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Meteorology

Spatiotemporal variability of precipitation and surface temperature in the southern mesoregion of amazonas, Brazil, during the occurrence of enso

Variabilidade espaço-temporal da precipitação e temperatura de superfície na mesorregião sul do amazonas durante a ocorrência de enos

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ABSTRACT

Impacts of El Niño – Southern Oscillation (ENSO) climatic phenomena in the southern mesoregion of the Amazon is still poorly understood. Thus, the objective of this study was to analyze the impacts of ENSO of moderate and strong categories on precipitation (ppt) and surface temperature (ts) in the southern mesoregion of Amazonas. The research was carried out with ppt data obtained by the product TRMM_3B43 and ts of the product MOD11C3 in the municipalities of Apuí, Boca do Acre, Canutama, Humaitá, Lábrea, Manicoré and Novo Aripuanã. The Niño Indices were obtained from the National Oceanic Atmospheric Administration. Ts was organized into averages and ppt in seasonal totals from 1998 to 2019, to obtain its provisional climatological normal in the dry and wet seasons. The results showed that ENSO significantly influenced the pattern of ppt and ts in the southern mesoregion of Amazonas. El Niño (EN) had more impact on changing the pattern of ppt and ts than La Niña (LN). The largest reductions in ppt and increases in Ts occurred in the EN periods of 1998/01 and 2015/16, while the occurrence of LN decreased the ppt more expressively in the periods of 2007/08 and 2011/12.

Keywords: Climatic variables; Global warming; Atmospheric circulation

RESUMO

Os impactos dos fenômenos climáticos el niño – oscilação sul (enso) na mesorregião sul da amazônia ainda são pouco conhecidos. Este estudo teve como objetivo analisar os impactos do enos de categorias moderada e forte sobre a precipitação e temperatura de superfície da mesorregião sul do amazonas. A pesquisa foi realizada em sete municípios da mesorregião sul do amazonas: apuí, boca do acre, canutama, humaitá, lábrea, manicoré e novo aripuanã. As precipitações foram obtidas pelo sensor trmm_3b43, enquanto as temperaturas da superfície foram obtidas pelo produto mod11c3. Os índices oceânicos niño foram acessados diretamente no portal national oceanic atmospheric administration. Foram calculadas as médias aritméticas e totais sazonais para o período compreendido neste estudo (1998 a 2019), no intuito de obter as normais climatológicas provisórias de temperatura da superfície e precipitação, respectivamente, nos períodos seco e chuvoso. Os resultados demonstraram que o enos, em ambas as categorias analisadas, exerceu influência significativa sobre as variáveis abordadas no estudo, visto que os comportamentos dessas foram alterados durante a ocorrência do evento. Os impactos do el niño sobre a precipitação e temperatura de superfície foram maiores que os do la niña. Os períodos de 1998/01 e 2015/16 sofreram as maiores reduções de precipitação e aumento de temperatura de superfície. Durante a ocorrência do la niña, as precipitações nos períodos de 2007/08 e 2011/12 apresentaram anomalias negativas mais expressivas. Todavia, as temperaturas de superfície não foram tão afetadas pelo evento.

Palavras-chave: Amazônia; Variáveis climáticas; El Niño; La Niña

1 INTRODUCTION

The Amazon rainforest plays important roles in maintaining the regional and global climate. It contributes to the availability of 70% of all Brazilian fresh water and provides important environmental services, such as storage and absorption of excess carbon from the atmosphere and transport of water vapor to the atmosphere (SILVA JÚNIOR *et al*., 2019; ROCHA *et al*., 2015). The Amazon is located in the equatorial region and has a hot and humid climate, where rainfall is the main climatic factor, as it distinguishes between wet and dry seasons (PEDREIRA JUNIOR *et al.*, 2020). Variability in the climate pattern, whether due to deficiency or excessive rainfall, across the Amazon region, causes drought and flood events (MARENGO; ESPINOZA, 2016). As well as precipitation, the surface temperature provides information on the physical properties of the local climate (LIMA; AMORIM, 2011; QUERINO *et al*., 2016), being an important variable for the maintenance of the planetary climate system due to its connection with the greenhouse effect and global warming (PAVÃO *et al*., 2015).

Among the climatic phenomena that occur in the Amazon region, El Niño - Southern Oscillation (ENSO) causes seasonal and annual variations in the Amazon climate, such as extreme drought and flood events. ENSO is a phenomenon with consequences on a global scale, which refers to the coupling of the ocean and atmosphere and occurs in the tropical portion of the Pacific Ocean. It is divided into two phases: the cold La Niña (LN) and the hot El Niño (EN). It is accepted that droughts occur in EN events and excessive rainfall in LN events throughout the Northern region of Brazil (MOLION, 2017; MOURA *et al*., 2019). However, measuring these variations in the Amazon region becomes a challenge due to the vast area and the scarcity of instruments (SANTOS *et al*., 2019).

The difficulty in measuring surface climatic variables in the Amazonian mesoregion demands alternatives, such as data obtained by sensors installed in orbital satellites. These data can be used in climate studies at regional, continental and global geographic scales (SANTOS *et al*., 2019; SICILIANO DA SILVA JÚNIOR *et al*., 2018) and in long time series, making it easier to identify characteristics and trends over time (MOURA *et al*., 2019). Among the remote sensing products to characterize precipitation and surface temperature, we highlight the Tropical Rainfall Measuring Mission (TRMM) and the MOD11 product of the Moderate-Resolution Imaging Spectroradiometer (MODIS).

Given the importance of identifying the impacts of ENSO on the climate of the Amazon region, the objective of this study was to evaluate the spatiotemporal variability of precipitation and surface temperature in the southern mesoregion of Amazonas, and its relationship with moderate and strong ENSO events.

2. MATERIAL AND METHODS

2.1. Study area

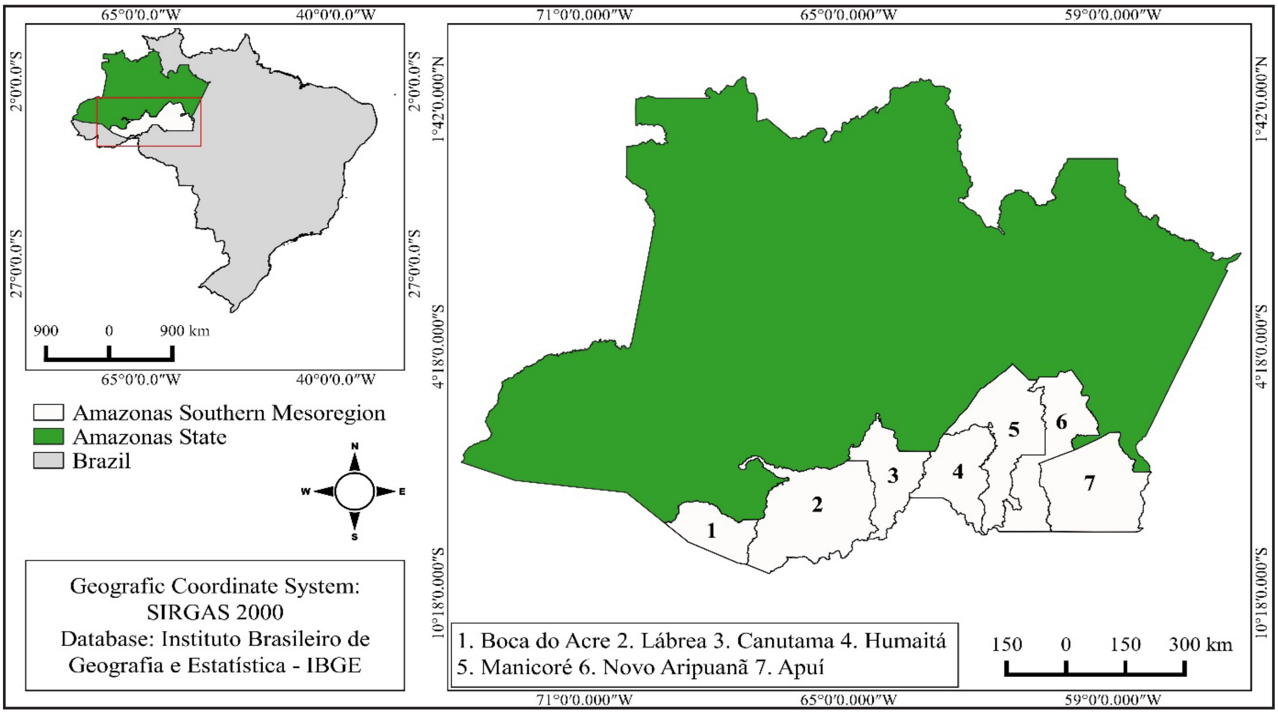
The southern mesoregion of Amazonas is composed of ten municipalities, which are economically linked to two activities: timber production and livestock (MARTINS, 2019; TAVARES e CORDEIRO, 2017). The study was carried out in seven of the ten municipalities in the mesoregion: Apuí, Boca do Acre, Canutama, Humaitá, Lábrea, Manicoré and Novo Aripuanã (Figure 1). The climatic seasonality of this region is characterized by a prolonged wet season (October to April), a short dry season (June to August) and two transition seasons in May and September (PEDREIRA JUNIOR *et al*., 2018). These seasons occur due to a combination of factors, in which the most important is the availability of solar energy (PAVÃO *et al*., 2017, 2016). The climate classification of each municipality, according to the classification by Thornthwaite and Matter, is described in Table 1 (MARTINS, 2019).

Table 1 – Municipalities, geographical coordinates, Thornthwaite and Matter climatic classification, precipitation (Ppt; mm) and annual average air temperature (Tair; ºC) according to the Climatological Normal (CN) of each municipality in the southern mesoregion of Amazonas. NOTE: The CN and the climate classifications of Canutama and Novo Aripuanã are not available

Municipalities	Geographical Coordinates	Climate	Ppt (mm)	Tair (°C)
Apuí	07º 11' S, 59º 53' W, 135m	B2rB'4a'	1589,0	25,8
Boca do Acre	08º 45' S, 67º 23' W, 116m	B3WA'a'	2078,3	25,9
Canutama	06° 32' S, 64° 22' W, 55m	-	-	-
Humaitá	07º 30' S, 63º 01' W, 58m	B4WA'a'	2079,9	26,4
Lábrea	07º 15' S, 64º 47' W, 75m	B2WA'a'	2099,8	26,4
Manicoré	05° 48' S, 61° 18'W, 45m	AWA'a'	2946,2	26,5
Novo Aripuanã	05° 07'S, 60° 22' W, 20m	-	-	-

Source: Authors (2022)

Figure 1 – Location of municipalities in the southern mesoregion of Amazonas, Brazil



Source: Authors (2022)

2.2. Data used

The rainfall (ppt) of each municipality was obtained by the TRMM_3B43 sensor, installed on board the Tropical Rainfall Measuring Mission (TRMM) satellite (https://disc.gsfc.nasa.gov/), which produces images with a spatial resolution of 0.25° (approximately 27.83 km). In this study, 44 ppt images were downloaded, corresponding to the seasonal periods from January 1998 to December 2019. The May ppt was included in the wet season and the September ppt in the dry season, so that all days of the year were considered in the analyzes.

The surface temperature (Ts) was obtained from the product MOD11C3 of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board the TERRA satellite (https://lpdaac.usgs.gov/products/myd11c3v006/#tools), with a spatial resolution of 0.05° (approximately 5.56 km) and monthly temporal resolution. In this study, 239 monthly images of Ts from February 2000 to December 2019 were downloaded since the images only began to be captured by the MODIS sensor in February 2000.

The Oceanic Niño Index (ONI), based on the variation in the surface water temperature of the Pacific Ocean, was downloaded from the National Oceanic Atmospheric Administration (NOAA, 2020) (www.nws.noaa.gov). In this study, only years of moderate and strong occurrence of ONI were used (Table 2).

Table 2 – Intensity, sea surface temperature (SST) anomaly in the equatorial Pacific and years of occurrence of the El Niño and La Niña events

Events	Intensity	SST Anomaly (°C)	Years
El Niño	Moderado	1,0 a 1,4	2002/03, 2009/10
	Forte	≥ 1,5	1998/01, 2015/16
La Niña	Moderado	-1,0 a -1,4	1999/00, 2000/01, 2007/08
	Forte	≤ 1,5	1998/99, 2010/11, 2011/12

Source: Authors (2022)

2.3. Data analysis

All images were geographically cut and spatially resampled to a spatial resolution of 0.01 °, using QGIS 2.8 to make them compatible in the format of the study areas. Subsequently, the seasonal averages of the entire study period (1998 to 2019) were calculated, which were considered Provisional Climatological Normals (PCNs) for the southern mesoregion of Amazonas. Anomalies were calculated by the seasonal difference between the seasonal ppt obtained by TRMM and the Ts obtained by MOD11 and the ppt and Ts of PCN during the period of ENSO activity.

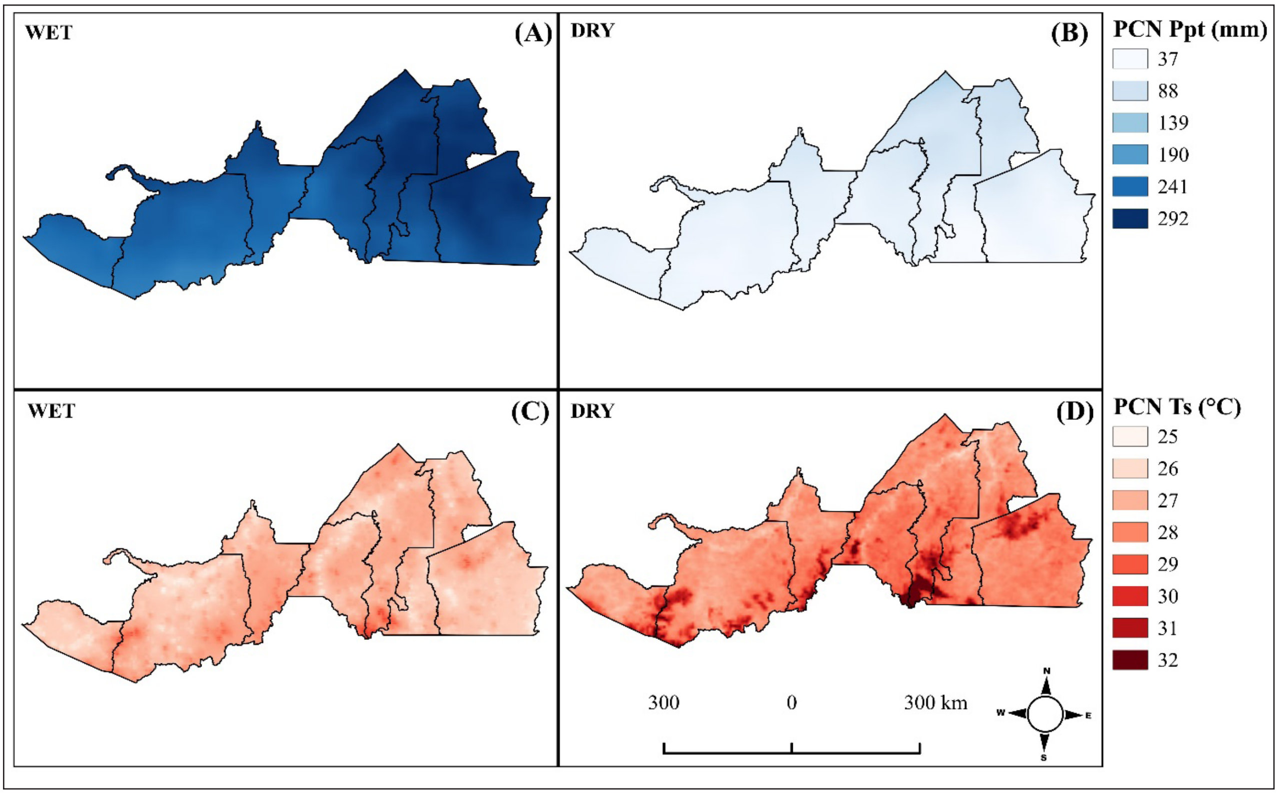
3. RESULTS AND DISCUSSION

3.1. Determination of provisional climatological normal

The Provisional Climatological Normal (PCNs) of precipitation (ppt) of the southern mesoregion of Amazonas varied from 37 to 88 mm in the dry season and from 190 to 292 mm in the wet season (Figures 2A and 2B). It is noted that the highest rainfall (between 241 and 292 mm) in the wet season occurred in the eastern region, mainly in Novo Aripuanã, Manicoré and Apuí, while the ppt in the other municipalities was up to 190 mm in the wet season. There was no great variation in ppt during the dry season between municipalities, with ppt between 37 mm (south of Apuí, Manicoré, Boca do Acre and Lábrea) and 88 mm (north of Novo Aripuanã, Manicoré and Apuí). The municipalities of the Madeira River sub-basin (Humaitá, Novo Aripuanã, Manicoré and Apuí) had higher ppt, in both seasons, than in the municipalities of the Purus River sub-basin (Boca do Acre, Lábrea and Canutama). These results agree, in part, with those obtained by (COUTINHO *et al*., 2018), who observed a higher ppt in the sub-basin of the Madeira River than in the Purus River in the wet season, reversing the trend in the dry season.

The PCNs of the surface temperature (Ts) of the mesoregion ranged from 25°C to 28°C in the wet season (Figure 2C). The lowest Ts in the wet season occurred in most of Apuí, Lábrea and Boca do Acre, while the highest Ts occurred in small regions of Humaitá and Novo Aripuanã. Ts in the dry season was higher than in the wet season, ranging from 28°C and 32°C (Figure 2D). The largest Ts in the dry season (from 31 to 32 ° C) occurred in the south of Manicoré, Novo Aripuanã, Canutama, Lábrea and Boca do Acre, and in the north of Apuí. Some small areas between Humaitá and Novo Aripuanã had a minimum of 25°C. These results were also observed by (Pavão *et al*., 2017) in Apuí, where the Ts in the dry season was on average 20% higher than in the wet season. The lower variation of Ts in the wet season is due to the thermohydroregulatory effect of the surface when there is greater water availability on the surface, as the available energy is used primarily for evapotranspiration followed by sensible heat flux (BIUDES *et al*., 2015).

Figure 2 - Provisional climatological normal (PCN) of precipitation (Ppt) in the dry (A) and wet (B) seasons and surface temperature (Ts) in the dry (C) and wet (D) seasons in the southern mesoregion of Amazonas



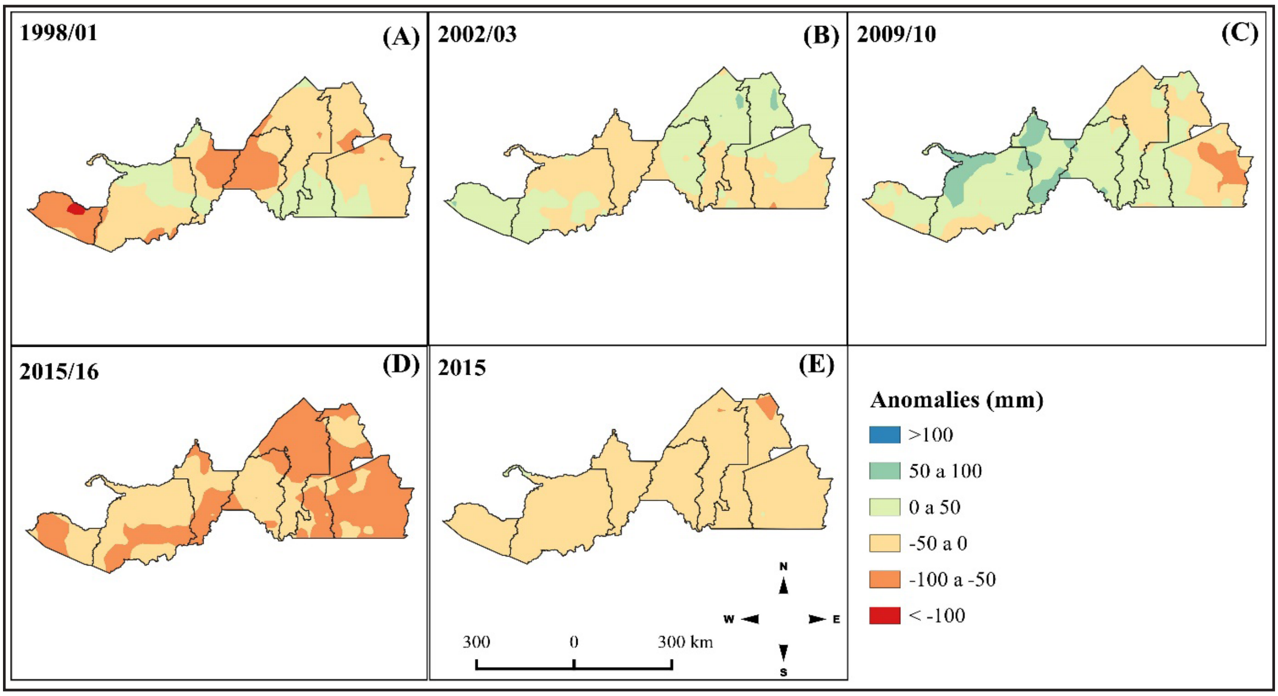
Source: Authors (2022)

3.2. Effect of El Niño and La Niña on Precipitation

The El Niño (EN) events changed the ppt pattern in the southern mesoregion of Amazonas in all seasons analyzed (Figure 3). The 1998/01 strong EN event reduced ppt in the wet season in Boca do Acre, Canutama and Humaitá with values greater than 100 mm in some areas (Figure 3A), but also increased in ppt in Lábrea, Manicoré, Novo Aripuanã and Apuí, up to 50 mm. The 2002/03 moderate EN event reduced the ppt to the east of the southern mesoregion of the Amazon more in the wet season, especially in Apuí, and less in Canutama and north of Lábrea (Figure 3B). While the 2009/10 moderate EN event reduced ppt in the wet season less intensely, except for a small portion south of Apuí (Figure 3C), but increased the ppt in Canutama Lábrea by up to 100 mm.

The 2015/16 strong EN event reduced ppt homogeneously across the southern mesoregion of Amazonas by up to 100 mm in the wet season (Figure 3D). It should be noted that the largest reductions in ppt occurred in the eastern region, in almost all of Manicoré, Novo Aripuanã and Apuí. In the dry season of 2015, the EN reduced the ppt by up to 50 mm homogeneously in the southern mesoregion of Amazonas, except in some small portions of Novo Aripuanã, Manicoré and Lábrea (Figure 3E).

Figure 3 – Anomalies in the spatial distribution of precipitation in the wet (A, B, C, D) and dry (E) seasons during the El Niño events in the southern mesoregion of Amazonas



Source: Authors (2022)

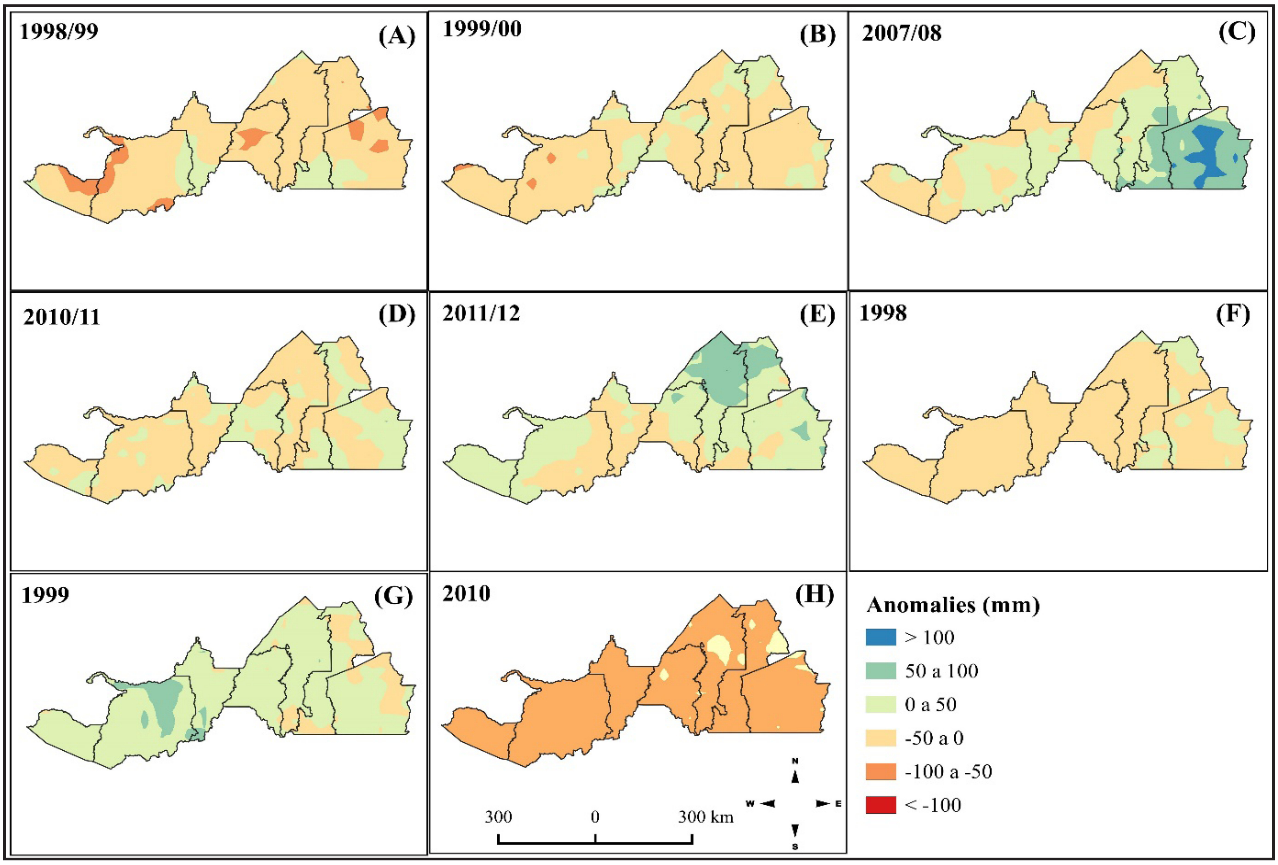
These results corroborate with previous studies that highlighted the influences of ENSO in the ppt of the Amazon (ESPINOZA *et al*., 2011; LEWIs *et al*., 2011; MARENGO, 2009). The difference in the effects of EN in the municipalities may be related to the performance of positive Sea Surface Temperature (SST) anomaly in the central and eastern Equatorial Pacific occurring in different areas. These anomalies cause changes in the Walker Cell, with displacement of the ascending branch to the region of Peru. Consequently, the Walker Cell subsiding branch operates more in the eastern portion of the Amazon, reducing convective activity over the southern mesoregion of Amazonas (SOUZA *et al*., 2015). The 2009 EN peak occurred from November to April 2010, and caused positive anomalies in southwestern Amazonia, central Bolivia and northern Mato Grosso (LEWIS *et al*., 2011), but also reduced ppt in an area of 3 million km^2 of the Amazon region (MARENGO *et al*., 2011).

Among the events analyzed, the 2015/16 EN stands out as one of the strongest events since 1950 (L'HEUREUX *et a*l., 2017). This event started in the southern summer of 2015 and extended until the fall of 2016, a period that included the wet (2015/16) and dry (2015) seasons of the mesoregion. The negative anomaly of the ppt in this period was more evident from October 2015 to January 2016 (PANISSET *et al*., 2018). This event was so strong that the ppt was about 6 mm day^{-1} smaller than Climatological Normal from September to November 2015 in the Amazon and northeastern Brazil (PEREIRA *et al*., 2017).

The 1998/99 strong La Niña (LN) event increased ppt in the wet season by up to 50 mm in Novo Aripuanã, Apuí, Canutama and Lábrea (Figure 4A). These results did not differ much from the 1999/00 moderate LN event, when the negative ppt anomalies were less intense (Figure 4B). Positive ppt anomalies in the wet season in the 2007/08 moderate LN event were more present than in previous years (Figure 4C). The municipalities most affected with an increase of up to 50 mm in ppt during the wet season were Apuí, Novo Aripuanã and Manicoré, and the others had negative ppt anomalies concentrated in the western and southern portions of the southern mesoregion of Amazonas.

The 2010/2011 strong LN event increased ppt in the wet season above 50 mm in some regions, being more concentrated in the east of the southern mesoregion of Amazonas (Figure 4D), however, the decrease in ppt by up to 50 mm was most frequent in most municipalities. It is noteworthy that the LN events of 1998/99, 1999/00 and 2010/11 were preceded by long episodes of MS of strong and moderate intensity, which significantly impacted the region's climatic variables and may have influenced the dynamics from LN. Still in 2010, there was a considerable reduction in ppt both in the dry and wet season, despite the LN having been of strong intensity (Table 2). During the wet season of 2010, almost the entire southern mesoregion of Amazonas had an increase of up to 50 mm in ppt but decreased between 50 and 100 mm in the dry season. This LN event may have been caused by the warming of the waters of the North Atlantic, which resulted in a major drought (ESPINOZA *et al*., 2011; MARENGO *et al*., 2008).

Figure 4 - Anomalies in the spatial distribution of precipitation in the wet (A, B, C, D and E) and dry (F, G and H) seasons during the La Niña events in the southern mesoregion of Amazona



Source: Authors (2022)

In the strong LN of 2011/12, the north of Manicoré and Novo Aripuanã and some portions of Apuí had greater ppt increases during the wet season, ranging from 50 to 100 mm (Figure 4E). The other municipalities presented positive anomalies of up to 50 mm, with emphasis on Boca do Acre and Apuí. A small portion to the south of the southern mesoregion of Amazonas also had the same reductions. During this period there was a strong flood in the Amazon basin with a pattern different from other humid years in the Amazon, such as 1999 and the first half of 2009 (COUTINHO *et al*., 2018; SATYAMURTY *et al*., 2013). This episode suggests that the LN was the main force of the abundant rains in the western Amazon.

The ppt during the dry season of 1998 in Boca do Acre, Lábrea, Canutama, Humaitá and a large part of Manicoré was 50 mm smaller than the PCN (Figure 4F). In the other municipalities there was an increase of up to 50 mm, but the reduction of ppt by up to 50 mm stood out in most of the southern mesoregion of Amazonas. Unlike 1998, the 1999 LN increased the ppt in much of the southern mesoregion of Amazonas, with Lábrea and the south of Canutama standing out (Figure 4G). Similar to the dry season of 1998, the LN of 2010 stood out by reducing the ppt by up to 50 mm in the dry season in most municipalities in the mesoregion, except in some locations in Humaitá, Manicoré, Novo Aripuanã and Apuí (Figure 4H).

The ppt in the Madeira sub-basin (covers Humaitá, Manicoré, Novo Aripuanã and Apuí) during the wet season is greater than in the Purus sub-basin (covers Boca do Acre, Lábrea and Canutama), with an inverse pattern in the dry season (COUTINHO *et al*., 2018). This validates the results obtained in the wet seasons of 2007/08 and 2011/12 and in the dry of 1999, which were accentuated by the LN of moderate and strong intensity. The Purus sub-basin is most affected by floods (91.7% of the ppt above the average in LN years), and the Madeira sub-basin is most affected by droughts (90% of the ppt below the average in years of LN) EN) (COUTINHO *et al*., 2018), which partially corroborates the results obtained in this study.

3.3. Effect of El Niño and La Niña on Surface Temperature

During the moderate EN of 2002/03, the surface temperature (Ts) in the wet season of the entire southern mesoregion of Amazonas was up to 1.5°C higher than the PCN, but there were places with an increase of 1.5 and 3ºC to the south of Humaitá, Manicoré and Novo Aripuanã and above 3ºC in some points of Manicoré and, still, there were places with a decrease in Ts from 1.5 to 3º in Lábrea and Apuí (Figure 5A). The pattern of change caused by the moderate EN of 2009/10 in the wet season was similar to that of 2002/03, with small places where the Ts decreased in the south of Humaitá, Manicoré and Lábrea (Figure 5B).

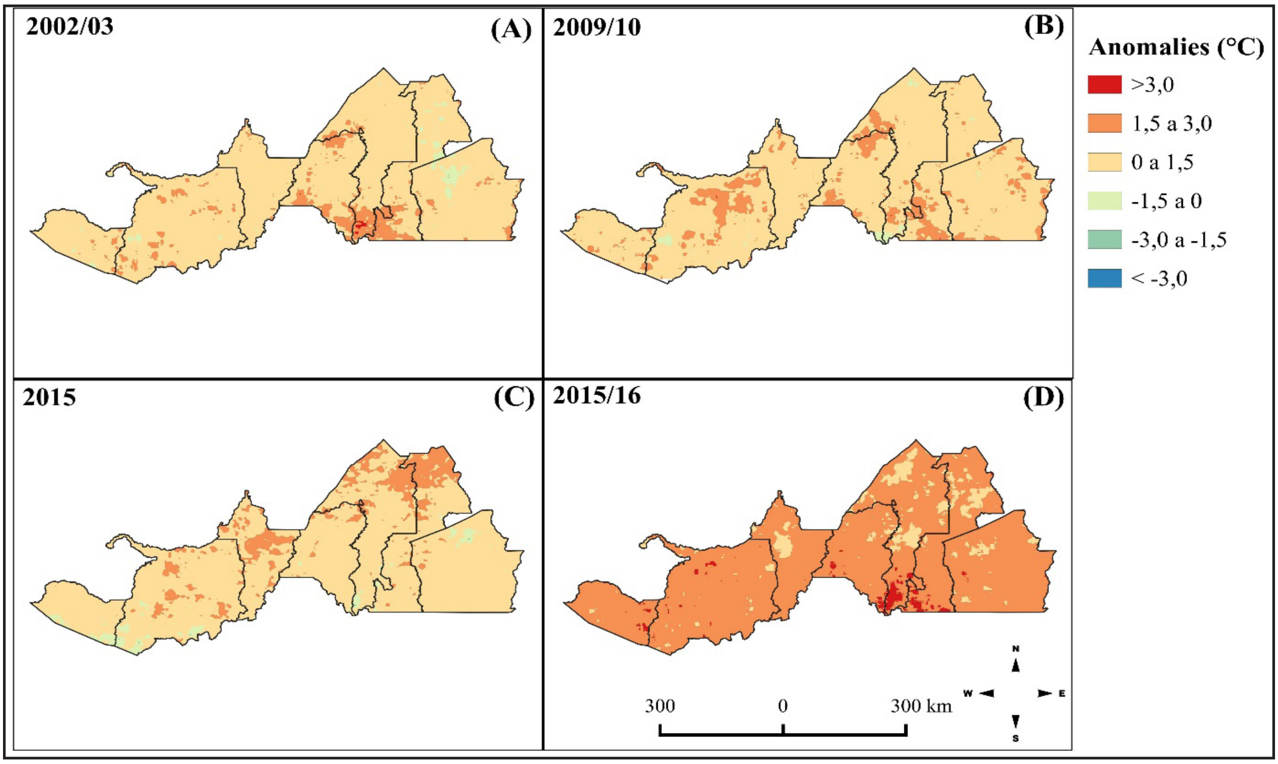
The strong EN of 2015/16 caused more intense anomalies of Ts in the wet season (Figure 5D). In most of the southern mesoregion of Amazonas, Ts increased from 1.5 to 3°C in relation to PCN and increased by more than 3°C in southern Humaitá, Manicoré and Novo Aripuanã. However, the 2015 EN had a less pronounced effect in the dry season, increasing Ts from 1.5 to 3 ° C in the northern and central portions, and decreasing Ts in some points in the southern mesoregion of Amazonas (Figure 5C).

The most intense effect of ENSO on ppt and Ts in the Amazon during the wet season has been reported in some studies (YOON; ZENG, 2010). The area with increased Ts in the Amazon increased from June to September (83%) and from October to January (90%) (PANISSET et al., 2018), partially supporting the results of this study. As an effect of the more intense Ts anomaly in the wet season of 2015/16 compared to the dry season of 2015, one can mention the greater number of hot spots in the Western Amazon in 2016 than in 2015 (DA SILVA JÚNIOR, L. A. S. *et al*., 2018).

The Ts during the wet season of the 2000/01 moderate LN event was up to 3ºC lower than the PCN in the entire southern mesoregion of Amazonas (Figure 6A), but the Ts increased in the extreme regions (east / west), mainly in Apuí and Boca do Acre. Unlike LN 2000/01, the increase in Ts up to 1.5ºC was predominant in the southern mesoregion of the Amazon in the events of moderate LN of 2007/08, strong LN of

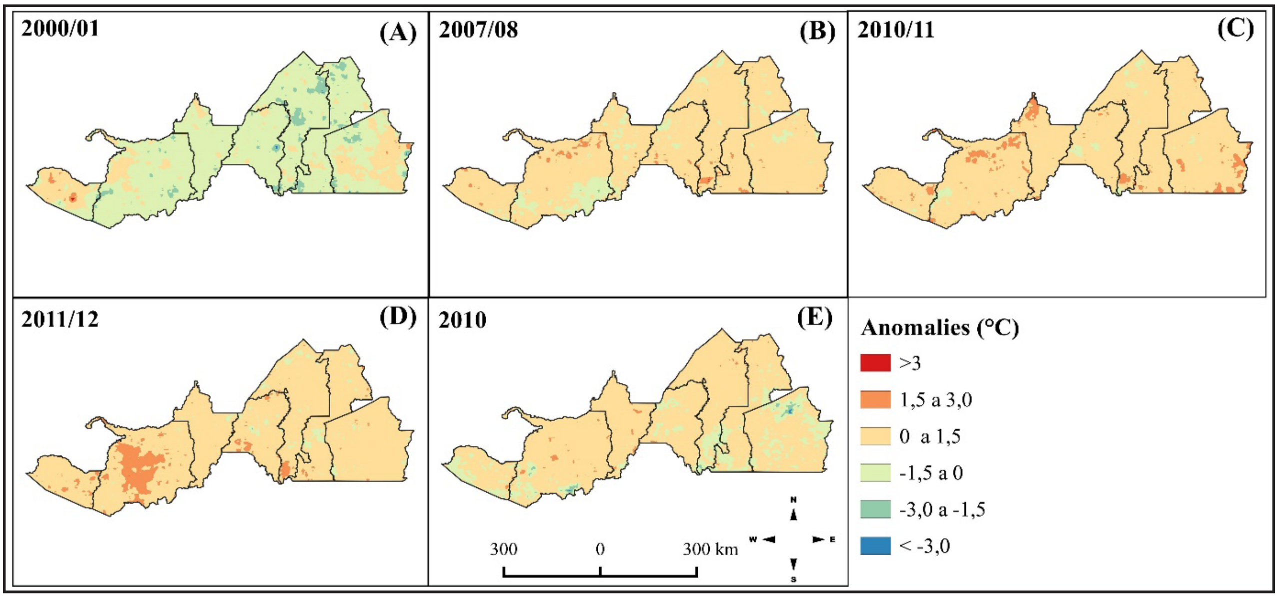
2010/11 and strong LN of 2011/12, with only a few Ts decrease points up to 1.5°C in a small portion of Lábrea, Canutama and Apuí (Figure 6B, 6C 6D). It is noteworthy that the 2011/12 strong LN increased Ts from 1.5 to 3ºC in a larger area in Lábrea registered increases in Ts from 1.5 to 3ºC (Figure 6D). Finally, the increase in Ts in the dry season of 2010 predominated throughout the southern mesoregion of the Amazon, but there were portions of Apuí and Lábrea where Ts decreased by up to 3°C (Figure 6E). The low spatial variability of Ts anomaly in the dry season is due to the difficulty of cold front intrusion during LN events in the region (PANISSET *et al*., 2018). These intrusions increase the variability of Ts in the dry season, while positive anomalies of Ts are induced by droughts linked to the Temperature of the North Atlantic Sea Surface may not be able to overcome the natural variability during this season.

Figure 5 – Anomalies in the spatial distribution of surface temperature in the wet (A, B, and D) and dry (C) seasons during the El Niño events in the southern mesoregion of Amazonas



Source: Authors (2022)

Figure 6 – Anomalies in the spatial distribution of surface temperature in the wet (A, B, C and D) and dry (E) seasons during the La Niña events in the southern mesoregion of Amazonas



Source: Authors (2022)

4 CONCLUSIONS

ENSO modified the pattern of ppt and Ts in the southern meso region of Amazonas. The effects of El Niño were greater than those of La Niña. The events that occurred in 1998/01 and 2015/16 reduced the ppt more and increased the surface temperature more than the other events studied. During the La Niña events, the decrease in precipitation was more significant in the periods of 2007/08 and 2011/12, but the surface temperatures were not as affected by the events. Seasonally, the wet season of the southern mesoregion of Amazonas was more sensitive to the effects of El Niño (reduction of ppt) and, although the results of La Niña were not as intense, its negative anomalies were more present during the wet season.

It is suggested in future works approaches on a larger regional geographic scale, covering a larger number of municipalities and allowing a better understanding of the spatial variability of anomalies during ENSO events. The growing collection of climatic data obtained by sensors coupled to satellites, currently available is an important resource for understanding climatic behavior in any region of the planet. The production of knowledge on this topic will certainly help the various sectors of society in their quest to mitigate the effects of changes and / or occurrences of climatic anomalies.

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