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Verification of the role of the low level jets in Amazon squall lines

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ABSTRACT

In this study we present a climatology of the Amazon squall lines (ASLs), between the years 2000 and 2008, using satellite imagery and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses. The ASLs we are interested in are typically formed along the northern coast of Brazil and sometimes propagate for long distances inland. Results show that, on average, an ASL occurs every 2 days. ASLs are more frequent between April and June and less frequent between October and November. The years of 2005 and 2006 showed 25% more cases than the other years. This might be related to an increase of the Atlantic sea surface temperature. Of the total number of ASL cases, 54% propagated less than 170 km, 26% propagated between 170 and 400 km, and 20% propagated more than 400 km. We also studied the occurrence of low level jets (LLJs) associated with the coastal ASLs. Although LLJs are always present in the environment before the formation of the ASL and even on days without ASL cases, important differences were found, mainly related to the LLJ depths.

1. Introduction

The main characteristics of the atmospheric circulation over Northern Brazil have been studied for a number of decades. Molion (1993) classified the macroscale and the mesoscale circulations of Amazonia into three groups characterized by: *i*) diurnal convection resulting from surface heating under favorable large-scale conditions, *ii*) squall lines with origin in the North-Northeast coast of Brazil, and *iii*) mesoscale and large-scale convective clusters associated with the intrusion of frontal systems that interact with the Amazon region.

Amazon squall lines (ASLs) may form along all the Amazon River basin. Greco et al. (1990) categorized Amazonian convection into three separate categories: as coastal occurring systems (COS), basin occurring systems (BOS), and locally occurring systems (LOS). The main differences between these systems are in their geographical location, propagation and life cycle. The COS are particularly important as they are extensive, form along Brazil's northern coast, and propagate across the basin. These authors found that these systems have an average length of between 1000 and 2000 km but can often reach more than 3500 km. They also found that these ASLs propagate with velocity of 50–60 km h^{-1} with life cycle between 24 and 48 hours. Another result is that 12 of these systems occurred during the second phase of the Amazon Boundary Layer Experiment (ABLE 2B), and they alone produced 40% of the rain recorded during the whole experiment. This experiment was carried out between April and May 1987 to improve the understanding of the atmospheric and chemical processes of the central Amazon rain forest. Given the importance of the COS, Cohen (1989) further separated them into three groups according to the distance travelled: *i*) coastal line of convection (CLC) for the lines that propagated less than 170 km, *ii*) squall line type 1 (SL1) for the lines that propagated more than 170 km and less than 400 km, and *iii*) squall line type 2 (SL2) for the ASL that propagated more than 400 km.

A number of studies in the region suggest that the coastal ASLs may have their origin in the sea breeze circulations

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(Kousky, 1980; Sun and Orslanski, 1981), or in wave patterns that propagate in the tropical region (Houze, 1977).

According to Kousky (1980), once a cumulonimbus develops along a sea breeze front, a line of active convection might continue to propagate inland, possibly as a squall line. He noted that a breeze front penetrated far inland when the mean flow was perpendicular to the coast, whereas limited penetration of the breeze front occurred when the mean flow was more parallel to the coast or even directed toward the ocean. Sun and Orslanski (1981) studied the effects of sea–land contrast, viscosity, and diurnal variation of the planetary boundary-layer stratification related to trapezoidal instability. Their results showed that mesoscale internal gravity waves associated with local trapezoidal instability can be excited by the sea-breeze circulation near the coast where cloud bands originate and thus propagate inland. The period of these tropical mesoscale waves depends on the diurnal variation of the stratification as well as on the viscosity level. These authors also used a linear model to investigate the mechanism responsible for the propagation of the coastal squall lines. Their results showed that the breeze circulation produced a propagating wave associated with trapezoidal instability due to the diurnal variation of the boundary-layer temperature profile.

The behavior of a storm also depends on the atmospheric thermodynamic instability and the vertical wind profile. Weisman and Klemp (1986) showed that the vertical wind shear directly influences the organization, propagation, and lifetime of the systems. This organizational facet of the system is due to the ability of its gust front to activate new convective cells, and for its updraft to interact with the vertical wind shear to produce a larger and quasi-stationary storm structure. In the presence of a wind shear the system tends to follow the main flow. This causes an increase in the low-level convergence and the penetration of warm and moist air through the system front which is feeding the storm.

The article by Mansfield (1977) is among the first studies to relate a low level jet (LLJ) to the development of squall lines. Observational and numerical studies (e.g. Whiteman et al. 1997; Parsons et al., 2000; Lackman, 2002) showed that LLJs, associated with several convective systems, are responsible for part of the increase in water vapor content in the low levels of the atmosphere. This increase may play an important role in the general circulation, the generation and maintenance of the convective processes in both the mid-latitudes and the tropics.

Cohen (1989) used a number of sequences of infrared satellite images to document the monthly frequency, dimensions, and propagation velocity of the coastal ASLs between 1979 and 1986. Her results showed that most of the ASLs form during the southern hemisphere winter, coming from the East-Northeast quadrant with a mean speed of 16 ms^{-1}. She also analyzed the squall lines that formed during the ABLE 2B experiment and found the presence of a stronger and deeper LLJ, in the large-scale environment, on the days which experienced squall lines.

Silva Dias and Ferreira (1992) discussed whether a simple linear model is capable of indicating the dependence of the velocity of propagating unstable solutions on the vertical profile of the wind. In their model, a storm was represented as a package of internal gravity waves. They analyzed four cases with different atmospheric conditions of wind shear and storm formation and found a relative wind speed maximum around 800 hPa associated with an easterly propagating mode of 13 ms^{-1} for the cases whose wind profile corresponded to the occurrence of squall lines. Moreover, for these cases both the depth of the LLJ and the wind shear were greater, in agreement with the results of Cohen (1989). Accordingly, for the cases whose wind profiles corresponded to the non-occurrence of squall lines, the model consistently produced only unstable non-propagating modes.

Cohen et al. (1995) also studied the large-scale atmospheric conditions associated with the convective systems present during the ABLE 2B experiment. They confirm that the maximum mean zonal wind occurred around the 800-hPa level, and that there was a layer of constant velocity whose depth varied among the cases studied. They also showed that two large-scale mechanisms, namely easterly waves and tropical heat sources, may contribute to the occurrence of these LLJs.

Most of the studies that have tried to analyze the role of the LLJs on the development and propagation of the coastal Amazon squall lines spanned a relatively short time period and were focused on a certain period of the year. One can wonder whether these features still hold if the LLJ characteristics are analyzed for a larger and more heterogeneous time period. Other questions arise such as what is the difference in the environment of the formation of each ASL type and whether there is a special characteristic that favors the propagation of some of these systems.

Since the coastal ASLs are very important for the local and regional climate in view of their role as a rain-producing system and for their contribution to the mass, water, and energy balance of the tropics, a broader understanding of their dynamics, including the presence of the LLJs and their role in the system propagation, is necessary. In this study we document the association between coastal ASLs and LLJs for a 9-year period as a first step towards a more comprehensive documentation of the ASL dynamics.

2. Data and methodology

Initially a count of the coastal ASL occurrences between January 2000 and December 2008 was made, following the methodology proposed by Cohen (1989), which consists of a subjective analysis of infrared satellite imagery. They were analyzed in order to identify the systems that form on the northern coast of Brazil as a result of the development of the breeze fronts. The images have a time resolution of 30 minutes, cover all the Amazon basin area and consist of infrared and water vapor GOES-10 satellite products. To identify squall lines in the images we looked for convective cloud bands in the infrared images organized in line and aligned with the coastal contour between 10:00 UTC and 18:00 UTC.

Fig. 1 depicts a sequence of images of a coastal ASL that occurred on 21 July 2001. The ASL, shown in Fig. 1, reached 1200 km maximum length and 170 km width, and propagated southwards. It formed around 14:15 UTC (or 10:15 local time), and its lifetime was around 9 hours, with a northwest–southeast orientation. This ASL propagated more than 280 km

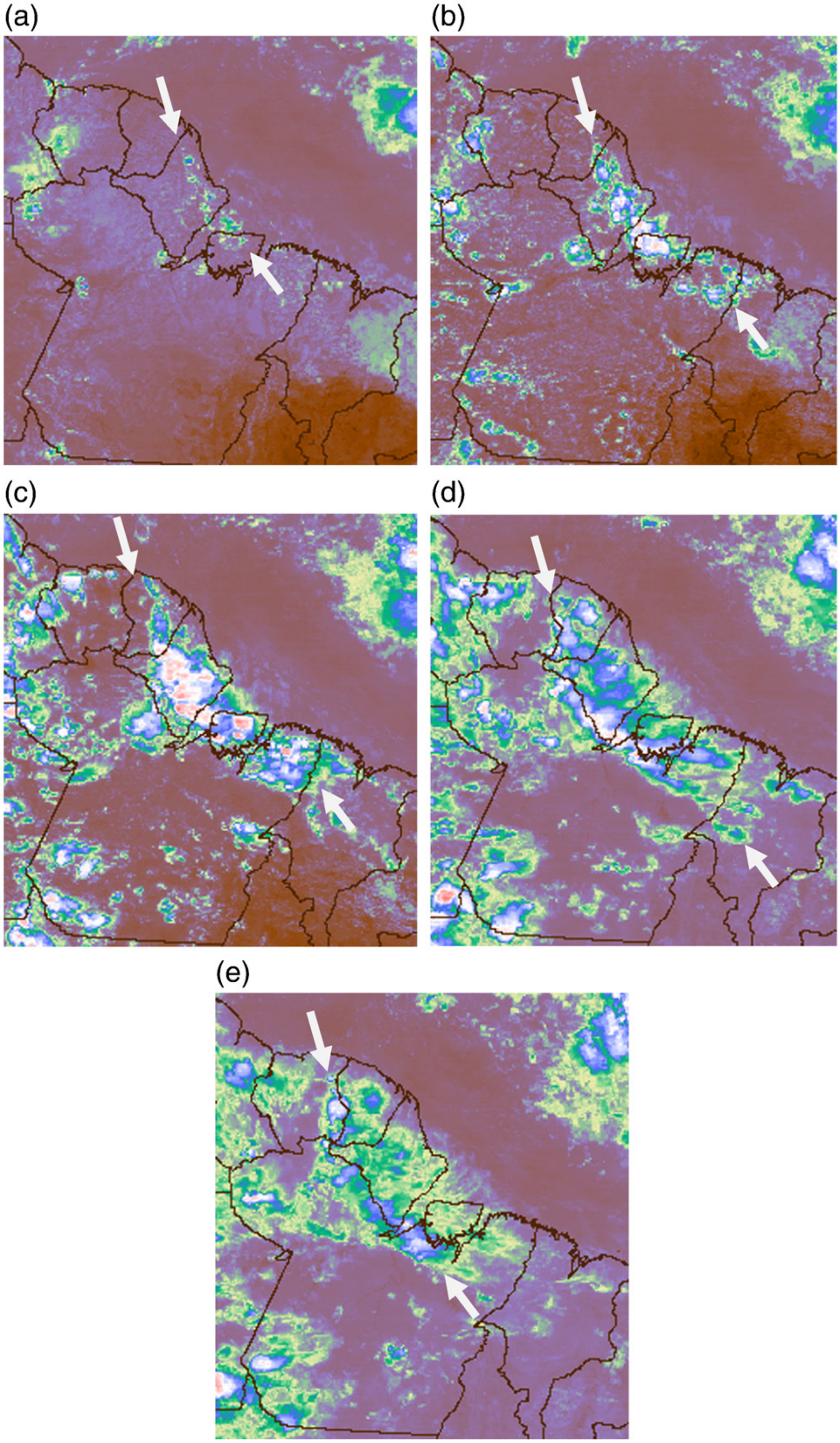

Fig. 1. GOES 10 satellite images for the formation region of an ASL that occurred on 21 July 2001 for the times (a) 14:15 UTC, (b) 16:45 UTC, (c) 19:15 UTC, (d) 22:15 UTC and (e) 23:45 UTC. Arrows indicate the ASL limits.

with a mean speed of 34 ms^{-1}. Therefore, following Greco et al. (1990), this ASL can be considered a COS, and, according to Cohen (1989), this COS is of the SL1 type. All the cases for the period were analyzed and categorized according to the distance travelled as coastal line of convection (CLC) for the lines that propagated less than 170 km, squall line type 1 (SL1) for the lines that propagated more than 170 km and less than 400 km, and squall line type 2 (SL2) for the ASL that propagated more than 400 km.

Next, an analysis of the horizontal wind was performed using the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis for the same period of images. The retrieved values are horizontal wind with information on low level jet (LLJ) occurrence, wind speed and level of maximum wind. This reanalysis set has a resolution of $1.5° \times 1.5°$, and the values used in this study correspond to the nearest grid point to Belém (1.38°S; 48.48°W). (See Fig. 2 for the location of Belém and other features of this study.) An ideal dataset for all these demonstrations could be the original atmospheric soundings, but these archives have many gaps in time that may give a false appearance to the results. Because we work with a large-scale characteristic of the tropical atmosphere, the reanalyses are the better dataset to work with.

Fig. 3 shows the difference of zonal component of wind velocity between original soundings in Belém city and reanalyses at a point near Belém (indicated in Fig. 2) for June 1 to 22, 2001, as an example. It should be noted that the greatest differences are at high levels above 500 hPa and on most days, the reanalyses overestimated the velocity values. The regions under 500 hPa, where the differences are lowest, have more impact on storm development according to many authors in the literature. Although the study with reanalyses has limitations, they still are the better dataset option, whereas soundings have considerable discontinuity.

A preliminary analysis showed that the meridional component makes a very small contribution to the total wind. Therefore, the analyses of this work will consider the zonal wind alone. In order to obtain information about a typical basic state, representative of the conditions preceding storm formation, we use data from 12:00 UTC (9:00 local time). We chose this time because at 18:00 UTC the data tends to be contaminated by the mesoscale circulations and may no longer be representative of the large-scale environment. The LLJs were characterized by identifying a maximum velocity between the 900 and 600-hPa levels. Then the intensity and level of occurrence of the LLJs and their direction were determined.

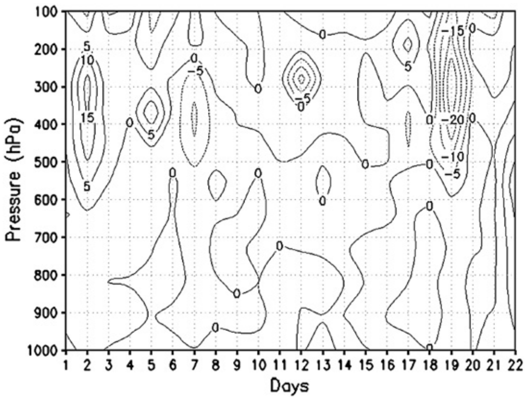

Fig. 3. Difference of zonal component of velocity between original soundings in Belém city and ECMWF reanalyses in a point near Belém for June 1 to 22, 2001.

Finally, the analysis was completed by using the sea surface temperature (SST) from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) for the same period, with resolution of $2.5° \times 2.5$. The average values are taken for a point in the Atlantic Ocean, at 1.0°N; 35.0°W. This area was chosen in order to evaluate the relationship between the SST, the LLJs and the ASLs. The location is shown in Fig. 2.

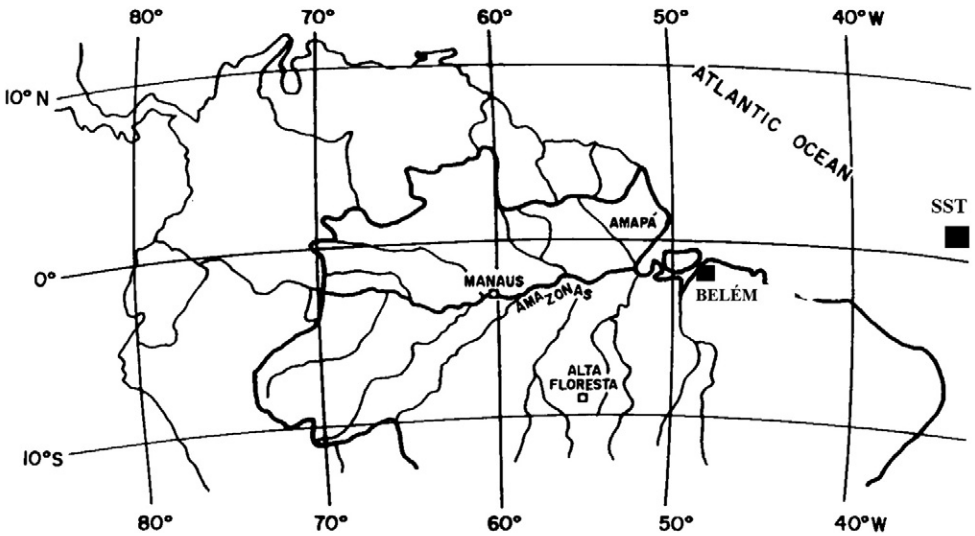

Fig. 2. Map of the region under study showing the city of Belém, the Amazon river basin, and the point where the values of sea surface temperature (SST) were taken in the Atlantic Ocean (adapted from Cohen et al., 1995).

3. Results and Discussion

The counting of coastal ASLs in the satellite images made it possible to evaluate both the annual and monthly distributions of the ASL cases. Of the total of 2987 images available for the January 2000 through December 2008 period, 1436 showed the presence of an ASL that formed along the northern coast of Brazil. This corresponds to an average occurrence of one ASL every 2 days, obtained by dividing the number of ASL by the number of days in the period from 2000 to 2008. This does not mean that an ASL actually occurs every other day, only that the average occurrence period is 2 days. Fig. 4 shows the distribution percentage according to the ASL category. Of the total number of cases, 775 (54%) are of the CLC type, 375 (26%) are of the SL1 type, and 286 (20%) are of the SL2 type. These numbers suggest that there must be a mechanism that acts in roughly half of the cases to favor the propagation of the ASL for long distances.

Although only 20% of the ASLs travel more than 400 km, Rickenbach (2004) studied a coastal ASL that propagated southwestwards for 3000 km from its origin, following the mean flow into the Amazon basin. This line was 1000 km long, had mean velocity of 13 ms^{-1}, and a 48-hour lifetime. He pointed out that this type of long-distance travelling ASL contributes both to the occurrence of a secondary maximum in cloudiness during the night over the interior of the basin and to the nighttime rain that frequently falls in the Amazon.

Fig. 4 also shows the percentage of LLJs present in each type of coastal ASL. Of the 1436 cases, 1254 (87%) have a LLJ. This percentage is roughly the same for each ASL category, that is, 89% of CLC, 85% of SL1, and 86% of SL2. This suggests that the presence of a LLJ per se is not enough to allow one to differentiate between the ASL types.

Fig. 5 shows the monthly distribution of ASLs and LLJs for the period of this study. The ASLs are more frequent from April to July, corresponding to part of the rainy season and part of the transition from wet to dry season in the region. These are the months when the SL2 type is more frequently observed. This result supports the studies by Cohen (1989) and Cohen et al. (1995). Fig. 5 also shows that the variation in the occurrence of LLJs follows the variations of the ASL cases (i.e., the higher the number of ASLs the higher the number of LLJs). April and May were the months with most ASLs and also the two months with most LLJs.

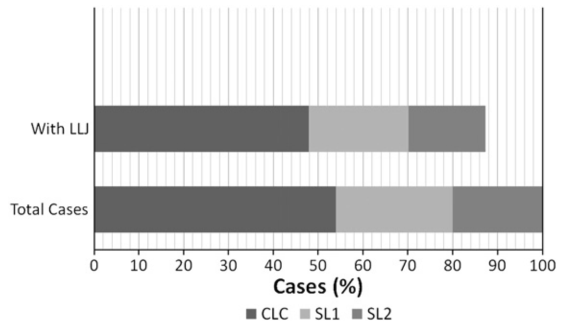

Fig. 4. Distribution of squall line cases (bottom), and cases with the presence of low level jets [LLJs] (top) between January 2000 and December 2008 for each ASL type.

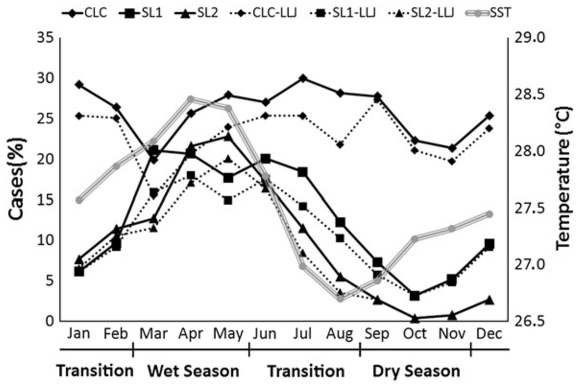

Fig. 5. Monthly distributions of the coastal Amazon squall line cases (continuous lines) and the corresponding occurrence of low-level jets (dotted lines). Below we show the time periods of Wet Season (Mar–May), Dry Season (Sep–Nov) and Transition Season (Dec–Feb) and (Jun–Aug). The heavy line is the mean sea surface temperature for the point shown in Fig. (2).

The annual distribution of ASLs is shown in Fig. 6. The years of 2005 and 2006 showed about 25% more coastal ASL cases in comparison with the other years. Even though 2005 and 2006 showed an increase in all the ASL types, the number of ASLs of the SL1 type does not seem to be much higher than in the other years. The increase is more pronounced for the ASLs of the CLC and SL2 types. This suggests that during 2005 and 2006 the conditions were more favorable for the formation of standing ASLs and for the very long distance travelling ASLs.

Fig. 6 also shows that the LLJ cases follow the tendency of the ASL cases. Therefore, an increase in the LLJ cases is also observed in 2005 and 2006. This confirms that LLJs are intrinsic characteristics of the development environment of the ASLs regardless of whether or not they propagate.

The year of 2005 is special because it registered the worst drought in 40 years in the central-south Amazon. According to Marengo et al. (2008), this drought was caused by warm anomalies in the north tropical Atlantic, a reduction of the moisture transport by near surface trade winds, and a weakening of the vertical velocity that caused less development of convection and rain. According to these authors, the northern part of the Amazon basin where coastal ASLs form

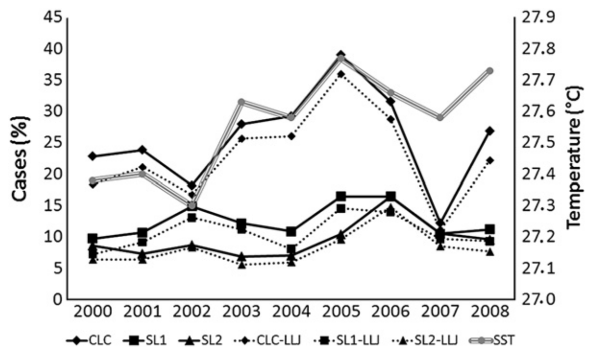

Fig. 6. Annual distributions of the coastal Amazon squall line cases (continuous lines) and the corresponding occurrence of low-level jets (dotted lines). The heavy line is the mean sea surface temperature for the point shown in Fig. (2).

did not suffer from the drought. Although coastal ASLs are among the main rain-producing systems in the Amazon, the region is vast, and large-scale systems are responsible for most of the rain. Therefore, Marengo et al. (2008) verified anomalous patterns both in the SST and in atmospheric circulation that resulted in negative anomalies of rain in central-south Amazon. Indeed, in this part of the Amazon, the ASL of the SL2 type that frequently arrives during the night is already in the dissipation phase of its lifetime, causing weak rain episodes (Rickenbach, 2004).

As such changes in the SST patterns were observed in this study, they might have contributed more to formation and propagation of the ASLs in 2005 since a warmer SST favors the formation of more easterly waves that can reach the northern coast of Brazil (Shapiro and Goldenberg, 1998). These easterly waves may be responsible for the deepening of the LLJs (Burppe, 1972; Cohen et al, 1995; Diedhiou et al., 1999). Garner et al. (2009) noticed a tendency of an increase in the Atlantic SST for the period between 1980 and 2006. They detected more tropical cyclone activity in 2005 and 2006.

Fig. 6 suggests that an increase in the Atlantic SST causes an increase in the ASL cases. The correlation coefficient between SST and total cases of ASL was 0.62. This is significant for the confidence level of 99.5%. Fig. 5 also shows mean monthly SST for comparison. This result therefore allows us to speculate that increasing the SST in certain areas can favor the formation of more coastal ASL, and can indirectly lead to deeper LLJs through the intensification of the easterly waves. However, these points need to be addressed in more detail in a future study.

Although low level jets are present in most of the cases of formation and development of the Amazon squall lines, there are some important differences between coastal and propagating lines. Fig. 7 shows the mean profiles of the zonal wind for the days without an ASL and for the days with an ASL, as well as for the CLC, SL1 and SL2 cases. It can be seen that the LLJs associated with the coastal lines are about 0.8 ms^{-1} less intense than those of the propagating lines that reach more than 400 km (see Table 1). The mean intensity of the LLJ associated with SL1 is about 0.4 ms^{-1} less than those associated with SL2. Also, for both the days with and without an ASL, the mean intensity of the maximum low level wind is about 9 ms^{-1}. This result suggests that it may not be the LLJ intensity that determines the ASL type. It seems that the LLJ's

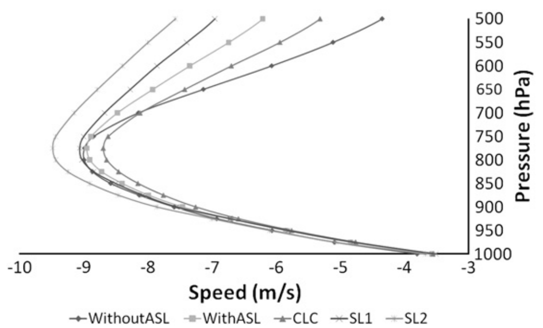

Fig. 7. Mean profiles for all days without ASLs, with coastal Amazon squall line cases (with ASLs), coastal lines of convection (CLC), squall line type 1 (SL1) and squall line type 2 (SL2).

Table 1
Mean value of maximum intensity of LLJ and their standard deviation for days without and with ASL formation and CLC, SL1 and SL2.

	Mean	Standard deviation
Without ASL	−9.0	3.0
With ASL	−9.0	2.5
CLC	−8.7	2.5
SL1	−9.1	2.4
SL2	−9.5	2.4

depth plays a more important role in this. Fig. 7 further shows that the LLJ is deeper in SL2 cases than in days without an ASL formation. In this discussion, all the calculated averages and differences are significant to the 99.5% confidence level, according to the Student's t-test.

In order to explore the depth dependence, we devised an index (ΔN), which consists of the difference between the pressure at the level of maximum wind and the pressure of the level above which the wind is one third of the maximum value. Fig. 8a shows the frequency distribution of ΔN for cases observed between 2000 and 2008 for CLC and for squall lines that propagated (SL1 + SL2) [SL]. SL1 and SL2 cases have been combined because the difference in depth is clearer. In fact, the differences between SL1 and SL2 LLJ depth did not indicate a pattern. The frequency distribution of ΔN is relative to the total number of cases of each ASL type. One can see that CLC had a tendency to have a shallower LLJ than SL, because 43% of CLC cases had depth between 101 and 300 hPa, and 43% of SL cases had depth between 301 and 500 hPa. This is confirmed by Table 2, which shows the mean depth and central value of the distribution. For CLC total cases, the mean LLJ depth was 363.03 hPa while for SL total cases the LLJ depth was 444.60 hPa, about 22% deeper than in CLC cases. It seems that the depth of the LLJ is a factor that influences the existence of a propagating ASL. Our results are in agreement with those of Cohen et al. (1995) and Silva Dias and Ferreira (1992), who examined the period between April and May 1987. They found that a more intense and deeper LLJ is associated with propagating systems like SL2. When the LLJ was weaker and shallower, the model utilized by Silva Dias and Ferreira (1992) produced a stationary mode, indicating the absence of a propagating disturbance.

To gain insight into the LLJ characteristics that may have contributed to the increase of the ASL cases in 2005 and 2006, Fig. 9 displays the average zonal wind velocity profiles for the first 5 years (2000–2004), for the 2005–2006 period, and for the two following years (2007–2008). In the discussion that follows, all the calculated averages and differences are significant to the 99.5% confidence level, according to the Student's t-test. Fig. 9a shows the profiles for all the ASL types for each period. The 2005–2006 period presents a stronger jet in comparison with the two other periods, whose average characteristics are more similar. Fig. 9b displays the difference between the mean CLC type cases and the total average shown in Fig. 9a for each period. In general, the LLJ intensity was close to the mean value only for the 2007–2008 period. For the two other periods (which present more CLC type cases, see Fig. 6), the average LLJ is weaker. Fig. 9c is the same as Fig. 9b, but for SL1 type cases. Again the 2007–2008 period exhibited a mean LLJ which was slightly weaker than the

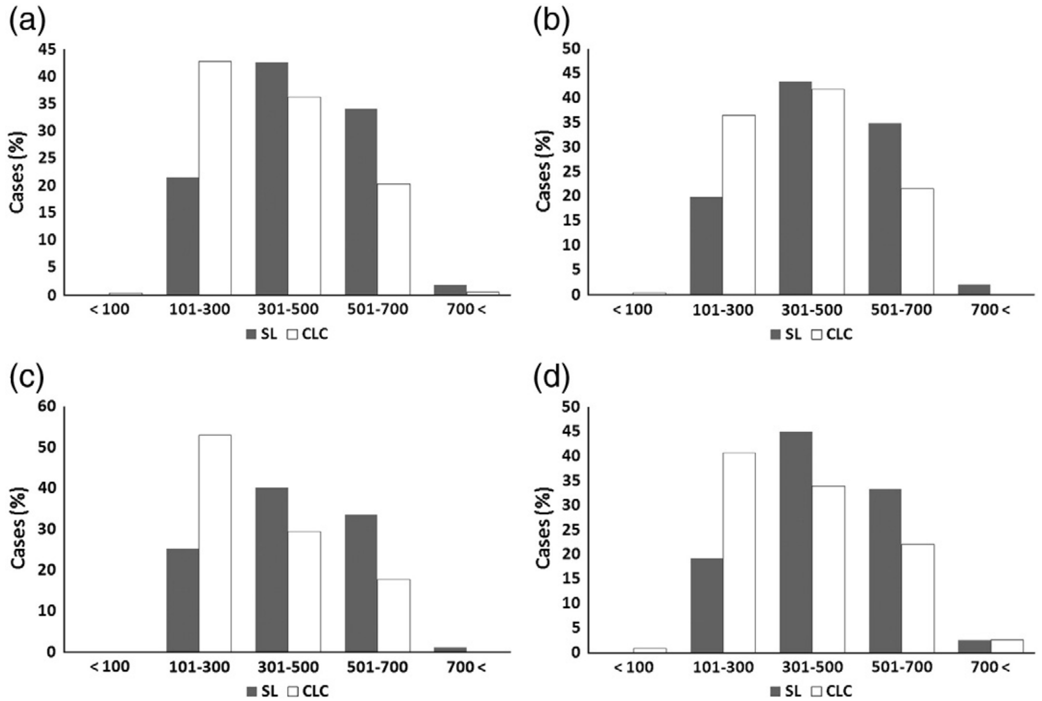

Fig. 8. Frequency distribution of an LLJ depth index (ΔN) for all CLC and SL cases (a), for CLC and SL between 2000–2004 (b), 2005–2006 (c) and 2007–2008 (d).

average of all cases for the period, whereas the two other periods showed a more intense mean LLJ. Nevertheless, this difference does not seem to impact the number of SL1 type cases, which is not very different for the three periods (see Fig. 6). Fig. 9d is the same as Fig. 9b–c, but for the SL2 type cases. In this case the wind is stronger than the average of all cases for all the periods. While the 2000–2004 and 2007–2008 periods are very similar, the 2005–2006 period presents a stronger LLJ. This might be related to the increase in the ASL of the SL2 type for this period.

Looking at the other graphs in Fig. 8 that show the frequency distribution of ΔN for CLC and SL in 2000–2004 (Fig. 8b), 2005–2006 (Fig. 8c) and 2007–2008 (Fig. 8d), it seems that for 2000–2004 ΔN in both CLC and SL was preferred between 301 and 500 hPa. For 2005–2006, ΔN was 101–300 hPa for CLC type and 301–500 hPa for SL. Finally, for the 2007–2008 period, ΔN had the same configuration as 2005–2006, with the majority of CLC cases between 101–300 hPa, and SL cases with ΔN between 301–500 hPa. Thus, in the period when an increase of ASL occurrences was observed, the LLJ depth tended to be greater for propagating SL than for CLC. This information can be confirmed for Table 2, which shows the mean and central value of ΔN.

Table 2
Mean and central values (in parentheses) for all CLC and SL cases between 2000–2004, 2005–2006 and 2007–2008.

	CLC	SL
Total	363.03 (350)	444.60 (450)
2000–2004	375.85 (375)	448.84 (450)
2005–2006	339.46 (300)	436.01 (450)
2007–2008	372.27 (350)	448.67 (450)

Our results suggest that the LLJs are a mechanism that is almost always present in the wind profile of the coastal area of northern Brazil but with certain differences between the periods with and without ASL formation. There are also differences between the ASL types in terms of the possibility of propagation. Propagating ASLs are characterized by a more intense LLJ than those that do not propagate. However, the most remarkable characteristic we have found here is the relationship between the LLJ depth and the tendency of an ASL to propagate. We found that deeper LLJs are associated with traveling ASLs.

In this case, LLJ can have the propriety to modify the environment favoring the propagation of ASL. Since the temperature and mixing rate vertical profiles near the equator show extremely low day to day variability, the presence of LLJ, and its depth, is fundamental in providing mid-level inflow into the cloud system that will intensify cloud-scale downdrafts and thus provide intense cold pools at the surface (Betts, 1976). These aspects will be studied in the near future using numerical simulations.

4. Conclusions

Amazon squall lines (ASLs) are a subject of paramount interest for studies of local and regional climates. ASLs are responsible for exporting large amounts of energy and are thus also important for the global climate. Since they are one of the mechanisms responsible for the precipitation over the Amazon River basin, the importance of a more thorough understanding of their dynamics has become more obvious in recent years. Since most of the studies on ASLs covered a specific period of time, usually related to an experimental

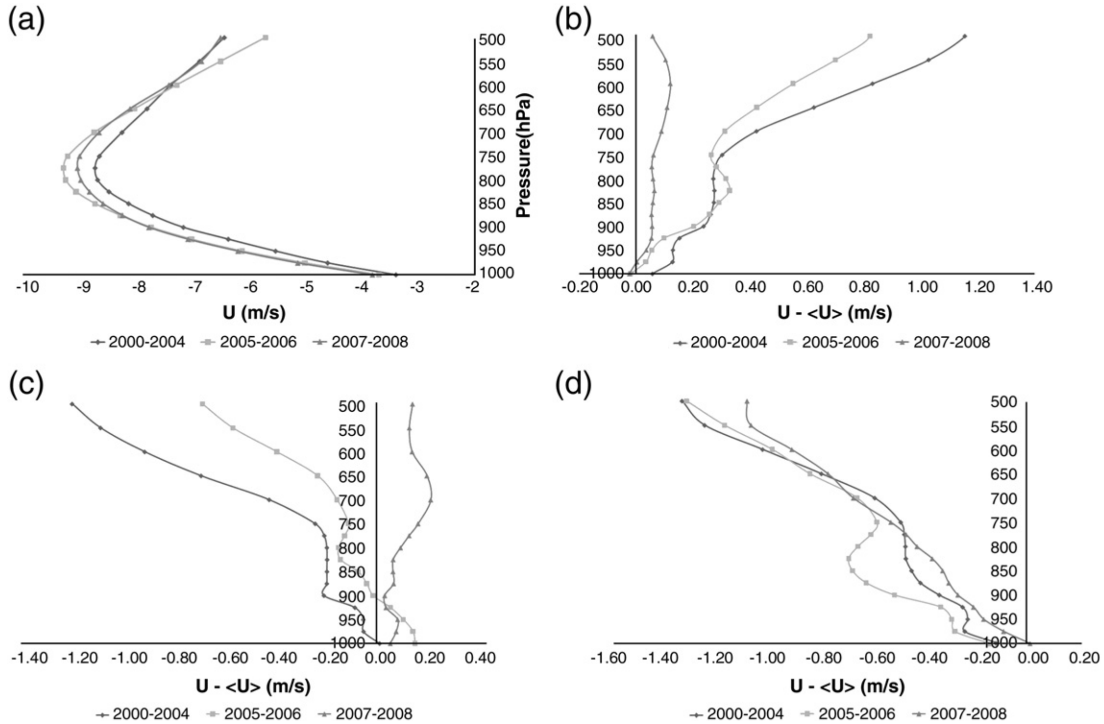

Fig. 9. Mean zonal wind profiles of all Amazon squall lines for 2000–2004, 2005–2006, and 2007–2008 (a); and differences between mean profiles in each period and CLC (b), SL1 (c) and SL2 type (d).

field campaign, we used satellite imagery and reanalysis data to produce a more comprehensive climatology of the coastal ASL cases that occurred between January 2000 and December 2008. Most of the studies on ASLs acknowledged the presence of low level jets (LLJs) in the large-scale environment as a mechanism that could help to explain the genesis and propagation of ASLs. Therefore, we also produced climatology of the occurrence of LLJs related to the ASL cases in order to clarify certain aspects of this relationship.

Our results showed that of the 1436 ASLs identified in this study, 54% were of the CLC type, 26% of the SL1 type, and 20% of the SL2 type. The months with most ASL cases were April to July. The years of 2005 and 2006 had 25% more cases in comparison with the other years in this study. LLJs were present in 87% of the ASL cases. This percentage roughly follows the seasonal cycle and the annual distribution of the ASL cases. The years of 2005 and 2006 presented more intense and well-defined LLJs in comparison to the other periods. In general, propagating ASLs were associated with more intense and deeper LLJs, in comparison with the coastal lines and days without ASLs.

Although we managed to find a number of differences in depth and intensity of the LLJs associated with propagating lines in comparison with the coastal lines, they do not seem to ultimately define the characteristics of the ASLs. Indeed, we need to advance in the physics of other mechanisms that can shed light on this matter. Future work includes a more detailed study of other features that may be related to the dynamics of the Amazon squall lines, such as thermodynamic stratification and atmospheric ducting.

Acknowledgments

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