A case study with extreme low-level jet in southern Brazil

Um estudo de caso com extremo jato de baixo nível no sul do Brasil

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ABSTRACT
This study aimed to analyze a period of intense Low-Level Jets (LLJ) in southern Brazil that occurred in a year of intense El Nino-South Oscillation signal. Observational data were collected by radiosonde data carried out at Salgado Filho airport, which measured values of the order of 30 ms\(^{-1}\) in intensity at 700/750 meters in height and a predominant direction of 270 degrees. The LLJ’s are horizontal vortices in the low-level turbulence process, optimizing the transport of energy and water vapor at the mesoscale; they are low-cost energy structures with maximum transport efficiency. In general, their modeling by numerical models at high resolution is difficult because they have a thin layer with a small thickness of the order of 50 meters and have a non-linear nature in the turbulence processes. However, global reanalysis models, in general, cannot represent the optimization effects in the turbulent process performed by LLJ. However, there is a tendency to represent the magnitude of the wind modulus, an approximation of this value by the current state of the art in global reanalysis modeling in models, in this case, the maximum wind. This implies that global models generally underestimate flows at low levels, in general, as they do not represent the optimization effects associated with LLJ. In this case study, we tried to use an extreme situation of occurrence of LLJ for analysis, therefore, the regional climate model RegCM-4.9 in high spatial resolution was used to simulate the period from May to June 1997. The analyses were concentrated in June 1997. The initialization and boundary conditions were used from the EC-EARTH historical of the Earth system model based on the operational seasonal forecast system of the European Center for Medium-Range Weather Forecasts (ECMWF). It was observed that the simulation result could significantly underestimate the wind intensity and the processes associated with the LLJ with the initialization model, with low information resolution, the global initialization models do not have adequate resolution for this type of simulation.

Keywords: regional climate model, low-level jet, El Nino-South Oscillation.
RESUMO
Este estudo teve como objetivo analisar um período de intenso Jatos de Baixo Nível (JBN) no sul do Brasil, ocorrência em um ano de intenso sinal El Niño-Oscilação Sul. Os dados observacionais foram coletados por meio de dados de radiossondagem realizada no aeroporto Salgado Filho, que mediu valores de ordem de 30 ms\(^{-1}\) de intensidade a 700/750 metros de altura e direção predominante de 270 graus. Os JBN são turbilhões horizontais em processo de turbulência de baixo nível, otimizando o transporte de energia e vapor d’água na mesoescala, são estruturas energéticas de baixo custo e com máxima eficiência de transporte. Em geral, sua modelagem por modelos numéricos em alta resolução é difícil, pois possuem uma camada delgada com pequena espessura da ordem de 50 metros e possuem uma natureza não linear no processo de turbulência de mesoescala. No entanto, os modelos de reanálise global em geral não podem representar os efeitos de otimização no processo turbulento realizado pelo JBN. Porém, há uma tendência de representar a magnitude do módulo de vento, uma aproximação desse valor pelo estado da arte atual em modelagem de reanálise global em modelos, neste caso o vento máximo. Isso implica que os modelos globais geralmente subestimam os fluxos em níveis baixos em geral, pois não representam os efeitos de otimização associados ao JBN. Neste estudo de caso procurou-se utilizar uma situação extrema de ocorrência de JBN para análise, portanto, o modelo climático regional RegCM-4.9 em alta resolução espacial foi utilizado para simular o período de maio a junho de 1997. As análises se concentraram no mês de junho de 1997. A inicialização e as condições de contorno foram usadas a partir do histórico EC-EARTH do modelo do sistema terrestre baseado no sistema operacional de previsão sazonal do European Center for Medium-Range Weather Forecasts (ECMWF). Observou-se que o resultado da simulação poderia subestimar significativamente a intensidade do vento e os processos associados aos LLJ associados ao modelo de inicialização, com baixa resolução de informação, os modelo globais de inicialização não possuem resolução adequada para este tipo de simulação.


1 INTRODUCTION
Different observational studies and numerical simulations (Pitchford and London 1962, Bonner 1968, Stensrud 1996, Higgins, et al. 1997, Whiteman, et al. 1997, Igau, et al. 1998, Parsons, et al. 2000 and Lackmann 2002, Corrêa 2005; Corrêa, et al. 2012 and Shapiro, et al. 2016) carried out in different regions of the planet showed that inside the Planetary Boundary Layer (PBL) there is usually a narrow vertical strip containing maximum winds that occur at heights of about 100 meters or more, and whose extreme values are in the range of 10 to 40 ms\(^{-1}\), known as Low-Level Jet (LLJ). This work seeks to discuss the dynamics and interaction of atmospheric movements of a certain meteorological scale (LLJ - microscale-mesoscale) that interconnect with the airflow in other meteorological scales (mesoscale and large scale) of great importance. In which it carries out intense energy exchange, latent and sensitive heat, responsible for the significant transport of water vapor, and also act in the night convection process and in the generation of intense convection and are low-cost structures to be generated and carry out transport with maximum transport efficiency. The location of this study layer
occurs in the lower atmosphere, it is a region close to the surface in which it presents low-level jets and flows, which interact vertically with other synoptic structures existing in the atmospheric dynamics, with Upper-Level Jets and present seasonal and intraseasonal variability. Corrêa, *et al.* (2002) carried out a spectral analysis of the reduction in wind speed above the maximum Low-Level Jets (LLJ) cores in Porto Alegre with radiosonde data showing that the decay intensities were associated with low frequencies. Turbulence within the Planetary Boundary Layer (PBL) contains information about space and time scales in meteorological systems. This memory is associated with the decrease in the wind above the Low-level jets. The vertical wind profile showed the occurrence of LLJ, which is associated with several different factors and scales. During the El Nino events, the intensity of the decrease in wind speed was greater, the jets having speeds of about 30 ms$^{-1}$, with a decrease in wind speed of about 10 ms$^{-1}$ or more. In situations where the southern oscillation index (IOS) was close to neutral, low frequencies did not occur and baroclinic frequencies predominated. When the IOS was significant, positive or negative, there was a low frequency and baroclinic. Low frequencies are associated with blocking systems and planetary circulation scales. The analysis used the spectral analysis of the vertical shear profile below 3000 meters. Corrêa, *et al.* (2010) showed a structure strongly stratified at low levels over the Rio Grande do Sul, to the south of Brazil, with the possibility that the Serra Geral orography induces a low-level transverse circulation with LLJ, being one of the necessary conditions for the deep nocturnal convective trigger at the mesoscale level. A dynamic behavior that must be marked is that the vertical profile of the wind at low levels is the register composed of the different synoptic scales and forcings associated with the non-linear convective nature of the physical process. That compose it, being a register or a type of memory at the mesoscale level of turbulence and convection, which must retract the stratified structure and its decoupling in relation from the surface and above the maximum speed core of the LLJ, also at this highest level, there must be a degree of decoupling with the existence of the LLJ below, proportional to its magnitude of the LLJ. The use of regional climate modeling has made great strides in recent years, which has allowed us to have simulations of the order of a few kilometers (2 to 3 km), Copolla, *et al.* (2021). With this development, can use these simulations in high spatial resolution to generate detailed studies of situations that characterize phenomena of relevant synoptic interest. However, as Regional Climate models can simulate the main dynamic characteristics at the mesoscale level, between these circulations associated with the LLJ, which can vary from mesoscale to a continental scale, and with the significant existence of transport and convergence of mass and energy carried out by LLJ. It would certainly affect the time scales of the daily cycle of convection intensity, about a significant extension on the surface and
regionally. The integration of the regional model initialized with conditions of the Intergovernmental Panel on Climate Change (IPCC) models with the different scenarios could respond to this dynamic at the mesoscale level and its extremely non-linear nature. Although this work is a case study, this initial work will allow us to analyze possible limitations of the scenarios of the IPCC models in terms of the dynamics of mesoscale circulations. Therefore, this work sought to analyze simulations with two non-hydrostatic cores different from RegCM-4.9 (MM5 and Moloch Non-hydrostatic) for a situation with intense LLJ that occurred in Porto Alegre in the Rio Grande do Sul in June 1997.

2 METHODOLOGY

2.1 LLJ AND MAXIMUM WINDS (MW) CLASSIFICATION

The LLJ’s are classified according to the intensity and vertical shear of the wind module, following the classification proposed by Bonner (1968) and modified by Whiteman et al. (1997), in which a new category (weak LLJ) proposed by Corrêa et al. (2001), and modified by Corrêa (2005), which is shown in Table 1. For situations that do not characterize LLJ, a classification for Maximum Winds (MW) is used, using a classification similar to the previous one, but without the vertical shear criterion associated with jet situations and also without the class of Weak LLJ. The synoptic scales described show the occurrence of LLJ at different times of the year and different time scales, in which it shows predominant cycles between 1 to 5 days but can vary on a scale from 1 to 10 days, according to Nicolini et al. (2002). Corrêa et al. (2002) carried out a spectral analysis of the decreasing wind speed above the LLJ in El Nino-South Oscillations (ENSO) situations over Porto Alegre, in southern Brazil. Observing that the decay of the velocity modulus above the LLJ core is associated with different physical forcings with different time scales involved. This shows a type of memory of turbulence processes and their association with turbulent structures, resulting in cycles of occurrence of LLJ oscillating in periods of 14 to 20 days and with decay differences with velocity modulus in the order of 12 to 20 ms$^{-1}$, in the LLJ of greater wind speed intensity. This decay of the velocity module above the LLJ core is associated with the decoupling in the vertical wind profile and the gain realized by the optimized transport within the turbulent process at the mesoscale level in the processes associated with convection, a type of memory of this process.
Table 1 - Classification of LLJ and MW their associated intensities, in ms\(^{-1}\). Vertical decrease of the wind profile above the magnitude value of the LLJ.

<table>
<thead>
<tr>
<th>Category</th>
<th>LLJ</th>
<th>Maximum Value (ms(^{-1}))</th>
<th>Decrease (ms(^{-1}))</th>
<th>Category</th>
<th>MW</th>
<th>Maximum Value (ms(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>weak</td>
<td>&gt; 6</td>
<td>≥5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LLJ-0</td>
<td>≥10</td>
<td>≥5</td>
<td>MW-0</td>
<td>≥10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LLJ-1</td>
<td>≥12</td>
<td>≥6</td>
<td>MW-1</td>
<td>≥12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LLJ-2</td>
<td>≥16</td>
<td>≥8</td>
<td>MW-2</td>
<td>≥16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LLJ-3</td>
<td>≥20</td>
<td>≥10</td>
<td>MW-3</td>
<td>≥20</td>
<td></td>
</tr>
</tbody>
</table>

2.2 LLJ's CONCEPTUAL DYNAMIC MODEL

In southern Brazil, a well-defined geographic feature is the existence of a Serra Geral mountain, which occurs in the three southern states of Rio Grande do Sul, Santa Catarina, and Paraná, which follows the coast with a significant unevenness in relief. Its shape and height of the order of 1400 meters at its highest point cause a great impact on circulations at low levels. Corrêa (2005) showed that this structure is strongly stratified in the lower atmosphere near the surface, through the Principal Components Analysis (PCA) in the vertical profile of the Wind, allowing differentiating in its dynamic structure, two levels of height with LLJ or predominant Maximum Winds (MW) flow, which characterize the transport in the low levels in the atmosphere. This fact resulted from the development of this work, in which he described part of the turbulent nature of this transport within the Planetary Boundary Layer (PBL). The stratified structure of the vertical wind profile can be observed with the following seven combinations of profiles: (1) an isolated LLJ at the level of 950 hPa or closer to the surface, (2) an isolated LLJ at the level of 850 hPa or higher, (3) an isolated MW flow at the level of 950 hPa, but which does not characterize the existence of LLJ, (4) an isolated MW flow at the 850 hPa level, but which does not characterize the existence of LLJ, (5) an LLJ at the level of 950 hPa and an MW flow at the level of 850 hPa, (6) an MW flow at the level of 950 hPa and an LLJ at the level of 850 hPa and (7) an MW flow at the level of 950 hPa and an MW flow at the level of 850 hPa. Furthermore, it showed the association of intense LLJ with maximum daily precipitation at 7 am, associated with the transport mechanism and optimization of water vapor convergence and formation of thunderstorms during the night and dawn, one of the peaks of maximum daily rainfall. Figure 1 shows the predominant directions of flows and LLJ, the direction with the letter A, in which the flow or LLJ follows the relief of the coast over the Atlantic Ocean at the level of 950 hPa, this level
corresponds to heights approximately of the order of 250 to 500 meters. This flow and LLJ follows the coastal relief from the east of the Serra do Mar and manage to enter the continent from the northwest of The Rio Grande do Sul. Another situation characterizes the MW or LLJ flow that comes from the direction of the letter B to the west of the relief da Serra do Mar is forced to ascend and arrives over Rio Grande do Sul, corresponding to pressure levels in the order of 850hPa, and with a height in the order of 800 to 1500 meters. There may be situations with the existence of only the letter B or letter A or both, characterizing transverse circulations, which have an impact on nocturnal convection in the formation of clusters and deep convection until events with tornadoes in special cases. The MW and LLJ flows with the letter A and B can be associated with the processes of initiation and intensification of nocturnal convection as a dynamic theoretical model of the trigger balance of the convective process. The MW and LLJ flow with the letter C characterize flows of post-frontal situations after passing frontal systems as cyclonic vortices, with a tendency to LLJ of levels in the order of 950 hPa. The LLJ flow with the letter D can be associated with ocean breeze processes with an LLJ structure level of 950 hPa.

Figure 1 shows the predominant directions over the State of Rio Grande do Sul of the MW and LLJ flows.

3 REGIONAL CLIMATE MODEL
This work is developed looking for the use of a regional climate model in high spatial resolution to generate a case study to compare the intensity observed by radiosonde data at Salgado Filho Airport
with simulations performed with the RegCM-4.9 model in high resolution using two types of MM5 and the Moloch non-hydrostatic core, Davolio, et al. (2007). This technical possibility allows describing the development of a non-hydrostatic version of the regional climate model RegCM4, which is linked with the advances associated with the use of regional climate models, according to the work of Copolla, et al. (2021). The non-hydrostatic dynamic core of the MM5 mesoscale model is introduced in RegCM4, with some modifications to increase the stability and applicability of the model for long-term climate simulations. As well as MM5 non-hydrostatic core with recently available explicit microphysical schemes is also described. RegCM4 is currently being used in different projects for regional climate simulations in spatial resolutions aimed at representing convection processes. Therefore, the initialization and the boundary conditions of the historical model EC-EARTH were used based on the operational seasonal forecast system of the European Centre for Medium-Range Weather Forecasts (ECMWF), Hazeleger, et al. (2012), such as the initial and boundary condition of RegCM4.9, Giorgi et al. (2012) and Giorgi et al. (2015). The Community Land Model (CLM) version 4.5 (Oleson et al. 2008) was also used, it is the earth's surface model developed by the National Center for Atmospheric Research (NCAR) as part of the Community Climate System Model (CCSM), described in detail in Collins et al. (2006). This work aims to analyze the simulations of the historical EC_EARTH model / RegCM4.9 stored, between May 1 and July 1, 1997. The wind data observed in this work were obtained from the Brazilian Air Force Command Database. Table 1 shows the configurations and parameterizations used in the two simulations performed, seeking to use a strategy of using high spatial resolutions to obtain and observe the simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lateral boundary conditions scheme</strong></td>
<td>Relaxation, exponential technique, 18 points Marbaix et al. (2003)</td>
</tr>
<tr>
<td><strong>Planetary Boundary Layer (PBL) scheme</strong></td>
<td>Holtslag PBL, Holtslag (1990)</td>
</tr>
<tr>
<td><strong>Cumulus Convection schemes</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Over land</strong></td>
<td>Tiedtke (1996)</td>
</tr>
<tr>
<td><strong>Over ocean</strong></td>
<td>Kain-Fritsch (1990), Kain (2004)</td>
</tr>
<tr>
<td><strong>Moisture scheme</strong></td>
<td>Explicitmoisture (SUBEX, Pal et al. (2000))</td>
</tr>
<tr>
<td><strong>Ocean Flux scheme</strong></td>
<td>Zeng et al., 1998</td>
</tr>
<tr>
<td><strong>Zeng Ocean model roughness formula to used</strong></td>
<td>1- &gt; (0.0065<em>ustar</em>ustar)/egray</td>
</tr>
<tr>
<td><strong>Calendar</strong></td>
<td>Gregorian</td>
</tr>
<tr>
<td><strong>Globdatparam ssttyp</strong></td>
<td>EC-EARTH historical</td>
</tr>
<tr>
<td><strong>Globdatparam dattyp</strong></td>
<td>EC-EARTH historical</td>
</tr>
</tbody>
</table>
Land surface model | CLM4.5
---|---
Vertical levels | 
Domain 1 | 23
Domain 2-MM5 | 41
Domain 3-Moloch | 41

<table>
<thead>
<tr>
<th>Domain 1</th>
<th>168 x 188 grid points</th>
<th>31584 points</th>
<th>25 km horizontal resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain 2</td>
<td>168 x 188 grid points</td>
<td>31584 points</td>
<td>3 Km horizontal resolution</td>
</tr>
<tr>
<td>Domain 3</td>
<td>168 x 188 grid points</td>
<td>31584 points</td>
<td>3 Km horizontal resolution</td>
</tr>
</tbody>
</table>

Figure 2 shows the different domains used in simulations with the RegCM-4.9 climate model.

Figure 2 - Domain 1 – (a) - 25 km spatial resolution with 23 vertical levels, Domain 2 – (b) - 3 km spatial resolution with 41 vertical levels with MM5 non-hydrostatic core and Domain 3 – (b) - 3 km spatial resolution with 41 vertical levels and Moloch non-hydrostatic core.

Sources: Of own authorship.

4 RESULTS
4.1 INTRA-SEASONAL AND SEASONAL SCALES EL NIÑO-SOUTHERN OSCILLATION

There may be a very large meteorological variability, from year to year, over the southern region of Brazil. Associated with these changes, the Tropospheric Upper-Level Jets (ULJ) show significant and intense seasonal changes. The southern hemisphere in winter has a higher temperature gradient between Equator/Pole, resulting in more intense and persistent ULJ’s. In the summer, the ULJ’s have weaker gradients and wind values, but continue to operate, in a weaker way. LLJ’s coupled with ULJ’s follow this behavior seasonally. The data from radiosonde carried out at the International Airport Salgado Filho in Porto Alegre, according to Corrêa, et. al. (2001) reveal that the LLJ’s showed values on average more intense in the winter, around 20% higher, and the height of the LLJ’s showed differences of 40% between the winter/summer months, being lower in the winter. Such variation can
be intensified in situations of El Niño-South Oscillation (ENSO), in which studies of Long Wave Radiation (LWR) and anomalies of Sea Surface Temperature (SST) show the existence of teleconnections over the Pacific and the Atlantic Tropical, influencing rainfall in South America, according to Hoskins and Ambrizzi (1993), Figueroa (1997), Veiga, et al. (2002), Kayano, et al. (2019) and Hurtado & Agosta (2020), Pacific TSM anomalies influence monsoon rains in South America (MSA), modulating the intensity of the South Atlantic Convergence Zone and the high-level cyclonic vortex. When the influence is of the Atlantic Ocean, the meteorological systems that cause rain would be of local dynamics, in which the negative SST anomalies would produce temperature gradients between the ocean and the strongest continent, and with greater intensity in the anticyclone circulation, increasing the transport of humidity for the continent and, consequently, increasing the amount of rain in the MSA region. This indicates that the occurrence of regional effects interacts with large-scale ones, causing variations due to remote and local forcing. In the years of ENSO, there is an implementation of the intensity of the ULJ's, remote connection of the Pacific, in a way that presents a flow pattern in the upper troposphere that characterizes blocking situations, being linked to intense rainfall, as they occur in the southern region of Brazil, Uruguay, and Argentina, have already been studied by Kousky and Cavalcante (1984). Chu (1991), investigated the climatic anomalies in Brazil, associated with ENSO, noting that in the years of El Niño the rainfall in the southern region of Brazil tends to be above normal from April to December and from March to July of the following year, with the highest values in May and June. In such situations of ENSO, the ULJ’s are more intense and persistent, staying above normal, as there is the coupling already described by Uccellini and Jonhson (1979), the LLJ’s also present much more intense values. 1997 was characterized by an intense sign of ENSO. Figure 3(a), with the IR GOES-8 image of June 20 at 12 UTC and 2(b) of June 23 at 12 UTC, shows a characteristic ULJ blockade over Argentina and south of Brazil, showing a triangular shape with medium/high clouds over the region. Figures 4(a), 4(b), and 4(c) show, from the 21st to the 23rd of June, the occurrence of intense LLJ's of the LLJ-3 type, with speeds of the order of 30 ms$^{-1}$ and the direction of 300/310 degrees and height of 700/750 meters, according to radiosonde carried out at Salgado Filho International Airport in Porto Alegre.
Figure 3 - The IR GOES-8 image of June 20, 1997 at 12 UTC and 2(b) of June 23, 1997 at 12 UTC, shows a characteristic ULJ blockade over Argentina and south of Brazil.

Sources: https://redemet.decea.mil.br/.

Figure 4 – The vertical wind profile over Salgado Filho airport in Porto Alegre city (a) 21st June at 12 UTC, 3(b) 22st June at 12 UTC and 3(c) 23st June at 12 UTC, shows the occurrence of intense LLJ’s of the LLJ-3 type, about 30 ms-1.

Sources: Of own authorship.
Figure 5 shows the different domains simulated for June 1997. The different domains were not able to represent the stratified structure associated with the LLJ, even at high spatial resolution and with 41 levels; it does not show the vertical decoupling that should exist with a period in which the existence of LLJ in the radiosonde data is observed. The vertical profile of the wind direction represented approximately the direction in the days observed with LLJ, the direction of 270 degrees, but without characterizing the existence of LLJ. In the case of the vertical profile of the wind intensity at the levels of 930 hPa, it does not present a closed LLJ core of intensity and no decay above this level. Limitations are inherent to the initialization data of the global model used to input the regional model as it does not have the necessary vertical resolution to characterize the LLJ structure. The RegCM-4 model initialized with the historical EC-EARTH model does not have the necessary vertical resolution, or it also represents the stratified structure of the planetary boundary layer. The dynamic process with the existence of the LLJ between the PBL and the lower atmosphere creates complex physical conditions and non-linearity. The physics of turbulence at low levels of the atmosphere with LLJ is very efficient and makes a balance and transport of energy in convection. This means that the Intergovernmental Panel on Climate Change (IPCC) scenario model in the historical EC-EARTH model, there is evidence to present limitations of transport physics at the mesoscale level at midlatitudes in this case study. The RegCM-4 model could significantly underestimate what happened during the case study period of the existence of LLJ with extreme values and intensities. An analysis with a larger number of cases could be useful to define this limitation.


**Figure 5** - June 1997 period with the temporal section of the Wind direction vertical Profile - 25 km resolution (a); (c) 3 km resolution with MM5 core and (e) 3 km resolution with Moloch core. The Wind intensity vertical profile - 25 km resolution (b) and (d) 3 km resolution with MM5 non-hydrostatic core. (f) 3 km with Moloch non-hydrostatic core.

![Image of figure 5](image_url)

Sources: Of own authorship.

**5 CONCLUSIONS**

In this case study, despite the great advances in climate modeling at the moment, it is conjectured that the model initialized with a history of EC-EARTH underestimated the dynamics associated with the stratified structure of the LLJ. It may not have the vertical resolution needed for this purpose. This situation makes it clear that future scenarios that could be generated by future EC-EARTH scenarios may have difficulty in representing processes at the mesoscale level associated with dynamics to turbulent processes with the transport carried out by the LLJ. The global initialization models do not represent with the necessary information quality the wind speed decline above the LLJ core, which underestimates the real transport carried out. As the regional climate model RegCM-4.9
can be initialized with different scenarios and global models, we will seek initializations and control conditions with a high spatial resolution to analyze other cases, seeking to expand the studies associated with LLJ in southern Brazil.
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