

# *Estimation of turbulence production by nocturnal low-level jets in Sao Paulo (Brazil)*

Cassia M. L. Beu<sup>\*a</sup>, Márcia T. A. Marques<sup>a</sup>, Walter M. Nakaema<sup>a</sup>, Yoshiaki Sakagami<sup>b</sup>, Pedro A. A. Santos<sup>b</sup>, A. C. de C. A. Moreira<sup>c</sup>, Eduardo Landulfo<sup>a</sup>

<sup>a</sup>Nuclear and Energy Research Institute, 2242 Lineu Prestes Av., Sao Paulo, SP, Brazil 05508-000

<sup>b</sup>Federal Institute of Santa Catarina, 9876 Light Ave., Florianopolis, SC Brazil 00555-9642

<sup>c</sup>PETROBRAS/CENPES/PDEDS, 950 Horacio Macedo Av., Rio de Janeiro, RJ, Brazil 21941-915

## ABSTRACT

Two Doppler lidars were recently used to collect data from the planetary boundary layer (PBL) in Sao Paulo city (23°32'S, 46 °38'W). The measurement campaign was carried out from December-2015 to February-2016, during the summer, which is the rainy season. Although Sao Paulo is the main city of a huge metropolitan region with more than 11 million of inhabitants and 7 millions of vehicles, according to the government agencies, the lack of PBL observational data is still a limitation for the atmospheric dispersion studies. Therefore, this work should contribute to the comprehension of PBL mechanisms and also for future atmospheric modeling studies. The data revealed that the nocturnal low-level jets (LLJs) frequently occurred along those 3 months, but its height is highly variable, from 100 m up to 650 m. It was also seen that the nocturnal LLJs can extend for several hours, right before the sunset until sunrise. This work aims to investigate the turbulence production by the nocturnal LLJs and its influence into the stable boundary layer (SBL).

**Keywords:** Doppler lidar, planetary boundary layer, low-level jets, turbulence

## 1. INTRODUCTION

The PBL is the lowest part of the atmosphere that is directly influenced by the Earth's surface [1] and understanding its processes are essential for dispersion modeling, air quality studies, wind energy, among others [2]. The PBL is highly variable because its behavior depends on many factors, as insolation, surface roughness, occupation, synoptic and mesoscale conditions. Due to the spatial and temporal scales (millimeters to kilometers and seconds to hours), PBL can be poorly represented by models, what can generate unreliable results. During daytime, solar radiation favors the development of the PBL, that is characterized for a well-developed layer, known as Convective Boundary Layer (CBL). As the solar radiation decreases, a Stable Boundary Layer (SBL) takes place. As a residual layer remains, the SBL acquires a multilayer structure, which is more complex than the CBL. The LLJs is a phenomenon that usually occurs during the nighttime as a result of radiative cooling and modifies the vertical fluxes into the PBL. LLJs formation mechanisms references are highlighted for [2] and [3]. The LLJs can be characterized by its pronounced maximum, also called LLJ nose. Although the typical SBL presents stable stratification, turbulence can remain under the LLJ due to strong shear [4]. That is called for some researchers as "upside-down boundary layer", that in summary means the turbulence is generated at levels above the surface (by the nocturnal LLJs) and is transported downward. In the absence of thermal turbulence, this mechanism can play an important role in controlling fluxes between the surface and the atmosphere. It has a direct impact in the air quality, both to the emission and to dispersion areas.

The Sao Paulo metropolitan region (SPMR) contains more than 11 million of inhabitants and 7 million of vehicles, according to the government agencies. This fleet is an important source of pollutant emissions into the atmosphere. Many efforts have been made to characterize the emitted species and to model the pollutant dispersion in SPMR [5, 6], but the lack of observational data and mainly PBL data is still a limitation for atmospheric dispersion studies.

\*cassia.beu@gmail.com; phone 55 11 3133-9252

During a 3-months campaign, wind vertical profiles were collected by 2 Doppler lidars. These datasets were the source for LLJs characteristics and turbulence production studies which are expected to contribute to comprehension of PBL mechanisms and future modeling studies.

## 2. METHODOLOGY

Doppler lidars has been successfully employed in wind profile measurements [7]. This technique has also been employed for some researchers for turbulence estimation [2, 3]. Detailed theory of the lidar technique and its advantages are described by [8] and [9]. Briefly, to measure wind speed, the lidar measures the Doppler shift of the light that was sent out to the atmosphere and is backscattered from particles in the atmosphere.

The turbulence was estimated only for cases that a LLJ was detected. The same criteria as [3] was applied to identify the LLJs.

## 3. DATA

Data were acquired by 2 Doppler lidars placed at the Center of Lasers and Applications (CLA) of the Nuclear and Energy Research Institute (IPEN) in the Sao Paulo University Campus.

Both lidars were manufactured by Leosphere, the first model, WLS70, were programed to retrieve information of 29 levels and vertical resolution of 50 m (from 100 to 1500 m) and the second model, Windcube V2 (hereafter V2), was set for 12 levels (40, 60, 80, 100, 125, 150, 175, 200, 225, 250, 270, 290 m) both lidars with a temporal resolution of 10 minutes. Data were collect continuously since December 15<sup>th</sup>-2015 until March 1<sup>st</sup>-2016, except for short energy interruptions. In this work, the turbulence kinetic energy (TKE) was estimated by the following equation:

$$TKE = 0.5 * (\sigma_u^2 + \sigma_v^2 + \sigma_w^2) \quad (1)$$

Where:

$\sigma$  is the standard deviation

$u$ ,  $v$  and  $w$  are the zonal, meridional and vertical wind components respectively,

Only data with availability greater than 80% were employed for LLJs and TKE statistics. Time is in UTC, which corresponds to local time plus 2, remembering that during summertime the daylight saving time is adopted in this Brazilian region. Taking data since 17 UTC until next day 10 UTC avoid to loss the generation and/or the dissipation of the LLJs. At Sao Paulo latitude, daytime lasts around 12 hours during summertime.

## 4. RESULTS

Comparing the vertical and horizontal TKE (not shown here), it was seen that vertical contribution represents only a small amount of the total TKE. For this reason, only total TKE will be showed hereafter. Firstly, all LLJs cases were considered (Figure 1). The mean for all LLJs events (called case 1) from the dataset revealed that total TKE is stronger at lower levels (among 100 and 200 m) and gradually decreases for the levels above until it vanishes, mainly above 400 m. Another interesting feature is that TKE strengthens just after sunset and weakens around 2 UTC (next day). Another relatively stronger TKE “event” occurs between 7 and 10 UTC. Analysis of individual LLJ showed that after sunset LLJ becomes stronger and higher and some hours before sunrise, the LLJ becomes lower. It is possible that as the LLJ becomes higher, the TKE weakens over the surface and as the moves downward, the TKE strengthen again.

Since previous analysis showed that LLJs are highly variable (not shown here), both in intensity as in height, it is important to investigate how the TKE behaves for LLJs different conditions and how it influences the surface. So some LLJs different conditions were selected to evaluate the TKE production. The second case (case 2) considers LLJs that maximum wind speed exceeded 7 m/s (Figure 2). This threshold was chosen because it represents approximately 60% of LLJs for this dataset. For LLJs stronger than 7 m/s, total TKE also is stronger if it is compared with all events (Figure 1). Again, the TKE decreases above 200 m level, but vanishes above 1000 m. It is worth to note that TKE seems to increase

earlier (since 17 UTC) lasting until approximately 5 UTC (next day). Although LLJ usually forms during nighttime, it was already detected during daytime over SPMR [5]. Differently from the previous case, the total TKE practically vanishes after 6 UTC.

The third case (case 3) considers LLJs events that the maximum wind speed is below 7 m/s (Figure 3) and it has more similar features to the first case. The total TKE completely vanishes above 400 m and is slightly weaker in the first 200 m. On the other side, stronger TKE is seen between 200 and 300 m and 19 and 22 UTC. In Figure 1, TKE is also observed between 7 and 10 UTC. Previous analysis for the same dataset showed that stronger LLJs tend to be higher and weaker tend to be lower (not shown here). Similar results were obtained by [3]. This tendency (weaker LLJs are lower) can explain the TKE that arises before the sunrise for case 3.

Both cases (LLJ maximum wind speed greater than 7 m/s or lesser than 7 m/s), indicate that there is TKE production below the LLJ, although, TKE is stronger for maximum wind speed greater than 7 m/s. TKE still is observed for LLJs cases which maximum wind speed is under 5 m/s (Figure 4). TKE has the same features than case 1 and 3, but is weaker. It seems that TKE intensity is related to the LLJ intensity. For this dataset, LLJs over SPMR are not as strong as have been recorded in others studies [2, 3]. Results showed that LLJs frequency with maximum wind speed between 10 and 16 m/s (that was the strongest wind speed recorded), is around 25% only. Figure 5 shows that for this condition (maximum wind speed greater than 10 m/s), there is no TKE production at the lowest level, although TKE between 150 and 350 m is relatively strong and just vanishes above 950 m.

TKE production starts early (before sunset) and lasts until 2-3 UTC, but almost completely vanishes after that. It is interesting to investigate what is the LLJ maximum wind speed that maintains TKE production at the lowest level. Figure 6 presents a selection the LLJs events which have maximum speed greater than 9 m/s and TKE production is again observed at the lowest level. It seems then, that TKE production at the lowest level decreases for maximum wind speed higher 10 m/s.

As maximum speed, the height is another parameter usually evaluated in LLJs studies. Since previously the LLJs were observed for variable height from 100 m to 800 m, it was intended to investigate how TKE from LLJs of different levels interacts with surface. Here, 3 levels are considered: LLJs under 300 m, LLJs between 300 and 600 m and LLJs between 600 and 800 m. For the lower LLJs category of this temporal series, LLJs height lesser than 300 m (Figure 7) is weaker, if compared to case 1 (Figure 1), gradually decreases levels above and also completely vanishes above 400 m. TKE production is considerable stronger for LLJs height between 300 and 600 m (Figure 8). It is observed right before sunset and lasts, at least, for the next 8 hours, but weakens after 2 UTC and remains very weak until sunrise. For LLJ which occurred between 600 and 800 m, a different behavior was observed (Figure 9). Although TKE production is stronger at the lowest levels, there are gaps in the levels above (mainly between 250 and 300 m) and here 1 interesting question come to the light: why these gaps occur? This question will be investigated latter.

The results above indicate that TKE production seems to be more important for stronger (but weaker than 10 m/s for the lower level) and higher LLJs. For this reason, the combination height (between 600 and 800 m) and maximum speed (<10 m/s) was reproduced. For this condition (Figure 10), it is seen that strong TKE production extend from the lowest level until 400 m, but a gap remains among 250 and 300 m, as case 9. LLJ maximum wind speed seems to be important for TKE production. Tests with weaker wind speed showed that TKE also decreases for the same height range (Figures not shown here). For LLJ maximum wind speed weaker than 10 m/s and height ranging of 300 to 600 m, the TKE production is continuous since the lowest level until 400 m, approximately and decreases with the height (Figure 11). Case 11 (Figure 11) is significantly different of case 10 (Figure 10), both in intensity as in vertical distribution. It means that LLJ height influences TKE production within the layer below it. For LLJ height ranging from 300 to 800 m and maximum wind speed between 7 and 10 m/s (figure not shown), the TKE is slightly stronger and last for longer time if compared to case 11.

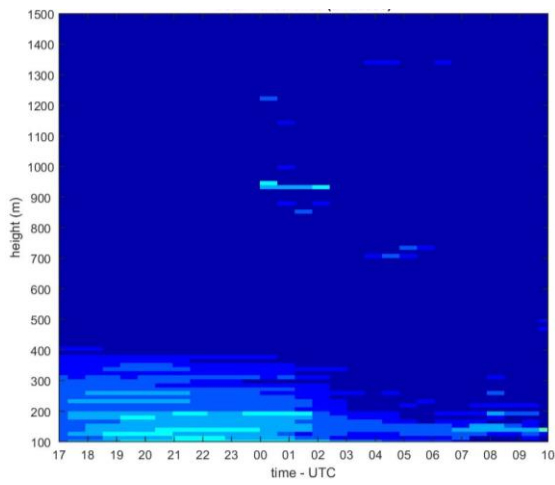


Figure 1. Mean total TKE ( $\text{m}^2/\text{s}^2$ ) for all LLJ events (case 1)

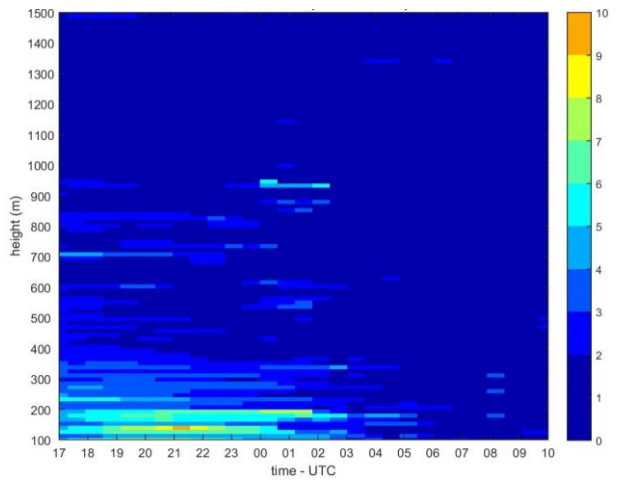


Figure 2. Mean total TKE ( $\text{m}^2/\text{s}^2$ ) for LLJ events that the maximum wind speed exceeds 7 m/s (case 2)

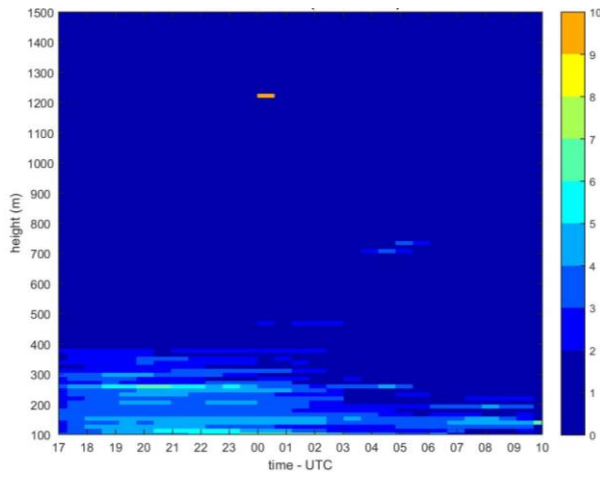


Figure 3. Mean total TKE ( $\text{m}^2/\text{s}^2$ ) for LLJ events that the maximum wind speed is below 7 m/s (case 3)

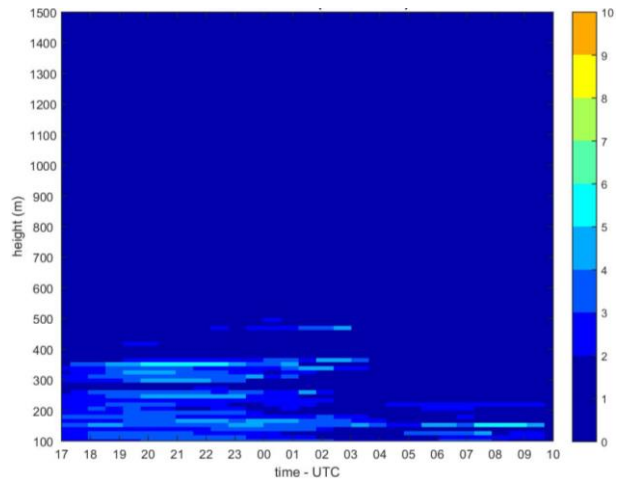


Figure 4. Mean total TKE ( $\text{m}^2/\text{s}^2$ ) for LLJ events that the maximum wind speed is below 5 m/s (case 4)

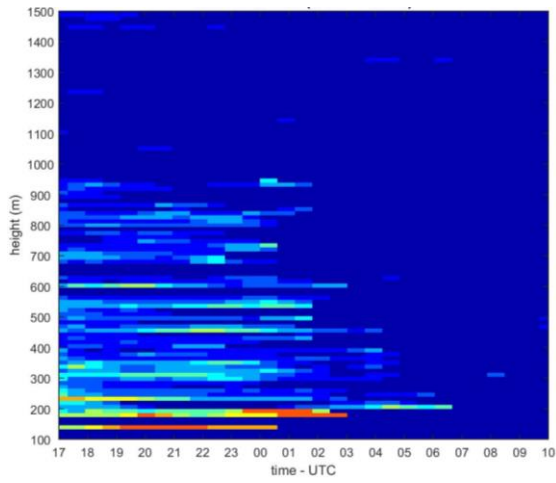


Figure 5. Mean total TKE ( $\text{m}^2/\text{s}^2$ ) for LLJ events that the maximum wind speed exceeds 10 m/s (case 5)

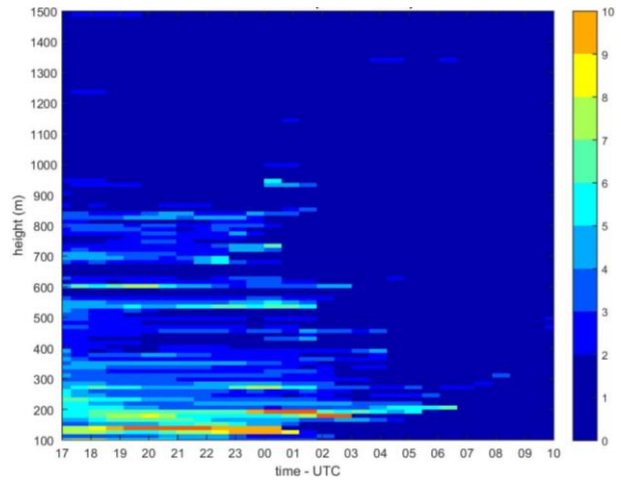


Figure 6. Mean total TKE ( $\text{m}^2/\text{s}^2$ ) for LLJ events that the maximum wind speed exceeds 9 m/s (case 6)

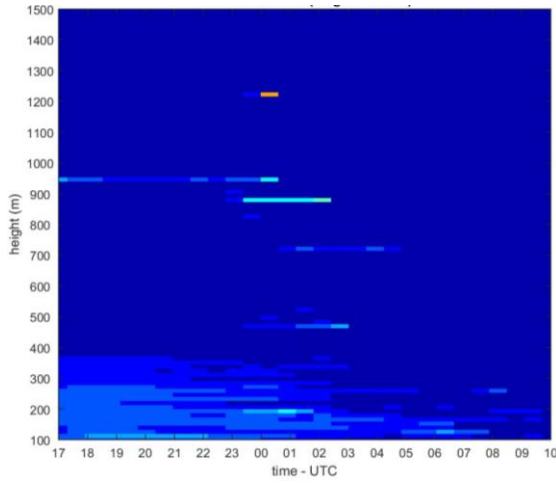


Figure 7. Mean total TKE ( $\text{m}^2/\text{s}^2$ ) for LLJ events lower than 300 m (case 7)

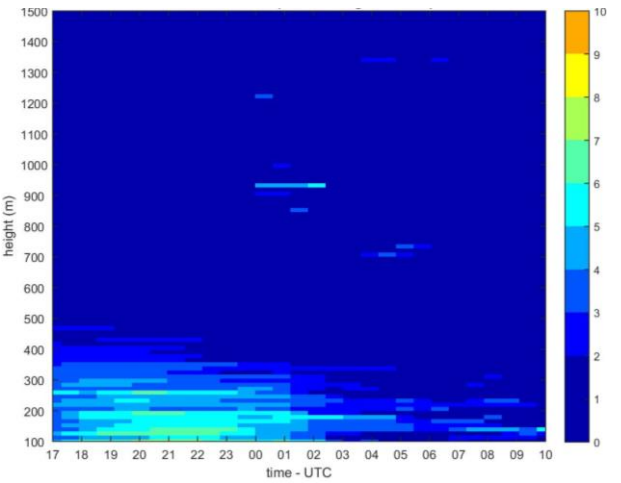


Figure 8. Mean total TKE ( $\text{m}^2/\text{s}^2$ ) for LLJ events between 300 and 600 m (case 8)

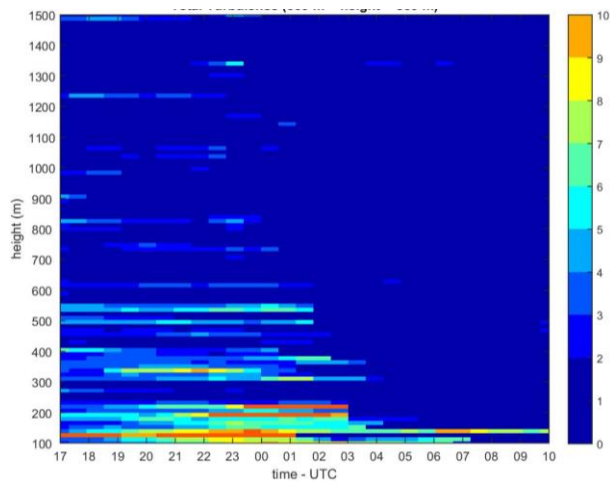


Figure 9. Mean total TKE ( $\text{m}^2/\text{s}^2$ ) for LLJ events between 600 and 800 m (case 9)

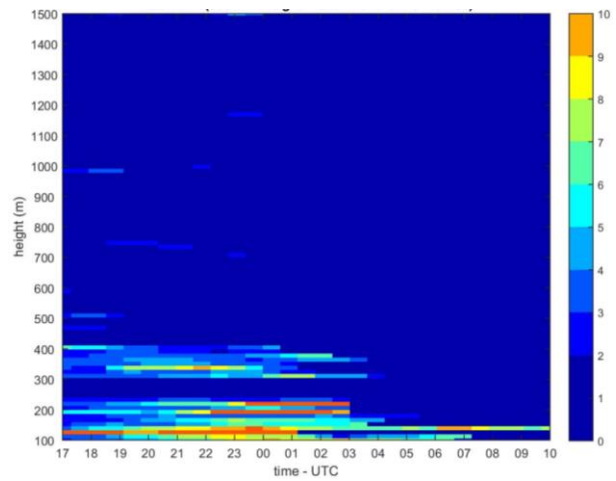


Figure 10. Mean total TKE ( $\text{m}^2/\text{s}^2$ ) for LLJ events between 600 and 800 m and maximum wind speed below 10 m/s (case 10)

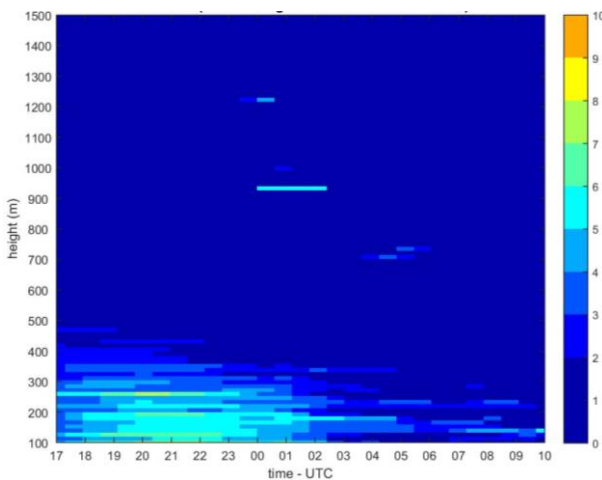


Figure 11. Mean total TKE ( $\text{m}^2/\text{s}^2$ ) for LLJ events between 300 and 600 m and maximum wind speed weaker than 10 m/s (case 11)

In according to [2], the variance of the vertical velocity can be considered an important characteristic for the intensity of vertical mixing in the SBL. For the purpose to evaluate lower levels, the variance of the vertical wind from lidar V2 data were plotted. The vertical resolution is about 20 m (more than twice the lidar WLS70). Two different events were chosen: the first is a LLJ of January 31<sup>st</sup> (Figure 12a) and corresponds to case 10 (Figure 10), that means high ( $600 \text{ m} < \text{LLJ height} < 800 \text{ m}$ ) and relatively strong (LLJ maximum speed  $< 10 \text{ m/s}$ ) LLJ. The second event is a LLJ of February 4<sup>th</sup> (Figure 13a) that corresponds to case 5. Although Figure 5 shows strong TKE, another important characteristic is the gap within the lowest level. TKE was also estimated for each event (Figures 12b and 13b). The comparison of Figures 12a and 13a shows strong contrasts between the 2 events. Variance is much stronger and lasting in Figure 12a than for February 4<sup>th</sup> event (Figure 13a). Figure 12b shows intermittent TKE for the whole period. On the contrary, the TKE almost completely vanishes after 22 UTC for the second event (Figure 13b).

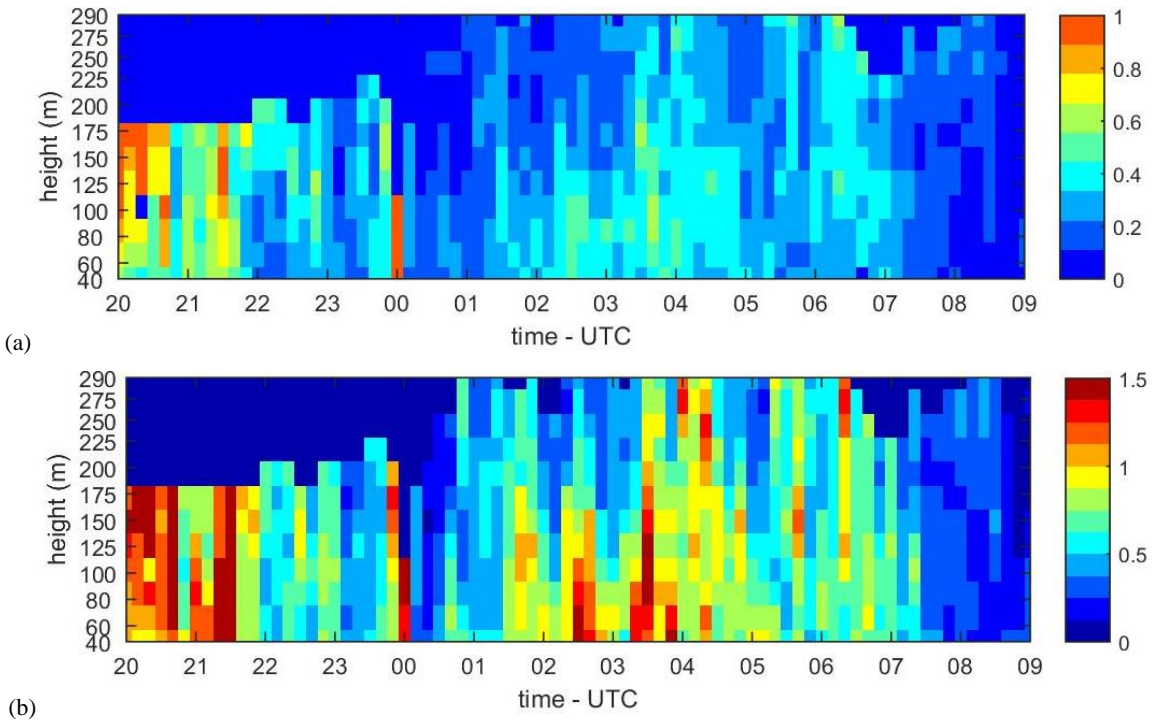


Figure 12. (a) vertical wind variance ( $\text{m}^2/\text{s}^2$ ) and (b) TKE ( $\text{m}^2/\text{s}^2$ ) for January 31<sup>st</sup>

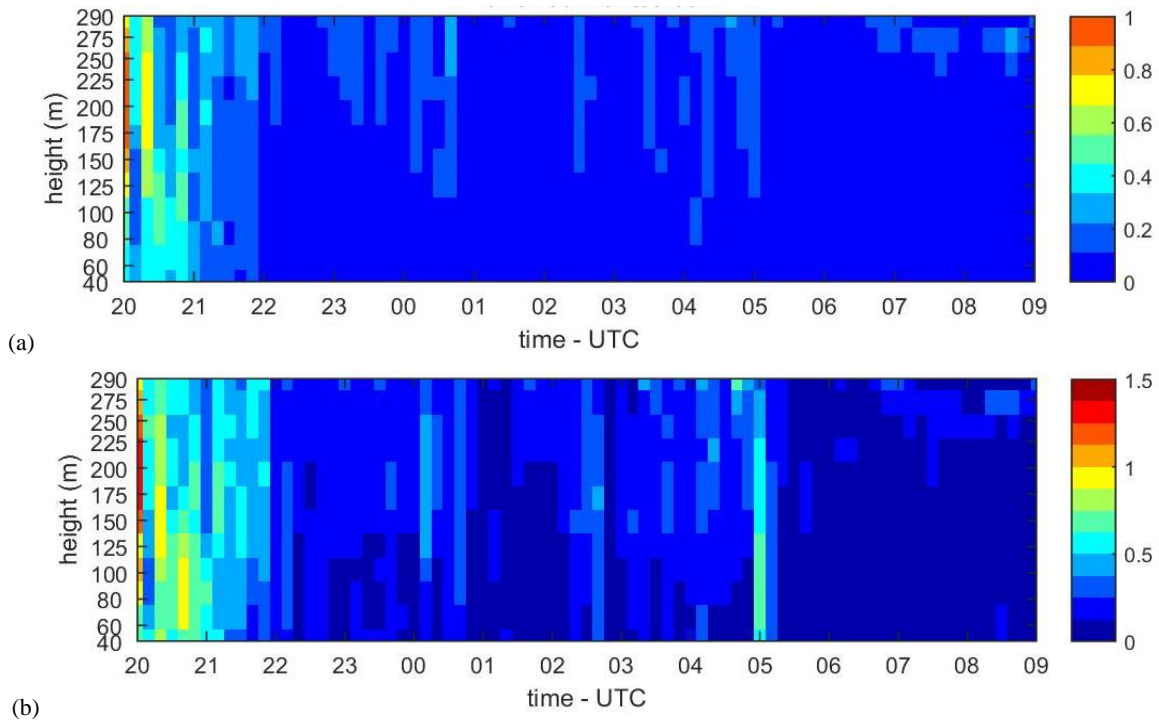


Figure 13. (a) vertical wind variance ( $\text{m}^2/\text{s}^2$ ) and (b) TKE ( $\text{m}^2/\text{s}^2$ ) for February 4<sup>th</sup>

## 5. CONCLUSIONS

Only few studies have been investigating the PBL over the SPMR and lack of observational data still is a challenge for pollution dispersion researchers. In this sense, the lidar technique can improve the atmospheric dispersion studies, since it provides high spatial (vertical profile) and temporal resolution, both conditions that are essential for PBL researches. The LLJs usually occurs within the SBL, which is more complex than the CBL, and probably many of its features are poorly represented by the models. LLJs produce mechanical turbulence and can generate vertical fluxes, even after the thermal turbulence vanishes.

For the 2015-2016 summer season, high LLJs frequency was detected over SPMR. Tests have shown that both intensity (LLJ maximum wind speed) as height of the LLJs produce different effects on TKE. Weaker LLJs produce less TKE than stronger LLJs. Results have shown that TKE production is also relates to the LLJ height and TKE is weaker for the lower LLJs. As stronger LLJs tend to be higher, it was seen that greater TKE is produced by the highest and strongest LLJ. One important feature is that for LLJ maximum wind speed greater than 10 m/s, less TKE is detected in the lowest level. Two cases evaluated individually showed that LLJ intensity and height can affect the vertical mixing and TKE distribution, although, others important conditions, as synoptic and mesoscale have not been evaluated.

This is just the initial work for this dataset and much still will be done. Future works includes extraction of others PBL parameters, as its height, for example. After these parameters were extracted, the next step is to test them with atmospheric dispersion models.

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