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Bioclimatic zoning of the Pantanal

Zoneamento Bioclimático Do Pantanal

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Abstract

Human thermal perception, or thermal comfort, is a critical variable that directly influences the health, productivity, and well-being of populations. However, specific studies on thermal comfort in the Pantanal and its sub-regions are scarce. This study analyzes the distribution of thermal comfort classes in the Pantanal and its sub-regions using the Universal Thermal Climate Index (UTCI) for the period of 1979 to 2023. The main objective was to assess thermal discomfort in the region, identifying comfort classes and examining the influence of El Niño-Southern Oscillation (ENSO) events on this index. The analysis, based on reanalysis climatic data and statistical techniques, mapped the areas most susceptible to thermal stress. The central and southern regions of the Pantanal, such as Porto Murtinho, stood out as the most uncomfortable due to heat, while sub-regions in the north, such as Cáceres and Poconé, showed lower levels of thermal stress. Additionally, it was observed that the months of October and November present the highest UTCI values, indicating extreme thermal discomfort due to heat during the spring. Summer was identified as the most uncomfortable season in terms of heat, while winter showed moderate heat discomfort. The investigation of ENSO events revealed a tendency for greater thermal discomfort during La Niña years. It is concluded that there is a progressive increase in heat-related thermal discomfort in the Pantanal region, with a particularly pronounced trend in the spring.

Keywords:
Bioclimatology, Climate zoning, ERA5-Heat, Biomes.

Resumo

A percepção térmica humana, ou conforto térmico, é uma variável crítica que influencia diretamente a saúde, a produtividade e o bem-estar das populações. No entanto, estudos específicos sobre o conforto térmico no Pantanal e suas sub-regiões são escassos. Este estudo analisa a distribuição das classes de conforto térmico no Pantanal e suas sub-regiões utilizando o Índice Universal de Clima Térmico (UTCI), no período de 1979 a 2023. O objetivo principal foi avaliar o desconforto térmico na região, identificando as classes de conforto e examinando a influência dos eventos El Niño-Oscilação

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Sul (ENOS) sobre esse índice. A análise, baseada em dados climáticos de reanálises e técnicas estatísticas, mapeou as áreas mais suscetíveis ao estresse térmico. As regiões centrais e sul do Pantanal, como Porto Murtinho, destacaram-se como as mais desconfortáveis devido ao calor, enquanto sub-regiões ao norte, como Cáceres e Poconé, apresentaram menores níveis de estresse térmico. Além disso, observou-se que os meses de outubro e novembro apresentam os maiores valores de UTCI, indicando desconforto térmico extremo para o calor durante a primavera. O verão foi identificado como a estação mais desconfortável para o calor, enquanto o inverno apresentou desconforto moderado para o calor. A investigação dos eventos ENOS revelou uma tendência de maior desconforto térmico durante os anos de La Niña. Conclui-se que há um aumento progressivo do desconforto térmico por calor na região do Pantanal, com uma tendência particularmente acentuada na primavera.
Palavras-chave:
Bioclimatologia, Zoneamento climático, ERA5-Heat, Biomas.

I. INTRODUCTION

Bioclimatology is the science that investigates the interactions between climate and living organisms (FANGER, 1970). Formally established in the 1930s, this field of knowledge seeks to understand how climatic conditions influence an individual's health, behavior, and thermal comfort or thermal sensation.

Thermal comfort refers to the condition in which a person is satisfied with the thermal environment around him. It is a state of well-being in which the person feels neither too cold nor too hot (SOUZA, 2019). This concept is objective and can be quantified through environmental parameters such as air temperature, relative humidity, wind speed, and thermal radiation. According to Fanger (1970), thermal comfort can be defined as "the mental condition that expresses satisfaction with the thermal environment."

Thermal sensation, on the other hand, is a subjective perception of each individual regarding the thermal environment. This perception can vary significantly between different people, regardless of environmental conditions (SOUZA, 2019). Thermal sensation is influenced by physiological factors such as metabolism, clothing, age, and sex, as well as psychological factors such as mood and personal expectations (PARSONS, 2003). For example, two individuals may experience different thermal sensations in the same room depending on how they are dressed, what they were doing previously, their personal preferences, and cultural backgrounds.

Over the years, various indices have been developed to measure thermal comfort and thermal sensation. Initially created for military purposes, these indices evolved into applications for urban and environmental planning. Among them, the Universal Thermal Climate Index (UTCI) is considered the international standard. Developed by the International Society of Biometeorology and introduced in 2009, UTCI is a multivariate index that combines climatic variables with physiological and clothing characteristics, providing a universal measure

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of thermal comfort and sensation (JENDRITZKY et al., 2012). The UTCI has been widely used in studies of thermal comfort in various regions and climates around the world. In Brazil, this index was calibrated, tested, and applied by Bröde et al. (2013), Hirashima et al. (2017), and Krüger et al. (2020), who concluded that it is a suitable index for the country due to its sensitivity to airspeed, radiation, and relative humidity in both heat and cold conditions.

The Pantanal, one of the largest continuous wetland areas in the world, is located in the Central-Western region of Brazil and is known for its rich biodiversity and unique climatic conditions. With high temperatures and humidity at certain times of the year, the Pantanal presents specific challenges for the thermal comfort of its inhabitants. However, as in the rest of Brazil, there is a lack of studies on human thermal comfort and/or thermal sensation in the Pantanal. A brief academic search found only the study by CID et al. (2015), which examines the relationship between external temperature and daily activity in a rodent species (*Dasyprocta azarae*) rather than the thermal conditions for humans.

The studies closest to addressing thermal comfort and sensation in the Pantanal biome are from the capitals of the states of Mato Grosso do Sul and Mato Grosso (Cerrado Biome). In Campo Grande, MS, research by Goulart et al. (2020) demonstrates that urban revitalization has improved the urban microclimate and thermal comfort, highlighting the importance of urban interventions. Cuiabá, MT, one of the hottest cities in Brazil, has been the focus of several studies on thermal comfort, such as those by Freitas and Grigorieva (2015), Silva et al. (2016), Martins, Pereira, and Souza (2021), Silva et al. (2022), and Justi et al. (2023). Although valuable, these studies focus on the city's geometry rather than the direct relationship between weather/climate and the human body. Neto (2024), in a review of thermal comfort and sensation in Brazil, highlights the lack of studies on this topic in the country.

Therefore, the objective of this study is to understand the spatiotemporal distribution of thermal sensation in the Pantanal biome, with the aim of providing a detailed analysis of thermal conditions and their variations over time. For this purpose, the UTCI index was used, calculated over the past four decades. The hypothesis considered is that heat discomfort predominates in the biome.

II. Materials And Methods

Study Area

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The Pantanal biome, located in the states of Mato Grosso (35%) and Mato Grosso do Sul (65%), covers an area of 140.000 km² and is composed of 13 municipalities. The region is home to approximately 400,000 inhabitants (IBGE, 2022).

The combination of flood cycles, geomorphology, climate, and fire ecology has shaped a biome that can be divided into eleven sub-regions, according to the classification by Silva and Abdon (1998) (Figure 1). The sub-regions of the Pantanal present a variety of phytophysiognomies, resulting in different types of vegetation, ranging from alluvial forests and Cerrado (savanna-like) areas to floodplains and savannas. This vegetation is adapted to the diverse environmental conditions, including monodominant species, specialist species, fire-dependent species, as well as species that are sensitive and intolerant to fire (POTT; POTT, 2022; SANTOS et al., 2022).

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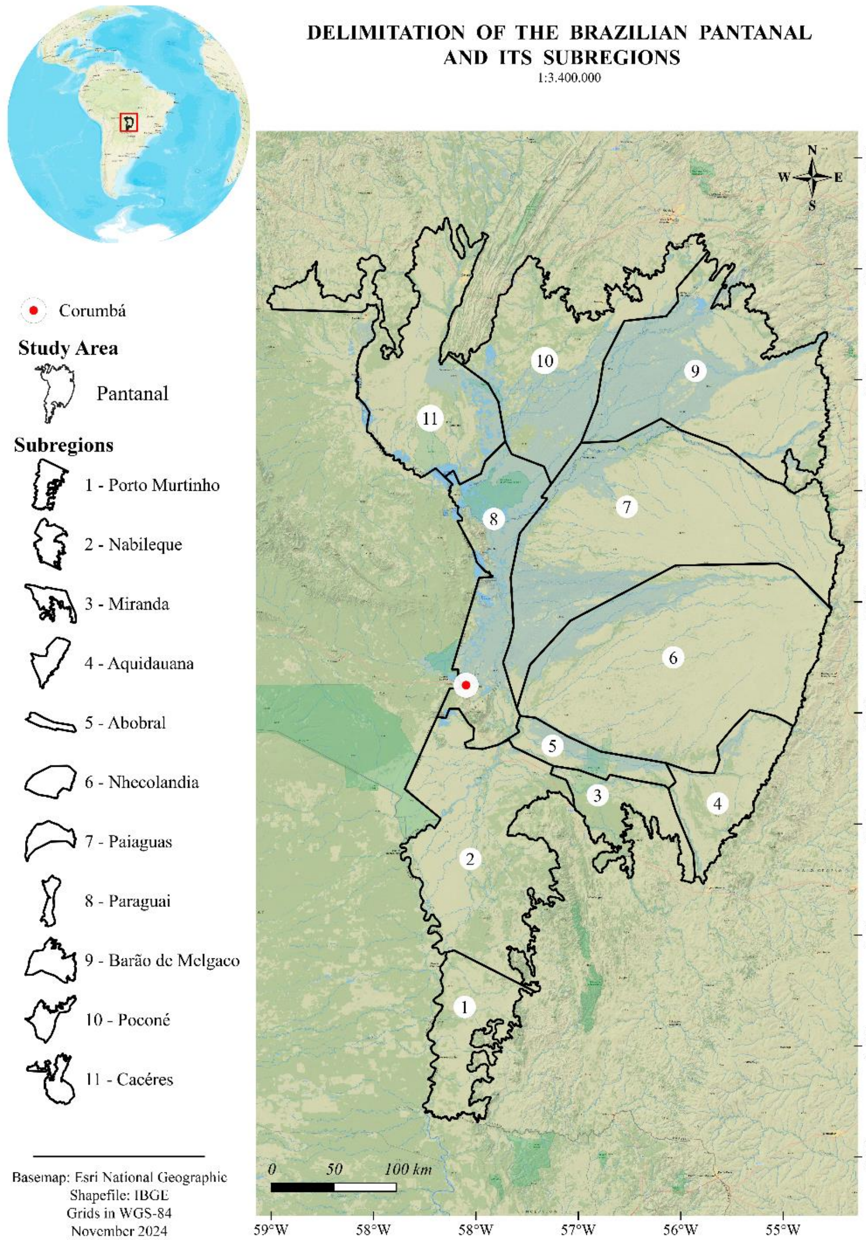

Figure 1 – Map showing the location of the study area. Corumbá, considered the capital of the Pantanal Biome, is represented by a red dot. In the upper left corner, a globe indicates the location of the Pantanal within South America. Each sub-region is identified by a specific shape and numbered.

Calculation of the Universal Thermal Climate Index (UTCI)

The data for the Universal Thermal Climate Index (UTCI) were calculated following international standards. Climatic data were obtained from ERA5-Heat (Human Thermal Comfort) reanalyses, using variables such as air temperature, mean radiant temperature, wind speed, and air humidity, with a spatial resolution of 0.25° x 0.25°. The temporal scale considered in this study covers the period from January 1, 1979, to December 31, 2023. The data manipulation was performed using the GrADS software. The physiological data used to

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calculate UTCI were based on the parameters recommended by the International Society of Biometeorology (ISB). These values are adopted by researchers and professionals applying this index, allowing for consistent comparison of results in different contexts. The calculation was based on an adult with a body surface area of 1.85 m², a weight of 73.4 kg, a body fat percentage of 14%, in a reclined position. The data included a basal metabolic rate of 87.1 W, a skin evaporation rate of 18 W, a cardiac output of 4.9 L/min, a skin blood flow rate of 0.4 L/min, a skin moisture rate of 6%, and a clothing thermal resistance of 0.5 clo.

The thermal stress classes were referenced from the Bioclimatic Zoning study by Neto (2020), which already provides the index calibrated at the national level (Table 1). This literature was chosen because, if the international scale had been used, the representation would have been limited to just one class.

Table 1 – Thermal Stress Categories for Brazil.

Category	Thresholds		HSL Colors
Extreme cold stress	-	14,0	#30123B
Very strong cold stress	14,0	15,9	#455BCD
Strong cold stress	16	17,7	#3E9CFE
Moderate cold stress	17,8	19,5	#18D7CB
No thermal stress	19,6	21,3	#ABFB38
Thermal comfort	21,4	23,1	#E6D839
Moderate heat stress	23,2	24,9	#FEA331
Strong heat stress	25	26,8	#EF5911
Very strong heat stress	26,9	28,6	#C22403
Extreme heat stress	28,7	-	#7A0403

Neto (2020), adapted by the authors

Data Analysis

The seasonal stations referred to correspond to the Southern Hemisphere, that is, to the austral summer, winter, autumn, and spring. Initially, the data distribution was verified using the D'Agostino test to determine whether the data followed a normal distribution, characterized by the bell-shaped Gauss curve. The normality of the distribution is an essential premise for the application of parametric tests. Additionally, density analyses were performed using density plots (kdeplot) and scatter plots. The t-test was employed to verify the significance of differences in UTCI values across the different seasons of the year, determining whether the average UTCI values for each season differ significantly. For data analysis and graph generation, the Python libraries pandas, NumPy, and Matplotlib were used, while QGIS was employed for finalizing the maps.

Additionally, the relationship between the El Niño-Southern Oscillation (ENSO) events and UTCI index values was evaluated. For this purpose, data related to ENSO events, as well as the classification of the intensity

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of El Niño and La Niña events, were obtained from the Oceanic Niño Index (ONI), as provided by NOAA (2024). El Niño and La Niña events were categorized as strong, moderate, or weak. The ONI measures sea surface temperature anomalies in the central and eastern equatorial Pacific region. El Niño events are characterized by positive anomalies (warming), while La Niña events are identified by negative anomalies (cooling). Table 2 presents the detailed classification of El Niño and La Niña events from 1973 to 2024, highlighting their intensity.

Table 2 – Classification of El Niño and La Niña Events

Category	Years
Strong El Niño	1982-83, 1997-98, 2015-16
Moderate El Niño	1986-87, 1991-92, 2002-03, 2009-10
Weak El Niño	1977-78, 1987-88, 1994-95, 2004-05, 2006-07, 2018-19
Strong La Niña	1988-89, 2010-11, 2023-24
Moderate La Niña	1973-74, 1998-99, 2007-08, 2011-12, 2020-21
Weak La Niña	1975-76, 1983-84, 1995-96, 2000-01, 2008-09, 2016-17, 2021-22

Table created by the authors based on NOAA data (2024)

To evaluate the relationship between UTCI values and ENSO events, Pearson correlation coefficients were calculated. The tests were conducted for each season of the year as well as for the annual average. T-tests were applied to determine whether the observed differences in UTCI values during different ENSO events were statistically significant, and p-values were calculated for comparisons between El Niño, La Niña, and neutral years.

III. RESULTS AND DISCUSSION

The annual average provides an overview of heat-related thermal stress in the Pantanal, consolidating the patterns observed in the Southern Hemisphere's seasonal stations (Figure 2). The central and southern areas remain the most affected. Porto Murtinho is consistently the most uncomfortable sub-region in terms of thermal stress throughout the year, with UTCI values indicating strong to extreme heat stress. On the other hand, In the northern part of the Pantanal, Cáceres, Poconé, and Barão de Melgaço stand out as the mildest sub-regions, presenting lower levels of thermal stress. It is important to note that only heat-related thermal stress values were found in both seasonal and annual averages, and no area presented cold-related discomfort.

During the austral summer, a large part of the Pantanal exhibits UTCI values in the "Very strong heat stress" and "Extreme heat stress" categories. The central and southern areas of the Pantanal are particularly affected, with the Nhecolândia and Porto Murtinho sub-regions being the most uncomfortable, while Cáceres and Barão de Melgaço are milder. In the austral spring, the pattern of elevated thermal stress continues, with

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much of the Pantanal displaying "Very strong heat stress." Again, Nhecolândia and Porto Murtinho are the most uncomfortable sub-regions, while Cáceres, Poconé, and Barão de Melgaço remain the mildest.

Thermal stress slightly decreases in the austral autumn, but it remains significant in many areas. The most uncomfortable sub-regions continue to be Nhecolândia and Porto Murtinho, while Cáceres, Poconé, and Barão de Melgaço remain the mildest. In winter, the Pantanal shows the lowest UTCI values, with many areas falling into the "Moderate heat stress" to "Thermal comfort" categories. Nhecolândia and Porto Murtinho still show high values, though lower compared to other seasons, while Cáceres, Poconé, and Barão de Melgaço remain the mildest sub-regions.

Other sub-regions, such as Aquidauana, Miranda, Nabileque, Paraguai, Abobral, and Paiaguás, also show elevated UTCI values, indicating significant heat-related thermal discomfort. These sub-regions follow the trend of heat discomfort, with no cold-related discomfort in the seasonal or annual averages. They are not as uncomfortable as Porto Murtinho but are not as mild as the northern region.

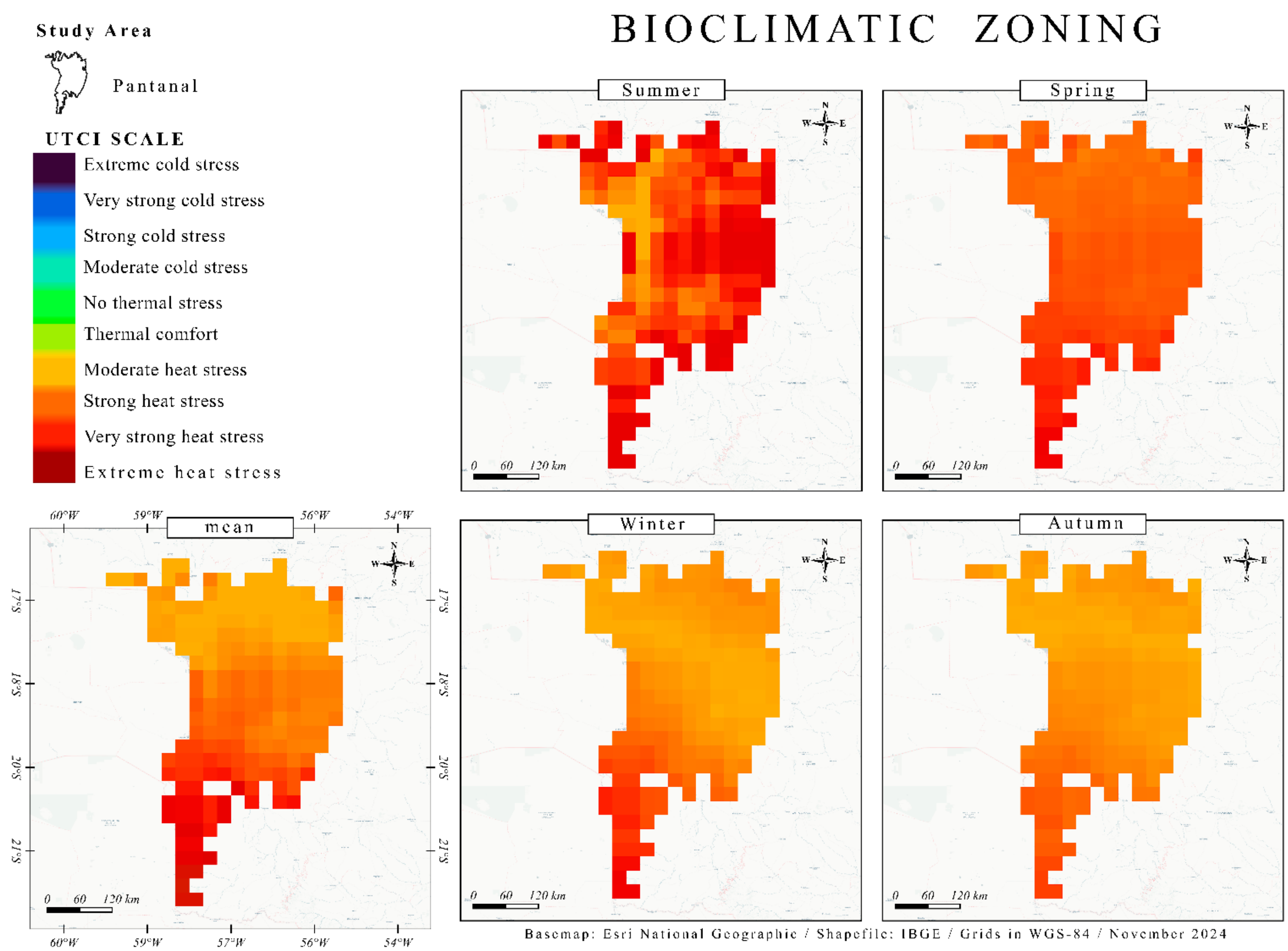

Figure 2 – Bioclimatic Zoning of the Pantanal: Seasonal Analysis of UTCI (1979-2023). The map presents the analysis of the Universal Thermal Climate Index (UTCI) in the Pantanal biome, divided into different seasonal periods: Summer, Autumn, Winter, Spring, and a 44-year average. The

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analysis is based on the UTCI classification, which categorizes thermal stress at different levels, ranging from extreme cold stress to extreme heat stress.

The main economic activity in the region, cattle ranching, along with other practices such as fishing, ecotourism, and agriculture, expose a large part of the local population to outdoor environments, where workers directly face adverse climatic conditions (WWF BRASIL, 2020; MINISTRY OF AGRICULTURE AND LIVESTOCK, 2023). The increase in thermal discomfort becomes an additional challenge for these workers, who are already subjected to long hours under intense sunlight.

Prolonged exposure to heat not only affects productivity but also poses health risks to these individuals. Studies indicate that increased thermal discomfort can lead to fatigue, thermal stress, and a higher incidence of health problems, such as dehydration, heat exhaustion, and even death (NETO, 2022). In the context of the Pantanal, where most work occurs in open fields, these effects are intensified, requiring more rigorous adaptation and protection measures to mitigate the negative impacts on local workers.

The annual UTCI chart reveals important trends regarding thermal conditions in the Pantanal (Figure 3). During the summer, UTCI values frequently range between 25 °C and 32 °C, indicating a predominance of moderate to strong heat stress conditions. For example, the years 2010, 2015, 2019, and 2023 stood out for presenting values above 30 °C, characterizing "Very strong heat stress," which implies significant periods of thermal discomfort for the region's inhabitants during these summers. The year 2023, in particular, recorded the highest UTCI values for all seasons, standing out as a period of extreme thermal stress and the most heat-uncomfortable year within the entire historical series analyzed. According to the World Meteorological Organization (WMO) report, 2023 was the hottest year on record, surpassing the previous record of 2016 (WMO, 2024).

On the other hand, the winter and autumn seasons present lower UTCI values. In winter, typical values range from 10 °C to 20 °C, with the years 1985, 2000, and 2023 registering temperatures close to 10 °C, indicating strong cold stress conditions. In autumn, values fluctuate between 15 °C and 25 °C, with years such as 1992, 2008, and 2023 presenting lower temperatures, reflecting moderate cold stress. These data suggest that thermal discomfort due to cold is more common during these seasons. In particular, the winter of 1985 was notable for having an average UTCI below 15 °C, characterizing very strong cold stress, while 1992 and 2023 in autumn also presented significant thermal stress due to heat.

Spring, with UTCI values ranging between 20 °C and 30 °C, generally reflects thermal comfort conditions, with occasional periods of moderate stress for both cold and heat. For example, the years 2005 and 2017 stood

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out for presenting temperatures above 28 °C, indicating moderate heat stress. The annual UTCI average, ranging between 22 °C and 28 °C, shows a balance between extremes of heat and cold throughout the year, highlighting the seasonal thermal variability of the region. However, the annual average in years such as 2015, 2019, and 2023, which recorded temperatures above 27 °C, points to periods of strong heat stress.

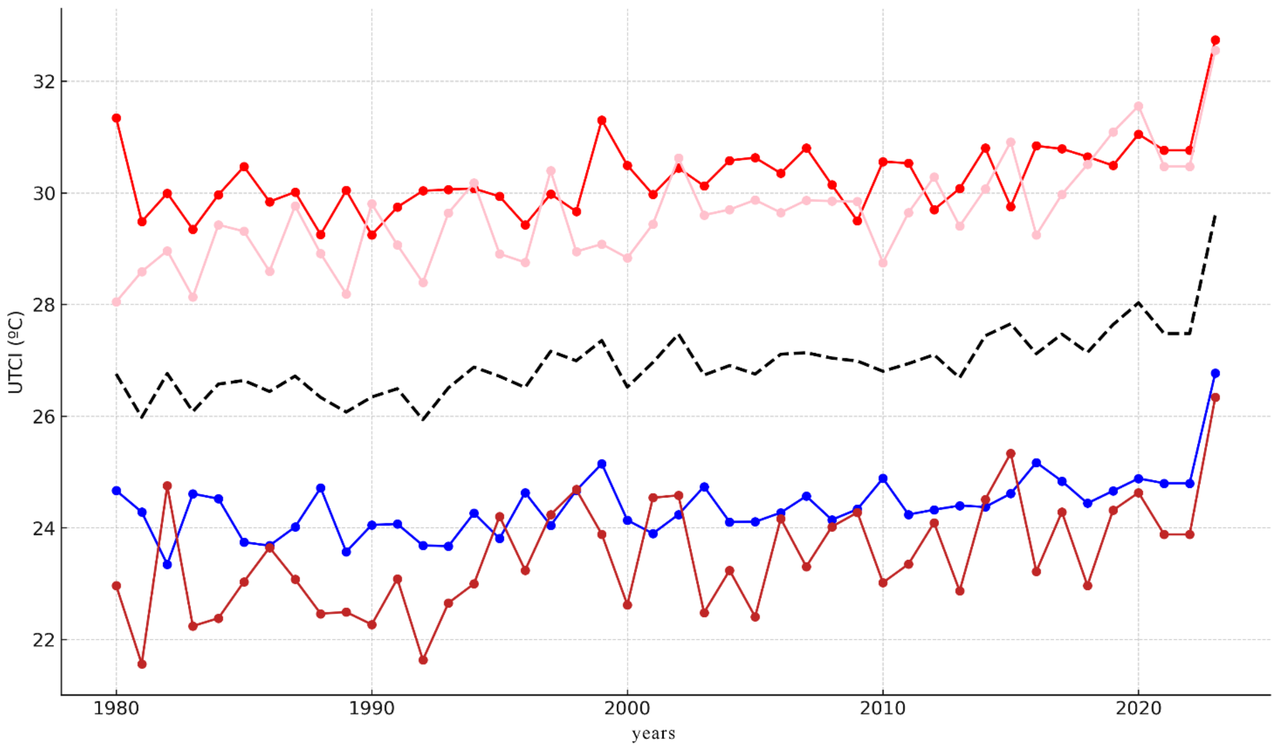

Figure 3 – Seasonal and Annual Averages of UTCI in the Pantanal (1979-2023). Each line represents a Southern Hemisphere season: summer (red), winter (blue), autumn (brown), and spring (pink), with the annual average shown as a black dashed line.

The density graph in Figure 4 below complements the information presented above. In summer, the most common UTCI values indicate a higher frequency of days with thermal discomfort due to heat. The high density at certain UTCI values highlights consistent periods of extreme heat. In autumn, there is greater variation in UTCI values, indicating milder conditions compared to summer, but still with significant periods of heat. The broader distribution of values suggests a gradual transition between the high temperatures of summer and the lower temperatures of winter.

Winter presents the lowest UTCI values, indicating cooler conditions and less thermal discomfort. Despite this, there are still days of considerable heat, though less frequent. The smaller variation in UTCI values during winter suggests a more thermally stable season in terms of comfort. In spring, UTCI values start to rise again, approaching summer conditions. The high density at certain UTCI values points to significant periods of thermal discomfort due to heat, similar to those observed in summer.

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Pantanal experiences more severe thermal conditions in summer and spring, with high thermal discomfort due to heat. Winter is the mildest season, with the lowest UTCI values, while autumn represents a transition between winter and summer conditions.

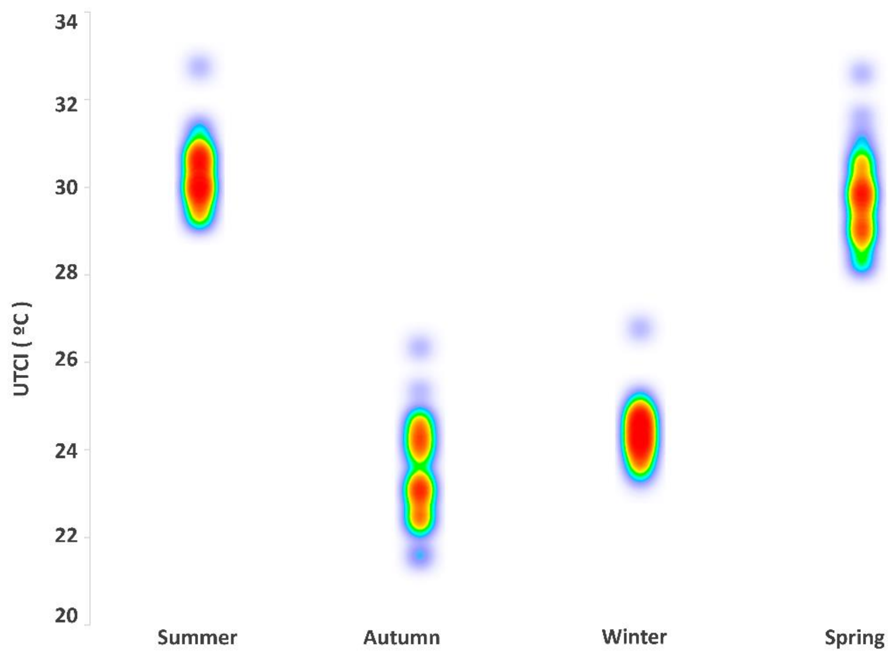

Figure 4 – Density of UTCI values by season in the Pantanal. Each column represents a season of the year, and the density of UTCI values is shown in a color gradient, ranging from green (low density) to red (high density).

The analysis of correlations between the annual average UTCI and the seasonal averages of the four seasons reveals significant and distinct correlations. Spring shows the strongest correlation with the annual average UTCI, with a correlation coefficient of 0.8566 and a p-value of 1.212 x10^(-13), indicating a highly significant relationship. The correlation observed between the annual average UTCI and autumn is also robust, with a coefficient of 0.8235 and a p-value of 6.744 x10^(-12).

Summer and winter show more modest but still significant correlations. The correlation coefficient for summer is 0.7348, with a p-value of 1.354 x10^(-8), while for winter, the coefficient is 0.7104 and the p-value is 6.600 x10^(-8). These results indicate that although all seasons have a positive correlation with the annual average UTCI, spring and autumn are the seasons that most influence the annual average, reflecting more pronounced seasonal variability during these times of the year.

The analysis of UTCI values over the years reveals significant trends of increasing heat discomfort across all seasons and in the annual average (Figure 5). The slope of each trend line shows a significant increase in UTCI

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values, suggesting a progressive warming in all seasons and in the annual average; geographically, there is an expansion of areas experiencing heat discomfort.

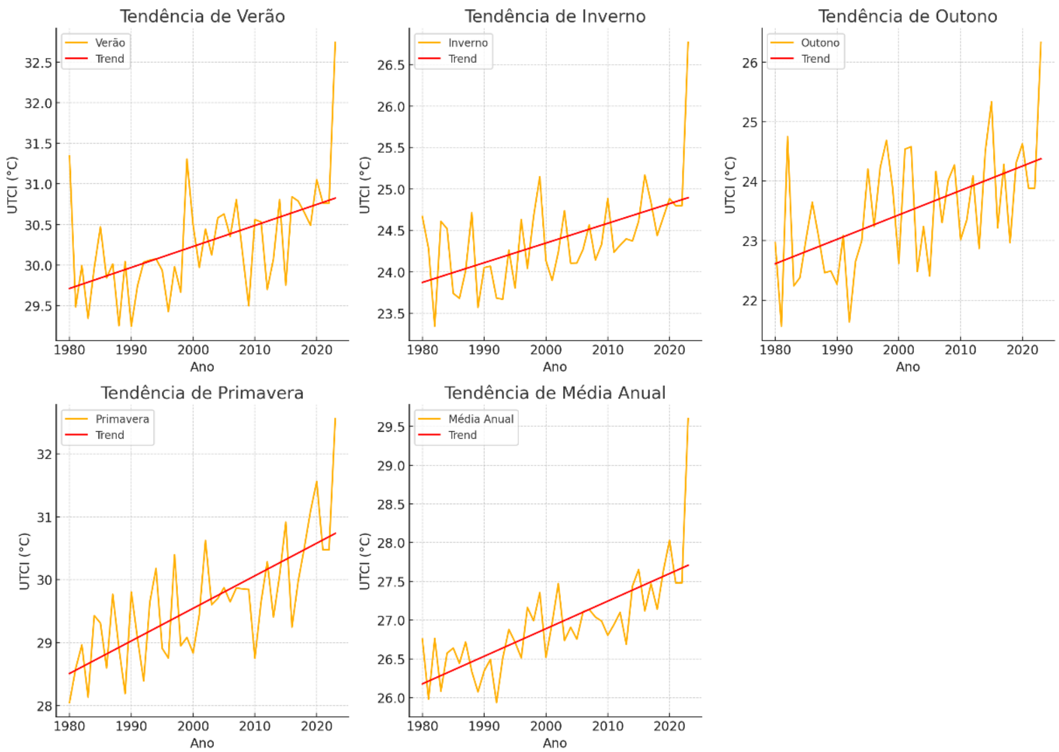

Figure 5 – Trends in annual UTCI values by season and annual average. The graphs show the trends in UTCI values over the years for each season (summer, winter, autumn, and spring) and for the annual average. The lines represent the observed annual UTCI values for each season, while the red lines indicate the linear trends of increase over time.

In summer, the slope of the linear regression is 0.0259 °C per year, with a correlation coefficient of 0.5083 and a p-value of 0.0004, indicating a significant increase in temperatures. This increase suggests that summers are becoming progressively more uncomfortable due to heat, resulting in greater thermal discomfort during this season. In winter, the slope of the linear regression is 0.0238 °C per year, with a correlation coefficient of 0.5412 and a p-value of 0.0001. This suggests a gradual warming during this season. The values indicate that, despite winters still having cold days, there is a clear trend of increasing heat discomfort, which may reduce periods of cold stress.

Autumn presents a slope of 0.0411 °C per year, with a correlation coefficient of 0.5271 and a p-value of 0.0002. This sharp increase in thermal stress during autumn indicates a significant change in the season's climate, which may be warming at a faster rate compared to winter and summer. Spring shows the strongest trend of increasing heat discomfort, with a slope of 0.0517 °C per year, a correlation coefficient of 0.7187, and a p-value of 3.93e-08. This substantial and consistent increase in spring temperatures suggests that the season

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is becoming significantly warmer, which may have important implications for thermal comfort and regional climatic patterns during spring.

The annual UTCI average also shows a significant increase, with a slope of 0.0356 °C per year, a correlation coefficient of 0.7327, and a p-value of 1.57e-08. This increase in the annual average indicates a general warming trend in the region, reflecting climate changes affecting all seasons. The significance of the p-values confirms that these trends are not due to chance but reflect real and consistent changes in the studied region's climate, resulting in a progressively more uncomfortable thermal environment due to heat.

UTCI values during La Niña years were, in general terms, slightly higher compared to El Niño and neutral years. For example, in 1998, a strong La Niña year, the annual average UTCI was 27.10 °C, a value above the general annual average. In contrast, 2015, a strong El Niño year, had an annual average UTCI of 26.85 °C, slightly below the general average. The annual UTCI averages during ENSO years and neutral years revealed that La Niña had a slightly higher average (27.06 °C), followed by neutral (26.91°C) and El Niño (26.88 °C) years. The results of the T-test indicated that there was no statistically significant difference between these values (El Niño vs. Neutral: p=0.9633, La Niña vs. Neutral: p=0.7936, El Niño vs. La Niña: p=0.7594).

In summer, the average UTCI values during La Niña years were slightly higher (27.06 °C) compared to El Niño years (26.88 °C) and neutral years (26.91 °C). Although this trend suggests an increase in thermal discomfort during La Niña years, T-tests showed that the differences were not statistically significant (El Niño vs. Neutral: p=0.1934, La Niña vs. Neutral: p=0.9312, El Niño vs. La Niña: p=0.1179). During winter, the average UTCI values in La Niña years (27.06 °C) were higher than in El Niño years (26.88 °C) and neutral years (26.91 °C). However, the observed differences were not statistically significant (El Niño vs. Neutral: p=0.8540, La Niña vs. Neutral: p=0.3779, El Niño vs. La Niña: p=0.1949).

The analysis of UTCI values in autumn showed that in La Niña years, the average was 27.06 °C, while in El Niño years it was 26.88 °C, and in neutral years it was 26.91 °C. Once again, statistical analyses confirmed that these differences were not significant (El Niño vs. Neutral: p=0.5131, La Niña vs. Neutral: p=0.4355, El Niño vs. La Niña: p=0.8985). In spring, UTCI values followed the same trend, with La Niña years presenting higher values (27.06°C) than El Niño years (26.88 °C) and neutral years (26.91 °C). However, as in the other seasons, these differences were not statistically significant (El Niño vs. Neutral: p=0.9705, La Niña vs. Neutral: p=0.7650, El Niño vs. La Niña: p=0.7450).

For the Pantanal region, El Niño events are generally associated with droughts, while La Niña tends to bring floods (ALHO; SILVA, 2012; MACHADO et al., 2015; BARROS et al., 2016; MARENGO et al., 2016; VOURLITIS

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et al., 2016; MARTINS DOS SANTOS et al., 2016; DINIZ et al., 2016). However, our results demonstrate that the relationship between these climatic events may be broader in the region, promoting changes in thermal comfort and sensation patterns. Neto (2020) conducted a bioclimatic zoning for Brazil, analyzing the distribution of thermal stress classes using UTCI. The study showed that, on a national scale, El Niño events are associated with increased heat discomfort, while La Niña events increase cold discomfort.

However, in this study focused specifically on the Pantanal, the results do not indicate a significant impact of ENSO on UTCI values. This suggests that, unlike the national scenario, the Pantanal does not show significant variations in UTCI values related to these climatic events. Silva and Abdon (1998) emphasize that the Pantanal is located at the same latitude and does not have significant topographic differences, as the region is predominantly flat, factors that have a great influence on UTCI at national scale.

Diniz et al. (2016) indicate that the strong El Niño of 2015-2016 was responsible for a significant increase in fire outbreaks in the Pantanal due to the drier and hotter conditions associated with this phenomenon, which in turn increased heat discomfort. However, higher temperatures do not necessarily define greater heat discomfort, as thermal exchange with the environment is closely related to humidity. Therefore, when comparing the hot and dry weather of an El Niño to the hot and humid weather of a La Niña, discomfort will be greater during La Niña episodes. This occurs because, in drier weather, the body's ability to exchange heat with the environment is greater. In contrast, during La Niña events, humidity increases, and the body's thermal exchange with the environment is hindered, increasing heat discomfort.

We observe that there is a tendency for greater heat discomfort during La Niña years; however, this relationship is not strong enough to be considered conclusive for the Pantanal region based on the statistical tests conducted here. Neto (2020) highlights that the higher wind speeds in the Pantanal are what make this area less uncomfortable due to heat compared to the Amazon region, the most heat-uncomfortable region in Brazil. Therefore, variations in thermal sensation classes in the Pantanal are more influenced by specific microclimatic characteristics of the region, such as wind speed and direction, humidity, cloud cover, solar radiation, and other variables. The existing literature provides valuable context but, underscores the need for more robust analyses to understand the relationships between atmospheric variables within the biome.

IV. CONCLUSION

The Pantanal, climatologically, is an area of thermal discomfort due to heat. The central and southern areas of the Pantanal, especially Porto Murtinho, are consistently the most uncomfortable throughout the year,

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presenting UTCI values that indicate strong to extreme heat stress. In contrast, northern sub-regions such as Cáceres, Poconé, and Barão de Melgaço stand out as milder, with lower levels of thermal stress, although they still experience heat discomfort.

In summer and spring, the Pantanal experiences the highest levels of thermal stress, with UTCI values in the "Very strong heat stress" and "Extreme heat stress" categories. During autumn, thermal stress slightly decreases, but it remains significant in many areas. In winter, the Pantanal shows the lowest UTCI values, with many areas falling into the "Moderate heat stress" to "Thermal comfort" categories.

The analysis over the years reveals a significant increase in UTCI values, indicating a progressive warming across all seasons and in the annual average. Spring shows the strongest trend of increasing heat discomfort, suggesting that this season is becoming significantly more uncomfortable. Although the values were not statistically significant in the tests, we cannot rule out that ENSO events, particularly La Niña, may have some impact. The variations in thermal sensation classes in the Pantanal are more influenced by specific microclimatic characteristics of the region.

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