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Low-Level Jet observational study for the Brazilian Nuclear Reactor region

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ABSTRACT

A doppler wind lidar was employed to investigate the features of the Low-Level Jet (LLJ) at Ipero, Sao Paulo State, Brazil. The Ipero Municipality already host a nuclear facility for uranium enrichment and a new plant, a nuclear reactor, is planned to be built there. The nuclear activities require a good understanding of atmospheric dispersion, as for normal operation conditions as for accidental emissions. The LLJ is a natural phenomenon that may occur within the Planetary Boundary Layer and plays an important role for the atmospheric dispersion. Knowing the LLJ characteristics is essential to evaluate the performances of the weather forecast models that are used as input for the atmospheric dispersion models. The field campaign results showed that the LLJs occur with high frequency at Ipero and that the Stable Boundary Layer (SBL) is shallow, which in turn is unfavored for pollutant dilution because all surface emissions remain confined within the SBL. The 2 weather forecast models evaluated didn´t reproduce the LLJ, despite their high horizontal resolution. The numerical models also underestimated the wind speed. Both the LLJ and the wind speed are key parameters for dispersion simulations. As the weather forecast models diverge of the observational data, they must be better parameterized for provide reliable simulations before being adopted as input for any atmospheric dispersion models. The field campaign (planned to extend for 1 year) data are essential for the parameterization of the numerical models.

Keywords: Low-Level Jet, Planetary Boundary Layer, Stable Boundary Layer, atmospheric dispersion

1. INTRODUCTION

For simplicity, the troposphere can be considered as a 2 layers system. The closest surface layer is called **P**lanetary **B**oundary **L**ayer (**PBL**). Above the PBL is the **f**ree **a**tmosphere (**FA**). These 2 layers present totally different characteristics. If compared to the FA, the PBL is a thin layer (thickness usually less than 2 km), where turbulence plays a fundamental role. On the contrary, FA is much thicker (10 km or more) and is dominated by the laminar processes.

The classical definition for PBL is: ***the part of troposphere that is directly influenced by the presence of the earth´s surface and responds to surface forcings with a timescale of about an hour or less***[1]. Although this definition is quite generic, it indicates that PBL characteristics are variable from a place to other, because depends on the surface´s coverage, and how it responds to the solar radiation and others forcings, as wind, for example. Furthermore, the temporal (1 hour or less) and spatial (few km) PBL typical scales add complexity to its dynamics. Even today, with high computational resources available, still is not viable to simulate atmospheric models in such resolution in an operational way. On the other hand, applying lower resolution to numerical models may cause the loss of important features of PBL to atmospheric dispersion simulations, for example. One way to try to solve this problem, is to parameterize the PBL features that the numerical models are not able to simulate on an operational routine. The experimental and field campaigns play a key role for a successful parameterization because the results can be compared against the observational data. As already said, the PBL strongly depends on solar radiation. That means that PBL has a diurnal cycle that changes quickly and involves many variables, as: season, terrain, latitude, cloudiness, aerosols and surface coverage, mainly. On a day without synoptic disturbances (that means, clear skies and high pressure) the PBL reaches the maximum height about midday (generally less than 2 km). The PBL height is a fundamental input for atmospheric dispersion simulations and its estimate should be trustworthy. During the period after the sunrise and before the sunset, the PBL is also called **C**onvective **M**ixed **L**ayer

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(**CML**) because the convective turbulence promotes the mixture of the atmospheric properties (temperature, humidity and other compounds, as pollutants for example) within this layer. It means that the turbulence has an important role in dilute gases that are harmful, minimizing the pollutant impacts to life. However, the convective turbulence totally decays with the sunset and the CML collapses. A layer called **S**table **B**oundary **L**ayer (**SBL**) forms and lasts until the next sunrise. The SBL is much thinner than the CML, concentrates all emissions from surface and the only turbulence source is mechanical. Mechanical turbulence can be generated by surface roughness and by the **L**ow **L**evel **J**et (**LLJ**). The turbulence generation by surface roughness is generally low, anyway, most of the time, it is associated to fixed obstacles/features and can be easily parameterized. On the other side, the LLJ is a dynamical feature that also has an own cycle and can impact the atmospheric dispersion, but its numerical modeling is not easy and requires observational studies before.

A jet generic definition is: a narrow current of fast-moving air. Jets can exist at different heights in the troposphere. Here, only jets within the PBL will be treated. Those jets are usually referred as LLJ or **N**octurnal **J**ets (**NJ**) because are mostly observed between sunset and sunrise. Some authors are also adopting the term **B**oundary **L**ayer **J**ets (BLJ), as reported by Davis[2] which also defined the LLJ as: vertical profile wind maximum which exhibits strong diurnal oscillation in height, speed and direction.

Beyond the mechanical turbulence associated, the LLJ plays other key roles for the atmospheric dispersion: (i) basically separates the SBL of the above layer and traps the surface emissions under it and (ii) can transport atmospheric gases and particles (urban and industrial emissions, volcanic ash, fire smoke, chemical and nuclear accidental plume) to longer distances. These aspects are extremely important for the atmospheric monitoring activities, especially after accidental events. The LLJ formation mechanisms are [3]: (a) inertial oscillation; (b) shallow baroclinicity; (c) terrain effects; (d) isallobaric forcing; and (e) vertical parcel displacement.

This work is the first phase of a PhD thesis which subject is to develop an atmospheric dispersion study for a new nuclear reactor planned to be built in Brazil. The new reactor is known as **R**eator **M**ultiproposito **B**rasileiro (**RMB**). The RMB main purposes are: (1) the production of radioisotopes and radiopharmaceuticals to supply the national demands (nowadays Brazil imports all the molibdenio-99, the most consumed radioisotope in nuclear medicine); (2) nuclear fuel irradiation and laboratory tests to evaluate the nuclear fuel structural integrity; (3) the development of scientific and technological researches with neutron beams. The nuclear activities in Brazil are low and the RMB represents an important advance in this area, with social benefits for the Brazilians citizens, once will improve the access to the nuclear medicine. The RMB will be built at Ipero municipality (23º21’S;47º41’W), Sao Paulo state, Brazil. The Ipero municipality already host a nuclear facility of the Brazil´s Navy where are developed technological researches and uranium enrichment. This facility motivated the development of the Ipero Project[4], that resulted in many thesis, dissertations and publications. The main objective of the Ipero Project was to determine the spatial and temporal evolution of the Planetary Boundary Layer (PBL) and its impact in the pollutant dispersion. It was during the field campaigns that the LLJ was observed for the first time at Ipero. The LLJ was observed at 71% of the nights during the 4 field campaigns between 1991 and 1993[5] (1 winter and 3 summer campaigns, totalizing 48 days), but the tethered balloon probing was limited for the environmental conditions and the LLJs frequency can be higher. The investigations revealed that 4 elements act for the LLJ formation at Ipero: inertial oscillation, anabatic winds, katabatic winds during the night and sea breeze. Among the suggestions for carry on this study[5] are: the conduction of observational campaigns with higher frequency sample and the development of new parameterizations to represent the LLJ and the associated dispersions. The presence of 2 nuclear facilities and new technology availability justify these investigations.

The remote sensing is being a powerful tool for the atmospheric researches, mainly in the last 40-50 years. More recently, the lidar technology has been applied and is well accepted for the scientific community. Many researches adopted the lidar for PBL studies and demonstrated that the results can be as good as the traditional methods[6]. The lidar technology presents various advantages in relatioship to the traditional methods, as for example: higher number of sampling than radiossondas, autonomy (lidars can operate for long time alone, while radiossondas and tethered baloons require operators) and high spatial resolution.

2. DATA

This work employs the data retrieved of the Windcube v2 lidar, from the Leosphere. The Windcube v2 is a doppler wind lidar that scans the atmosphere through the **D**oppler **b**eam **s**winging (**DBS**) technique[7] consisting of 4 beams with a zenith angle of 28° for the N, S, E, W directions and 1 vertical beam. The vertical beam provides a direct measurement of the vertical wind (w) and the others 4 beams estimate the radial velocity (V_r). Those 4 V_r form a set of equations (1) that allows to estimate the u and v components of the horizontal wind:

$$\begin{aligned} V_{r1} &= v_1 \cos \emptyset + w_1 \sin \emptyset \\ V_{r2} &= u_2 \cos \emptyset + w_2 \sin \emptyset \\ V_{r3} &= -v_3 \cos \emptyset + w_3 \sin \emptyset \\ V_{r4} &= -u_4 \cos \emptyset + w_4 \sin \emptyset \end{aligned} \tag{1}$$

where, $\emptyset = 62^o$ is the elevation angle, the indexes 1, 2, 3 and 4 stand for the directions N, S, E, and W, respectively. This set of equations can be solved for u and v. Assuming that the flow is homogeneous and letting $\overline{u_2}$=$\overline{u_4}$=$\overline{u}$, $\overline{v_1}$=$\overline{v_3}$=$\overline{v}$ and $\overline{w_1} = \overline{w_2} = \overline{w_3} = \overline{w_4} = \overline{w}$, equations for the mean velocity can be found (2):

$$\begin{aligned} \overline{u} &= \frac{\overline{V_{r2}} - \overline{V_{r4}}}{2 \cos \emptyset} \\ \overline{v} &= \frac{\overline{V_{r1}} - \overline{V_{r3}}}{2 \cos \emptyset} \end{aligned} \tag{2}$$

The complete scan spends 4 s, but the Windcube v2 algorithm calculates the wind components for each second, using the 4 last measurements. The 10 min means also are provided for the horizontal wind vector, vertical wind, the horizontal and vertical variances, the wind direction, Signal-to-Noise Ratio (SNR) and data availability. Its specifications are shown in Table 1.

Table 1: Windcube v2 lidar specifications

min and max height	40 to 290 m
data sampling rate	1 s
number of measurement heights	12
probed length	20 m
speed accuracy	0.1 m/s
speed range	0 to 55 m/s
direction accuracy	2°
wavelength	1.54 µm
shooting frequency	30000 Hz
pulse duration	200 ns

Since September/2017 the Windcube v2 is continually operating at Ipero and the retrieved LLJ aspects identified until January/2018 will be presented here, but the plans are to extend this campaign for one year. Before, the Windcube v2 was used for 2 other campaigns, at Sao Paulo and Cubatao municipalities, which already originated some works[8,9]. Although the maximum range is only 290 m, it is expected that the high spatial resolution (20 m), the high sample rate and the long observational period will contribute to find out PBL features that are unknown for Ipero region. For the Ipero experiment, the Windcube v2 was set up for the following 12 levels: 40, 60, 80, 100, 120, 140, 160, 180, 200, 230, 260 and 290 m.

For the case study, 2 forecast models running operationally at CPTEC/INPE[10] were chosen. The Brazilian Regional Atmospheric Modeling System (BRAMS) runs are currently available at a horizontal resolution of 5 km X 5 km, while the Eta model is available at a horizontal resolution of 15 km x 15 km. Some features of those 2 models are described in table 2.

Table 2: BRAMS and Eta models features

Features	***Model***	
	BRAMS	*Eta*
Horizontal resolution	5 km X 5 km	15 km X 15 km
Vertical levels	19	22
Number of variables	30	62
Output interval	6 h	3 h

2.1 Site

The new nuclear reactor (RMB) will be built at Ipero, Sao Paulo State, Brazil (Figure1). Ipero (23º21'S;47º41'W) is a predominantly rural municipality distant around 120 km from Sao Paulo municipality, the most populated city in Brazil. Ipero population is small, around 35 thousand people, in according to the governmental statistics. This population is equivalent to 170 inhabitants/km^2, against 1,300 inhabitants/km^2 in Sorocaba (the closest urban municipality) and 7,400 inhabitants/km^2 in Sao Paulo city. Previous works[4] demonstrated that the geographical characteristics add complexity to the atmospheric circulation at Ipero region and numerical models must be calibrated[11] to better reproduce the real conditions. Ipero is a complex terrain area of the Sorocaba river valley that extends from southeast to northwest approximately. In the southwest portion of this valley, there is the Araçoiaba hill that exceeds 900 m (almost 400 m higher than the mean elevation) and presents slopes around 50% at its southeast face (Figure 2).

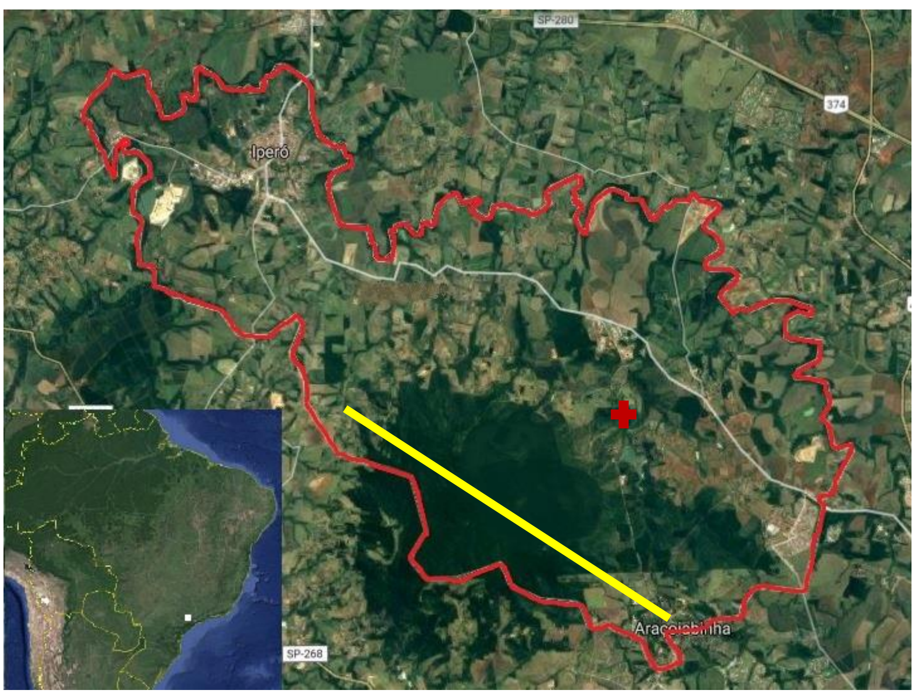

Figure 1: Ipero municipality map (red polygon) and its localization in Brazil (white dot). The yellow line is the Araçoiaba Hill section (see figure 2) and the red cross is the lidar position. Source: Google Earth.

Figure 2: Araçoiaba Hill elevation profile (yellow line of the figure 1). Source: Google Earth.

2.2 Methods

The 10 min means of the horizontal wind retrieved by the Windcube v2 were used to identify the LLJs. Data with availability less than 80% was discarded because previous tests indicated that this data could be erroneous due to environmental conditions, as rainfall, for example. After filtering the data, the vertical profiles were constructed, which allowed to inspect and identify visually the LLJ. Figure 3 shows the vertical wind profile starting at 18 UTC of September17th and extending until the next day at 12 UTC. The local time is UTC minus 3 h, but during the daylight-saving time that started at October 15th, the local time is UTC minus 2 h. The late spring and early summer days are long at this latitude. The sunset was at 21:01 UTC and the sunrise was at 9 UTC at September 17th and 18th, respectively. From figure 3 it is possible to see the transition of a homogeneous PBL (light winds – speed between 2 to 4 m/s within the layer) before the sunset to a stratified PBL after the sunset. After 21 UTC the wind speed strengthens and quickly reaches 8 – 10 m/s. Later, around 3 UTC (0 h local time) the wind intensifies more and reaches 10 – 12 m/s. The figure also shows the wind weakening after 4 UTC, although a new nucleus surges after 9 UTC. This figure exemplifies a typical LLJ event that usually forms after the sunset and only vanishes after the sunrise.

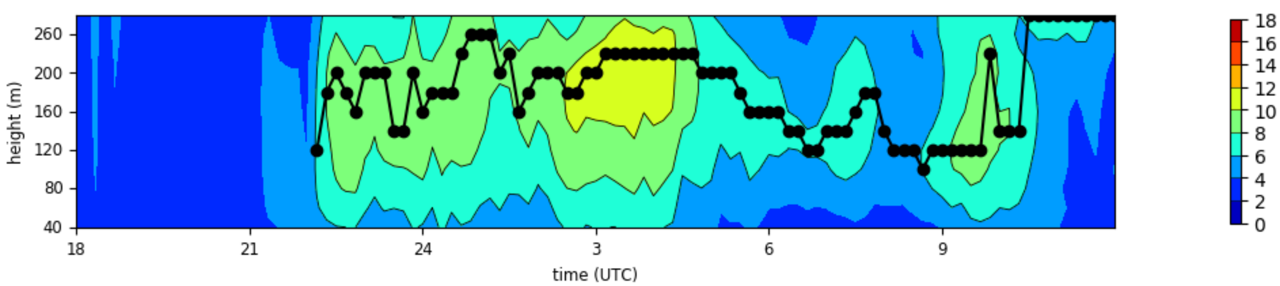

Figure 3: Vertical profile of the horizontal wind speed (m/s) – September 17th – 18th. Speeds higher than 6 m/s are contoured. Black dots indicate the H_{LLJ}.

For this work, only LLJs which completely developed below 290 m (as figure 3 event) were considered. The first step was to identify the vertical profile maximum speed greater than 5 m/s and its height, that are called LLJ speed (V_{LLJ}) and LLJ height (H_{LLJ}), respectively. A LLJ must have weaker winds above and below the H_{LLJ}. So, as the second criterion, some level above and below the H_{LLJ} must be at least 0.5 m/s weaker than V_{LLJ}. This same condition was adopted by[12]. They, that also worked with a doppler lidar, noticed that using greater threshold implied in negligent important profiles and LLJs. Our previous tests agreed with their results[12].

3. RESULTS

Even for a shallow layer (below 290 m), the LLJs have been observed with high frequency for the 6 months from August/2017 to January/2018. The number of days with LLJs, the total of profiles identified and the cumulative distribution of V_{LLJ} are illustrated in figure 4 (a) – (f) for each month. In according to the data retrieved from the Windcube v2, December and January had the least number of days with LLJs.

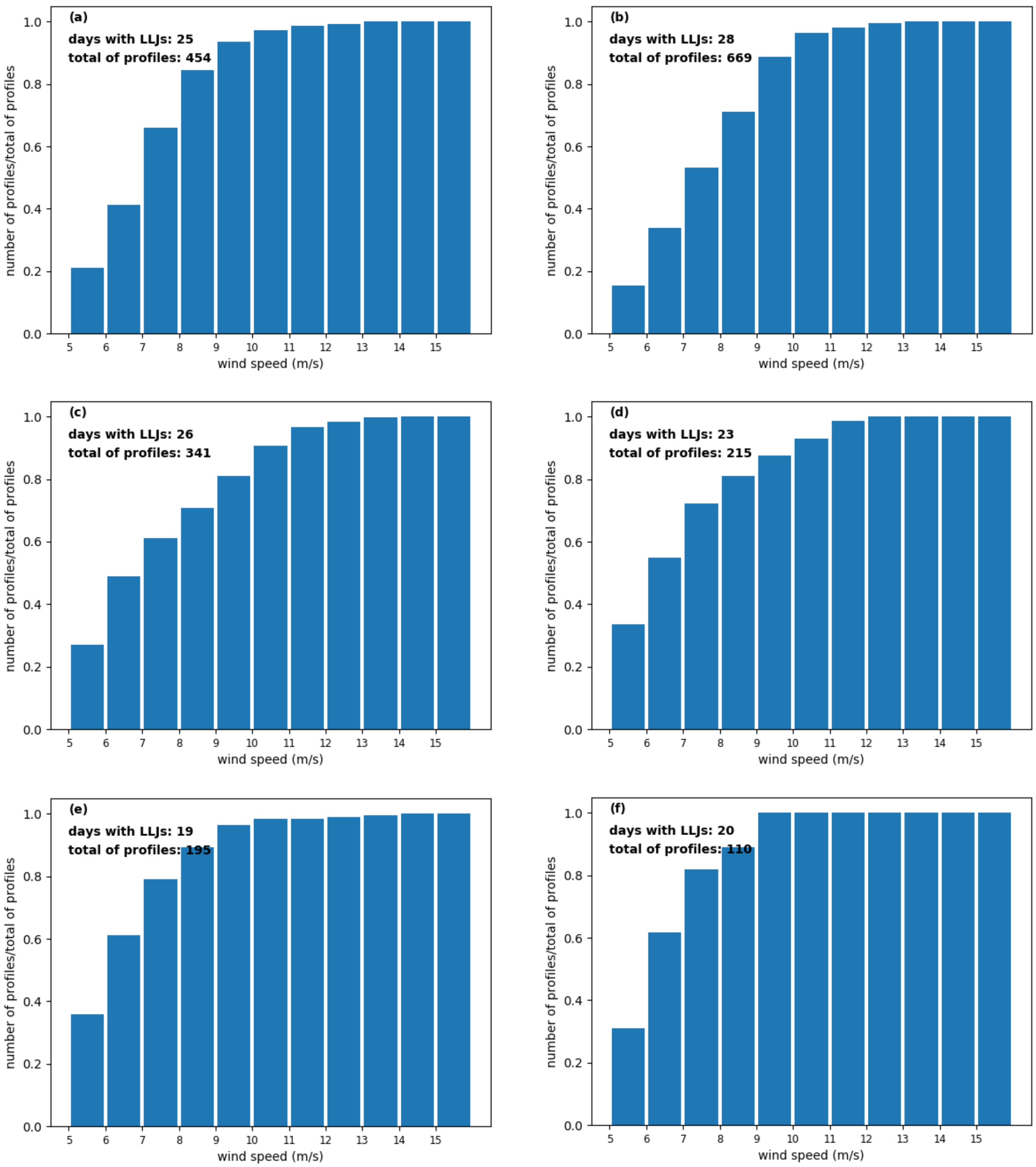

Figure 4: Cumulative distribution of VLLJ for: (a) August/2017; (b) September/2017; (c) October/2017; (d) November/2017; (e) December/2017 and (f) January/2018.

January had 20 days with LLJs and 110 profiles, against 28 days with LLJs and 669 profiles in September/2017. Although the Windcube v2 have been operating uninterrupted since August, one consideration must be done before directly compare the results, because data availability decreases during rainfall and dense cloudiness events and the climatological characteristics have a strong impact over these results. Ipero has its dry and wet seasons well defined. July and August are the drier months while December, January and February are the wetter months. The climatological precipitation of Ipero region is shown in figure 5. The monthly mean precipitation ranges from 32 mm in August to 212 mm in January. The wetter environment also favors the formation of fog, especially during early mornings and even without rainfall, the data availability decreases. The number of days that the data acquisition was impaired due to rainfall or fog are: 2, 1, 2, 7, 10 and 8, for August, September, October, November, December and January, respectively. During all the period, a total of 11 days exhibited strong wind shear below 290 m, but didn´t match the criteria adopted here (a maximum wind speed and a weaker wind above within the 290 m layer). This indicates that the H_{LLJ} may be higher for those 11 days. The cumulative distribution of V_{LLJ} (Figure 4) seems to indicate that the LLJ intensity weakens as summer (Southern Hemisphere) and rainy season approximates. This aspect is confirmed in figure 6, which exhibits the number of profiles/total of profiles versus V_{LLJ}. August presented a maximum number of profiles (almost 25%) for $7 \leq V_{LLJ} < 8$ m/s, while for December the maximum (~ 35%) is between 5 and 6 m/s. Almost 60% of January profiles is between 5 and 7 m/s and September had almost constant distribution since 5 to 10 m/s. Generally, V_{LLJ} is under 11 m/s and only few profiles exceeded this value, as shown in figure 6. This LLJ intensity (V_{LLJ}) is comparable to that found out to southeastern Kansas[12].

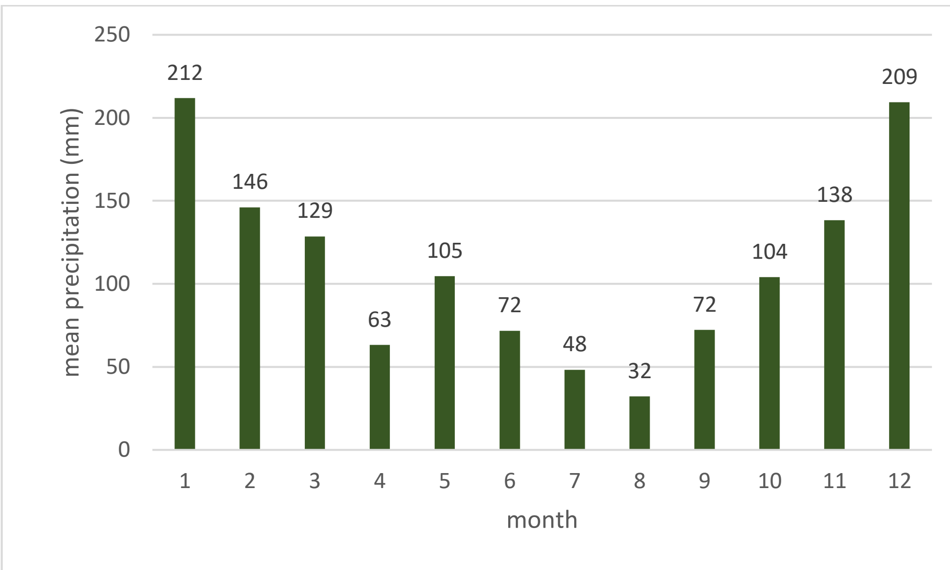

Figure 5: Climatological precipitation of Ipero region. Data recorded from 1961 to 1990 by Brazilian National Institute of Meteorology.

All the LLJs analyzed here, had for some instant of their life cycle completely within the layer below 290 m, however, the LLJs can extend for many hours as showed in figure 3 and their characteristics as V_{LLJ}, H_{LLJ} or even direction can change along their life cycle, mainly if their formation mechanism is the inertial oscillation. The inertial oscillation is the balance when the frictional force vanishes and only the pressure gradient and Coriolis forces act over an air parcel[13]. The frictional force vanishes because the vertical mixing ceases after the onset of the of surface cooling at late afternoon/evening and the middle and upper portion of the PBL decouples from the surface layer. As a result, the wind becomes supergeostrophic, originating the LLJs. At Ipero, the LLJs are mainly from south and south-southeast during August, September and October (late winter and spring – Southern Hemisphere), as shown by the Figures 7 (a) – (c) and (e). The November and January LLJs (Figures 7 (d) and (f)) also showed a contribution from east-southeast and less contribution from south. This range of direction maybe associated both with the inertial oscillation and with seasonal features due to climatologic variability of the synoptic systems.

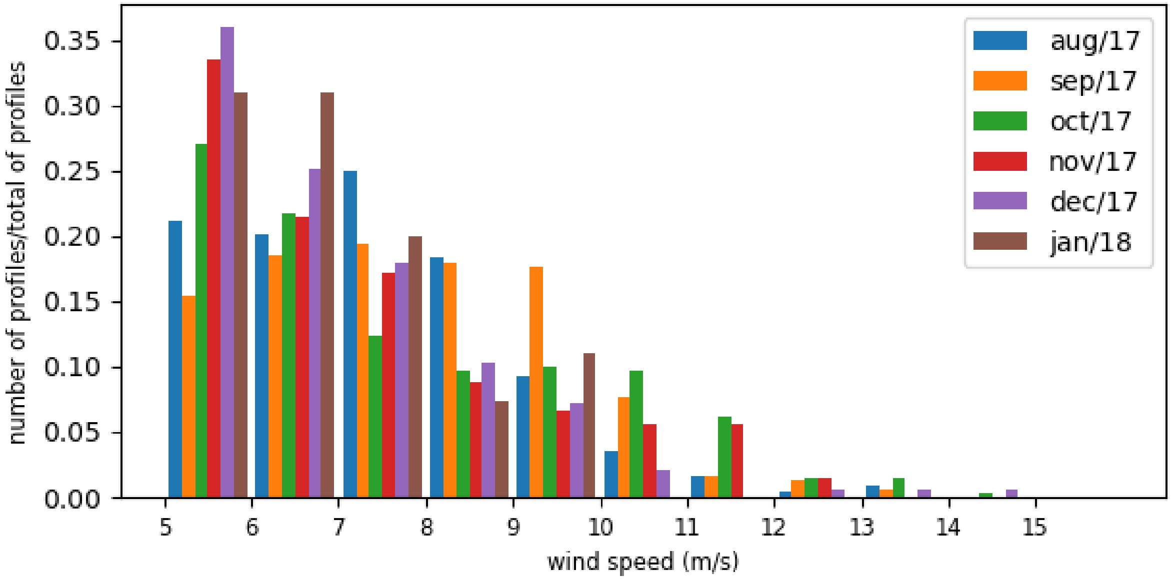

Figure 6: Distribution of profiles (number of profiles/total of profiles) versus LLJ wind speed (V_{LLJ}).

Yet, in relation to the general characteristics of the LLJs, one more aspect was retrieved from Windcube v2 data: the LLJ height (H_{LLJ}). We see from figure 8 that the number of profiles increases with the height and the major amount of LLJs were detected between 120 and 230 m. Above 230 m, the amount of LLJ clearly decreases for the 6 months analyzed. The stronger LLJs ($V_{LLJ} \geq 12$ m/s) were only detected at the higher levels ($H_{LLJ} \geq 120$ m). This characteristic was also observed at Kansas[12]. The H_{LLJ} is one of the methods to estimate the **S**table **B**oundary **L**ayer (**SBL**) height. Briefly, the SBL is the layer where all emissions from surface are confined during the night[1] and shallow SBL is worrisome from the dispersion point of view. Figure 8 shows that the SBL is shallow at Ipero region and during August (late winter), the H_{LLJ} concentrate between 120 and 140 m. It is worth to investigate if the numerical modeling (input for atmospheric dispersion models) can simulate this aspect.

As it is known, the LLJ is also called Nocturnal Jet because it is often observed during the night. However, sometimes it also occurs during the daytime, as shown in figure 9. Only a few number of profiles were observed between 12 and 16 UTC, and this number decreases from the winter to the summer (August to January). Perhaps the colder weather acts to extend the life cycle of the LLJs. As the afternoon to evening transition time approximates (16 – 20 UT), the number of profiles increases in relation to the previous interval. Practically for the 6 months, the greatest amount of LLJs were detected between 0 and 8 UTC. After 8 UTC, the number of profiles decreases for 2 reasons: the first can be the weakening of the LLJ and the second reason can be because the maximum wind (V_{LLJ}) is above 290 m, as we noticed that sometimes the LLJ forms close to the surface and becomes higher with the time before completely vanishes. The almost constant number of profiles since 20 UTC until 8 UTC (day +1) confirms that the LLJs can last for many hours.

3.1. Case Study

The purpose of this case study is to investigate deeply the characteristics of a LLJ. The September 17th – 18th event (figure 3) was chosen because practically all its cycle life happened within the layer below 290 m. As was said before, the LLJ is a method to estimate the SBL height and shallow SBL is a worrisome feature for atmospheric dispersion, since all emissions from surface will be confined within this layer. Firstly, it is interesting to look in which synoptic conditions this LLJ developed. The satellite image from September 18th 00 UTC (figure 10) shows that clear sky conditions dominate over center-southern Brazil, except for an apparently thin cloudiness that extent from southern Sao Paulo state to southeastwards.

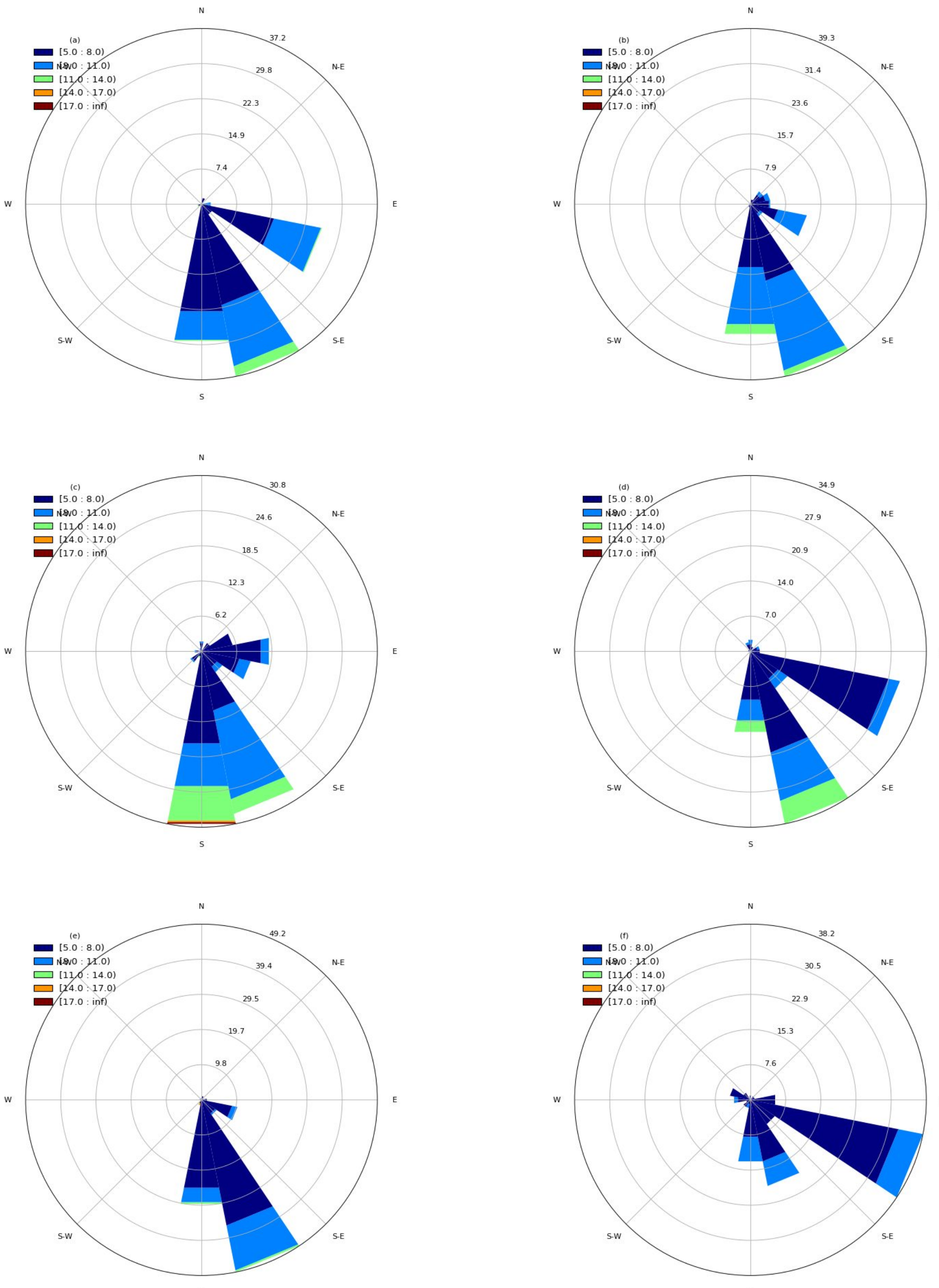

Figure 7: Windroses of the LLJs for: (a) August/2017; (b) September/2017; (c) October/2017; (d) November/2017; (e) December/2017 and (f) January/2018. The legend indicates de windspeed and the internal circles indicate the amount of LLJs (in percentage).

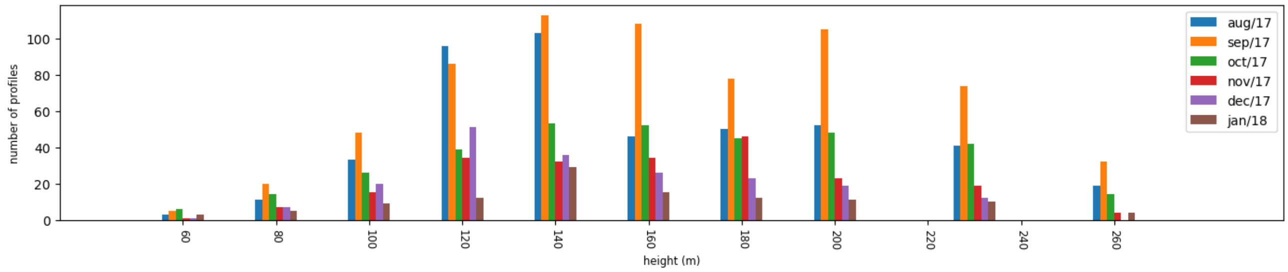

Figure 8: Number of LLJs versus height.

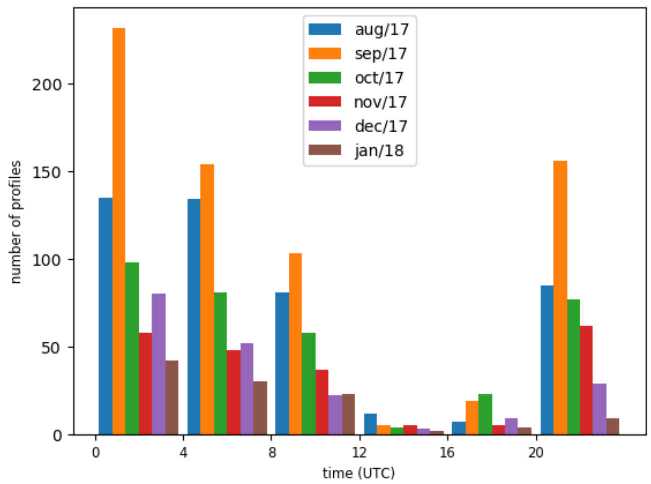

Figure 9: Number of LLJs versus observed time (UTC).

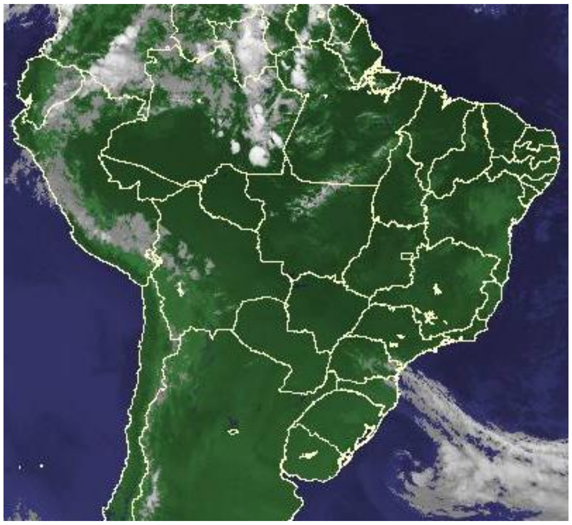

Figure 10: Satellite image (GOES 13) from September 18th 00 UTC. Source: CPTEC/INPE

Synoptic conditions are better understood by the analysis of some meteorological fields, as: pressure, temperature and winds. These simulated fields available by CPTEC/INPE[10] are analyzed and presented next. For this purpose, the BRAMS model running at a horizontal resolution of 5 x 5 km was chosen.

Examining the mean sea level pressure and the 500 hPa geopotential height for September 18th 00 UTC (figure 11a), we see a well-defined cyclonic system at both levels which is the cloudiness observed offshore (figure 10). This cyclonic system is associated with the cold front at the southern portion of the Sao Paulo state. This configuration generates pressure, geopotential and mainly temperature gradients over Sao Paulo state, area that includes Ipero region. Figure 11b shows that exist a strong temperature gradient from Sao Paulo northwestern to the coast direction. The northeastern winds transport heat from lower latitudes and decelerate over Sao Paulo. The analyzed fields indicate that the LLJ developed under a pre-frontal condition, although in according to the literature, the LLJs generally occurs under non-perturbed conditions (high pressure situations). Twelve hours after, synoptic conditions remained practically unaltered, supporting the temperature, pressure and geopotential gradient over Sao Paulo state (not shown).

(a) (b)

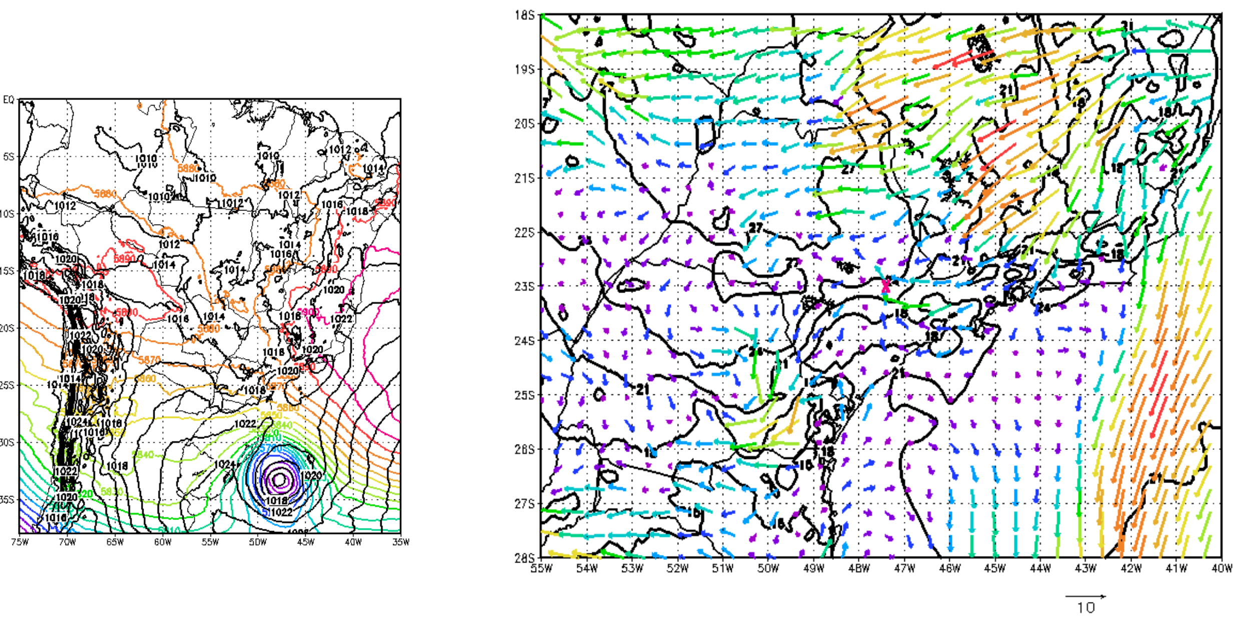

Figure 11: (a) Mean sea level pressure (black lines) and 500 hPa geopotential height (colored lines); (b) 850 hPa horizontal winds (vectors) and 2 m air temperature (black lines) for September 18th 00 UTC.

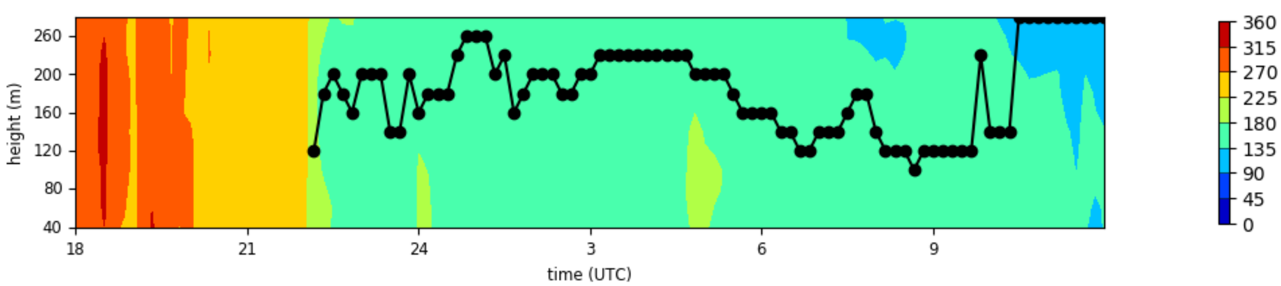

Figure 12: Vertical profile of the wind direction (degrees) – September 17th – 18th. Black dots indicate the H_{LLJ}.

Although the simulations indicated that the north-northeasterly winds dominated on the synoptic scale, figure 12 shows that the wind direction changes drastically during the evening transition (period that precedes the SBL onset). The vertical profile of the wind direction is practically homogeneous (north-northwestern) at 18 UTC, but in the next 4-5 hours the wind direction turns counter-clockwise and after the LLJ onset, the south-southeastern winds dominate within the layer. This counter-clockwise (for the Southern Hemisphere) mechanism is called inertial oscillation. As said before, the inertial oscillation is the balance when the friction force vanishes. Taking the horizontal momentum equations (3) for the geostrophic equilibrium:

$$\frac{du}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv$$

$$\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + fu \quad (3)$$

where u, v, ρ and f are respectively: the zonal and meridional wind components, the air density and the Coriolis parameter.

Taking the geostrophic (subscript g) and agestrophic (subscript a) partitions for the horizontal wind components (4) and (5):

$$u = u_g + u_a$$

$$v = v_g + v_a \quad (4)$$

$$u_g = -\frac{1}{\rho}\frac{\partial p}{\partial y}$$

$$v_g = -\frac{1}{\rho}\frac{\partial p}{\partial x} \quad (5)$$

the momentum equations (3) becomes:

$$\frac{du_a}{dt} = fv_a$$

$$\frac{dv_a}{dt} = -fu_a \quad (6)$$

Taking $\frac{d(du_a/dt)}{dt}$ and using $\frac{dv_a}{dt}$, we obtain a linear ordinary equation (7) for f constant

$$\frac{d^2u_a}{dt^2} = -f^2u_a \quad (7)$$

The equation (7) has a solution of the form:

$$u_a = C_1 \cos ft + C_2 \sin ft$$

where C_1 and C_2 are constants. At t = 0, $u_a = u_{a0}$, $v_a = v_{a0}$ and:

$$u_a = C_1$$

$$v_a = C_2 \tag{8}$$

Then, the equations for the ageostrophic winds are:

$$u_a = |v_{a0}| \cos(\psi_0 - ft)$$
$$v_a = |v_{a0}| \sin(\psi_0 - ft) \tag{9}$$

where $|v_{a0}| = \sqrt{u_{a0}^2 + v_{a0}^2}$ and ψ_0 is the angular constant designating the orientation of the ageostrophic wind at the start of the adjustment process.

A full inertia circle described by (9) is completed at time $t = 2\pi/f$, but $f = 2 * 7{,}2x10^{-5} * sen\phi$ and ϕ is the latitude. For Ipero (latitude ~23º), the full circle takes almost 31 h after the start of the adjustment process. The strongest amplification of the LLJ occurs on night following days during which winds in the upper boundary layer were most retarded by surface friction (abundant insolation, deep mixing and deep boundary layers)[13]. This means that more efficient is the turbulence (and more subgeostrophic is the wind) during the day, more intense is the LLJ (and more supergeostrophic is the wind).

The counter-clockwise turn is seen to the 40, 120, 200 and 290 m levels (figure 13) for the September 17th – 18th. The start is indicated by the arrow labeled 18 UTC. Around 22 UTC we see a suddenly turn from southwestern to southern. The strongest wind occurs later at 120, 200 and 290 m, consecutively. While the wind strengthens at higher levels (120, 200 and 290 m), it is observed to weakens at the lowest level (40 m), illustrating the forward and backward inertial oscillation, respectively[14]. The inertial oscillation is a strong mechanism for LLJ formation at Ipero, but the terrain effects and the sea breeze also contribute[5].

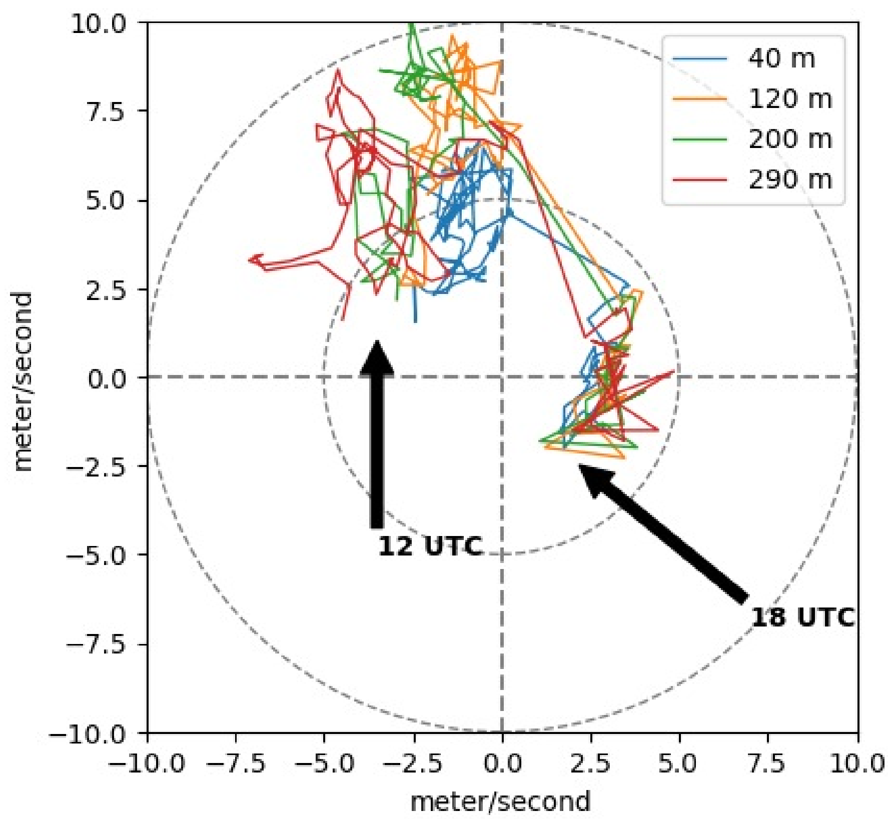

Figure 13: Hodograph starting at 18 UTC of September 17th

As the transition from CML to SBL takes place, the turbulence usually decreases due to the convection weakening. During the night (SBL) the vertical mixture is generally weak because only the mechanical turbulence contributes to it. However, the wind shear due to the LLJ can boost the vertical mixture and also can acts over the atmospheric dispersion. The **T**urbulence **K**inetic **E**nergy (**TKE**) is a measure of the intensity of turbulence and is defined as (10):

$$TKE = \frac{1}{2}(\overline{\sigma_u^2} + \overline{\sigma_v^2} + \overline{\sigma_w^2}) \tag{10}$$

where σ_u^2, σ_v^2 and σ_w^2 are the wind component variances and the overbar is the mean.

The TKE were calculate for this event and its vertical profile is shown in figure 14. This figure exhibits a clear transition from the convective regime at 18 UTC for a non-convective regime in the next 2 hours. During this period the TKE decreases quickly and practically vanishes within the layer about 21 UTC. Later, at the same time the LLJ was identified, a suddenly increasing of the TKE is observed and remains intermittent until 6 UTC (next day). This TKE is generated mechanically by the LLJ wind shear and transported to the surface, what took researchers adopt the term ***upside down PBL*** for occasions like this, once, normally the TKE is generated at the lower levels and transported to higher levels. The LLJ also produces turbulence above the LLJ as is indicated by the highlighted area (red square). That TKE above the LLJ can causes the entrainment of cleaner air from the **R**esidual **L**ayer (**RL**) to the SBL and can also affect the atmospheric dispersion. This hypothesis should be investigated deeply in a next paper. After 6 UTC the TKE almost totally vanishes, but it comes to light again after 9 UTC (6 local time) and this time due to the convective activity once the sunrise already occurred. A previous study[8] showed us that the TKE amount depends on the LLJ intensity (V_{LLJ}) and height (H_{LLJ}): stronger and higher LLJs produce more TKE, but less TKE is detected at surface for those LLJs.

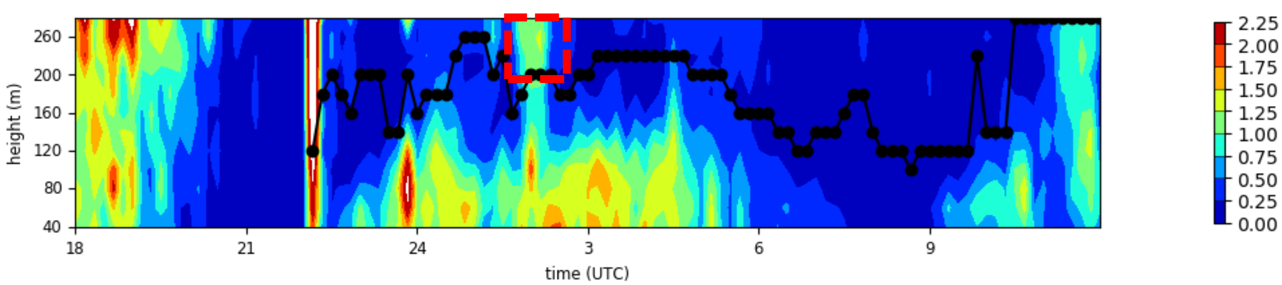

Figure 14: Vertical profile of the TKE (m^2s^{-2}). September 17th – 18th. Black dots indicate the H_{LLJ}

3.2. Numerical Simulations

Once we are interested in implementing a dispersion model operationally, their possible inputs must be carefully evaluated before the implementation. The possible inputs for a dispersion models are: observational data, that generally are insufficient in terms of amount and weather forecast models. Some dispersion models accept as observational data as weather forecast models, but the last are been widely employed for this purpose because the weather forecast models offer higher spatial and temporal resolution. However, only the data amount is not enough. The weather forecast models must reproduce reasonably the real conditions. The numerical modeling is in constant development and the atmosphere is already well simulated for synoptical scale, however the mesoscale and microscale still are a challenge because the physical features need to be parametrized. In this sense, 2 weather forecast models running operationally by CPTEC/INPE[10] were chosen to evaluate the simulation of the LLJ features of September 17th – 18th, because we are looking for a computationally viable alternative to implement the dispersion model. The BRAMS and Eta are regional models, but despite their high horizontal resolution, both models reproduced an almost homogeneous layer (in terms of wind speed) from surface until at least 500 m height, approximately (figures not shown). That means that the LLJ detected by the lidar was not simulated by the models. Data retrieved by the lidar also showed that the inertial oscillation is one of the mechanisms that acts within the PBL (figure 13). Although BRAMS neither Eta simulated the LLJ, both reproduced the counter-clockwise wind direction change through the night until the next day as shown in figure 15. Barbs are a visual resource that indicates the direction where the wind comes from and its speed. For example, the first blue barb (Eta 100 m) of figure 15 indicates that the wind is blowing from northwestern, approximately. The wind speed is indicated by the kind of the increment at the tip. However, here, the wind speed should be ignored, since for better visualization, the wind components were multiplicated by a constant factor. The yellow and red barbs represent the 40 and 100 m, respectively, data retrieved by the lidar. Comparing observed and simulated data, it is possible to see that the counter-clockwise direction change is forecasted most of the time, except at the end of the period (12 UTC) that the simulations forecasted easterly winds while the observational data are from southeast. The Eta 100 m simulation also delayed the counter-clockwise turn between 18 and 24 UTC.

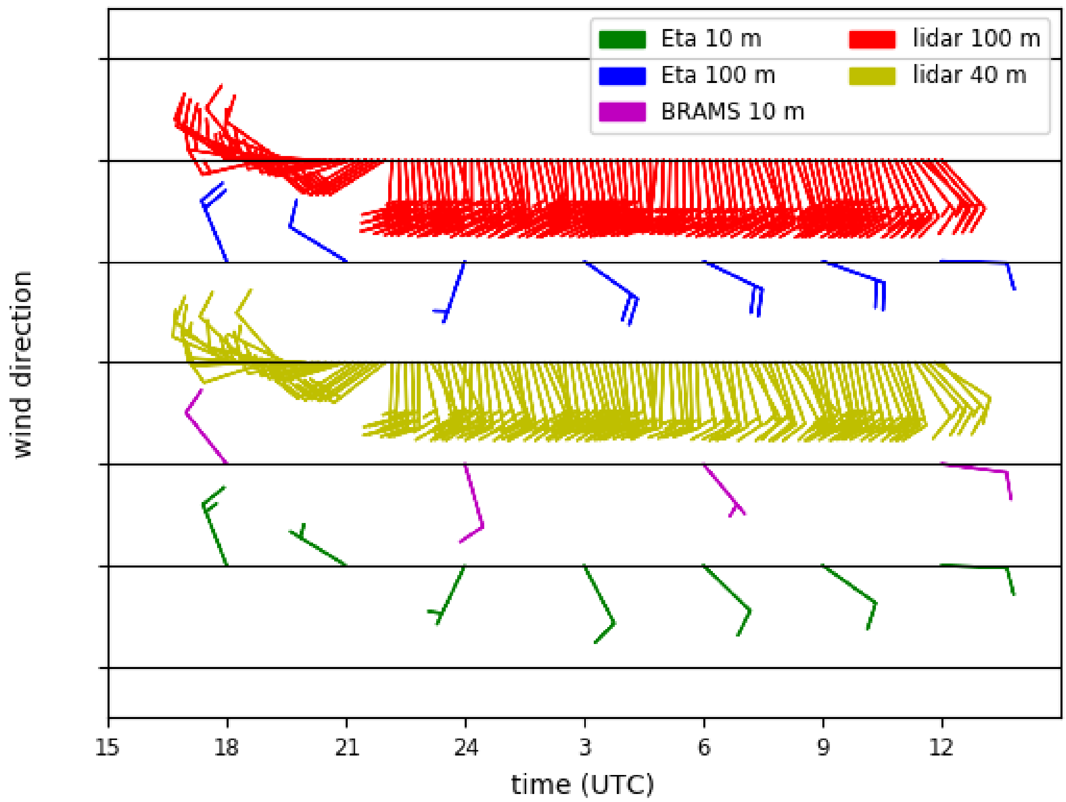

Figure 15: Wind barbs for BRAMS and Eta simulations and for lidar data. September 17th – 18th.

The wind speed, however, reveals to be a bigger problem, at least for this event. Observational data is much stronger than simulations, as it is seen in figure 16. The red line indicates the 100 m height wind speed retrieved by Windcube and the blue dots are the 100 m height wind speed simulated by Eta. Except for the first point (18 UTC – 15 local time), the Eta simulation underestimated the wind speed and the resulting Mean Absolute Error (MAE) is 2.59 m/s. The 10 m wind speed simulated by Eta presents almost the same value that the 100 m height, which indicates a quasi-homogeneous layer unlike the observations. In according to the simulations, the models didn´t promote the decoupling of the surface layer that was seen by the observational data and this divergence can cause serious consequences for the atmospheric dispersion results.

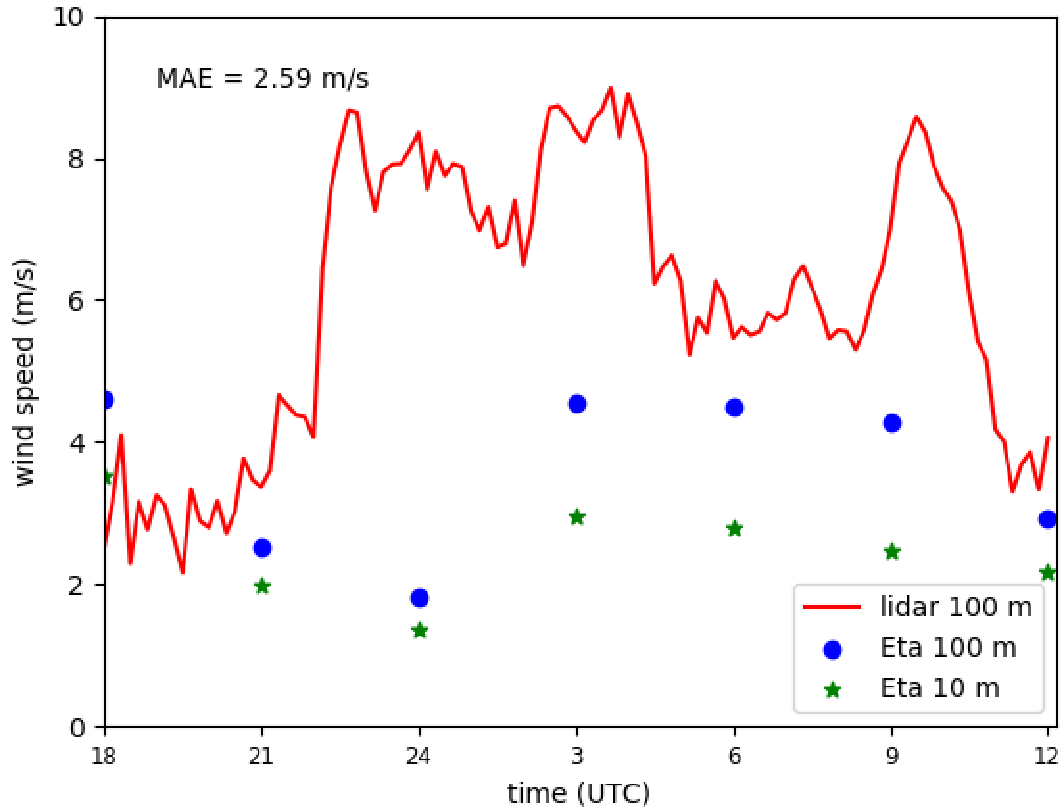

Figure 16: Observed and simulated wind speed (m/s). September 17th – 18th.

The last evaluation is for the Stable Boundary Layer (SBL) height that is available by BRAMS, only. As BRAMS output is each 6 hours, only 2 points are available to the same period of the H_{LLJ}. In according to figure 17, the BRAMS estimation for the SBL is fairly comparable to lidar data estimation. This comparison would be improved if more points were available. A dispersion simulation running with BRAMS probably will consider the SBL height constant (around 150 m) between 0 and 6 UTC (September 18th), but the lidar estimation shows that the SBL height reaches 250 m between 1 and 2 UTC and this difference can alters the pollutant concentration estimation for the same emission. Another important result is that the SBL height remains shallow for the whole period. The evening to night transition is more critical because the layer depth is around 50 m, followed by the morning transition when the SBL height falls to 100 m. Comparing figures 17and 14 let clear that SBL height and mechanical turbulence are strongly associated.

4. CONCLUSIONS

For 6 months the Windcube v2 lidar operated continuously at Ipero, Sao Paulo, Brazil. This extensive campaign confirmed previous results[5] that the LLJs occur frequently over the region. Even during the raining season, when data availability decreases, it was detected high number of days with LLJs. The LLJs occurred basically every day and even when the adopted criterias weren´t met, data suggest that the LLJ can be formed above the lidar range. The LLJ maximum wind speed peaks between 5 and 8 m/s and the stronger profiles occurred in greater number during late winter – early spring, decreasing during the forthcoming months. The LLJ preferential direction is from south – east/southeast, but the inertial oscillation makes the wind within the layer turns counter-clockwise during the night – early morning. In terms of height, most of the LLJ were detected between 120 and 230 m, but winter and early spring presented more profiles between 120 and 140 m. This result indicates that the SBL is shallow and that surface emissions are confined under this thin layer. An accidental release in that condition will cause a high pollutant concentration close to the surface. Although in small number, some LLJ events were also detected during daytime, mainly during August (winter). Those events and their development conditions should be carefully investigated. For the case study a classical LLJ event was chosen (nocturnal LLJ), although developed under a pre-frontal condition (warm advection and strong temperature gradient). Since its formation at 22 UTC (19 h local time) approximately until next day around 10 UTC (7 h local time) the LLJ remained within the 290 m layer. That means that the SBL height was shallower than 290 m. Although the synoptical circulation was north-northeastern, the inertial oscillation took place and the winds turn counter-clockwise within all the layer. This result open some questions: can the synoptical condition impact the LLJ development? Can the LLJ be stronger or develop faster under no synoptical disturbances (weak temperature gradient and weak winds) or under a post-frontal condition (cold advection)? These questions should be answered with further case studies. Strong turbulence was detected under the LLJ and it certainly contributes for mixing the emissions from surface through the SBL. The turbulence may also entrain cleaner air from the Residual Layer into the SBL, which, in turn contributes to dilute the pollutant concentration. The 2 regional numerical models evaluated didn´t reproduce the LLJ, but the inertial oscillation was simulated. The wind fields indicated that the BRAMS and Eta simulate a homogeneous layer and the wind speed is much weaker than the observed. The SBL height was available only by the BRAMS, but since its output is each 6 hours, just 2 points can be compared with our estimation. The BRAMS simulation and our estimation are comparable, but due the BRAMS output interval (each 6 hours only), the temporal SBL height variations couldn´t be evaluated. The 2 operational numerical models, despite their high spatial resolution, didn´t reproduce the LLJ. In this case, before being adopted as input for a dispersion model, the weather forecast models must be adjusted to provide reliable simulations. The data retrieved during the field campaign will be essential for this purpose.

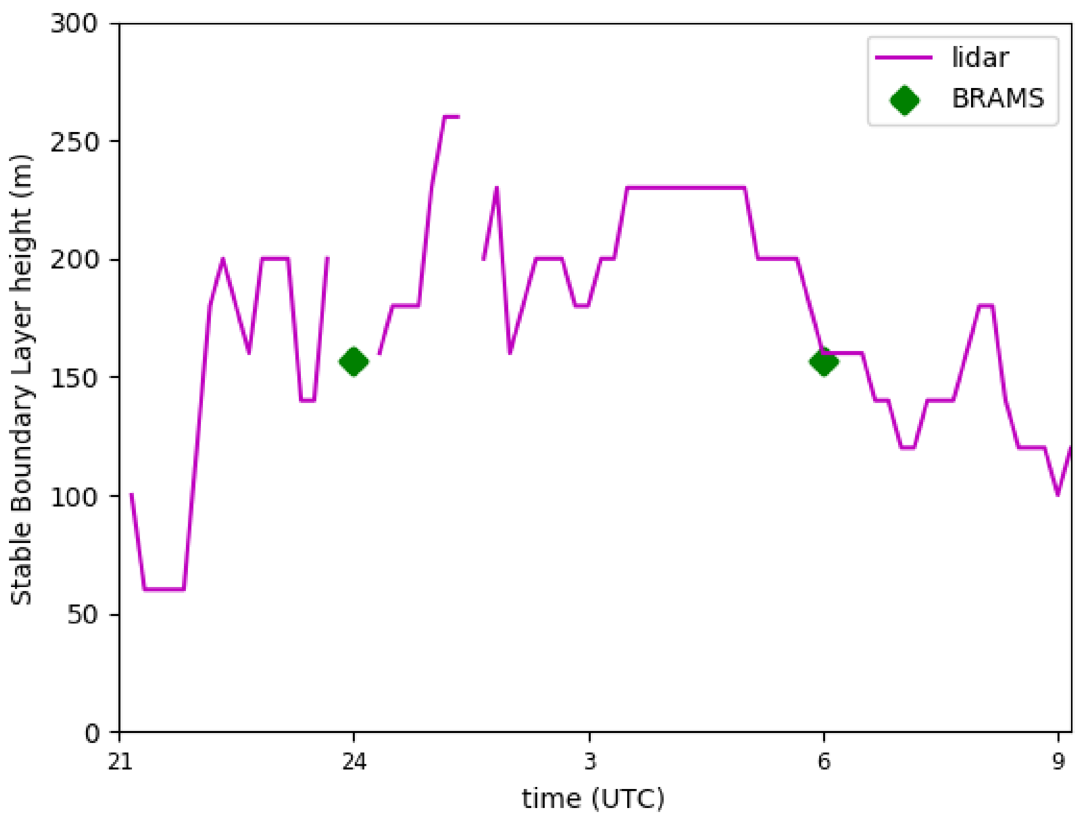

Figure 17: Stable Boundary Layer height estimation (m)

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