Sciences, 67*(8), 2679–2689. doi:10.1175/2010JAS3289.1

Zheng, Z., Gao, Z., Li, D., Li, R., Li, Y., Hu, Q., & Hu, W. (2018). Interaction between the atmospheric boundary layer and a stand-alone wind turbine in Gansu—Part II: Numerical analysis. *Science China Physics, Mechanics & Astronomy, 61*(9), 94712. doi:10.1007/s11433-018-9214-1