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Bioclimatic zoning for Brazil

João Batista Ferreira Neto[1]
[1] Universidade de São Paulo, São Paulo, SP, Brasil
joao.geo@usp.br
0000-0002-7144-2901

Gabriel Pereira[2]
[2] Universidade Federal de São João del-Rei, São João del-Rei, MG, Brasil
pereira@ufsj.edu.br
0000-0002-2093-9942

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Bioclimatic zoning for Brazil

Abstract

The impact of weather conditions on human experience can be assessed through bioclimatic indices that measure thermal comfort. This study adopted the Universal Thermal Climate Index (UTCI) to analyze the distribution of thermal stress categories across the entire Brazilian territory. From 1979 to 2020, the results present a first climatological norm for thermal comfort in Brazil. Increasing values were observed for extremes of discomfort in both cold and hot situations. Furthermore, there was a decrease in cold-related stress categories, while heat discomfort classes showed an increase. The results revealed a connection with ENSO events, highlighting that El Niño contributes to increased thermal discomfort due to heat, whereas La Niña is associated with thermal discomfort due to cold.

Keywords: ERA5, climate change, bioclimatology.

Zoneamento bioclimático para o Brasil

Resumo

O impacto das condições meteorológicas na experiência humana pode ser avaliado por meio de índices bioclimáticos que mensuram o conforto térmico. Este estudo adotou o Índice Climático Térmico Universal (UTCI) para analisar a distribuição das categorias de estresse térmico em todo o território brasileiro. No período de 1979 a 2020, os resultados apresentam uma primeira normal climatológica para o conforto térmico no Brasil. Valores crescentes foram observados para os extremos de desconforto, tanto em situações de frio quanto calor. Houve, ainda, uma diminuição nas categorias de estresse relacionadas ao frio, enquanto as classes de desconforto por calor demonstraram aumento. Os resultados revelaram uma conexão com os eventos ENOS, evidenciando que o El Niño contribui para o aumento do desconforto térmico por calor, ao passo que o La Niña está associado ao desconforto térmico por frio.

Palavras-chave: ERA5, mudanças climáticas, bioclimatologia.

Zonificación bioclimática del Brasil

Resumen

El impacto de las condiciones meteorológicas en la experiencia humana puede evaluarse mediante índices bioclimáticos que miden el confort térmico. Este estudio adoptó el Índice Climático Térmico Universal (UTCI) para analizar la distribución de las categorías de estrés térmico en todo el territorio brasileño. En el período de 1979 a 2020, los resultados presentan una primera norma climatológica para el confort térmico en Brasil. Se observaron valores crecientes para los extremos de incomodidad, tanto en situaciones de frío como de calor. Además, hubo una disminución en las categorías de estrés relacionadas con el frío, mientras que las clases de incomodidad por calor mostraron un aumento. Los resultados revelaron una conexión con los eventos ENOS, evidenciando que El Niño contribuye al aumento del malestar térmico debido al calor, mientras que La Niña está asociada al malestar térmico por frío.

Palabras clave: ERA5. cambio climático, bioclimatología.

Introduction

The ability to maintain an adequate body temperature is crucial for human health. Environments that exceed physiological limits of thermal comfort whether due to extreme heat or intense cold are associated with a significant increase in mortality risk (Changnon *et al.*, 2000). Studies indicate that extreme temperatures have a more pronounced impact on health than other meteorological phenomena, especially among vulnerable groups such as the elderly (Golden *et al.*, 2008). Beyond survival, thermal stress impairs both physical and cognitive performance, affecting productivity, learning, and quality of life (Nelson; Spollen, 1987; Mendell, 2005; Hassanain, 2015; Iftikhar, 2015; Haverinen-Shaughnessy; Moschandreas; Shaughnessy, 2015).

In the Brazilian context, Floss and Barros (2020) highlight the increasing number of clinical cases related to heat stress in primary healthcare, such as skin rashes, headaches, and gastrointestinal discomfort. If not properly managed, heat exhaustion may progress to heat stroke, a severe condition that can lead to coma or death. Likewise, intense cold environments increase the risk of hypothermia, particularly among the elderly and other vulnerable populations (Golin *et al.*, 2003).

The relationship between thermal variations and public health impacts has been confirmed in several studies. Urban and Kyselý (2021) demonstrated that extreme temperature variations both hot and cold are associated with increased mortality rates, especially among the elderly and vulnerable populations. More broadly, climate, as highlighted by Höppe (1993), exerts one of the greatest influences on human activity a foundational principle of Bioclimatology since the 1930s.

Recent extreme climate events, such as heatwaves and cold spells, further highlight the interconnection between the environment and human well-being (Seltenrich, 2015). To evaluate this complex interaction between environmental conditions and human physiological response, the Universal Thermal Climate Index (UTCI) was developed. UTCI integrates atmospheric variables air temperature, relative humidity, wind speed, and mean radiant temperature into a comprehensive physiological model of human thermoregulation (Jendritzky *et al.*, 2012; Di Napoli *et al.*, 2021).

Unlike simplified indices, UTCI is based on the multi-node Fiala model, simulating universal physiological mechanisms such as sweating, modulation of blood flow, and metabolic adjustments. It is suitable for application across different climate zones. Its applicability has been tested in temperate, subtropical, and tropical zones (Jendritzky *et al.*, 2012; Ge *et al.*, 2017; Vinogradova, 2019; Di Napoli; Pappenberger; Cloke, 2020; Chen *et al.*, 2024; Zheng *et al.*, 2024). Only under extremely cold conditions, such as in polar regions, may its application be limited, as shown by Nie *et al.* (2022).

From this perspective, bioclimatic zoning emerges as an essential tool for identifying areas with similar thermal patterns based on the human experience of comfort. Supporting climate adaptation strategies, urban planning, and environmental management, zoning is particularly relevant in countries with high environmental diversity such as Brazil.

Thus, the objective of this study is to map thermal comfort zones in Brazil based on UTCI data for the period 1979 to 2020, identify spatial and temporal patterns of thermal stress, and discuss the relationships between these patterns and climatic, topographic, and ENSO-related variables.

Materials and methods

Data

This study used Universal Thermal Climate Index (UTCI) data derived from the ERA5-HEAT reanalysis dataset, developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5-HEAT is a derived product of ERA5, combining atmospheric variables to compute UTCI globally with high spatial and temporal resolution.

The dataset, in NetCDF format, spans from January 1, 1979, to December 31, 2020, totaling 42 years of hourly meteorological information. All data were retrieved in UTC time, with no conversion to Brasília local time. Therefore, all analyses refer to UTC standard time.

The following atmospheric parameters were used to compute UTCI:

- Air temperature at 2 meters above ground level (°C);
- Wind speed at 10 meters (m/s);
- Relative humidity (%);
- Mean radiant temperature (MRT).

UTCI Calculation

UTCI represents the equivalent temperature that results in the same thermal load on the human body under reference conditions.

Its formulation is based on the validated multi-node Fiala physical model (table1), suitable for various climatic contexts. The mathematical expression of UTCI can be summarized as:

$$UTCI = Ta + f\ (Ta, RH, V, MRT)$$

Where:

- Ta = air temperature (°C);
- RH = relative humidity (%);
- V = wind speed (m/s);
- MRT = mean radiant temperature (°C);
- f = polynomial function modeling the combined effects of these variables.

The physiological parameters recommended by the International Society of Biometeorology (ISB) were adopted for this study, based on a standard adult.

Table 1 – Adopted physiological parameters

Variable	Value
Basal metabolic rate	75.1 kcal/h or 87.1 W
Dermal blood flow	0.4 L/min
Skin hydration	6%
Transepidermal water loss (TEWL)	18 W
Body fat percentage	14%
Body weight	73.4 kg
Body surface area	1.85 m²

Source: Prepared by the authors.

Statistical Analysis

Prior to any statistical analysis, the D'Agostino normality test was applied using RStudio software to verify whether data distribution allowed the use of parametric tests.

Correlations between mean UTCI, latitude, altitude, and other physical factors were assessed through simple linear regression, with significance set at $p < 0.05$. The Pearson correlation coefficient (r) was used to evaluate the strength of the relationships, with $r \geq 0.7$ considered strong.

Additionally, simple linear regression was applied to the time series of pixel counts in specific thermal stress categories (cold and heat) from 1979 to 2020, aiming to identify spatial modification trends over time. The correlation coefficient (r), coefficient of determination (r^2), and p-value were calculated to evaluate the strength and statistical significance of detected trends.

Cartographic Production and Spatial Processing

The hourly UTCI time series in NetCDF format was processed using the Grid Analysis and Display System (GrADS) software, version 2.2.1.oga. In this environment, geostatistical analyses were performed, including interpolation using ordinary kriging, and conversion of NetCDF files to GeoTIFF format. The resulting GeoTIFF was then imported into QGIS version 3.17, where the final Brazilian bioclimatic zoning map was produced.

The UTCI thermal stress scale was adapted to Brazilian conditions, considering the national average and adjusting category thresholds relative to the global scale, as described in the results section.

Results and discussion

Brazilian Overview

The Brazilian territory covers a wide range of latitudes up to 38° and presents a topography ranging from sea level to elevations of 2,993 meters. Based on the 42-year analysis, a bioclimatic zoning was established using the mean values of the UTCI, encompassing all thermal stress categories (Figure 1).

Although Brazil generally exhibits a predominance of heat-related thermal stress, areas of cold stress were identified in high-latitude regions (particularly in the South) and in elevated zones (such as mountain ranges in the Southeast and South). These patterns reflect the country's climatic diversity, influenced by both latitude and altitudinal variation.

It is noteworthy that the areas experiencing the greatest cold stress coincide with regions of higher elevation or higher latitude, such as the mountain ranges of Rio Grande do Sul, Santa Catarina, and Paraná, as well as isolated areas in the Southeast and even parts of the Northeast (Bahia). In contrast, most of the territory especially the North, Northeast, and Central-West regions shows predominance of very strong or extreme thermal stress due to heat.

The average UTCI across Brazil for the 42-year period was 21.31°C, which aligns with the "thermal comfort" level on the global UTCI scale. However, it was observed that direct application of the global scale did not adequately reflect Brazil's thermal reality. The original UTCI scale was designed to cover planetary extremes, including severe cold in polar regions and extreme heat in deserts conditions not found in Brazil.

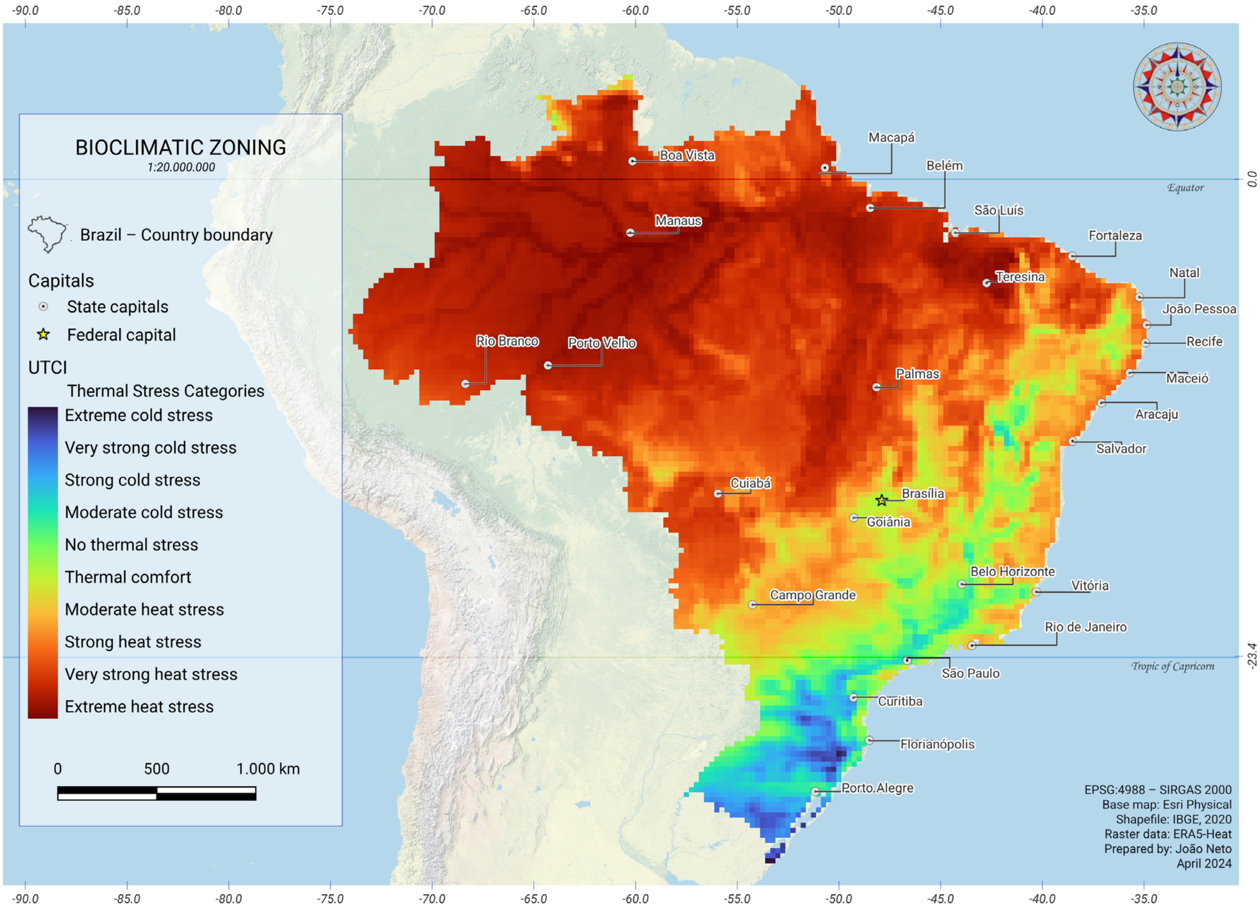

Figure 1 – Brazilian Bioclimatic Zoning Map.

Source: Prepared by the authors.

Using global thresholds masked Brazil's internal climatic variability, resulting in an artificially homogeneous representation of national thermal comfort. To address this, the classification scale was recalibrated based solely on the maximum and minimum UTCI values observed within Brazilian territory during the analysis period.

Thus, a new thermal stress categorization was created from the actual range of UTCI recorded in Brazil between 1979 and 2020, respecting the country's climatic diversity and better highlighting areas affected by thermal discomfort due to heat or cold, as represented in Figure 2 below.

Based on this adjustment, Brazil is generally characterized by a predominance of heat-related thermal discomfort, with localized exceptions associated with high altitude or southern latitudes.

Figure 2 – Thermal Stress Categories for Brazil.

Source: Prepared by the authors.

Bioclimatic Zoning of Brazilian State Capitals

The analysis of mean UTCI in Brazilian capitals over the 1979–2020 period revealed distinct thermal stress patterns (Table 2). For clarity, results were grouped by thermal stress categories rather than by geographic region.

Most capitals in the North and Northeast regions experience strong or very strong thermal discomfort due to heat, while capitals in the South exhibit moderate to strong cold stress. Capitals located in transitional zones, such as Brasília, tend to display thermal comfort or reduced stress conditions.

Manaus (AM) recorded the highest thermal discomfort due to heat, while Curitiba (PR) registered the highest cold-related discomfort.

It is important to note that the data represent the UTCI climatological norm over the 42-year period and do not refer to seasonal extremes.

Table 2 – Mean Thermal Stress Categories in Brazilian Capitals (1979–2020).

Thermal Stress Category	Capitals
No thermal stress	Brasília (DF)
Thermal comfort	Vitória (ES)
Slight cold stress	Belo Horizonte (MG), São Paulo (SP), Porto Alegre (RS), Florianópolis (SC)
Moderate cold stress	Curitiba (PR)
Moderate heat stress	Rio de Janeiro (RJ), Recife (PE), João Pessoa (PB), Maceió (AL), Salvador (BA), Aracaju (SE)
Strong heat stress	Cuiabá (MT), Campo Grande (MS), Goiânia (GO), Fortaleza (CE), São Luís (MA), Belém (PA), Macapá (AP), Palmas (TO), Rio Branco (AC), Amapá (AP)
Very strong heat stress	Manaus (AM), Boa Vista (RR), Porto Velho (RO), Teresina (PI)

Source: Prepared by the authors.

Spatial Distribution of Thermal Stress Categories in Brazil

Figure 3 shows the percentage distribution of thermal stress categories in Brazil, based on annual mean UTCI values from 1979 to 2020. The chart was derived by classifying each pixel in the ERA5-HEAT dataset, using the thresholds recalibrated to the Brazilian climatic context. A total of 32,761 pixels were analyzed across the national territory.

A significant 32% of the territory falls into the "very strong heat stress" category, covering 2,722,458 km². Following that, 28.97% of the pixels correspond to areas of "strong heat stress," totaling 2,455,838 km². Together, these two categories encompass over 60% of Brazil, confirming heat as the dominant factor in national thermal discomfort.

The "thermal comfort" (10.5%) and "no thermal stress" (5.7%) classes are mostly concentrated in transitional climate zones, particularly in the Southeast.

Conversely, the least represented areas are those with elevated cold-related thermal stress, accounting for only 1.4% (119,847 km²) in the "very strong cold stress" category and 0.4% (29,980 km²) in the "extreme cold stress" category. Both are predominantly located in the southernmost region of Brazil.

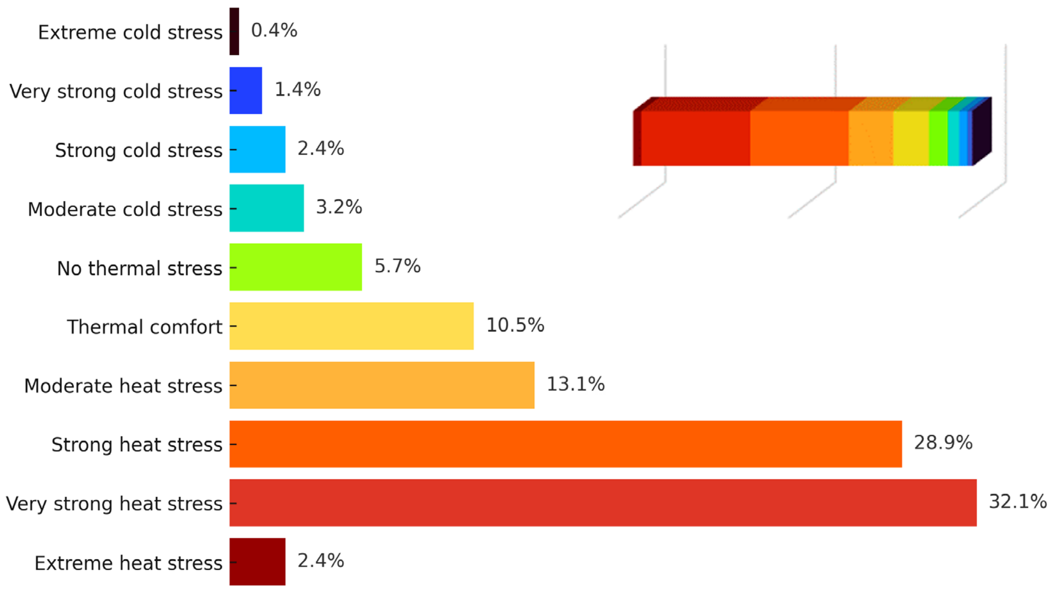

Figure 3 – Proportional Distribution of Thermal Stress Categories in Brazil.

Source: Prepared by the authors.

Figure 4 shows that annual maximum UTCI values across Brazil consistently exceeded 30 °C, indicating persistent levels of extreme heat stress. The year 2010 recorded the highest maximum (32.85 °C), while the lowest maximum occurred in 1981 (30.10 °C).

The municipality of Piracuruca, in Piauí state, recorded most of the highest heat stress values, positioning it as one of the most thermally adverse areas in the country.

In contrast, annual minimum UTCI values showed greater variability, with a range of 5.82°C between the lowest value (2.48°C in 2011) and the highest minimum (8.33°C in 2017). These extremes of cold-related discomfort were concentrated in Chuy, in Rio Grande do Sul, which reported the most occurrences of extreme cold stress.

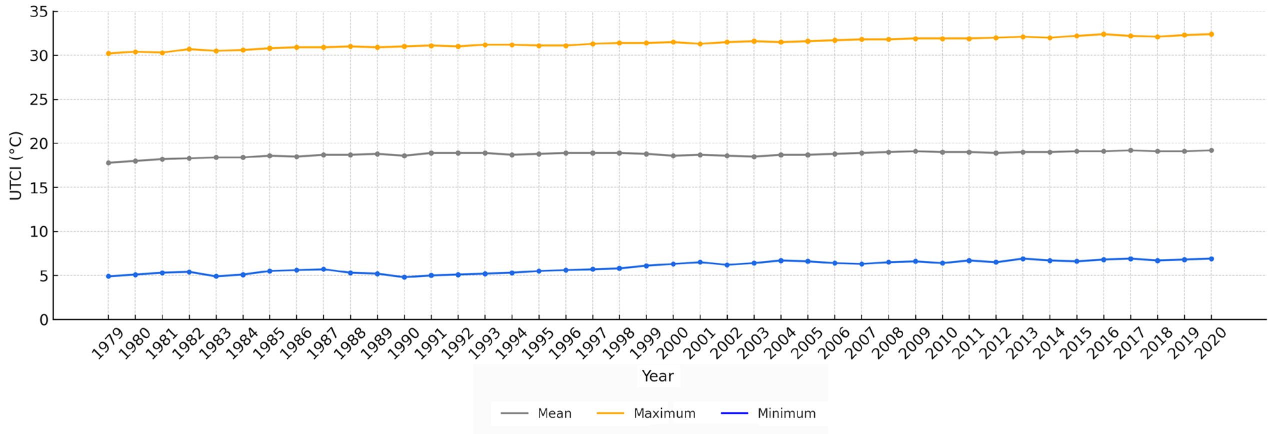

Figure 4 – Annual UTCI Variability in Brazil.

Source: Prepared by the authors.

Spatial and Temporal Variations of Thermal Discomfort in Brazil

Regarding annual means, a reduction was observed in both the area and the number of days associated with cold-related thermal stress and thermal comfort categories except for the "extreme heat stress" category, which showed a clear increasing trend.

Simple linear regression analysis indicated a strong correlation for the expansion of heat-stress-related areas ($r = 0.75$; $r^2 = 0.56$; $p = 0.02$), as well as a significant decline in cold-stress-related areas ($r = -0.73$; $r^2 = 0.53$; $p = 0.03$).

In 1980, a year considered neutral regarding the El Niño–Southern Oscillation (ENSO), the area affected by extreme heat stress was 1,515,658 km². This nearly doubled by 2019 another neutral year reaching 2,991,958 km², which represents an increase of approximately 97.4%.

The smallest variation was found in the "strong heat stress" category, which decreased by just 0.8% compared to initial 1979 values. This suggests that areas previously classified as having lower discomfort levels are progressively shifting into higher thermal stress categories.

Historically cold-stressed regions are now transitioning into thermal comfort zones, while previously comfortable areas are experiencing heat-related discomfort. This transition is particularly evident in the North and Central-West regions of Brazil, with the Pantanal standing out for the most pronounced intensification of extreme heat.

The Southern region exhibited the highest variability, encompassing all thermal stress categories throughout the year, reflecting the effects of seasonality.

Years marked by widespread and intense heat-related discomfort measured by spatial extent, number of days, and UTCI values frequently coincided with El Niño episodes. According to Marengo, Alves and Soares (2009) and Nobre *et al*. (2012), El Niño events are associated with increased temperatures and reduced precipitation in central-southern Brazil. Conversely, La Niña years tend to amplify cold-related discomfort, especially in winter, due to increased incursions of cold air masses.

Notable examples include the El Niño events of 1986/87, 1997/98, and 2014/15 classified as strong by NOAA which aligned with peaks in heat-related discomfort. Thus, the association between interannual UTCI variability and ENSO phenomena is supported by recent climatological literature.

Comparative spatial analysis showed no significant correspondence between UTCI mean values and Köppen climate classification as proposed by Alvares *et al*. (2014).

Cartographic analysis revealed that approximately 71% of Brazil's territory exhibited thermal discomfort patterns not aligned with Köppen's climate types. Statistical comparison between the two variables through simple linear regression indicated a weak correlation ($r = 0.25$; $r^2 = 0.06$; $p = 0.12$), reinforcing the lack of significant association between traditional climate classification and thermal comfort categories at the national level.

Köppen classification, which relies on physical parameters such as air temperature, precipitation, relative humidity, and atmospheric regimes, is essential for defining major climate zones. Vegetation, as an expression of adaptation to climate, reinforces these zones by delineating characteristic phytophysiognomies in different regions.

However, UTCI incorporates physiological and subjective elements (such as thermal perception, metabolism, and individual psychological state), capturing aspects of human thermal comfort that go beyond traditional physical variables. As a result, classifications based solely on physical parameters may not fully represent the thermal experience at a given location.

The uneven global distribution of solar energy leads to significant latitudinal variation in UTCI values, with higher latitudes generally associated with lower UTCI values. Earth's curvature, axial tilt, atmospheric transparency, variable daylength, and solar incidence angle contribute to this uneven heating. Consequently, equatorial regions exhibit higher temperatures and UTCI values, while polar regions show lower thermal conditions.

Topography is another key factor modulating thermal conditions. As elevation increases, air temperature tends to decrease approximately 1°C per 100 meters, according to the dry adiabatic lapse rate. These altitudinal differences are also reflected in vegetation patterns and thermal comfort, following Humboldt's rule, which equates altitudinal and latitudinal thermal gradients.

Importantly, locations at the same latitude may display very different UTCI values due to elevation differences. For example, the summit of Mount Roraima in Venezuela, at 2,739 meters, shows a mean UTCI of 19.32°C (moderate cold stress), while Presidente Médici, in Rondônia just 100 km to the south and at 185 meters altitude records a mean UTCI of 28.85°C (strong heat stress).

Ge *et al*. (2017), Vinogradova (2019), and Di Napoli, Pappenberger and Cloke (2020) analyzed the influence of latitude and elevation on UTCI values in broad geographical contexts, including China, Russia, and Pakistan. These studies confirm that, in general, UTCI values decrease with increasing latitude and that local topography significantly modulates thermal perception.

In Brazil, the relationship between elevation and mean UTCI was assessed using linear regression. Although the trend suggests that higher elevations are associated with lower UTCI values, the statistical test yielded a p-value greater than 0.05, indicating the relationship was not significant at the 95% confidence level. Still, the overall behavior supports the theoretical link between altitude and perceived temperature reduction.

Outliers such as southern Rio Grande do Sul where low UTCI values occur even in low-altitude areas are likely attributable to specific regional climatic conditions, such as the influence of polar air masses. In general, the data show a trend of decreasing UTCI with increasing elevation in Brazil, although this relationship is modulated by local factors like latitude, atmospheric circulation, and vegetation cover.

Northern Region

The Northern Region of Brazil is largely characterized by very strong thermal stress due to heat, with a mean UTCI of 29.2°C. The Universal Thermal Climate Index (UTCI) shows a strong correlation with humidity levels and mean radiant temperature two key factors influencing the perception of heat-related discomfort (Bröde *et al.*, 2010). Accordingly, the basins of the Solimões, Juruá, Purus, Matuará, Manicoré, Negro, and Amazon rivers stand out in the cartographic representations as zones of extreme heat stress.

In Amaturá, located along the Solimões River in the state of Amazonas, the average UTCI reaches 30.36°C, representing a condition of extreme thermal adversity.

In Tocantins, the region surrounding the Araguaia River also emerges as an area of marked heat stress. In addition to riverine areas, the municipality of Presidente Figueiredo (AM) appears as a thermal stress hotspot in the Northern Region, with a mean UTCI of 29.97°C.

Conversely, conservation units such as Pacaás Novos National Park (Rondônia), Montanhas do Tumucumaque National Park (between Amapá and Pará), and the Nascentes da Serra do Cachimbo Biological Reserve (southern Pará) register average UTCI values of 25.12°C, indicating moderate heat stress.

In northern Roraima, the elevated terrains of the Serra do Aracá and Serra do Sol exhibit conditions classified as "no thermal stress," with a mean UTCI of 22.93°C. These elevated and cooler areas contribute to the region's thermal diversity, even within a broader context of widespread heat discomfort.

Northeastern Region

The Northeastern Region of Brazil is predominantly characterized by strong thermal stress due to heat, with a mean UTCI of 28.9°C. However, considerable disparities exist across states.

The northwestern states Maranhão, Piauí, and Ceará face extreme heat-related discomfort, with UTCI values above 27°C. In contrast, eastern states Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, and Bahia show moderate heat stress, with a regional mean UTCI of 25.27°C.

The municipality of Piracuruca in Piauí stands out as the most thermally uncomfortable location in the region, with a mean UTCI of 30.34°C, classified as extreme heat stress. The elevated thermal sensation in Piracuruca is not solely due to its proximity to the Equator, but also results from semi-arid atmospheric conditions that intensify surface heating. According to Molion and Bernardo (2002), low cloud cover, low relative humidity, atmospheric subsidence linked to the Walker Circulation, and the influence of the South Atlantic Subtropical High all contribute to surface overheating and reduced evaporative cooling.

On the other hand, Boninal in Bahia reports the lowest mean UTCI in the region at 17.48°C, indicating moderate cold stress. Boninal lies in the Chapada Diamantina, a mountainous region with elevations reaching 2,033 meters, dense vegetation, and rugged terrain (*e.g.*, Morro da Areia, Morro do Cruzeiro), all of which contribute to cooler temperatures and reduced UTCI values. Vegetation positively influences outdoor thermal comfort, especially in hot climates (Silva; Ferreira; Freitas, 2012).

Central-Western Region

The Central-Western Region of Brazil shows a mean UTCI of 28.14°C, indicating strong thermal stress due to heat. The region's states Mato Grosso, Mato Grosso do Sul, Goiás, and the Federal District have a typical tropical climate marked by a rainy season in summer (November to March) and a dry season in winter (April to October).

Areas associated with the Pantanal and Araguaia River basin exhibit the region's highest heat-related discomfort, with UTCI averages near 28.85°C. In contrast, higher elevation areas like the Central Plateau show milder values, such as Brasília (DF) with a mean UTCI of 21.59°C.

According to Boin *et al.* (2019), the Pantanal has a tropical climate, with high summer temperatures and lower winter temperatures, shaped by tropical air masses and occasional cold fronts. Although summer sees the highest absolute air temperatures, biometeorological analysis reveals that spring often presents the highest thermal discomfort due to heat.

This counterintuitive result stems from a combination of local factors. In spring, direct solar radiation is intense, relative humidity remains low (a residue of the dry season), and cloud cover is minimal, which increases radiant heat load on the human body. Thus, even if air temperatures are lower than in summer, the perceived heat can be greater due to higher mean radiant temperature (MRT) and limited evaporative cooling.

During summer, although air temperatures are higher, frequent rainfall increases cloudiness and natural ventilation, reducing direct radiation and moderating MRT. As a result, thermal discomfort in summer may be less severe than in spring.

Even in winter, many areas of the Pantanal maintain moderate to strong heat-related discomfort, especially in the central and southern lowlands, where intense solar radiation and low humidity sustain the heat load on the body.

In short, in the Central-West particularly in the Pantanal thermal discomfort cannot be explained by air temperature alone. It is the product of a complex interaction among air temperature, solar radiation, humidity, and regional atmospheric dynamics.

Southeastern Region

The Southeastern Region of Brazil reports a mean UTCI of 22.80°C, generally indicating no thermal stress. The region's varied relief featuring mountain ranges like the Serra da Mantiqueira, Serra do Mar, Serra da Canastra, Serra do Caparaó, and Serra do Espinhaço directly influences spatial thermal comfort variations.

Higher elevations in these mountain systems register the lowest UTCI values, around 17.85°C, indicating moderate cold stress. For example, the headwaters of the São Francisco River in the Serra da Canastra show a mean UTCI of 18.1°C.

As the São Francisco flows to lower altitudes and latitudes toward the border between Minas Gerais and Bahia UTCI values rise to around 25.75°C, reflecting moderate heat stress. This increase is linked to rising temperatures, decreasing elevation, and decreasing wind speeds and latitude.

The hottest areas in the region are found in northern and northwestern Minas Gerais and in western parts near the Central-West, such as Rio de Janeiro (RJ), which has a mean UTCI of 25.71°C moderate heat stress due to the combination of high air temperatures and high humidity.

Southern Region

The Southern Region of Brazil records the lowest average UTCI values, with a regional mean of 15.2°C, indicating strong cold stress. Rio Grande do Sul and Santa Catarina stand out, with areas of extreme cold stress, especially in municipalities such as Chuí, São Francisco de Paula, Cambará do Sul, and Jaquirana (RS) and São Joaquim, Urupema, and Urubici (SC).

In Paraná, statewide averages indicate lower cold stress compared to the other southern states. However, this average includes the entire territory and may not reflect local extremes, such as in Curitiba, which as shown in Table 2 is the coldest capital and the most thermally uncomfortable in the region.

Among all Brazilian coastal regions, the southern coast shows the greatest thermal variation, from 21.58°C in northern Paraná to 11.98°C in southern Rio Grande do Sul. The South is also the only region in Brazil to experience all UTCI thermal stress classes throughout the year, ranging from extreme cold stress in winter to extreme heat stress in summer.

The Southern Plateau, with its many escarpments and mountain ranges (notably the Serra do Mar), contains the region's highest elevations, exceeding 1,500 meters. These zones record the lowest UTCI means.

The northeastern Rio Grande do Sul and southeastern Santa Catarina experience greater cold discomfort due to their highland location. In contrast, northwestern RS and southwestern SC, with lower altitudes, register higher UTCI values.

The southern tip of Rio Grande do Sul stands out as the only place in Brazil where low UTCI values are found in low-altitude areas, likely due to its latitude and the influence of high-energy atmospheric events, such as cyclones and strong winds especially in winter.

This region is favorable for extratropical cyclone formation (Reboita, 2008), which brings increased cloud cover, above-average rainfall, strong winds, and abrupt temperature changes. According to Jantsch & Aquino (2020), most cyclones forming over Patagonia or the Plata River mouth (Argentina/Uruguay) cross southern Rio Grande do Sul on their path to the Atlantic Ocean.

An extreme example of this dynamic is found in Santa Vitória do Palmar (RS), where winter-like temperatures can be observed even during summer (Gobo, 2017).

Conclusion

The study of thermal comfort and sensation is a complex and nuanced field that requires an integrated understanding of environmental physical variables as well as human physiological and psychological behaviors. This interaction involves factors such as acclimatization history, sociocultural perceptions, and adaptive responses in a world increasingly shaped by accelerated climate change driven by human activity.

The use of the Universal Thermal Climate Index (UTCI) proved to be an appropriate tool for evaluating thermal comfort in Brazil, as the index is grounded in universal physiological mechanisms that govern human response to thermal environments. While cultural and psychological factors may influence individual perception of thermal discomfort, they do not invalidate the objective physical assessment provided by UTCI, which remains a robust reference for human exposure to thermal stress.

The results revealed significant changes in thermal discomfort categories across the national territory from 1979 to 2020, contributing to the establishment of Brazil's first climatological norm for thermal comfort, and enabling the delineation of thermal stress zones.

The original hypothesis that UTCI would directly correlate with Köppen climate types was refuted at the national scale, as the data showed stronger associations with variables such as altitude and latitude. This reinforces the importance of incorporating local and regional factors into thermal comfort assessments, rather than relying solely on traditional climatic classifications.

A trend of increasing heat-related discomfort was observed in several regions of Brazil, while areas historically associated with cold discomfort showed signs of reduction. Climate phenomena such as El Niño and La Niña influenced thermal stress patterns intensifying heat stress during El Niño and cold stress during La Niña episodes.

Given Brazil's vast territorial extent and diverse topography, each region displayed distinct responses to thermal stress, with different discomfort categories sometimes coexisting within the same region.

The study of thermal comfort in Brazil still requires deeper investigation to understand how physical, physiological, and sociocultural factors interact and shape the human thermal experience.

Understanding these dynamics especially in the context of escalating climate instability is essential for developing climate-adaptive urban planning and environmental management strategies. Improving thermal comfort diagnostics can inform public policies that enhance living conditions, reduce socio-environmental vulnerability, and support the development of more resilient urban and tourism spaces under future climate scenarios.

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