

Toward Understanding Low Level Jet Climatology over West Texas and its Impact on Wind Energy

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Abstract. Low Level Jets (LLJs) are defined as regions of relatively strong winds in the lower part of the atmosphere. They typically occur between 100 and 1500 m above ground level (ABL) and can be found in every continent. In particular, LLJs are a common feature over the Great Plains in the United States. It has been reported that 75 % of LLJs in the Great Plains occur at night and with seasonal patterns. Our preliminary results have corroborated some of the LLJ known characteristics, but also shown the lack of a clear three-dimensional picture of how the phenomenon is displaced over West Texas (precise location, timing and lifespan). This paper is focused on the development of a detailed LLJ climatology and its weather correlates for West Texas. Using the 200-m tower data (Reese, Texas), profiler and Mesonet data, and WRF runs, a 4-dim model is introduced which summarizes the main features of the LLJ over the aforementioned region and shows its patterns along the year. Furthermore, we also demonstrate the importance of LLJs for wind energy production. It has been observed that during a LLJ event the level of turbulence intensities and TKE are significantly much lower than those during unstable conditions; as a result, cyclical aerodynamic loads on turbine blades are diminished. The major salient results from this study include: the vertical shears in LLJs are very large, causing higher static loads. Finally, the WRF model has accurately captured the beginning of the LLJ event; however, the local maximum wind speed at the LLJ “nose” has been under-predicted by approximately 15%, which highlights the difficulties WRF still faces in predicting this phenomenon.

1. Theory

A LLJ is a fast stream of air that occurs in the lower layers of the atmosphere. Unless other jets occurring in the upper layers of the troposphere, they are not permanent and their lifetime are usually associated with a diurnal cycle [1]. At first, this phenomenon attracted the attention of atmospheric researchers as a contributory cause for the strong episodes of night thunderstorms over the plains. Now they are also studied because of their influence over the wind energy production.



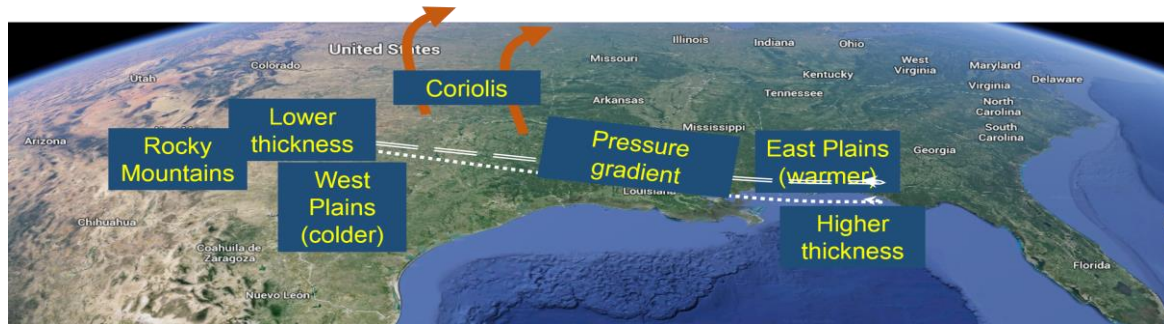


Figure 1. Mechanisms of production of LLJ on the US Great Plains (base map: Google Earth).

LLJs are often produced in the region of the Great Plains in the United States as shown in Figure 1. About 75 % of LLJs in the Great Plains occur at night and they develop more often during the summer season. The height of the maximum wind often coincides with the height of the top of the nocturnal inversion, and it is between 300 and 700 m above the ground level. Leaside cyclogenesis and leaside troughing on the eastern slopes of the Rocky Mountains are instrumental for the production of the low-pressure gradients required for the development of the LLJ. Another feature of LLJs in the Great Plains is the veering of winds at night across all the heights. The maximum veering occurs just before dawn, corresponding to the maximum low level stability. LLJs disappear during the day due to the convective mixing within the boundary layer [2]. There are several mechanisms that have been proposed to explain the formation and development of LLJs [1]:

The first mechanism is inertial oscillation, i.e., eddy viscosity variations through the day effect LLJs. During the daytime, the boundary layer is more coupled with the surface layer and friction makes wind subgeostrophic. Friction decreases at night when the turbulent mixing disappear, thus decoupling of the outer boundary layer from the surface layer occurs. The imbalance between the pressure gradient and the Coriolis forces induces an inertial oscillation of the wind with a period of $\frac{1}{2}$ pendulum day (meaning a wind speed maximum about 8 hours after the end of the turbulence mixing in mid latitudes).

The second explanation is shallow baroclinicity. In zones with significant variations in the landform, heat fluxes produce strong baroclinicity within the boundary layer. Strong geostrophic forces are thus created that generate LLJs parallel to the low-level horizontal temperature gradient. This component of LLJs is constant or variable throughout the day if the temperature gradient behaves constant or variable, respectively. Baroclinicity may also be produced by a sloping terrain: The Great Plains has the Rocky Mountains at West. During the day, the air surface is heated, thus at the same level, air is warmer in the West than in the East. During the night the situation reverse, the surface cools, thus at the same level, air is cooler in the West than in the East; that provokes a daily cycle and LLJs at night. The mountain range can also block a mass of cold air; this creates a gradient of temperature normal to the string of mountains. When the flow becomes geostrophically balanced, a LLJ develops parallel to the string of mountains.

The third influencing factor used to explain LLJ is terrain effects. Complex terrains may produce both slope and valley wind systems that may produce LLJs. Therefore, flow can accelerate due to horizontal pressure gradient and terrain blocking. Another probable cause for LLJs is the isallobaric forcing on which LLJs are influenced by upper-level jet streaks and synoptic scale forcing. And yet another occurrence cause of LLJs is attributed to the vertical parcel displacement, i.e., vertical displacement of air parcels within a baroclinic environment produces an increase in the ageostrophic wind component and then a LLJ event. The LLJs in the Great Plains of US are mainly characterized by the first two mechanisms.

In terms of wind energy and resources, LLJs may indeed have a direct impact over the wind turbines performance. As Figure 2 shows, the lower portion of LLJ (as low as 40m above ground level), is well within the current heights of wind turbines. Given the existing interest in increasing

further the size of wind turbines, particularly in Europe, the need to further understand the possible impact on LLJs is indeed critical. A major concern is the fact that the axial speed across the rotor changes drastically in the presence of LLJs, thus the aerodynamic loads on the blades will introduce an additional moment. Clearly, the energy from the wind is substantially increased because of the jet; this potentially can improve the Capacity Factor (CF) of the wind turbine farm, ie, the ratio of actual energy produced in a year compared to the maximum possible at rated power. Nevertheless, the negative side-effects must be assessed: LLJs can also increase the thrust forces over the structure and augment the fatigue cycles.

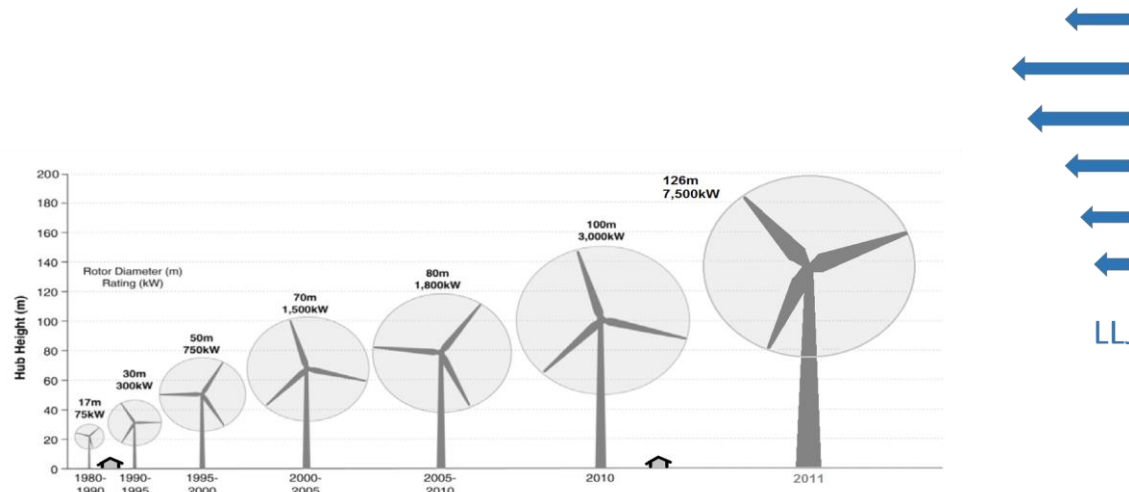


Figure 2. LLJ and height of wind turbines, (base picture from Wikimedia).

Therefore, the impact of LLJs on wind turbine farms cannot be ignored. Wind energy industry is growing at a fast pace and there are ambitious plans to increase the share of wind energy inside the US energy matrix up to 20% by 2030. The US installed capacity reached 60,000 MW in 2012, just behind China with 75,500 MW. The state of Texas led within the US, reaching one fifth of the total US installed capacity of 12,212 MW [3]. The goal of Texas is to increase in 5,000 MW the current installed capacity by 2015 [3]. Despite its success, wind energy has still a long way to go to challenge the prevalence of conventional fuels. As the demands on wind energy are increased, new knowledge is needed to perfect technology and increase performance, endurance and availability.

In this paper, we will determine the main features of LLJs based on observational data and numerical simulations with WRF. We will also introduce the impact of LLJs over wind turbine farms. Section 2 provides details of the observational data, section 3 shows the results obtained so far, and section 5 formulates conclusions.

2. Data sets

The experimental part for this research is obtained by analyzing the measurements data from the West Texas Mesonet 200 m Met tower located at Reese Center, Lubbock, Texas (<http://www.depts.ttu.edu/nwi/facilities/200-m-tower.php>) [14]. Input data come from sensors at 10 different levels, from 1m to 200m. The resolution of measurements is 50 Hz. Wind speed and direction is obtained with 3-dimensional sonic anemometers located at each level. When needed, data is confirmed and extrapolated with measurements from the Mesonet SODAR at the same location.

Wind vector is defined according to the meteorological data convention. The wind vector is originally decomposed in three orthogonal vectors (u , v , w). The horizontal wind, which is directed normal to the plane of the wind turbine blades is calculated as the vector sum: $U = \bar{u} + \bar{v}$, where \bar{u} is

the East zonal Wind component and \bar{v} is the Northern zonal wind. The raw data, with high frequency $f = 50$ Hz, are organized into spans of 10 minutes each one.

Observations from measurements have been compared with results obtained from Weather Research and Forecasting (WRF) modelling. We have used WRF 3.4.1 which has a bug-fixed YSU scheme (<http://www2.mmm.ucar.edu/wrf/users/wrfv3.4/updates-3.4.1.html>) [15]. The WRF has the potential of extrapolate conclusions from observational data to other places where measurement infrastructure is not viable. In terms of mesh configuration, we have employed a high vertical resolution within the rotor layer (~ 0 -100 m). Consequently, 5 points has been clustered below 100m, making a vertical resolution of approximately 20m. Furthermore, Nunalee & Basu [9] have performed a sensitivity analysis of the vertical resolution on numerical simulations (WRF) of coastal LLJ. The number of gridpoints below 3000m was doubled without obtaining significant differences in the wind speed from the baseline case. In addition, Bernier & Bélair [10] also found that increased vertical resolution to not significantly improve or degrade the quality of wind forecasts for wind energy applications. Therefore, in this investigation, we are using a similar near-surface vertical resolution as utilized by Nunalee & Basu [9] in their refined case (27m), which ensures the obtainment of reliable numerical results. Furthermore, the WRF model (and almost all other atmospheric models) uses some variations of the standard Monin-Obukhov similarity theory for the surface layer parameterization. Thus, no one really has a flexibility to just choose any physical parameterization. Having said that, each PBL scheme possesses its own compatible surface layer scheme (all using M-O similarity). Moreover, some surface layer schemes use artificial clipping (e.g., not allowing TKE to go below a certain threshold; not allowing the surface friction velocity to go below 0.1 m/s). Jimenez et al. [11] revised the YSU model's SL scheme and removed all the artificial clippings. In our opinion, it is the most realistic surface layer parameterization currently available in the WRF; hence, it has been used in present simulations. WRF parameters are shown on **Error! Reference source not found.**

Table 1. WRF parameters.

WRF version	3.4.1
Domains	6 km (outer), 3 km (inner).
Vertical levels	51, up to 15km (5 points below 100 m).
Planetary Boundary Layer scheme	YSU (bug-fixed)
Surface Layer	Revised MM5 scheme
Radiation scheme	RRTMG (for both shortwave and longwave)
Land Surface	NOAH
Microphysics	WSM 5 class
Cumulus	Kain-Fritsch (only activated for outer domain where $dx > 5$ km).

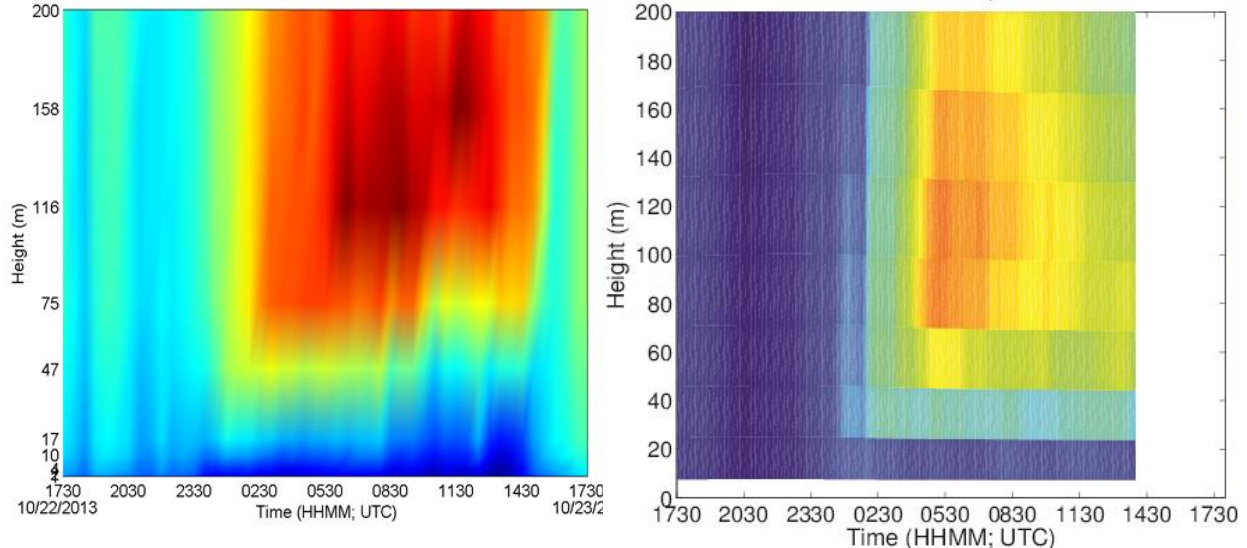
3. Results and discussion

3.1. Wind patterns from observational data and WRF.

Typical LLJs have been detected by examining the vertical profile of the horizontal wind to determine whether or not a rapid increase in wind speed appears and a peak is produced. Wind speed decreases below and above that peak, giving the vertical profile curve a typical nose-like shape.

From observational data, LLJs have been detected to develop recurrently during the nights as observed from the 200 m tower data. In Lubbock the LLJ duration is large enough and not as intermittent as coastal LLJ in [9]. Figure 3a shows a wind speed plot on which a LLJ was clearly detected on October 23, 2013 from 02:30 to 14:30 Universal Time Coordinates (UTC). In order to convert to local time (Lubbock, TX, US), one has to subtract 6 hours to the UTC time. In this case we used sonic anemometers measuring at 10 levels up to 200m. As can be seen, the phenomena can be noticed under the current height span of wind turbines, which currently reach around 200 m above the ground level. Figure 3b displays a simulation performed with WRF under similar conditions. The starting time of the LLJ was appropriately captured by WRF, but the numerical values were slightly

underestimated. For instance, the peak value of wind speed was 12 m/s for WRF instead of 14 m/s from experimental observations. The discrepancies might be attributed to the few vertical levels employed in simulations, and further analysis must be carried out.



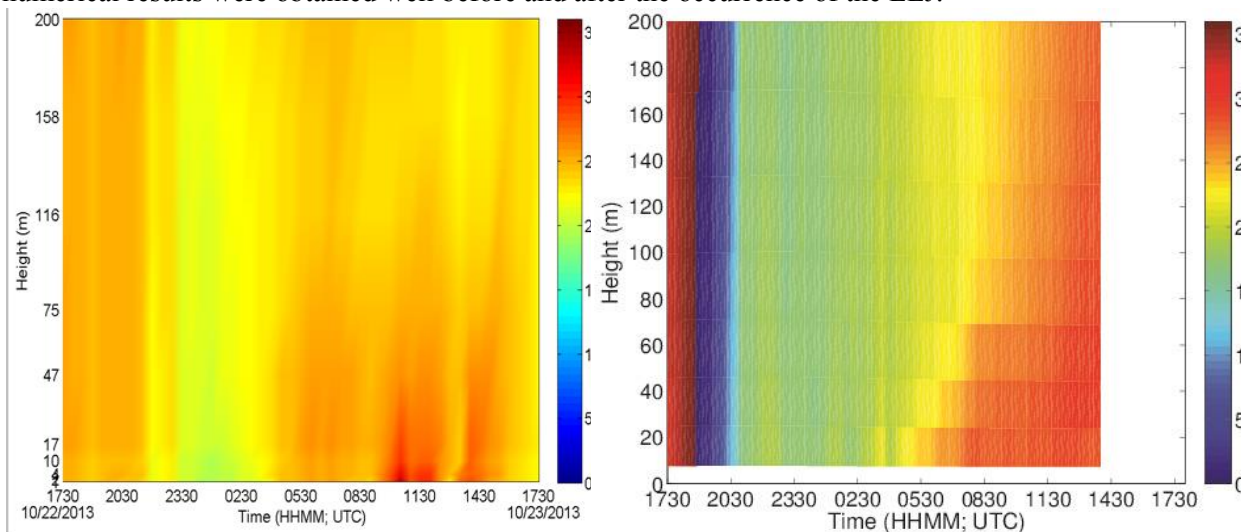
a) Observational data from 200 m MET tower.

b) Numerical predictions from WRF.

Figure 3. LLJ Wind velocity, October 23, 2013.

However, during the day (no LLJ) strong convective mixing prevents stratification from being produced, thus results in a smooth wind profile with the increase in height. By contrast, during the night, the absence of convective mixing leads to a diminishing in interactions between layers, thus a strong stratification is provoked. Wind begins to accelerate near sunset, peaks around midnight and decelerate near dawn. This particular LLJ event could be noticed at heights as low as 47 m, well within the range of current wind turbines height.

Wind direction on the same day can be observed on Figure 4a. The core of the LLJ is shown encircled. Southwestern winds are predominant during the daytime, but they veer at nighttime across all the height range to become a southern wind. WRF (Figure 4b) appropriately predicted the wind direction in the LLJ core. On the contrary, significant discrepancies between observations and numerical results were obtained well before and after the occurrence of the LLJ.



a) Observational data from 200 m MET tower

b) Numerical predictions from WRF

Figure 4. Wind direction in degrees, October 23, 2013.

3.2. Vertical profile of wind speed.

In this and the following sections, we are comparing results obtained for three different situations: a diurnal unstable condition, a nocturnal stable condition with production of LLJ, and a nocturnal stable conditions without LLJ.

Figure 5 displays samples of the vertical profile of the wind speed. In figure 5a, three different LLJ events are shown on which a peak of speed were observed at heights below 200 m above the ground level. In figure 5b, a comparison is held among three different conditions: diurnal unstable, nocturnal stable with production of LLJ, and nocturnal stable without LLJ. Curve fitting is shown for each case, according to the power law expression: $U = kz^\alpha$, and the fitting error is obtained as $\frac{HWS_{obs} - HWS_{num}}{HWS_{obs}} \times 100\%$.

As can be seen, stable conditions are well fitted by the power law with low shear coefficient α . The shear coefficient obtained is even lower for diurnal unstable conditions, well below the value of 1/7 often used in wind energy projects. On the other hand, the fitting for LLJ is very poor.

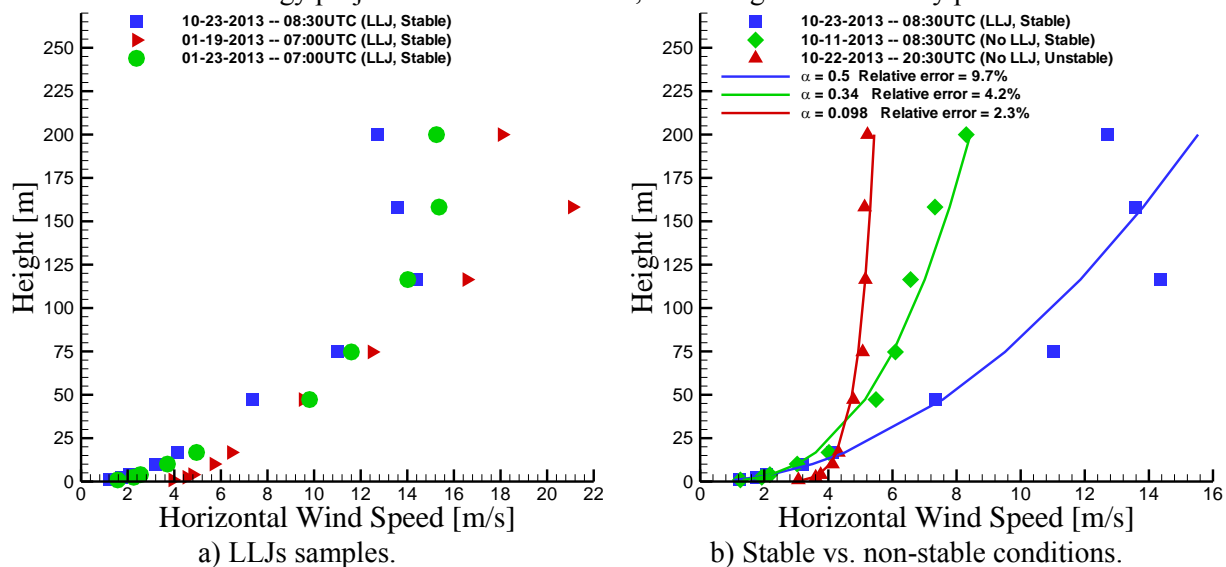


Figure 5. Wind velocity profiles at different conditions.

We can also see the rate of change of wind speed with height on **Figure 6**. Shear is more abrupt with stable conditions, attributed to the decoupling of atmospheric layers. The inflexion point on the LLJ curve correspond to a peak of wind velocity (nose).

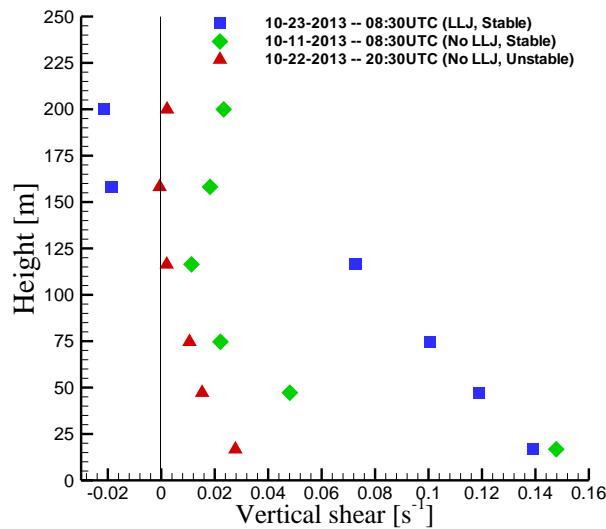


Figure 6. Vertical shear for three different conditions.

3.3. Stability.

A characterization of the boundary layer conditions is obtained by analyzing two parameters: potential temperature (θ) and Bulk Richardson number, Ri_b . Potential temperature (**Error! Reference source not found.**) provides an independent measure of real gradient and thus is more effective than the actual temperature. In the unstable condition, the gradient of potential temperature favors convection, buoyancy is produced and homogenization takes place among the atmospheric boundary layer. The opposite occurs with both stable cases on which there is an inversion of temperature, layers become independent and equilibrium is restored with Coriolis forces. LLJ differentiates from the other stable case with a more accentuated gradient of temperature and a different profile convexity.

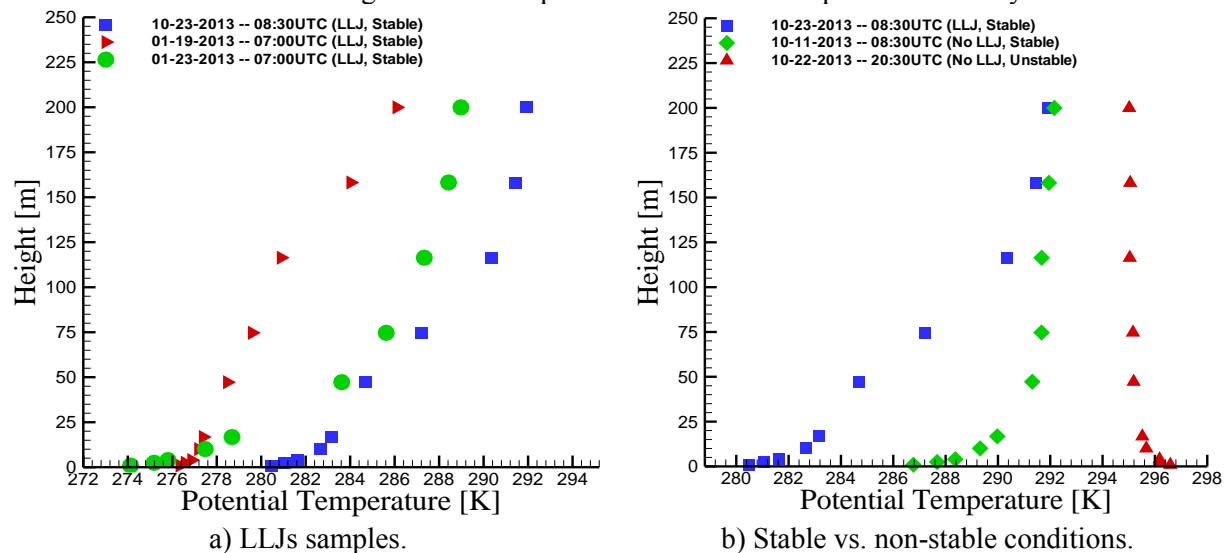


Figure 7. Vertical variation of potential temperature.

The dimensionless Bulk Richardson number, shown on **Figure 8**, is calculated as $Ri = \frac{g\Delta\theta_v/\theta_v}{(\Delta U)^2 + (\Delta V)^2} \cdot \Delta z$.

It represents the ratio of thermally produced turbulence to turbulence generated by vertical shear. The higher its absolute value, the more important free convection is compared with forced convection. As can be expected Ri_b is negative for the stable conditions. The LLJ shows very little buoyancy below the nose. Above the nose, a concavity in the curve indicates a slight increase in the buoyancy.

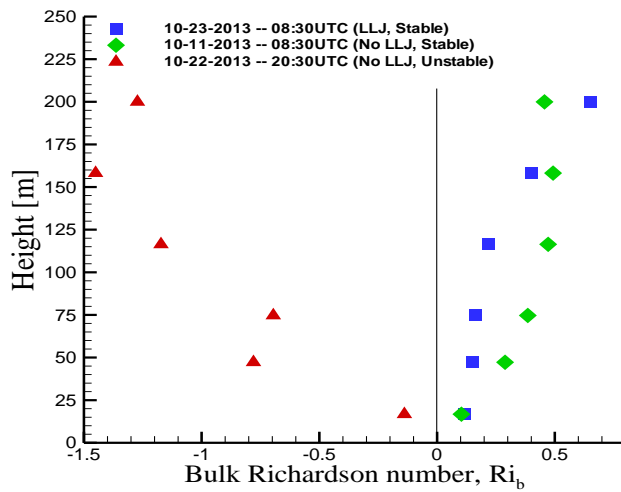


Figure 8. Vertical variation of Bulk Richardson number.

3.4. Analysis of turbulence.

Figure 9 depicts the horizontal and vertical variances for the same cases previously analysed. The level of turbulence fluctuations is several orders of magnitude larger for the unstable condition, with approximately similar values of horizontal and vertical variances in the zone 75-200m. By contrast, the LLJ is a long, quasi-laminar structure.

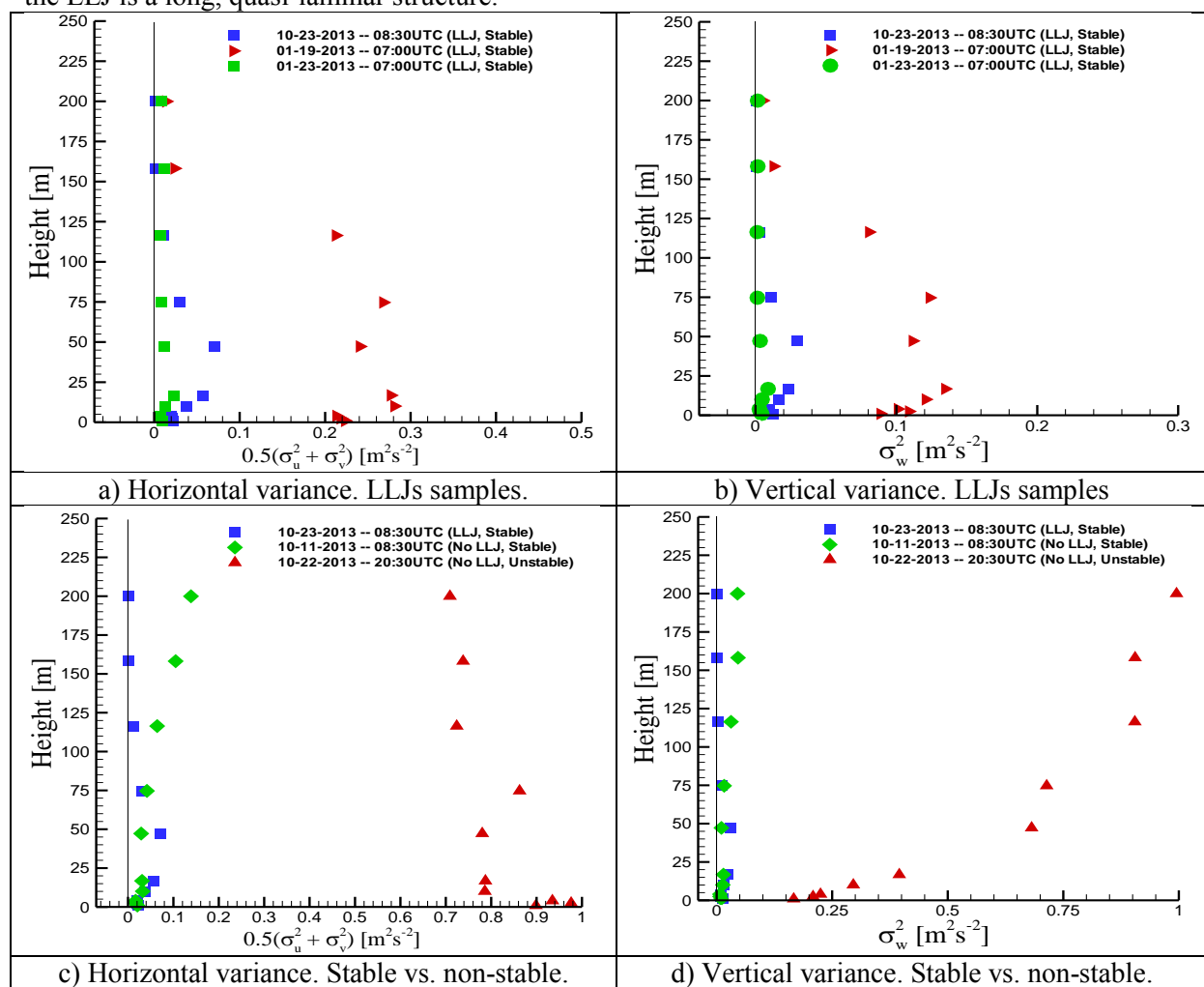


Figure 9. Vertical variation of wind speed variances.

Same conclusions can be obtained by examining the variation of turbulent kinetic energy, $TKE = \frac{1}{2}(\sigma_u^2 + \sigma_v^2 + \sigma_w^2)$, along the vertical axis. As can be seen on Figure 10, TKE is substantially lower under the presence of a LLJ event, attributed to a sustained wind current that keeps fluctuations to lower values, forcing a more organized flow.

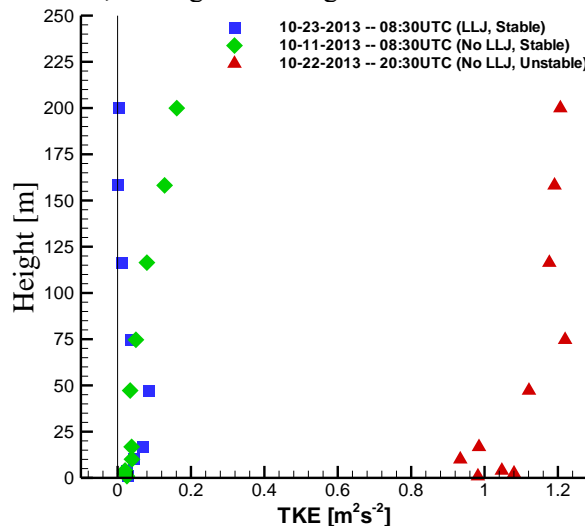


Figure 10. Vertical variation of the turbulent kinetic energy (TKE).

4. Conclusions

The phenomenon of LLJ has an important impact at the heights of current wind turbines. They have both beneficial and detrimental effects for the production of wind energy and the stability of wind turbine structures. The potential for power output is significantly augmented, proportionally to the cube of the mean wind speed. Nevertheless, several contradictory issues must be taken into account.

Turbulent kinetic energy (TKE) and turbulent intensity are significantly lower during the occurrence of the LLJ. The low values of TKE may influence the cyclic loads over the wind turbine, however future numerical simulations by means of FAST would confirm it.

In future works, we will ascertain the hypothesis of a possible relation between LLJs and the quasi-laminarization of the flow, which could have an effect over the recovery of the wind in the wake after the wind turbine. Flow quasi-laminarization may occur when the flow experiences a very strong acceleration. Therefore, turbulent production and Reynolds stresses significantly decrease; however, the flow doesn't become completely laminar because it contains a residual value of velocity fluctuations, particularly, of the horizontal component. Furthermore, according to Narashimha and Sreenivasan [13], this phenomenon can also be observed at high Reynolds numbers and even under neutral conditions (i.e., $Ri = 0$) mainly attributed to the presence of a very strong favorable pressure gradient.

Acknowledgements

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