An Acad Bras Cienc (2022) 94(3): e20201739 DOI 10.1590/0001-3765202220201739
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

GEOSCIENCES

Analysis of meteorological variables interaction associated with the environment of formation of Amazonian squall lines

CLÊNIA R. ALCÂNTARA, IZANA O. CARNEIRO & GABRIELLE B. OLIVEIRA

Abstract: The relationships among humidity, air temperature, wind, and vertical velocity with formation and propagation of Amazonian squall lines (ASL) is analyzed in this study. One year of data (2005) is verified by counting ASL cases according to their classification (propagated and non-propagated) to understand more clearly how the variation of these variables over this year influences their environment of formation. The results show an increase in humidity on days with ASL, with the highest occurrence during the wettest months. Furthermore, system propagation toward the interior of continent seems to be strongly related to the moisture content that reaches the coast, through the winds that blow from the ocean from both by the Northeast Trade Winds, of the North Atlantic Subtropical High, and by the Southeast Trade Winds, of the South Atlantic Subtropical High. Higher moisture content from the sea corresponds to a higher wind intensity toward the coast. A relationship between continent/ocean temperature gradient and the ASL amount and types formed is also demonstrated. Such information is extremely relevant because of the great importance of these systems in the extreme north and northeast regions of Brazil, particularly at the Amazon, given the difficulty of predicting them due to their complexity.

Key words: Amazon, annual variation, humidity, temperature, wind.

INTRODUCTION

One of the most relevant and common atmospheric systems in the northeastern Brazil and Amazon region is the Squall Line (SL), which are organized groups of cumulonimbus clouds that move simultaneously, responsible for high rates of precipitation in these regions. As Cavalcanti (1982) state, their existence is related to the circulation of sea breeze and daytime oscillation, and they are important for transport of heat to high troposphere. Its maximum activity is typically observed at nightfall. According to Alcântara (2010), they extend 1000 to 2000 km but can reach 3500 km. They propagate at a speed between 50 and 60 km h^{-1}, and they last approximately 48 h. The life cycle of these systems can be categorized into six stages: genesis, intensification, maturity, weakening, re-intensification, and dissipation, as shown by Garstang et al. (1994).

According to Cohen et al. (1995), the classification of SL is based on their horizontal propagation inland: CSL are Coastal Squall Lines, which propagate at less than 170 km; PSL1 are squall lines with type 1 propagation, between 170 and 400 km; and PSL2 are squall lines with type 2 propagation, which exceed 400 km. One factor that can be directly associated with the propagation of Amazonian Squall Lines (ASL) are the low level jets (LLJ), because, as observed by Oliveira et al. (2016), the occurrence of LLJ follows the occurrence variations of squall lines; furthermore, according to Alcântara

(2010), intense jets are more common in PSL than in the SL. However, this factor is not the only one responsible for making ASL spread over hundreds of kilometers, but it can be just one of the contributing elements for its spread (Alcântara 2010).

Because of their complex and multiscale characteristics, in which several processes at different time and space scales make up the final system, the ASL become difficult to simulate and predict. For this reason, the analysis of variables behavior in ASL formation environment, such as specific humidity, air temperature, horizontal wind, and vertical velocity, is of great importance in the effort to understand how these systems are formed, intensified, and propagated.

MATERIALS AND METHODS

Study area

The study region comprises latitudes of 10° N and 20° S and longitudes of 20° and 60° W (Figure 1), covering Guyana, Suriname, French Guiana, and the states of Amapá, Pará, Tocantins, Goiás, the Northeastern states and parts of Minas Gerais, Mato Grosso, and Espírito Santo.

Data

Information regarding the days with (withASL) and without (withoutASL) ASL was obtained from the climatology performed by Alcântara et al. (2011), in which the days with CSL, PSL1, or PSL2 were counted between the years 2000 and 2008. The method used for identification and classification of ASL followed the methodology proposed by Cohen et al. (1989). Within this nine-year period, the chosen year of study was 2005, owing to the large number of ASL in the region

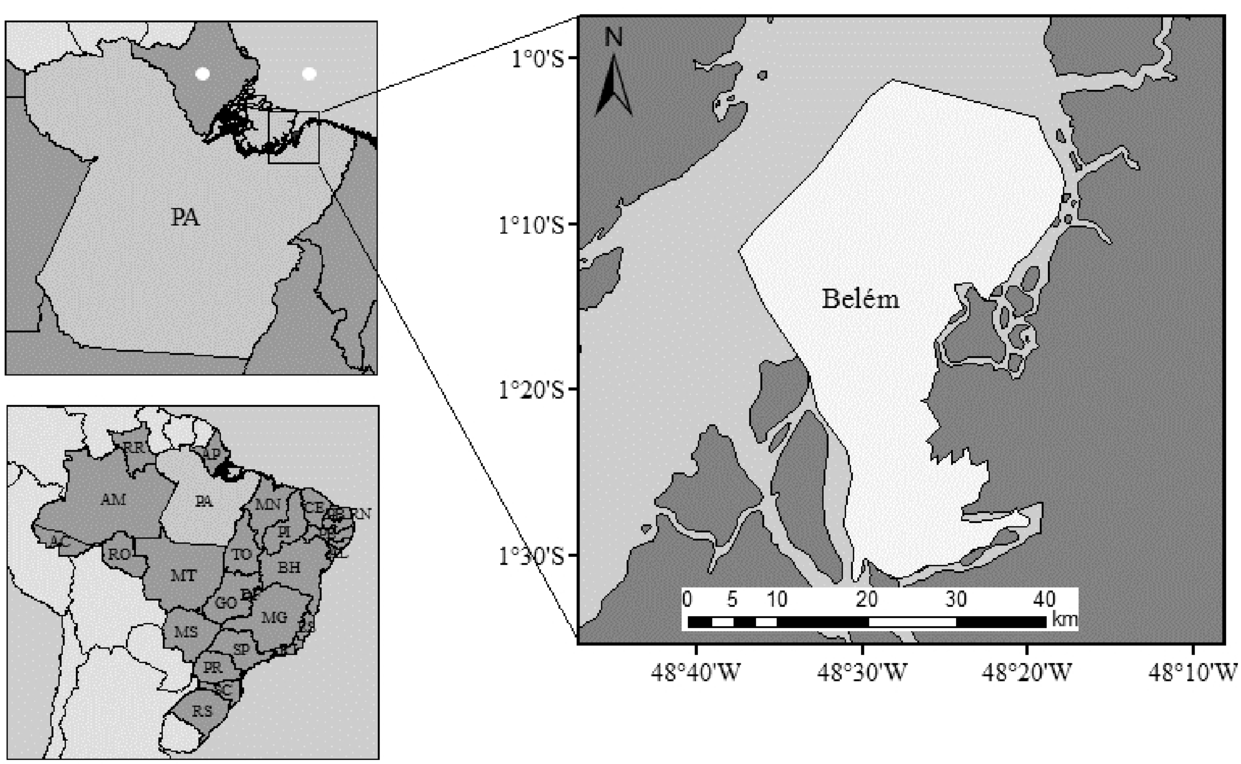

Figure 1. **Area of ASL study with emphasis on Belém - PA. The white circles in the upper left figure represent the points used to calculate the temperature differences (ΔT) listed in Table I.**

near Belém, a number well above the average observed by Alcântara et al. (2011).

For this study, data from ERA-Interim of the European Centre for Medium-Range Weather Forecasts were used. These data were downloaded at a grid resolution of 0.75° × 0.75°, the equivalent of approximately 83 km by 83 km. They were manipulated through the Climate Data Operators (CDO), NetCDF Operators (NCO), and Grid Analysis and Display System (GRADS) software to calculate the average monthly fields for the year 2005. Specifically, the differences were analyzed in terms of their daily means with and without squall lines by GRADS for the variables: specific humidity (g kg^{-1}), temperature (K), and horizontal wind at the level of 1000 hPa and for the variable vertical velocity (Pa/s) at 775 hPa.

The 1200 UTC schedule was chosen for the following analyses to facilitate the observation of variables at a time prior to the formation of systems under study. The analysis of these variables was necessary, because they are some of the most important in the process of convective system formation.

RESULTS AND DISCUSSION

This session discusses the main results of large-scale characteristics associated with the differences in monthly daily means with and without ASL.

The year 2005, in particular, had an ASL high frequency (Alcântara et al. 2011), and the large-scale configuration presented was influenced by an El Niño event, which had already lasted since October 2004 (Marengo et al. 2011). In addition to the performance of El Niño, during the study period, sea surface temperature (SST) of North (South) Tropical Atlantic showed positive (negative) anomalies, i.e., higher (lower) temperatures than climatological average. Thus, North (South) Atlantic Subtropical High was less (more) intense and, consequently, trade winds from the northeast (southeast) were less (more) intense on northern coast of South America (Serrão et al. 2015). This kept Inter-Tropical Convergence Zone (ITCZ) from reaching its position further south of the equator and, consequently, affected rainfall regime in the northern and northeastern regions of Brazil.

Figure 2 illustrates monthly distribution of ASL cases number in 2005. A total of 240 cases can be observed, with highest numbers recorded between rainy season months (March, April, and May) and the transition to dry season (June, July, and August) in the region. In the following months (September, October, and November), the number of ASL cases recorded decreased considerably, coinciding with the dry season. Of

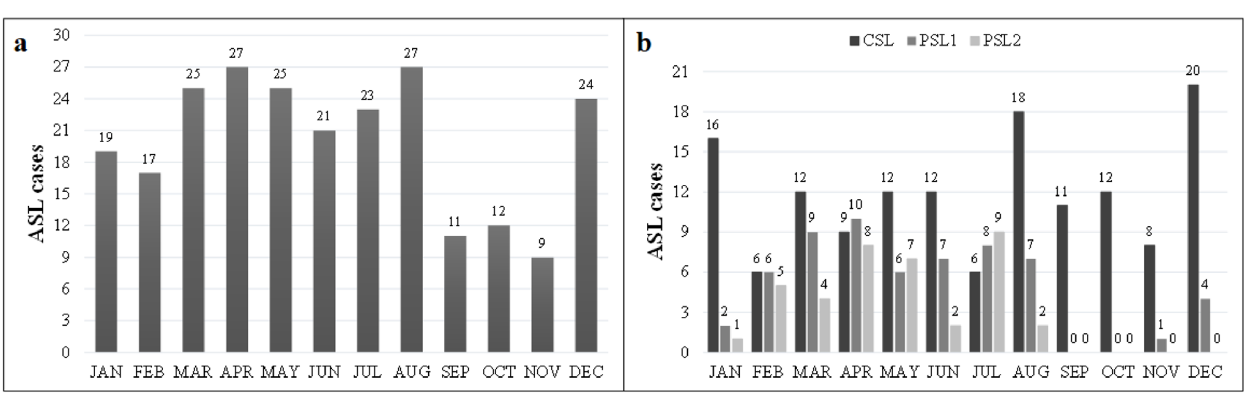

Figure 2. (a) Frequency histogram of ASL for the year 2005; (b) Frequency histogram of ASL according to their classification by propagation.

the total ASL registered in the period, 142 (59%) were of type CSL, 60 (25%) PSL1, and 38 (16%) PSL2 (Figure 2b).

The occurrence of El Niño phenomenon, associated with positive dipole in the North Tropical Atlantic in 2005, brought, as a consequence, a decrease in precipitation in southern and western parts of the Amazon basin and became known in the literature as the Great Drought of 2005 (Marengo et al. 2011, Lewis et al. 2011, Serrão et al. 2015). Thus, the large-scale circulation configuration established in this year may have induced ASL development on the northern coast of Brazil, especially those of type CSL, as seen in Figure 2b and in Alcântara et al. (2011), which demonstrates the analysis of nine years of data (2000-2008).

Figures 3 and 4 illustrate difference fields between the monthly averages of withASL and withoutASL days for each variable studied—specific humidity (g kg^{-1}), horizontal wind (m s^{-1}), temperature (K), and vertical velocity (Pa s^{-1}). Analyses and comparisons are made between months as well as quantity of events counted in each month, besides system propagation factor.

Analyzing the first quarter of the year (January, February, and March), the difference fields of specific moisture monthly averages

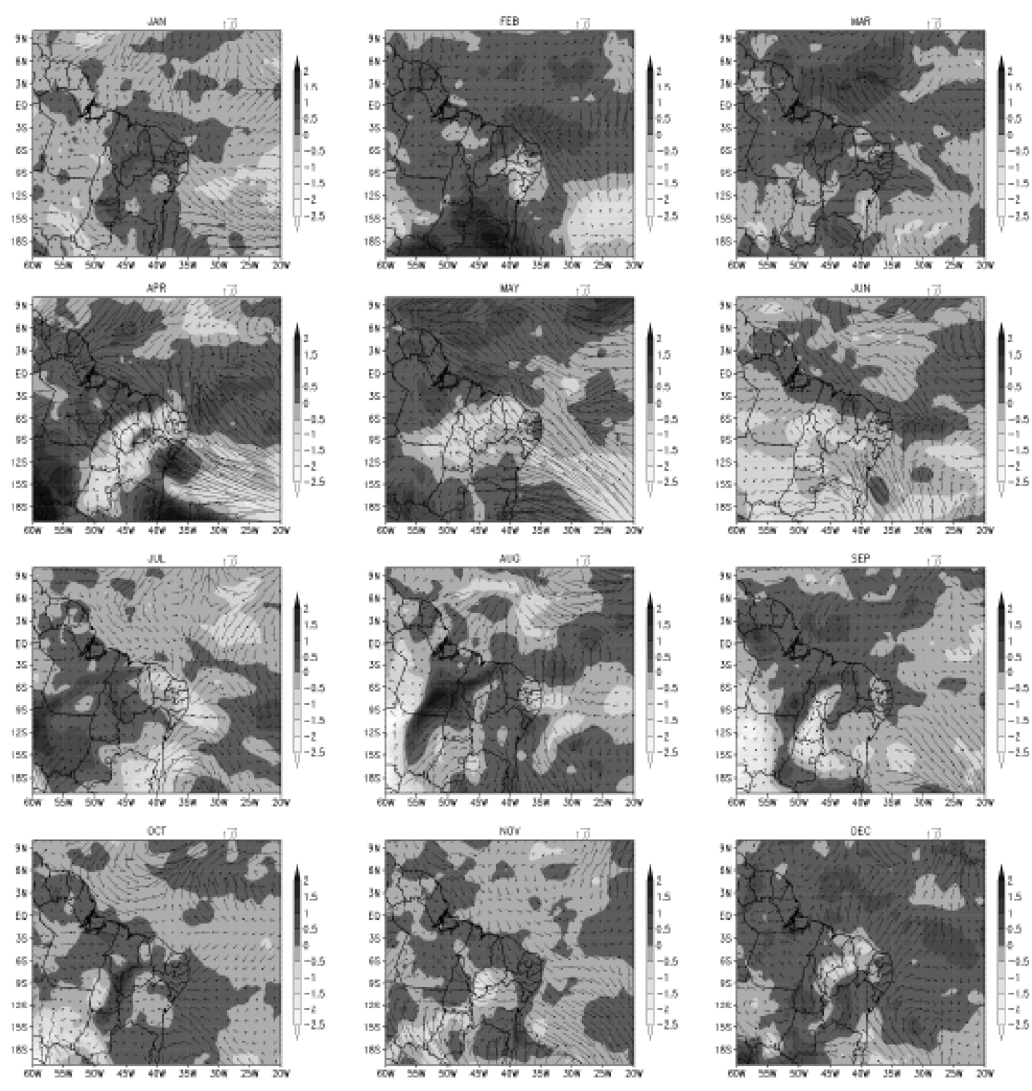

Figure 3. Difference between the monthly averages of withASL and withoutASL days for specific humidity (g kg^{-1}; shaded) and horizontal velocity (m s^{-1}; vector), at 1000 hPa.

at 1000 hPa (Figure 3) indicate the presence of humidity range associated with ITCZ near the 3° N latitude. Although there are no significant differences in January, there are more areas of positive moisture difference concentrated in coastal regions of north and northeast South America, more precisely in north and southwest of Amapá state and around the coast of Maranhão state. In February and March, the positive differences are more pronounced, clearly observing an almost continuous zonal range that extends from approximately 6° S to 6° N, with values reaching 1 g kg^{-1} in February and 1.5 g kg^{-1} in March close to 3° N.

Considering the time of variables analysis in question, it is proposed that the increase in the moisture content in the continent interior over Northern region, observed through the positive differences in February and March, is a factor that can favor system propagation. This is because in February (March), of the 17 (25) ASL occurrences, 11 (13) propagated inland, as shown in Figure 2b. Thus, more than half of systems formed spread to the interior of continent. Such comparisons show that more moisture on the ocean favors ASL formation, and the elevation of water vapor amount on coast and continental

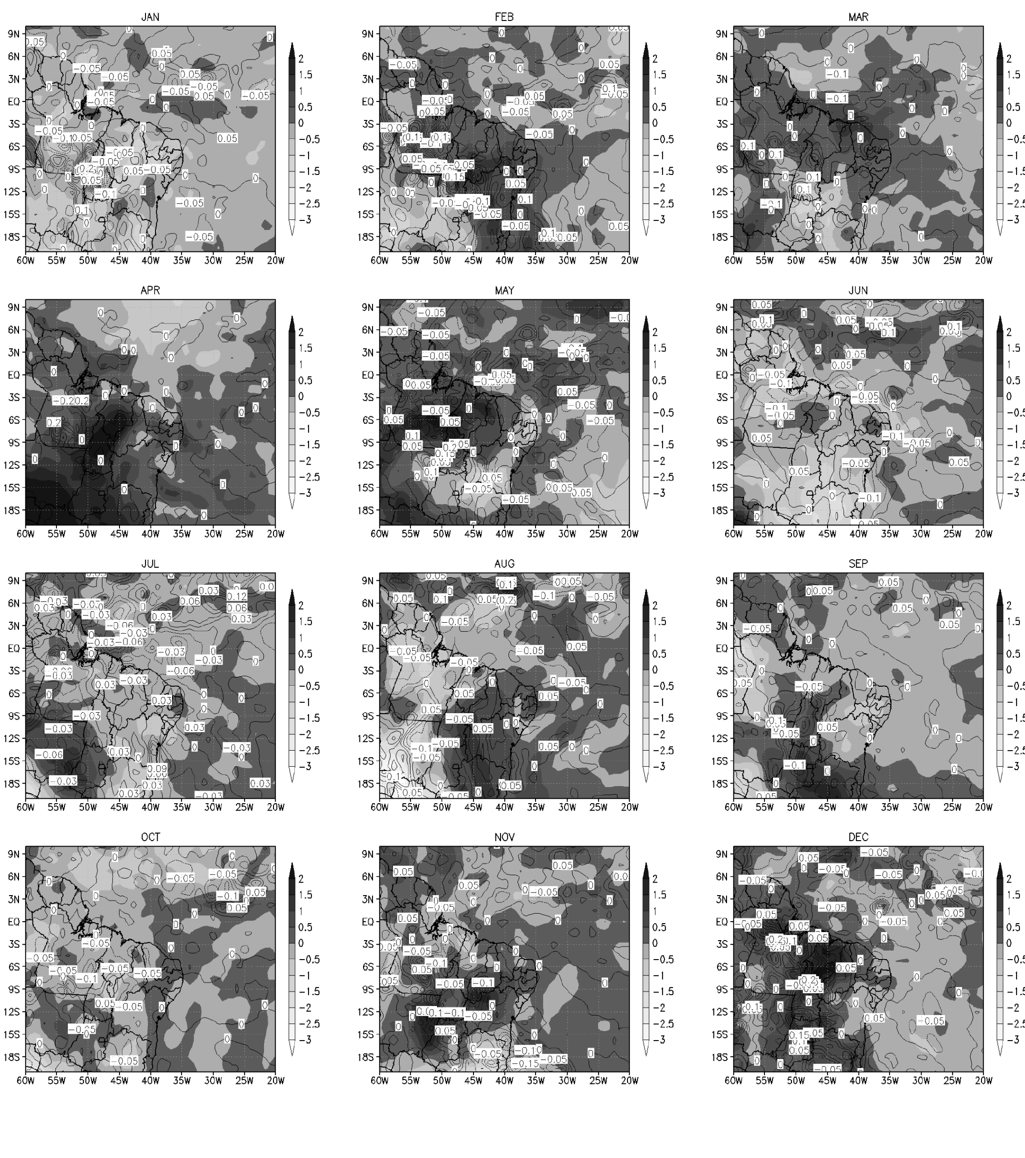

Figure 4. Difference between monthly averages of withASL and withoutASL days for temperature (K; shaded) at 1000 hPa and of the vertical velocity (Pa s^{-1}; contours) at 775 hPa.

interior can make the environment favorable for ASL propagation.

Figure 3 also shows a relatively less humid nucleus associated with the southeast trade winds (STW), more intense and closer to the continent on withASL days. This is shown by the negative differences of specific humidity between 20° to 35° W and below 6° S in January, assuming values that reach −1 g kg^{-1}. In February and March, this configuration is also observed, although more discretely, covering a smaller area in February and containing a less even distribution in March. In northeast, there is less moisture content in the averaged withoutASL days in the first three months, as there is a predominance of positive moisture differences in almost the entire region, mainly in January and March.

The horizontal wind analysis, in Figure 3, suggests that the SASH displacement and its drier core intensifies atmospheric flow, with more intense winds appearing around the equatorial band in the averaged withASL days, reaching Maranhão coast. This behavior leads to increased moisture transport to the northern part of South America. The contribution of humidity and intensification of ocean winds may be related to large number of ASL developed in the first quarter of 2005.

In studies by Gloor et al. (2013), it is suggested that since 1990, precipitation in northwestern Amazônia has increased by approximately 10% as a consequence of atmospheric water vapor transport from Atlantic to the region, and some authors, such as Vera et al. (2006), suggest that the prevailing sources of intense precipitation are local continental evaporation and vapor transport from nearby ocean regions.

Thus, as indicated by several authors (Oyama & Nobre 2003, Betts et al. 2004, Cox et al. 2004, Hirota et al. 2011, Spracklen et al. 2012), fluctuations in the moisture supply may be reflected in the stability of Amazon rainforest in terms of droughts or floods occurrence and, consequently, the formation of more intense and deeper systems.

The following quarter (April, May, and June) shows considerable ASL occurrence. In April, a total of 27 cases can be observed and in most of them, the system formed spreads, with PSL1 occurring in 10 days and PSL2 in 8 days (Figure 2). The moisture associated with ITZ is more evenly distributed in average withASL cases, verified by positive differences along equatorial band in the referred months in Figure 3; furthermore, the distribution of moisture throughout the interior of continent is a factor that can contribute to system propagation. The variable reaches values of up to 1 g kg^{-1} of difference near Paragominas-PA (3° S and 47° W), as well as in the central portion, southeast and southwest of Pará state. In May, of the 25 ASL observed, 6 are PSL1 and 7 are PSL2. In addition, areas of higher moisture content associated with ITCZ (around the equator) on withASL days, are identified by positive differences, which reach 1 g kg^{-1} in some localities. As already mentioned, the increased availability of moisture in the adjacent coastal and oceanic region seems to be a facilitator for ASL development. In June, these configurations are observed in a more discrete way, with positive moisture difference range displayed along north coastal region and north of Brazilian northeast, indicating that in these areas, there is greater average moisture over withASL days for the month mentioned. Although there is a large number of ASL in this month (21 cases), there is a drop in the ASL number that propagates—7 for PSL1 type and 2 for PSL2. This can be attributed to the lower average amount of humidity over the continent interior in withASL days compared with that in withoutASL days, because, outside coastal areas, differences in specific humidity are mostly negative.

In the frequency histogram (Figure 2), a high number of ASL occurs between January and May, with an even higher number between March and August. This may explain the finding of Negri et al. (2000) that the maximum rainfall occurs near Belém in these months, as it is known that squall lines contribute to an increase in local precipitation.

Regarding the wind (Figure 3) in this second quarter, the less humid nucleus associated with SASH has a greater average intensity over withASL days. With the strengthening of SASH, the southeastern trade winds enter the region parallel to the northern coast of South America with greater intensity, contributing to ASL development but possibly making it difficult for systems move inland (Serrão et al. 2015). This result is in agreement with Kousky (1980), who suggests that ASL has limited displacement when the flow at 850 hPa is parallel to the coast or toward the equator. In other words, it is suggested that the greater contribution of humidity in coastal region and adjacent ocean, in association with more intense SASH, leads to stronger and more humid winds entering the northern region of Brazil, making greater ASL development possible.

Continuing the analysis of Figure 3, in the following quarter (July, August, and September), an increase in average humidity in the less humid areas over northeast and southeast of Brazil (mainly in July and September) and also in the Tropical Atlantic Ocean region over withASL days was observed. In the equatorial area, the humidity range associated with ITCZ was not identified; only in Pará state were humidity cores above 17 g kg^{-1} was observed. In these months, the NTW influence is no longer observed. Therefore, SASH is observed to be much more intense in these months, in accordance with that demonstrated in previous studies regarding the intensity of SASH and NASH in 2005 (Marengo et al. 2011, Lewis et al. 2011, Serrão et al. 2015).

In July (Figure 3), much of the coast and its surroundings show differences in humidity, between −0.5 and 0.5 g kg^{-1}, with positive values in the continental area and negative values in the oceanic region; however, some areas exhibits values of up to 1 g kg^{-1} in the interior area of Pará and Maranhão states. In this month, there were 23 cases of ASL, 17 of which propagated, according to Figure 2. This fact may be related to the average humidity over the withASL days being higher than that over withoutASL days inland. In August, the high values of positive moisture difference over some continental areas are highlighted, exceeding 2 g kg^{-1} in southeast Pará, reaching 2 g kg^{-1} in the center of Maranhão, and 1 g kg^{-1} over the coast of Piauí and northwest Ceará. Moreover, along the coast and adjacent areas, the differences are mainly positive. This month had one of largest numbers of ASL cases in this study period, 27 days, with 18 days characterized as CSL, 7 days as PSL1, and 2 days as PSL2 (Figure 2). In September, the ASL number decreased considerably, with a total of 11 CSL. Analyzing the moisture difference field this month, although the positive differences are more distributed along coast and regions close to the ocean compared with previous month, difference values decreased over southwest Pará, central Maranhão, Piauí coast, and northwest Ceará.

Still, in the month of September, the SASH remained intense. However, less moisture was transported to the northern coast of South America, resulting in less ASL development, possibly due to reduced input of moisture. Therefore, the amount of moisture available in the equatorial belt, mainly near the coast, is a possible facilitator of ASL formation and, despite the greater intensity of southeast winds associated with SASH entering the continent, this amount of moisture is a limiting factor in systems propagation, considering that winds enter parallel to the coast, in accordance with the literature (Kousky 1980).

In October and November, the areas of positive moisture difference in Figure 3 are well distributed over north and northeast coast of Brazil, which seems to be a factor that favors CSL number, albeit small, formed in these months. Meanwhile, the negative differences over the ocean and continental interior may disfavor the ASL propagation, because in October, none propagated and in November, only one ASL propagated, not exceeding 400 km in its displacement to the interior (Figure 2). In December, almost entire area shown in the figure displays positive moisture differences, which means that, on average, there was more moisture on withASL days than on withoutASL days, both on the coast and over ocean, as well as inland. Consequently, the ASL quantity was significant again, with 20 CSL and 4 PSL2. Observing the negative moisture difference of the nucleus associated with the SASH, it is noted that in December, the extent and intensity of nucleus decreased, causing a greater moisture transport to northern region through STW. This configuration possibly contributed to the increase in ASL cases registered.

In the analysis of average monthly air temperature fields at 1000 hPa (Figure 4), two points were selected (illustrated in Figure 1), one over the continent (1° N, 52° W) and other over ocean (1° N, 48° W), to calculate the temperature differences between these areas, averaged over both withASL days and withoutASL days. A greater temperature difference between these two points indicates a greater temperature gradient between ocean and continent, contributing to sea breeze generation and fronts, which in turn, serves as ASL precursor (Kousky 1980, Cohen et al. 1995). The results of this analysis are presented in Table I.

It is noted that from January to July, in most months, the difference in temperature between these two points averaged over the monthly fields of withASL days is greater than the difference between these two points averaged over the withoutASL days, with opposite occurring in January and May. Most of these months demonstrate a high level of humidity in equatorial belt, associated with ITCZ. Therefore, the sea breeze effect shown here together with a greater contribution of humidity near the northern coastal region are two factors that contribute to ASL formation in these months, particularly the propagating ASL cases. In January, most of ASL are of type CSL and, from Table I, the average temperature difference is higher for days without ASL suggesting that a lower temperature difference in the days with ASL may be responsible for the absence of ASL propagation, even in a humid month. In addition, for temperature difference at 1000 hPa (Figure 4) between the average over withASL days and that over withoutASL days, negative differences predominate in the studied area, which can be another factor that explains the low amount of propagating ASL.

The months of February to May, in Figure 4, show extensive areas of positive temperature differences between withASL and withoutASL days, which include the coastal region. These months also present large areas of positive differences in terms of specific moisture, as shown in Figure 3, and are months with a high incidence of ASL, including those types that propagate. Between June and October, a good portion of areas exhibit negative temperature differences, with a reduction in the ASL amount in June and August and a general reduction in ASL occurrences, without any PSL, in September and October. In November and December, the positive

Table I. **Temperature difference (ΔT) (K) between two points (1 ° N, 48 ° W and 1 ° N, 52 ° W) in the average monthly fields of withASL and withoutASL days; comparison between these differences (>,<,=); and quantity of CSL and PSL (ΔASL) based on Figure 2.**

Month	ΔT withASL	Comparison	ΔT withoutASL	ΔASL
January	1.5	<	2.0	16 CSL 3 PSL
February	2.5	>	2.0	6 CSL 11 PSL
March	2.5	>	2.0	12 CSL 13 PSL
April	2.0	>	1.0	9 CSL 18 PSL
May	2.0	<	2.5	12 CSL 13 PSL
June	2.0	>	1.5	12 CSL 9 PSL
July	2.5	>	2.0	6 CSL 17 PSL
August	2.0	=	2.0	18 CSL 9 PSL
September	0.5	<	1.0	11 CSL 0 PSL
October	0	<	0.5	12 CSL 0 PSL
November	0	=	0	8 CSL 1 PSL
December	2.0	<	2.5	20 CSL 4 PSL

differences are again concentrated near the coast and inland. Although November presents the smallest ASL number (only 9 cases), one of the cases propagates; meanwhile, December shows a high number of cases. This analysis demonstrates that the highest temperature over the adjacent coastal, continental, and oceanic regions averaged over withASL days, together with the moisture content in this same region and the configuration of winds entering the continent, may come to influence the formation, quantity, and types of ASL cases and its propagation.

Analyzing the difference field of vertical velocity at 775 hPa (Figure 4), it is evident along the coast, inland, and some oceanic portions close to continent that in January and February and from May to August, there were many negative-valued contours (in Pa s^{-1}), indicating predominantly upward movements averaged over withASL days, that is, favorable to convection. According to Figure 2, these months are among the months with most ASL cases. In the remaining months, there are many contours with a zero value, indicating no difference between the averages of withASL and withoutASL days in areas mentioned. Therefore, the link between vertical velocity behavior and occurrence of convection associated with squall lines in the Amazon region is well recognized.

Table II summarizes the analysis of the variables under study, indicating the main

Table II. Temperature difference (ΔT) (K) between two points (1 ° N, 48 ° W and 1 ° N, 52 ° W) in the average monthly fields of withASL and withoutASL days; comparison between these differences (>,<,=); and quantity of CSL and PSL (ΔASL) based on Figure 2.

Variables	Wet months	Less humid months
Moisture	Greater contribution of moisture over the coastal region and interior of the continent	Lower moisture content in the coastal region
Wind	Stronger northeasterly trade winds entering the coast perpendicularly	Stronger southeast trade winds crossing parallel to the coast
Temperature	Higher temperatures over the coastal and interior regions of the continent and intensified breeze circulation	Reduction of temperature differences and unfavorable breeze circulation
Vertical velocity	More intense vertical velocity and favored deep convection	Predominantly null differences
System characteristics	ASL development with greater spread within continent	Little development of coastal ASL and inhibition of propagating ASL

characteristics that influence the development and propagation of ASL during the humid and less humid months of the region. In general, ASL develop more frequently and and move more inland during the wet months, when large-scale configurations present greater moisture input over the coastal region and interior of the continent, vertical velocity is more intense in the coast, the winds are perpendicular to the coast and there is a greater difference in temperature between continent and ocean. These configurations act favoring the ASL development and the wind direction associated with the greater input of moisture in the interior of the continent possibly favors their propagation. In less humid months, the development and propagation of ASL are disadvantaged due to the lower moisture content available in the formation region, winds are parallel to the coast, there are less intense vertical velocity and smaller temperature difference between continent and ocean, weakening sea breeze circulation.

Figure 5 illustrates a typical configuration of environment in which the chances of an ASL forming and propagating are high, synthesizing all the analysis done regarding the relation of studied meteorological variables and ASL environment of formation and propagation on the northern coast of South America. Thus, the high moisture content on ocean, coast, and inland (ellipses filled in gray) can favor formation and, especially, propagation of ASL. The more intense SASH (thicker circular black arrow) and NASH intensify the southeast and northeast trade winds (thin arrows), respectively, which must enter the continent perpendicular to the coast. Finally, temperature should be higher over continent (black dotted band) than over ocean (grey dotted band), indicating a temperature gradient that favors the sea breeze formation and its intensification and, in turn, possibly, the ASL formation.

CONCLUSIONS

The results suggest that moisture content available over coastal area of northern region and adjacent ocean directly contributes to ASL formation, i.e., a lower availability of moisture

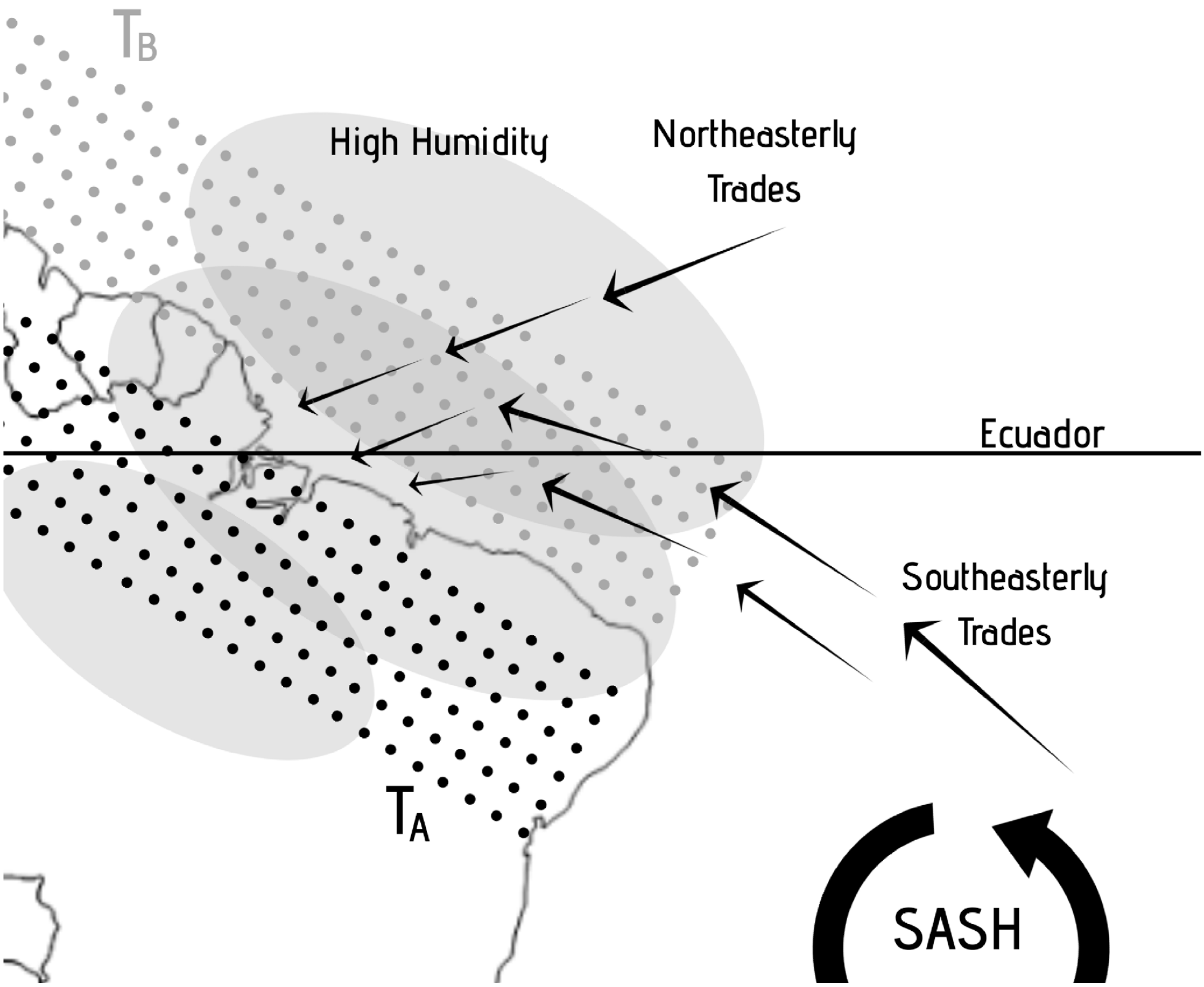

Figure 5. Conceptual model of variables combination that contribute to ASL formation and propagation. The filled gray ellipses represent high humidity; the dotted bands represent temperature differences over the continent (T_A) and over the sea (T_B); the thin arrows correspond to the trade winds, which blow from the northeast and southeast; the circular arrow symbolizes the intensified SASH. The elements of the figure are out of scale.

can lead to a decrease in ASL as well as a reduction in cases of propagating ASL. Thus, it is evident that ASL occur more frequently in the wettest months. Furthermore, the systems propagation inland seems to be strongly related to the moisture content reaching the coast through the winds blowing from ocean, both by NASH and SASH, with greater propagation in the event of greater levels of moisture over sea and higher wind intensities toward the coast. The direction in which this atmospheric runoff enters the continent also seems to impact whether or not the ASL are formed, especially propagating ASL. Thus, winds parallel to the coast seem to be more associated with absence of system or costal squall lines.

It is also noted that the difference in temperature between sea and continent is greater, on average, in withASL days than in withoutASL days. Moreover, in the months with greatest difference between these areas, there are a greater number of propagating ASL formed in relation to monthly total. This gradient favor formation and intensification of sea breeze and breeze front, possible ASL precursors. The importance of temperature difference between sea and continent and the consequent breeze generation also occurs even in a less humid month. Therefore, there can be a lot of PSL formation if temperature difference between these locations is large, as observed in July 2005. Lower temperatures on the coast and adjacent regions seem to be related to a lower incidence of ASL that propagate, while higher temperatures cause an increase in moisture content and their formation and propagation.

In relation to vertical velocity, when there is greater ASL occurrence, there convection formation seems to be favored, mainly along coastal region. On days without ASL formation and in periods of the year with less occurrence, this setting is not observed. This analysis exposes a relationship between vertical velocity behavior and system formation.

Acknowledgments

The authors would like to thank Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for funding this research through master's and doctoral scholarships and anonymous reviewers for their precious contributions.

REFERENCES

ALCÂNTARA CR. 2010. Um estudo da relação entre jato de baixos níveis e linhas de instabilidade da Amazônia. PhD Dissertation, Universidade de São Paulo - USP, São Paulo, 134 p. (Unpublished).

ALCÂNTARA CR, SILVA DIAS MAF, SOUZA EP & COHEN JCP. 2011. Verification of the role of the low-level jets in Amazon squall lines. Atmos Res 100: 36-44.

BETTS RA, COX PM, COLLINS M, HARRIS PP, HUNTINGFORD C & JONES CD. 2004. The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming. Theor Appl Climatol 78: 157-175.

CAVALCANTI IFA. 1982. Um estudo sobre interações entre sistemas de circulação de escala sinótica e circulações locais. thesis. Instituto Nacional de Pesquisas Espaciais - INPE, São José dos Campos, 133 p.

COHEN JCP, SILVA DIAS MAF & NOBRE CA. 1989. Aspectos climatológicos das linhas de instabilidade na Amazonia. Climanálise 4: 34-40.

COHEN JCP, SILVA DIAS MAF & NOBRE CA. 1995. Environmental conditions associated with amazonian squall lines: a case study. Mon Weather Rev 123: 3163-3174.

COX PM, BETTS RA, COLINS M, HARRIS PP, HUNTINFORD C & JONES CD. 2004. Amazonian forest dieback under climate-carbon cycle projections for the 21st century. Theor Appl Climatol 78: 137-156.

GARSTANG M, MASSIE HL, HALVERSON J, GRECO S & SCALA J. 1994. Amazon Coastal Squall Line. Pat I: Structure and Kinematics. Mon Weather Rev 122: 608-622.

GLOOR M, BRIENEN RJW, GALBRAITH D, FELDPAUSCH TR, SCHÖNGART J, GUYOT JL, ESPINOZA JC, LLOYD J & PHILLIPS OL. 2013. Intensification of the Amazon hydrological cycle over the last two decades. Geophys Res Lett 40: 1729-1733.

HIROTA M, HOLMGREN M, VAN NES EH & SCHEFFER M. 2011. Global resilience of tropical forest and savanna to critical transitions. Science 334: 232-235.

KOUSKY VE. 1980. Diurnal rainfall variation in the northeast Brazil. Mon Wea Rev 108: 488-498.

LEWIS SL, BRANDO PM, PHILLIPS OL, VAN DER HEIJDEN GMF & NEPSTAD D. 2011. The 2010 Amazon Drought. Science 331: 532.

MARENGO JA, TOMASELLA J, ALVES LM, SOARES WR & RODRIGUEZ DA. 2011. The drought of 2010 in the context of historical droughts in the Amazon region. Geophys Res Lett 38: 1-5.

NEGRI AJ, ANAGNOSTOU EN & ADLER RF. 2000. A 10-yr climatology of Amazonian rainfall derived from passive microwave satellite observations. J Appl Meteorol Climatol 39: 42-56.

OLIVEIRA GB, ALCÂNTARA CR & SOUZA EP. 2016. Caracterização de perfis de vento no ambiente de formação das linhas de instabilidade amazônicas. Ciência e Natura 38: 393-403.

OYAMA MD & NOBRE CA. 2003. A new climate-vegetation equilibrium state for Tropical South America. Geophys Res Lett 30: 2199-2203.

SERRÃO E, SANTOS C, WANZELER R, GONÇALVES L & LIMA A. 2015. Avaliação da seca de 2005 e 2010 na Amazônia: Análise da bacia Hidrográfica do rio Solimões. Rev Geogr Acad 9: 5-20.

SPRACKLEN DV, ARNOLD SR & TAYLOR CM. 2012. Observations of increased tropical rainfall preceded by air passage over forests. Nature 489: 282-285.

VERA C ET AL. 2006. Towards a unified view of the American monsoon system. J Clim 19: 4977-5000.

How to cite
ALCÂNTARA CR, CARNEIRO IO & OLIVEIRA GB. 2022. Analysis of meteorological variables interaction associated with the environment of formation of Amazonian squall lines. An Acad Bras Cienc 94: e20201739. DOI 10.1590/0001-3765202220201739.

Manuscript received on November 9, 2020;
accepted for publication on September 27, 2021

CLÊNIA R. ALCÂNTARA
https://orcid.org/0000-0002-6675-3844

IZANA O. CARNEIRO
https://orcid.org/0000-0003-1739-8732

GABRIELLE B. OLIVEIRA
https://orcid.org/0000-0001-9078-0845

Universidade Federal de Campina Grande, Unidade Acadêmica de Ciências Atmosféricas, Rua Aprígio Veloso, 882, 58429-900 Campina Grande, PB, Brazil

Correspondence to: **Clênia Rodrigues Alcântara**
E-mail: clenia.alcantara@ufcg.edu.br

Author contributions

CRA: Conceptualization, investigation, formal analysis, methodology, supervision, validation, review; IOC: Data curation, research, methodology, writing the original draft, reviewing, editing; GBO: Data curation, research, methodology, reviewing, editing.