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ARTICLE

"Friagem" Events in the Brazilian Amazon, Changes and Variability in Its Climatological Patterns

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ABSTRACT

Friagem events in the southwestern Brazilian Amazon including their changes, variability and climatological features during the 1979–2020 period were examined. The incursion of polar origin cold air mass into the region during austral autumn and winter, which leads to the abrupt drop of the air temperature, characterizes the friagem event. Sixty-five friagem events were identified during the analysis period. These events are more frequent in July and August, with a decreasing trend in both frequency and duration over the years. The average intensity was 14.8 °C, representing a 5 °C drop in relation to the average minimum air temperature in the study domain. Additionally, the most intense events occurred in La Niña years and during the positive phase of the Antarctic Oscillation. On the global scale, friagem event is associated with the zonal wavenumber 3-4 pattern in the 500 hPa geopotential anomaly field, with a northwest-southeast oriented anomalous anticyclone extending from the southeast Pacific, across southern South America to southwestern Atlantic, which is flanked to the northeast by an anomalous cyclone over southern Brazil and the adjacent Atlantic. Friagem is also associated with negative sea surface temperature (SST) anomalies in the central and eastern tropical Pacific resembling the La Niña pattern,

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and negative SST anomalies in the South Atlantic off southeast and south Brazil. This study contributes to improving our knowledge of the friagem events in the Amazon, highlighting the importance of monitoring in the context of climate change and interannual climate variability associated with El Niño and La Niña.

Keywords: Friagem; Brasilian Amazon; Wavenumber 3-4 Pattern; ENSO

1. Introduction

The North region of Brazil stands out for housing a large portion of the largest tropical forest in the world, known as the Amazon. This lush forest is distinguished by its vast biodiversity and the imposing presence of majestic rivers, such as the Amazon River, which holds the title of the most significant flow rate on the planet, estimated at approximately 175,000 to 212,000 m^3/s [1]. In addition to its size, it plays a crucial role in South America's (SA) climate regulation.

Due to its proximity to the equator, the northern region has an equatorial climate characterized by high temperatures and humidity throughout the year. However, during the austral autumn and winter months, a southern portion of the region is affected by a climatic phenomenon known as "Friagem" (plural: Friagens).

Friagem events involve the incursion of a cold front that moves over the central region of the Amazon during the dry season. Although the author's initial research focused on the Peruvian Amazon, his conclusions highlighted key aspects, such as the low annual temperature range in the Amazon (usually less than 2 °C), and the high diurnal temperature range of 15 °C or more during the austral winter. This abrupt drop in temperature is associated with the incursion of a cold air mass from the South, which, upon meeting the local air mass, triggers the formation of a cold front, giving rise to the Friagem [2].

Due to the major environmental changes identified during Friagem events, many studies have emerged to explore their atmospheric and synoptic configuration and their connections with large-scale circulation and then due to the impacts, mainly on agriculture, caused by the abrupt drop in temperatures during the occurrence of Friagem.

On June 26 and July 10, 1994, two significant cold air masses impacted the Amazon region [3]. The most notable features of these events were the substantial drops in minimum temperatures, which coincided with strong southerly winds. This indicates that cold advection was the primary mechanism causing the temperature decrease. In other areas such as Manaus (in Amazonas State) and Marabá (in Pará State), the cooling was further influenced by increased cloud cover. The duration of these Friagem events varied from 2 to 3 days. The June 26, 1994, event was associated with an anticyclonic disturbance off the coast of Chile, which entered SA and crossed the Andes south of 45°S. This process occurred in two stages: initially, a mesotropospheric trough east of the Andes, over central Argentina, caused substantial temperature drops. Subsequently, with the increase in the magnitude of zonal temperature gradients east of the cold advection zone at levels close to 700 hPa, it was ensured that cold advection was extended eastward, resulting in a local deepening of the upper-level trough, which would also end up contributing to the cooling of southeastern Brazil due to the associated southerly winds [4].

Another cold air incursion occurred in May 1993 over tropical and subtropical South America, east of the Andes [5]. Three stages in the evolution of the cold air incursion were observed: 1) an increase in the surface pressure over southern Argentina, creating a large-scale meridional pressure gradient between the anticyclone and the continental depression further north; 2) the barrier effect of the Andes, which caused a low-level ageostrophic flow to the south, which in turn advects the cold air towards the subtropics and 3) the horizontal advection of cold air by southerly winds maintains the strong temperature gradient against the dissipative effects of the strong surface heat fluxes [5].

Statistical analysis of principal components was also used to find wave patterns associated with Friagem events. The structure and dynamic processes of cold waves in SA were analyzed using the rotated extended empirical orthogonal function technique [6]. The results revealed distinct wave behaviors in South America's lower and middle troposphere and that upper-level waves propagate northeastward when crossing the Andes, consistent with Rossby wave dispersion. At lower levels, waves tend to conform to the shape of the mountain range, according to the theory of topographic

Rossby waves. The study also highlighted significant differences between cold waves over extratropical SA and the large cold air masses that penetrate tropical regions [6].

The quantile method was utilized to determine the intensity of Friagem events in Porto Velho, located in the southwestern region of Amazonas State [7]. Data from the meteorological station at Porto Velho International Airport – Gov. Jorge Teixeira de Oliveira, covering the period from April to October between 1983 and 2007, were analyzed. The 5%, 10%, 20%, and 40% quantiles were applied to calculate the average frequency of occurrences for each month and year, while the 35% and 65% quantiles were used to assess the intensity of Friagem events. The results indicated that, on average, between 11 and 13 Friagem events occur annually in Porto Velho [7]. These events were categorized as very weak (with 6 to 8 occurrences), weak (with 2 to 3 occurrences), and more intense (also with 2 to 3 occurrences). Additionally, a cyclical pattern was identified, revealing an approximately 10-year cycle of alternating maximum and minimum occurrences of Friagem events in the capital, highlighting the periodic nature of this climatic phenomenon over time.

An observational study investigated trends in Friagem events in the Brazilian Amazon Basin during the austral winter from 1980 to 2013 [8]. The study applied Mann-Kendall statistical significance tests and linear trend estimates using Sen's method. The study focused on events that reached the equator and the vertical structure of the atmosphere. The results revealed that of the 68 Friagem in the Amazon region, 23 cases crossed the equator. Furthermore, it was found that Friagem events were more intense in years of La Niña occurrence [8].

Some relationships between Friagem events and the EL Niño Southern Oscillation (ENSO) had already been identified [9]. The authors used daily data from the meteorological station in Porto Velho (Rondônia State) from 1983 to 2007. They observed a significant moderate Pearson correlation (r) between the frequency of very strong Friagem and the sea surface temperature (SST) anomalies of the tropical Pacific in La Niña years, indicating a link between these climate events. The "r" signs obtained in the calculation indicated that the more negative the SST anomaly of the central tropical Pacific and the more positive the southern oscillation index — SOI (La Niña), the greater the possibility of extreme Friagem events [9].

One of the key motivations for studying this phenomenon was the impact of Friagem events on populations, particularly in relation to agriculture [3,4]. Research indicated that during the intense Friagem that occurred in June and July of 1994, a significant frost led to a sharp decline in coffee production, which in turn caused a drastic increase in coffee prices [4].

Abrupt changes and alterations in tropical forests' environmental factors and the behavior of certain animal species due to Friagem events have also been observed. When exposed to adverse conditions, the anurans, which are tailless amphibians such as frogs and toads, often need to adjust their vertical microhabitat [10]. The observation was verified in southern Peru during five cold periods between 1997 and 1998, where anurans showed distinct behavior patterns on cold nights compared to nights with mild temperatures.

During cold weather periods, there is greater diversity, richness, and a more significant number of individuals in the hylid family, suggesting adaptations of these species to cold conditions. These results indicate how anurans respond to adverse weather conditions and highlight the importance of studying the impact of Friagem on the ecology of animals in tropical forests [10].

Urban populations are also affected by Friagem events, and this was verified in the southern Peruvian highlands [11]. Due to the intense drop in temperatures during Friagem events, between −15 °C and −25 °C, from June to August, environmental conditions can cause illness and death in the local population and more fragile animals. The authors proposed a quality housing model with a cost equivalent to locally built homes. The applied research results allowed the team to develop a basic housing model with essential information to be applied on a large scale in the country, serving as a reference in the construction area [11].

In this context, and because Friagem events are still one of the causes of the most extreme cold weather in the Amazon, compromising habitats and the health of the population, this article aims to expand previous research by examining Friagem events and their global connections in the southwestern region of the Brazilian Amazon during a recent period (1979–2020) not previously examined in the context of Friagem events. This analysis will contribute to a better understanding of the patterns and impacts of Friagem events in this tropical region.

2. Materials and Methods

2.1. Study Area

Figure 1 shows SA, in blue, the Brazilian territory. The red rectangle highlights the study area for identifying the Friagem events, 15° S to 7.5° S latitude and 75° W to 60° W longitude, covering the States of Acre, Rondônia, and the southern part of Amazônia.

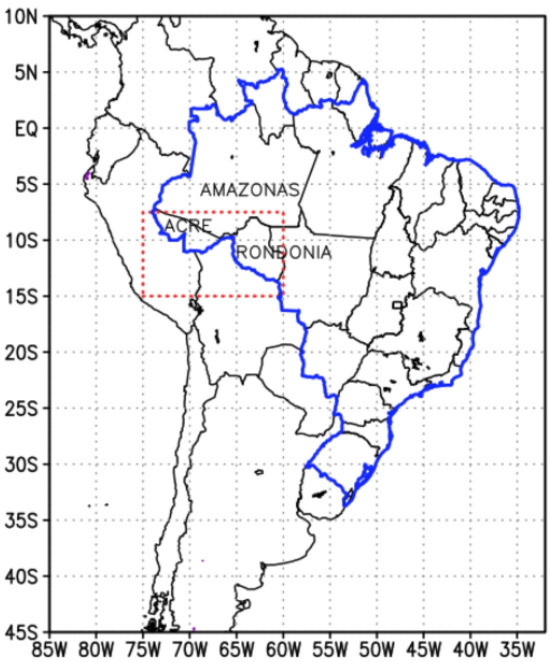


Figure 1. South America, Highlighting the Brazilian Territory in Blue and the Study Area in Red to Identify Friagem Events.

This unique region exhibits diverse microclimates, being characterized according to the Köppen classification as Af – tropical equatorial, in Acre, and Am – tropical monsoon, in Rondônia and the southern Amazonas States [12].

In addition, a broad extension of the globe between the latitudes of 20° N to 70° S was considered to highlight the global circulation associated with the Friagem events and to understand the climate patterns that affect the southwest of the northern region of Brazil.

2.2. Data and Methods

Daily minimum temperature (T_{min}) data with continuous spatial and temporal coverage were obtained from the Brazilian Daily Weather Gridded Data (BR-DWGD) database, with a spatial resolution of 0.1° x 0.1° covering the entire Brazilian territory for the period from 1979/01/01 to 2020/07/31. This database was constructed using observed data from 11,473 rain gauges and 1,252 meteorological stations distributed throughout Brazil [13]. These data are available at: https://sites.google.com/site/alexandrecandidoxavierufes/brazilian-daily-weather-griddd-data.

The circulation fields were obtained from the ERA 5 Reanalysis, the fifth generation of ECMWF's atmospheric reanalysis which covers the global climate from January 1940 to the present. ERA5, produced by the Copernicus Climate Change Service (C3S) at ECMWF. ERA5 provides many atmospheric, land, and oceanic climate variables [14]. For this study, we used the meridional and zonal wind components, air temperature, geopotential height, and mean sea level pressure at 00Z and 12Z for the following pressure levels: 1,000, 925, 850, 500, and 250 hPa. The data are available at https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation.

Weekly sea surface temperature (SST) data were obtained from the NOAA Optimum Interpolation (OI) SST V2 High Resolution product, with a spatial resolution of 0.25°, available at https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html [15].

Satellite imagery from the GOES satellite family was also used in both infrared (IR) and visible (VIS) channels. All images have a spatial resolution of approximately 10 km (0.1°) and are available every 3 hours at https://www.ncei.noaa.gov/data/.

To define the temperature threshold for identifying cold weather events in the study area (**Figure 1**), we used the method described in the work of Bitencourt et al. [16], according to which an event is considered a Friagem if it persists for at least 3 days. Initially, the daily averages T_{min} were calculated for each grid point (k) using

$$T_{min}(k,d) = \left(\frac{1}{N(k,d)}\right)\sum_{i=1997}^{2020} T_{min(i)}(k,d) \quad (1)$$

where k indicates the number of grid points; d denotes 1, 2, 3, ..., 365 (Julian days); N(k,d) represents the number of years with data available for grid point k on day d.

In addition, the daily standard deviation (σ) was calculated for each grid point. Thus, for each grid point, two data series are generated, one with 365 Tmin values and the other with 365 σ values.

$$\sigma(k,d) = \left(\sqrt{\sum_{l=1979}^{2020}\left(T_{\min(i)}(k,d) - \overline{T}_{min}(k,d)\right)^2}\right) \Big/ N(k,d) - 1 \quad (2)$$

Subsequently, we searched for periods of three or more consecutive days with values of

$$T_{min} \leq \ \overline{T}_{min} - \ \sigma \quad (3)$$

When this condition was met in at least 50% of the grid points in the study area, it was considered a Friagem event.

For each identified event lasting at least three days, the average T_{min} was calculated for each grid point to determine the intensity (INT) of the event. Subsequently, the average of all grid points in the study area was calculated, providing a single INT value for the area. Events with INT below the lower limit of the first quartile of the series were classified as Friagem events, as they have a potential impact due to low T_{min} values.

The severity level of the Friagem events, determined based on their duration, was also assessed and considered a moderate event lasting 3 to 6 days, a severe event lasting 6 to 9 days, and an extreme event lasting 10 days or more [17].

To analyze the atmospheric circulation fields associated with Friagem events, a composite of cases was created using the simple arithmetic mean of all events. Initially, the mean of the fields was calculated for each event, and then the mean of all events was calculated, resulting in a single mean field representing all events.

The same procedure was applied to satellite images. It is worth noting that the use of satellite images to recognize synoptic patterns is fundamental in weather forecasting and has been widely used in the climate context to establish synoptic climatologies [18], estimate rainfall, and detect intensely convective phenomena, such as tornadoes [19,20].

Additionally, anomalies in relation to the climatology were calculated for some atmospheric circulation variables (atmospheric pressure, zonal wind, and air temperature) and SST. The ERA5 anomalies were calculated for the atmospheric fields and for the SST, based on the climatologies from 1979 to 2020, at each time (every 12h for ERA5) and each week for the SST. For each Friagem event, temporal averages were performed, obtaining an average field of each variable for each event. The statistical significance of the compositions was tested using the Student's t-test to determine the significance of the means. In this test, the 95% confidence level was adopted.

Also, the relationship between the frequency of cold weather events and low-frequency climate variability indices, such as El Niño/Southern Oscillation (ENSO) and Antarctic Oscillation (AAO), was evaluated.

To identify the relationships between ENSO events, the Oceanic Niño Index (ONI) obtained from NOAA's Climate Prediction Center (NOAA-National Weather Service: https://ggweather.com/enso/oni.htm) was used. This index considers an ENSO event when the SST anomaly in the Niño 3.4 region remains at +/−0.5 °C or more for at least five consecutive months. The average ONI values are smoothed with a 3-month running mean filter and characterize El Niño (positive values ≥ 0.5 °C) or La Niña (negative values ≤ −0.5 °C) events. Generally, El Niño and La Niña episodes begin in the austral fall or winter of one year (0) and end in the following year (+1), with a peak in SST anomalies from November to January.

Due to the higher frequency of cold weather events during the winter, it was decided to analyze in this work the running quarters from April/May/June to August/September/October, as they cover at least one of the months of this season. This approach aligns with the research conducted on the relationships between cold air masses in Santa Catarina State and ENSO [21]. Therefore, the influence of one of the ENSO phases was observed in the months with the highest incidence of Friagem events. The winter of the year in which the event began was designated as year (0), while the winter of the subsequent year was designated as year (+1). The quarters June/July/August, July/August/September, and August/September/October were considered in year (0), while the quarters April/May/June and May/June/July were considered in year (+1).

For the analysis related to the Antarctic Oscillation (AAO), data from monthly averages of the AAO index obtained from the Climate Prediction Center/National Centers for Environmental Prediction (CPC/NCEP: https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml#forecast) for the period between 1979 and 2020 were used. The index values corresponding to June, July, and August were analyzed. Positive values of the index indicate a positive phase of the AAO, while negative values indicate a negative phase of the index.

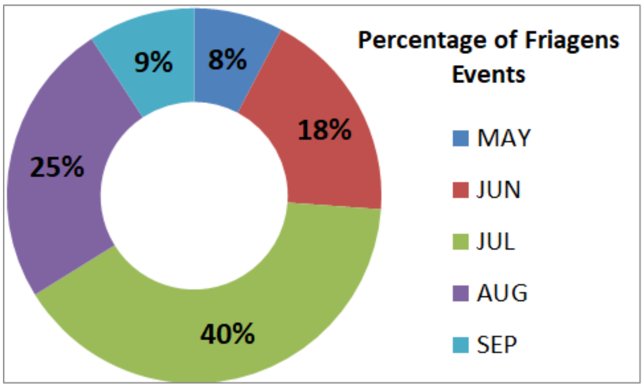
3. Results and Discussion

3.1. Monthly Frequency, Variability, Intensity, and Relationships with Low-Frequency Climate Indices (ENSO and AAO) of Friagem Events

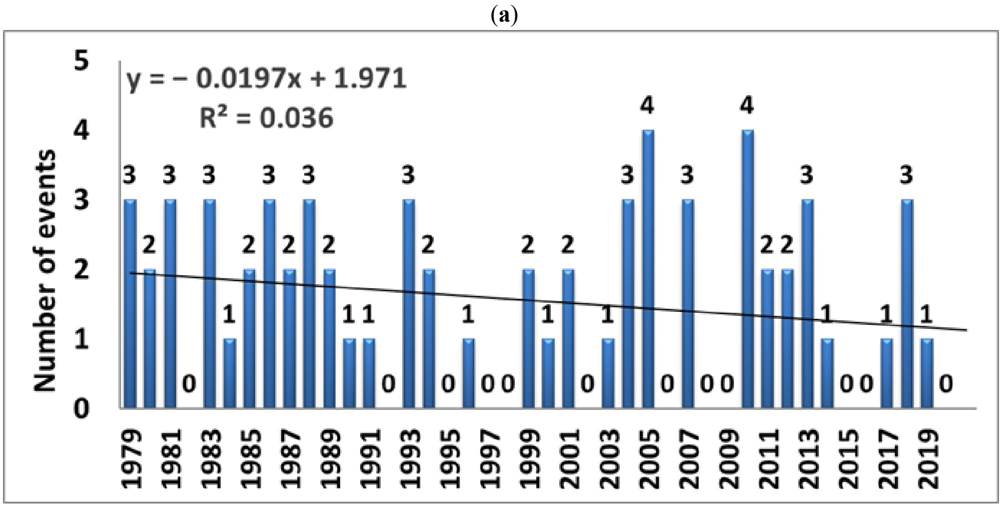
This section presents the characteristics of Friagem events: intensity, duration and frequency after applying the identification method, considering the selected area, which includes the states of Acre, Rondônia and the southern Amazonas (**Figure 1**).

Over the 42 years analyzed (1979–2020), 65 Friagem events were identified and distributed in the months of autumn (May), winter (June, July, and August), and spring (September) (**Figure 2**). The majority of events occurred in winter, with July representing 40%, followed by August at 22% (**Figure 2(a)**).

The methodology has been validated, as over 73.3% of the cases identified through it were documented in various studies[3,8,22–28]. Additionally, the Friagem events that occurred from 2013 to 2020 remain under-documented.



(**a**)



(**b**)

Figure 2. Monthly Distribution (**a**) and Interannual Variability of Friagem Events (**b**) for the Period 1979–2020.

The average intensity (INT) of cold weather events in the selected area (**Figure 1**) for the total number of events is 14.8 °C, with a standard deviation of 0.9 °C. The average value (1979–2020) of T_{min} for the study area in the months of Friagem events occurrence (May to September) is 19.8 °C. The INT compared to the average T_{min} represents a decrease of 5.0 °C.

The two significant cold weather events in June and July 1994 that impacted the entire Amazon region, deemed severe according to several studies[3,8,23], were also detected by the method utilized in this study. For specific days the events recorded minimum temperatures in Rio Branco (Acre) of 11.6 °C (June 27) and 9.6 °C (July 11)[3]. The decrease in T_{min} for July 11, about the average, was 6.9 °C. The July 1994 event that occurred from July 9 to 14 and was identified in the study had an average INT of 13.3 °C and lasted six days.

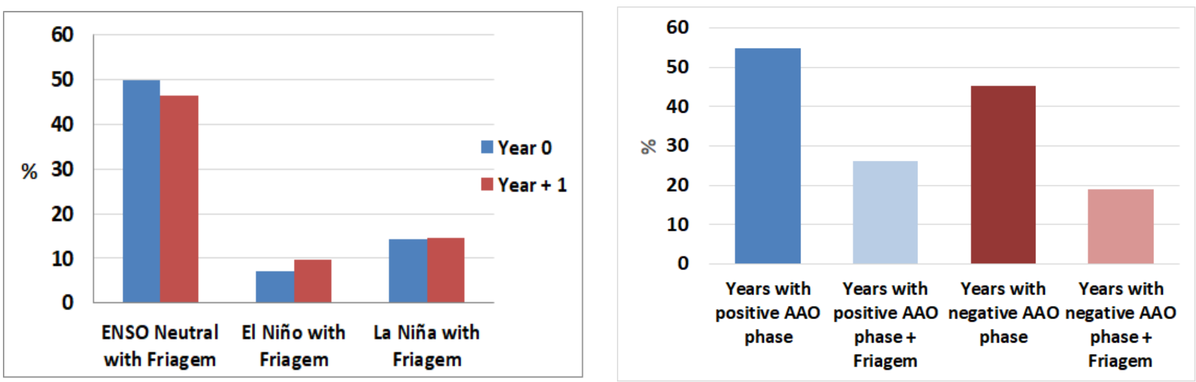
Regarding the number of events, although there was a tendency for the number of Friagem events to decrease over the period analyzed (**Figure 2(b)**), this trend was not statistically significant according to the Mann-Kendall test. The years 2005 and 2010 presented the highest number of Friagem events.

The average duration of Friagem events in the analyzed area was 4.7 days, with a standard deviation of 1.6 days. The maximum duration was 10 days for an event between July 9 and 18, 1988. This event was one of the most intense ever recorded that affected low latitudes in Brazilian territory[3,29].

Also, throughout the period analyzed, the number of days of these events (lifetime) showed a decreasing trend with statistical significance (α = 0.1) according to the Mann-Kendall test.

The degree of severity, identified by duration, indicated only one extreme Friagem event lasting 10 days during the analyzed period. There were 16 severe events, and moderate events were the most frequent (48).

The comparison of the frequency of Friagem events with climate indices showed that they were more frequent in ENSO neutral years, followed by La Niña years. Thus, disregarding neutral years, Friagem events occurred more frequently in La Niña than in El Niño years. This relationship between the frequency of Friagem events and ENSO phases does not depend on the ENSO stage (**Figure 3**), i.e., it was the same for the early winter (Year 0) of ENSO and for the winter in the late phase of ENSO (Year + 1) (**Figure 3(a)**).



(**a**) (**b**)

Figure 3. Frequency of Friagem Events and ENSO Phases for Winter Year 0 and Year + 1 (**a**). Frequency of Friagem Events for the AAO Phases in the Winter Period from 1979 to 2020 (**b**).

Also, the frequency of Friagem events per year was higher in ENSO neutral and La Niña years, as in 2005 (ENSO Neutral) and 2010 (La Niña winter), which recorded 4 events each.

Regarding the AAO index, there was a higher frequency of Friagens in the years of the positive phase of the AAO (**Figure 3(b)**), considering the winter period (higher event occurrence). Not all years identified in the positive or negative phase of the AAO had Friagens; the same occurred with the ENSO phases. However, the years with Friagens events were counted for each phase of the AAO.

Several studies that analyzed the relationship between cold waves and ENSO phases, focusing mainly on the southern region of Brazil, found a higher frequency of cold waves in neutral years[28]. However, concerning El Niño and La Niña years, it was shown that cold events are more frequent in La Niña years[30–32]. As indicated for some study, Friagem events in southwestern Amazon are more intense in La Niña years[7,8]. In the present study, it was found that they are more frequent in La Niña events.

The AAO, considered the primary mode of variability of the extratropical atmospheric circulation of the Southern Hemisphere acts on time scales ranging from intraseasonal to interannual[33], and is also related to the incursion of cold waves in the Southern region of Brazil. Several studies have shown that cold wave events occur more frequently in the positive phase of the AAO[28].

During the positive phase of the AAO, negative pressure anomalies occur over Antarctica, and positive anomalies occur at mid-latitudes. Thus, during the positive phase of the AAO, there is a greater chance of cold episodes occurring in the mid-latitudes[28,33,34].

3.2. Synoptic and Global Circulation Characteristics of Friagem Events in the Amazon

The synoptic-scale meteorological analysis of Friagem events in the Amazon region, focusing on its southwest region passing through Rondônia and Acre, involved observing and understanding the fields of temperature, pressure, clouds, winds and humidity. **Figure 4** shows the grid point average of the minimum temperature's mean intensity (INT) during Friagem events. It can be observed that the mean INT is approximately 16 °C in the States of Rondônia, Acre and Amazonas (southwest portion). The Central-West and Southeast regions of Brazil present lower values, but the lowest mean INT (2 °C) is in the south of Brazil during Friagem events.

Considering the minimum Tmin values during all cold weather events, temperatures in the States of Acre, Rondônia and Amazonas (southwest sector) reach up to 9 °C (**Figure 5**). In the Region South (Paraná State), values can reach negative values of up to −7 °C. Thus, it can be seen that cold weather events are marked by a significant reduction in air temperature in the southwest sector of the North Region, a large part of the Central-West Region, and a small portion of Brazil's Southeast and South Regions.

The cold air masses that cause Friagem events in the southwest of the Amazon region originate in higher latitudes located in temperate regions of the southern hemisphere. These air masses, also known as polar air masses, move over areas of high and medium latitudes, such as Patagonia (southern Argentina and Chile), southern Brazil, Uruguay and Paraguay until reaching tropical latitudes.

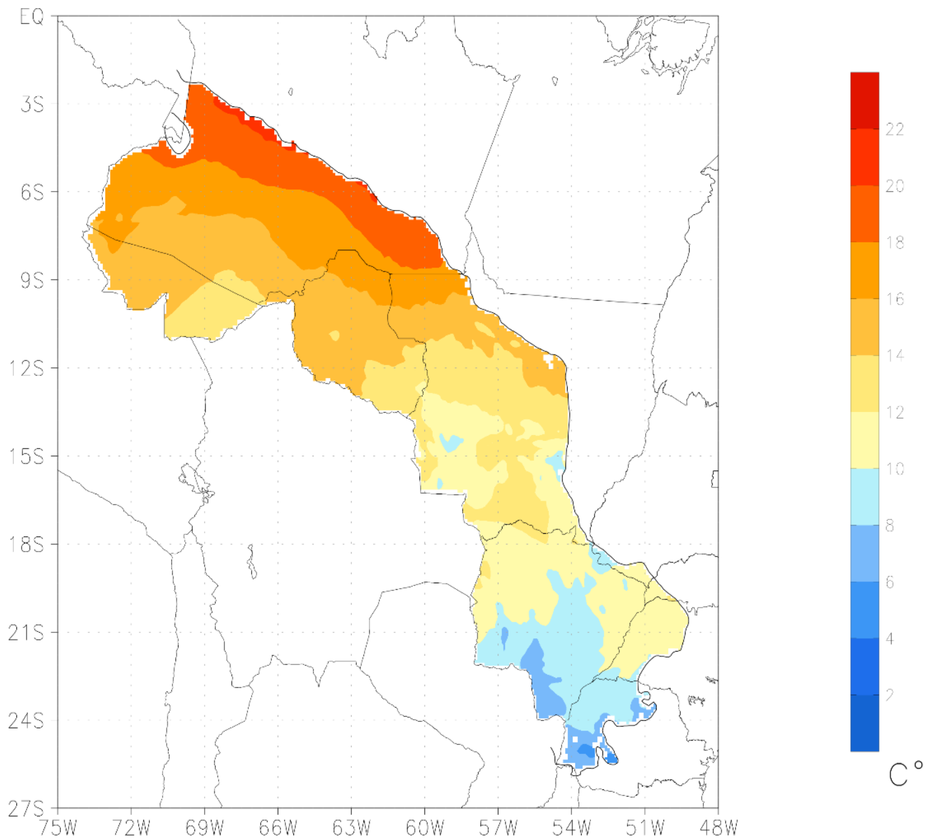


Figure 4. Average temperature (°C) intensity of Friagem events for 1979–2020.

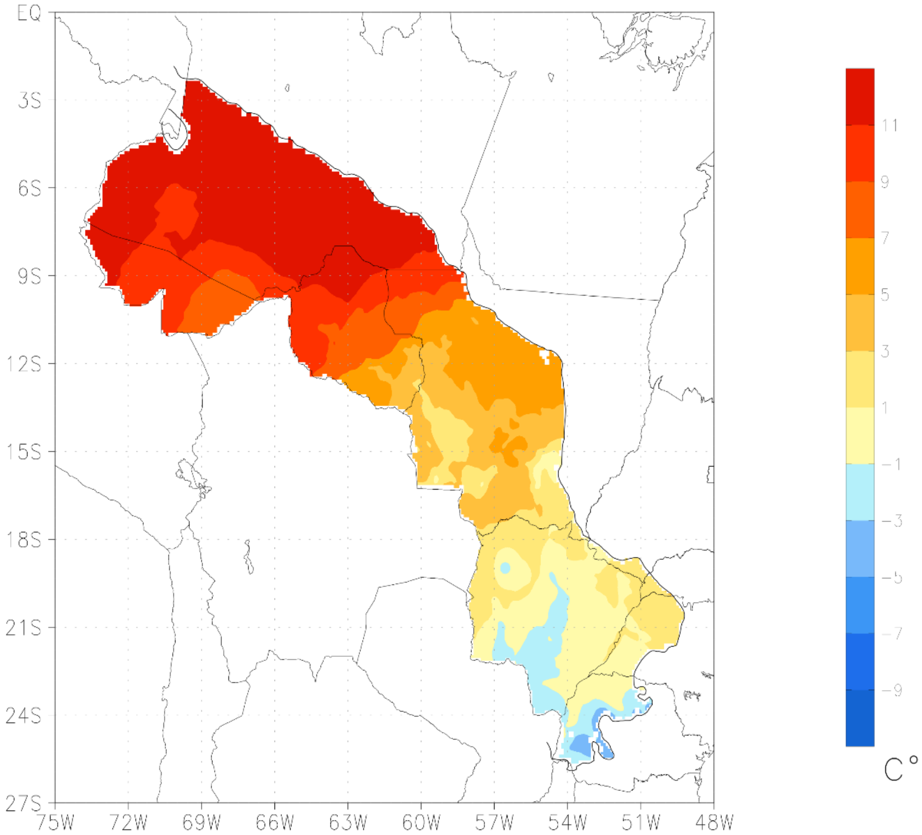


Figure 5. Minimum Tmin (°C) During Friagem Events for the Period (1979–2020).

The evolution of these cold air masses towards the Amazon involves some important atmospheric processes that precede the incursion of the mass of polar origin, such as the cold front. As the cold front moves, the cold air mass advances towards the Amazon region and may be altered by the region's topography, such as mountain ranges and valleys. As a result, there may be changes in the trajectory and intensity of the cold air mass, influencing the scope and magnitude of the Friagem events in the region.

The passage of a cold frontal system preceding the polar air mass causes a rapid drop in daily minimum and maximum temperatures. The average air temperature field at 1000 hPa for SA (**Figure 6**) for all Friagem events shows the temperature associated with the cold air mass that extends from eastern Argentina to the southwestern Amazonian region, visible by the cold "tongue" along the eastern side of the Andes (**Figure 6**). The nighttime cooling is typically pronounced, leading to low Tmin, often reaching values below 15 °C or even close to 10 °C in some areas of the southwestern Amazonian region, such as Rondônia State (**Figures 4** and **5**).

In the composition of satellite images in the infrared channel overlaid with the mean temperature field at 1000 hPa (**Figure 6**), areas with brightness temperatures below 273 °K (in colors) stand out, indicating precipitating cloud tops. Temperatures above 273 K may indicate the absence of clouds or the presence of non-precipitating clouds [35]. In the region extending from eastern Argentina to the southwest of the Amazonian, where the cold air mass associated with the Friagem operates, the brightness temperatures are above 273 K suggesting the absence of significant clouds or the presence of stable atmospheric conditions.

Friagem events are also associated with increased atmospheric pressure in the affected region. This occurs because, as cold air moves into warmer tropical areas, it becomes denser and heavier, leading to a rise in atmospheric pressure.

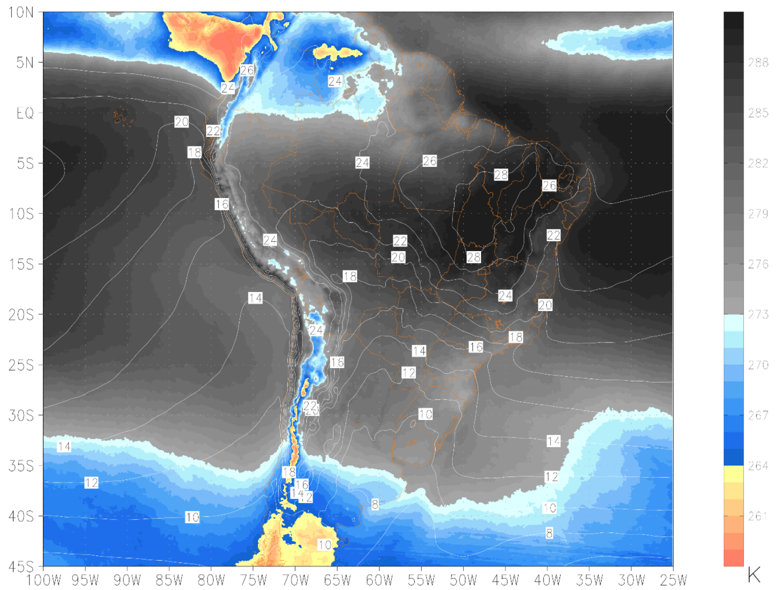


Figure 6. Mean Field of Air Temperature (°C) at 1000 hPa and GOES-East Thermal Infrared Image (°K) for All Friagem Events.

Figure 7 shows the synoptic configuration of the mean sea level pressure field, wind vectors, and a visible channel image of the GOES satellite for all Friagem events. A high-pressure system is observed extending from the northern region of Argentina, southern Bolivia, and Paraguay to the central west and part of the southeast of Brazil with a closed core (1023 hPa) over southern Brazil and Uruguay. This high-pressure system is associated with an inverted ridge extending north of Bolivia, the states of Acre and Rondônia in Brazil, and the Peruvian jungle. This positioning of the ridge is similar to the area of cold air described above in **Figure 6**. In this composition, it is possible to observe a high-pressure center in southern Brazil, but it influences the entry of cold air into the western Amazonian region.

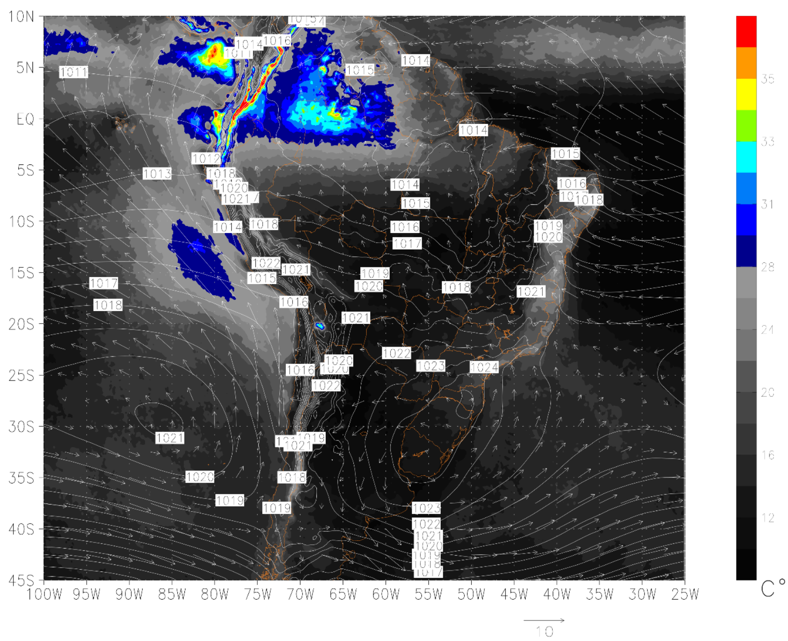


Figure 7. Mean Field of Sea Level Pressure (hPa), Wind Vector and GOES-East Visible Image (W sr^{-1} m^{-2}) for All Friagem Events.

This confirms that cold air masses advance being advected by high-pressure systems located at higher latitudes, which, like "engines," transport the cold air towards the equator.

Another feature of the pressure field (**Figure 7**) is the high-pressure system in the South Pacific near the coast of Chile, which characterizes a scenario of two high-pressure systems divided by an inverted trough over the Andes Mountain range. This synoptic configuration has been widely documented in different studies [3,36–38].

Canonically, a cold weather event is preceded by the existence of a migratory high-pressure system on the coast of Chile. In its movement, the system advances towards the center of SA, with cold air entering the Amazonian region. For this type of event, the term "The Well of the Andes" refers to the patterns observed in satellite images [37]. The high-pressure areas that transport cold air are represented in darker tones.

Friagem events are also related to the presence of clouds, especially stratiform clouds (layers of low clouds). When cold air meets the warm, humid air mass typical of the Amazonian region, low, thick clouds may form, which can lead to light rain or drizzle, as indicated by the grayish color tones in **Figure 7**.

During the passage of Friagem events, winds play a crucial role. Cold air advances over the region, pushing warmer and more humid air outwards and resulting in relatively strong winds. In the Friagem configuration, it is expected to observe winds blowing from the South or Southeast in the interior of Brazil, as illustrated in **Figure 7**. These winds advect cold air to the southwest region of the Amazonian region during Friagem events, a situation visible in **Figure 8**.

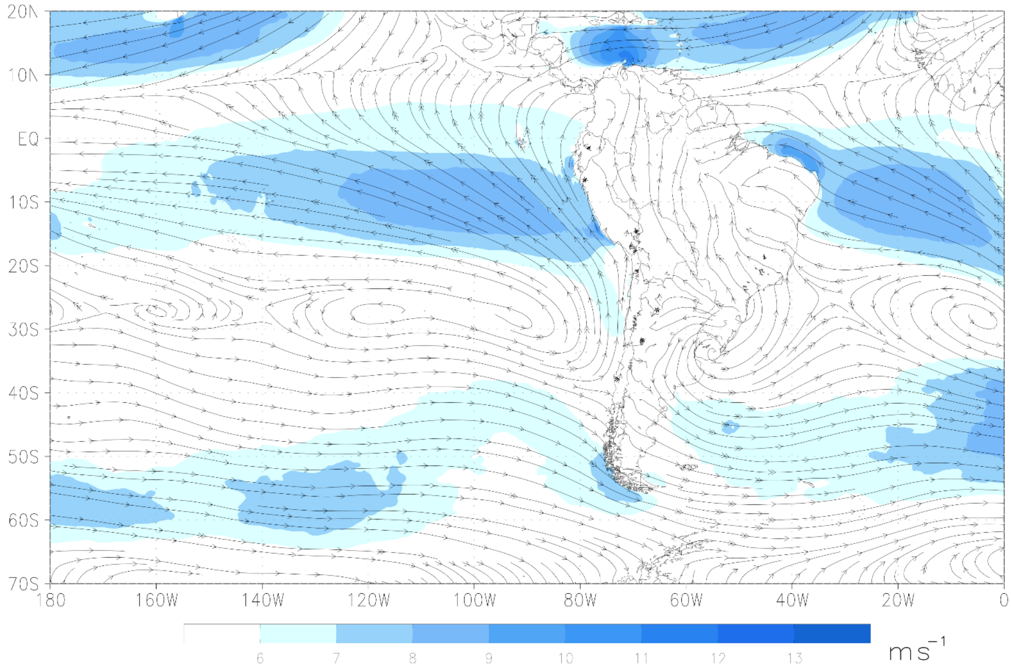


Figure 8. Mean Field of Streamline and Wind Magnitude (m/s) at 1000 hPa for All Friagem Events.

Figure 8 shows the streamline field at 1000 hPa and the wind magnitude. In addition to the anticyclone in the South Pacific near the coast of Chile, another transient anticyclone is noted over southern Brazil. The latter is the dynamic system that advects cold air to low latitudes, as observed in the southeasterly flow over central Brazil and extending to Colombia. The average wind speed is low (<6 m s^{-1}), being higher only in the oceanic sectors of the temperate and equatorial regions.

In the field of streamlines at 250 hPa and zonal wind magnitude (**Figure 9**), it can be observed that the circulation is dominated by an anticyclonic circulation over the entire northern part of Brazil and a broad westerly circulation at higher latitudes. During Friagem events, in this synoptic climatology, the entrance of the Jet Stream (winds above 30 m s^{-1}) is around the latitude of 25º S, blowing from northwesterly to southwesterly across Brazil. The Jet Stream appears to be coupled with the anticyclone over southern Brazil, observed at low levels (**Figure 8**). This dynamic configuration limits the anticyclone from advancing to low latitudes, favoring the semi-stationary advection of cold air at low levels.

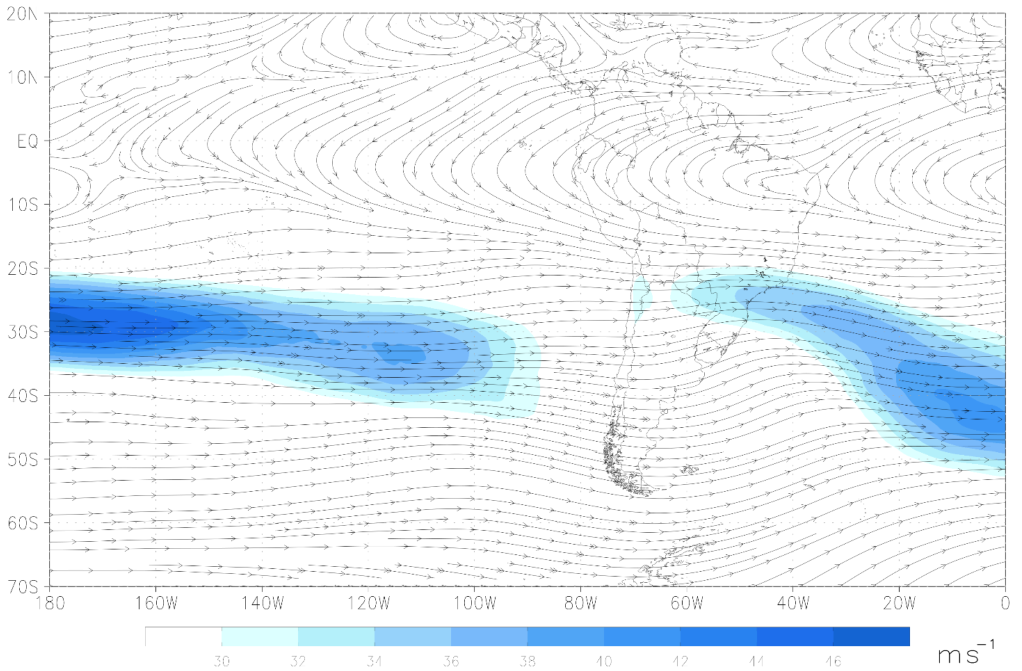


Figure 9. Mean Field Streamline and Wind Magnitude (m/s) at the 250 hPa for All Friagem Events.

Previous studies on cold air masses affecting southern and southeastern Brazil identified that families of synoptic-scale westerly waves propagate from the South Pacific to South America and superimpose on semi-stationary planetary-scale waves [22,23].

The map of the mean 500 hPa geopotential height anomalies for all Friagem events (**Figure 10**) presents a typical zonal wave pattern number 3 and 4 in the southern subtropics. As part of this pattern, an anomalous anticyclone-oriented northwest to southeast extends from the southeast Pacific, across southern SA to the southwest Atlantic, and is flanked to the northeast by an anomalous cyclone over southern Brazil and the adjacent Atlantic. This pattern resembles the atmospheric blocking pattern in this region [39]. This synoptic pattern of geopotential height anomalies at 500 hPa indicates strong dynamic support for a transient cold surface anticyclone over southern and central SA.

The surface temperature anomaly (**Figure 11**) clearly shows the significant negative anomaly over much of Brazil associated with Friagem. The axis of the anomaly is northwest-southeast oriented and follows the circulation pattern of southeasterly winds observed at low levels (**Figure 8**). The entire area with the negative anomaly is statistically significant at 95%. Although the Friagem event is an Amazonian phenomenon, much of central SA is influenced by the drop in temperature. Moreover, even countries such as Peru (Amazonian sector) and Colombia are under the influence of this phenomenon. Coupled with this negative anomaly, southern SA is influenced by an inverse pattern of positive temperature anomalies, although of smaller magnitude, and still statistically significant.

In the mean sea level pressure anomaly field (**Figure 12**), significant positive anomalies cover all of SA. The positive anomalies are more accentuated in the central regions of the continent, but they are also felt in the equatorial regions of the Atlantic and are weak in the Pacific. This anomalous pattern also extends to the southern parts of the continent. The system is clearly baroclinic, given that the negative geopotential anomaly at 500 hPa (**Figure 10**) shows an opposite sign over Brazil and the presence of the Jet at 250 hPa (**Figure 9**).

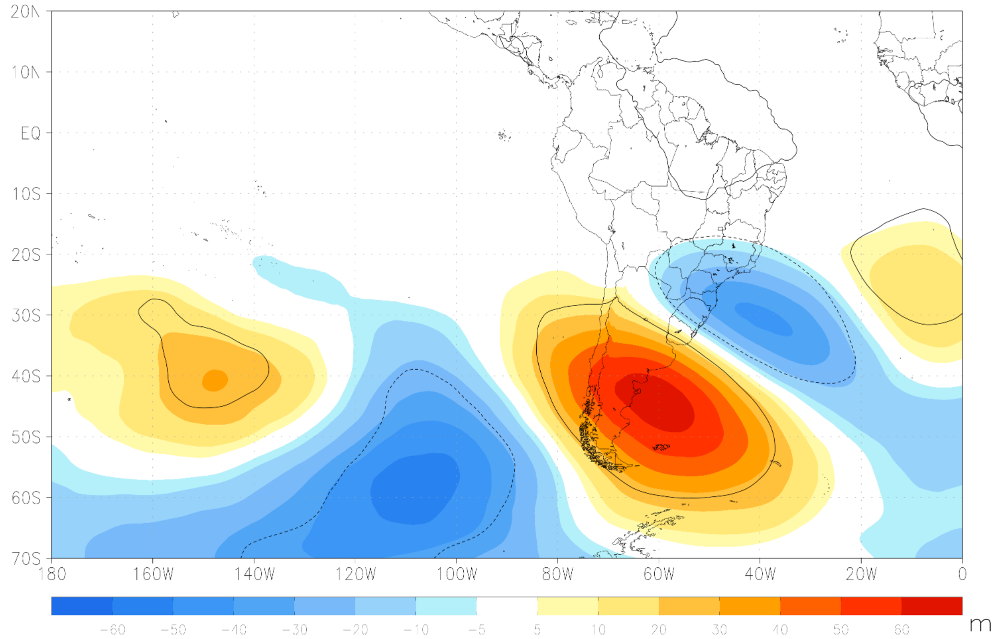


Figure 10. Mean Geopotential Anomaly Field (m) at 500 hPa for All Friagem Events. The Black Lines Delimit the Regions of Anomalies with Statistical Significance.

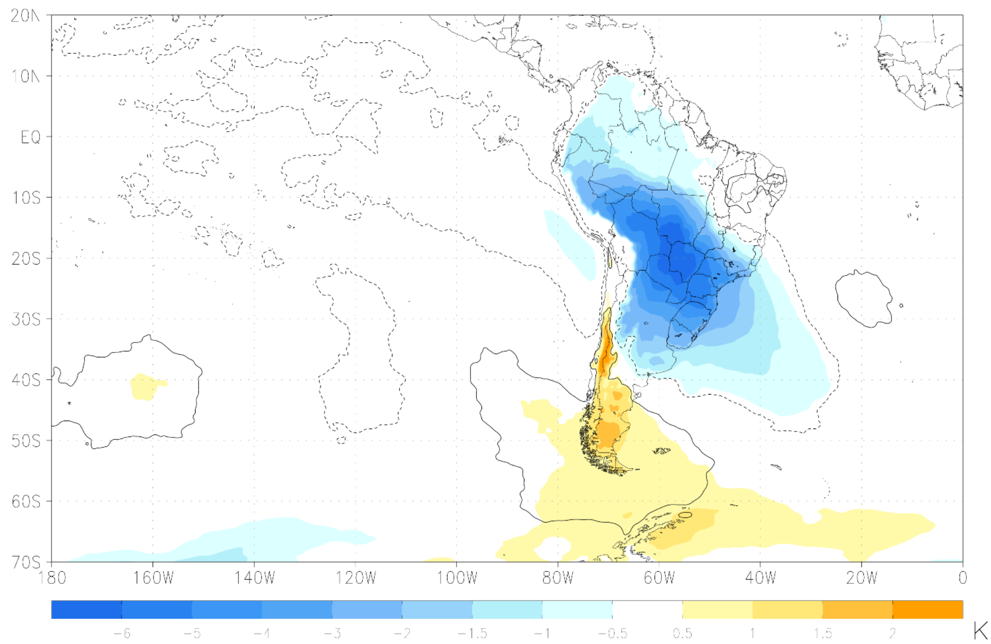


Figure 11. Mean Field of Air Temperature Anomalies (°C) at 1000 hPa, for All Friagem Events. The Black Lines Delimit the Regions of Anomalies with Statistical Significance.

Sea surface temperatures (SST) in the equatorial Pacific also exhibit a characteristic pattern in Friagem events. **Figure 13** shows negative SST anomalies extending along SA's west coast, with the largest magnitudes in the region near the coast of Ecuador and Peru. The SST anomaly pattern in the equatorial Pacific resembles a typical La Niña pattern and reflects the above-mentioned high frequency of Friagem events under La Niña conditions. Significant positive SST anomalies are noted in the equatorial Atlantic and less evident negative anomalies in the South Atlantic and Central Pacific. The positive SST anomalies in the equatorial Atlantic pattern would intensify the southeast trade winds (**Figures 7** and **8**), while the other negative anomalies would modify the migratory highs, generating the anomalous patterns in **Figure 12**. Another important configuration is the strong negative anomaly on the coast of the Antarctic continent and an equally strong, but spatially more restricted, anomaly on the southern coast of Brazil. In summary, this oceanic configuration possibly favors the persistence of the scenario of two high-pressure systems divided by an inverted trough over the Andes Mountain range (**Figure 7**).

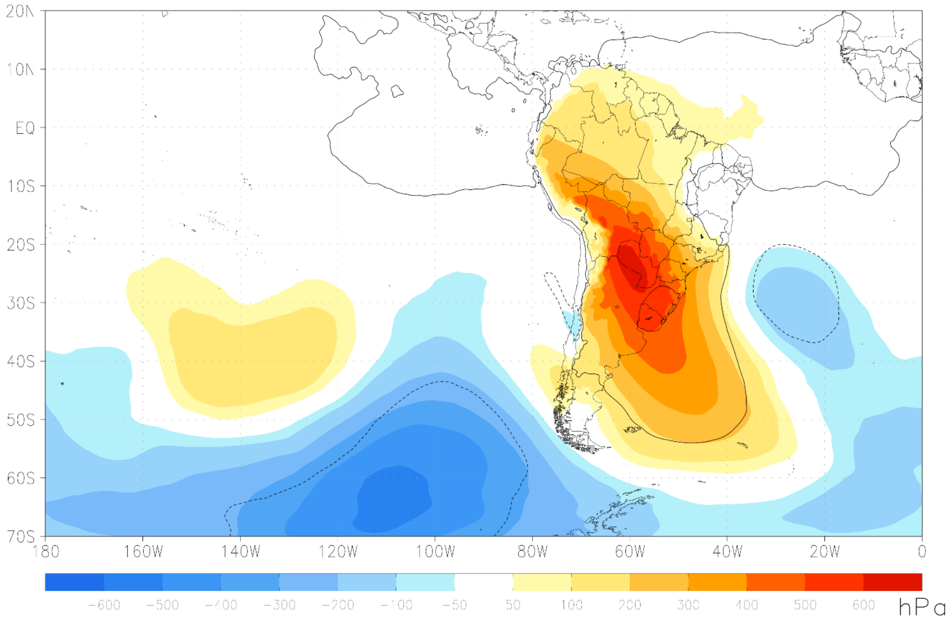


Figure 12. Mean Sea Level Pressure (hPa) Anomaly Field for All Friagem Events. The Black Lines Delimit the Regions of Statistically Significant Anomalies.

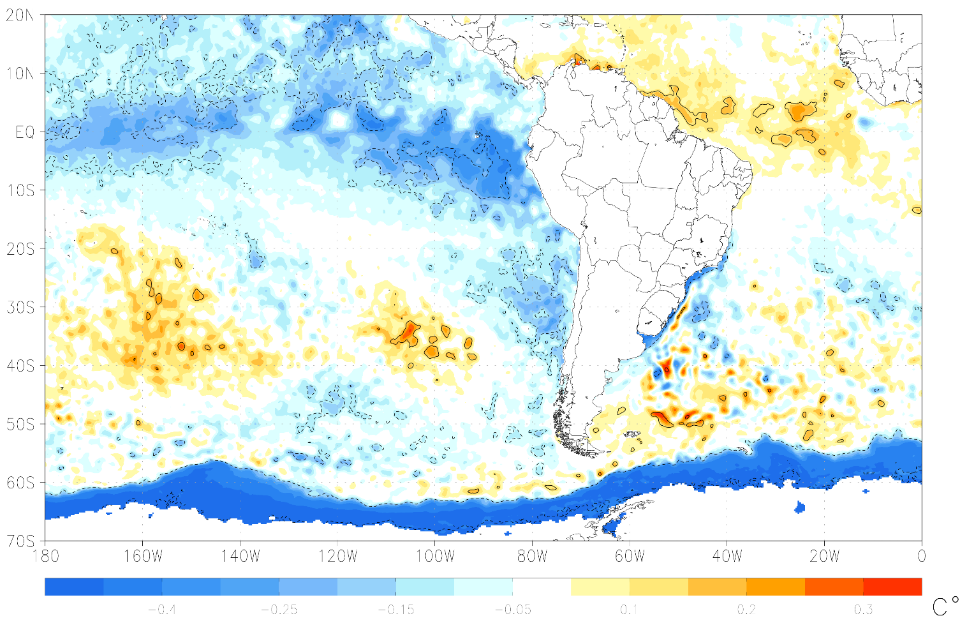


Figure 13. Mean Field of Weekly Sea Surface Temperature (°C) Anomalies for All Friagem Events. The Black Lines Delimit the Regions of Statistically Significant Anomalies.

4. Conclusions

This study aimed to describe the climate patterns associated with Friagem events in the southwestern Brazilian Amazon. It is considered a time series of the most recent T_{min} (1979–2020), a period during which some events have not yet been analyzed.

The most relevant results of the research identify a tendency to decrease the occurrence and persistence (lifetime) of Friagem events, with these events being much more frequent in July and August.

The circulation patterns described above, surface pressure, 1000 hPa streamlines, and 500 hPa geopotential fields (**Figures 7–9**) contain coherent features typical of the occurrence of previously documented Friagem events, such as the baroclinic wave pattern [38,40].

On a global scale, we also found that Friagem events are associated with a zonal pattern number 3 and 4 identified in the 500 hPa geopotential field, with a northwest-southeast oriented anomalous anticyclone that extends from the southeast Pacific, through southern SA to the southwest Atlantic and is flanked to the northeast by an anomalous cyclone over southern Brazil and the adjacent Atlantic. Our results also indicated that the anomalous high-pressure system in southern SA might be linked to anomalous patterns in the SST field. The SST anomaly pattern features negative anomalies extending throughout the equatorial Pacific. This configuration resembles a typical La Niña pattern. Studies show that the winter surface air temperature in western SA [41], including our study area, is strongly modulated by the ENSO with La Niña causing anomalous cooling in this region. Additionally, the results here showed that Friagem events occur mostly during winter, with the second-highest frequency of Friagem events during La Niña years. Also, the positive SST anomalies along the equatorial Atlantic are consistent with the intensification of the southeast trade winds which are part of the low-level circulation associated with Friagem events (**Figures 7** and **8**).

Therefore, the large-scale climate pattern, in addition to the synoptic ones, favors the occurrence of Friagem events and modulates their intensity. The climate scale is linked to the El Niño-La Niña phenomenon. Although a higher frequency of Friagem events has been identified in neutral years, it is in La Niña years that the frequency is higher when compared to El Niño years. In the synoptic scale modulation would be likely done by the SST in the South Atlantic and Central Pacific, which presented significant values.

Author Contributions

Conceptualization, N.N.M.B., M.B.R. and M.C.V.; methodology, M.B.R., M.C.V. and M.T.K.; software, M.B.R.; validation, M.C.V. and M.B.R.; formal analysis, M.B.R., M.C.V., M.T.K. and N.J.F.; writing—original draft preparation, N.N.M.B., M.C.V., M.T.K., N.J.F. and M.B.R.; writing—review and editing, M.B.R., M.T.K. and N.J.F.; visualization, N.N.M.B. and M.C.V. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data will be made available upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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