Trend Analysis and Temperature Prediction Using MODIS Time Series Images in the Metropolitan Regions of Campinas and Piracicaba - Brazil

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Abstract

This study examines land surface temperature (LST) trends and future projections in the Metropolitan Regions of Campinas and Piracicaba, São Paulo, Brazil, from 2002 to 2022. A time series of 15,091 MODIS LST images (MOD11A1 and MYD11A1 products, v6.1) was processed using Google Earth Engine to generate monthly composites, which were subsequently analyzed in ArcGIS Pro. Harmonic regression modeling identified seasonal and interannual temperature trends and simulated monthly temperatures through 2033. Eight municipalities, grouped by urban density, were selected for detailed comparison. The results indicate persistently higher LST values in highly urbanized areas, while municipalities with initially lower urbanization levels exhibited steeper warming trends over time. Projected January temperature increases between 2023 and 2033 range from 0.4°C to 1.0°C, with the most pronounced changes occurring in areas experiencing rapid land-use transformation. These findings are consistent with broader patterns of urban heat island intensification, emphasizing the combined effects of vegetation loss, impervious surface expansion, and urban densification. While the projections are statistical estimates based on historical trends, they provide valuable guidance for climate adaptation strategies and urban planning. This study demonstrates the utility of MODIS time series and multidimensional GIS analysis for monitoring and forecasting thermal dynamics in rapidly urbanizing regions.

1. Introduction

The Metropolitan Regions of Campinas (MRC) and Piracicaba (MRP), situated in the interior of São Paulo state, Brazil (Figure 1), have undergone rapid urban and industrial expansion. This development has contributed to increased atmospheric pollutant concentrations and intensified urban heat islands, thereby exacerbating impacts on socially vulnerable populations. Collectively, these regions comprise approximately 44 municipalities and a population of about 4.6 million inhabitants (IBGE, 2022). From a physiographic perspective, the regions are primarily located within the Paulista Peripheral Depression (*Depressão Periférica Paulista*), a structural zone characterized by lower elevations relative to the surrounding Cuestas and Plateaus. This topography can affect patterns of pollutant dispersion and heat accumulation (Ross, 1992; Poncano et al., 1981).

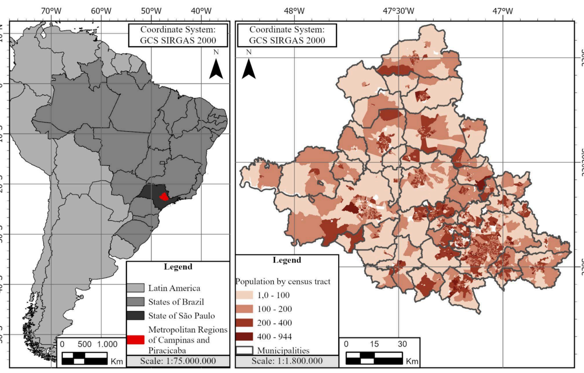

Figure 1. Location of the study area.

In addition to urban densification, the interior regions of São Paulo state are marked by significant industrialization and productive hubs. The MRC stands out in technological, petrochemical, automotive, pharmaceutical, and metallurgical industries, making it a key industrial and logistical corridor in Brazil (Seade, 2024; Sindicamp, 2024). The MRP, with its diverse base, emphasizes sugar-energy, metal-mechanic, automotive, and agro-industrial sectors (Takami & Mendes, 2016). Both regions are part of the São Paulo Economic-Industrial Complex (Cano, 2007), fostering an integrated urban-industrial area linked to the São Paulo metropolis (Lencioni, 2008; Sposito, 2013).

Urban expansion has led to a metropolitan continuum characterized by conurbations and active flows between cities, a phenomenon described by Lencioni (2008) as expanded metropolization. This polycentric urban network boosts the roles of the Campinas and Piracicaba regions as development hubs, but also increases pressure on natural resources and the environment (IBGE, 2021).

A major environmental impact of urban and industrial growth is the loss of native vegetation and green cover, as areas are converted for agriculture, industry, or housing. The removal of semideciduous forests, Cerrado, and riparian vegetation—once dominant in the Paulista Peripheral Depression—has given way to agricultural fields, urban areas, and industrial centers (Ab’Sáber, 2003; Dean, 1996; Ribeiro et al., 2009; Nalon et al., 2008). This reduction in vegetation increases soil sealing, lowers evapotranspiration, alters surface energy balance, and ultimately raises surface temperatures and heat islands in both urban and surrounding rural areas (Mendonça, 2005; Alves & Biudes, 2021; Pina & Ferreira, 2022; Silva et al., 2020).

Studies show that converting native vegetation to agriculture or urban land raises average soil temperatures and diurnal thermal ranges (Mendonça, 2011; Silva et al., 2020). Vegetation loss also reduces carbon storage and biodiversity, increasing vulnerability to extreme climate events (Ribeiro et al., 2009; Dean, 1996). Thus, analyses should consider both urban and rural impacts of native vegetation conversion, given their role in temperature increases and microclimate warming.

Thermal tropicalization of urban spaces (Monteiro, 1976) exemplifies the environmental changes from rapid urbanization and industrialization. Mendonça (2011) highlights that altered surface energy balance and increased thermal homogenization from vegetation loss heighten socio-environmental vulnerability, especially in dense areas. This underscores the need for planning policies that restore green spaces and mitigate heat islands.

The regions have well-defined dry winters and rainy summers, with a predominant humid subtropical (Cwa) climate (Dubreuil et al., 2018). Combined with urbanization and industrialization, these conditions increase susceptibility to pollution episodes and intensified heat islands, further amplifying risks for vulnerable populations (Marcandola Jr. & Hogan, 2010; Santos, 2020).

The MRC and MRP illustrate the interrelationship among urbanization, industrialization, and local climate change. The socio-spatial and environmental complexity of these areas underscores the necessity for integrated urban and environmental planning strategies that balance economic development with climate impact mitigation and enhanced urban resilience.

Understanding land surface temperature trends in rapidly urbanizing and industrializing regions is vital for climate mitigation and adaptation. This study analyzes surface temperature patterns in the MRC and MRP using MODIS (MOD11A1) data from 2002 to 2022, examines seasonal and annual trends, and predicts mean monthly temperatures for 2023–2033. The results aim to inform urban planning and policies to mitigate heat island effects.

2. Materials and Methods

This study utilized Land Surface Temperature (LST) images derived from the MODIS sensor, specifically the MOD11A1 (Terra satellite) and MYD11A1 (Aqua satellite) products, both in version 6.1 (Wan, 2021). Initially, scenes from the MOD11A1 product were downloaded and organized; however, data gaps were identified on certain days, particularly over urbanized areas within the study area. To address this issue, an integration strategy combining daily Terra and Aqua products was implemented to maximize spatial coverage. Ultimately, 7,631 images from the Terra satellite and 7,460 images from the Aqua satellite were compiled, resulting in a total of 15,091 scenes spanning January 1, 2002, to December 31, 2022.

The MOD11A1 and MYD11A1 products provide standardized daily Land Surface Temperature (LST) and emissivity values at a spatial resolution of 1 km and a temporal resolution of approximately 24 hours. These characteristics make them suitable for monitoring thermal trends at regional and metropolitan scales. As the original data are provided in Kelvin, all values were converted to degrees Celsius, the standard unit in Brazil.

Preprocessing was conducted using the Google Earth Engine (GEE) cloud computing platform, where custom scripts were developed to: (i) filter the MODIS dataset by the boundaries of the MRC and MRP; (ii) merge the Terra and Aqua scenes for each day, prioritizing the valid scene in cases of overlap; and (iii) aggregate the daily data into monthly averages to reduce noise from cloud cover and ensure a continuous time series. This process produced 252 monthly surface temperature compositions, which served as the input for subsequent analyses.

The monthly data were then imported into ArcGIS Pro software (version 3.5.2) and organized as a multidimensional raster. This structure enabled the 2002–2022 series to be analyzed as a continuous block of spatial and temporal information, facilitating the application of temporal analysis tools within the GIS environment. Temperature trend analysis was conducted using the Generate Trend Raster tool, which employed the harmonic model. According to ESRI (n.d.), the harmonic model is based on a periodic repeating curve and is most appropriate for describing data that exhibits cyclical patterns, such as temporal changes in temperature. Equation 1 presents the harmonic model applied in this study:

$$y = \beta_0 + \beta_1 t + \sum_{i=1}^{f} \alpha_i \cos\left(\frac{2\pi}{365.25}\omega_i t\right) + \gamma_i \sin\left(\frac{2\pi}{365.25}\omega_i t\right) \quad (1)$$

where
y = pixel's variable value
t = Julian date
ß0 = y-intercept
ß1 = rate of change
α, γ = coefficients of inter-annual or intra-annual changes
ω = I = integer frequency
f = harmonic frequency.

Given the pronounced annual thermal seasonality in the study region, a 12-month cycle was selected to align with the local climate regime.

The trend raster generated at this stage served as input for the time forecasting module in ArcGIS Pro. Using the trend identified in the historical series (2002–2022), the module estimated future monthly surface temperature values for January 2023 to December 2033. These predictions represent statistical extensions of the observed trend and should be interpreted as probable scenarios. However, extreme events, such as heatwaves associated with El Niño, may temporarily disrupt the harmonic pattern assumed by the model.

To enhance the spatial interpretation of the results, eight municipalities were selected and categorized according to total population, then organized into two distinct groups. The first group consists of municipalities with populations greater than 200,000, which are marked by high urban density and ongoing conurbation processes: Americana, Campinas, Limeira, Piracicaba, and Rio Claro. The second group comprises Conchal, Rio das Pedras, and São Pedro, each with populations below 100,000 and situated on the periphery of the metropolitan core. In all selected municipalities, the rural population is negligible, which permits the use of total population as a reliable indicator of urban conditions.

For each municipality, temporal profiles of land surface temperature were extracted for both the historical series and future projections. These profiles are presented in groups according to the previously described characteristics, as similar behaviors were observed within each group. This approach enabled comparison of seasonal oscillation, long-term trends, and the magnitude of warming across two distinct urbanization contexts.

Land use and land cover (LULC) data derived from the MapBiomas Collection 10.1 dataset are used to illustrate transformations within representative municipalities from each group, thereby supporting the interpretation and analysis of the results.

The selection of tools and models in this study was guided by a methodological testing approach to assess their applicability, strengths, and limitations in analyzing land surface temperature dynamics. The harmonic model and ArcGIS Pro's native tools (version 3.5.2) (ESRI, n.d.) were chosen for their integration within a widely adopted commercial platform, offering robust analytical capabilities and ease of use.

Accordingly, the analysis was intentionally limited to these resources to evaluate their effectiveness as an accessible and efficient framework for spatiotemporal analysis. This approach highlights how streamlined methodologies can yield valuable insights for territorial planning and environmental management.

3. Results

A map (Figure 2) was generated from the time series data to illustrate the spatial distribution of average temperatures in the study region. Warm colors represent higher temperatures, while cooler tones indicate milder conditions. December 2007 exhibited the highest average temperatures during the period analyzed, as shown in Figure 2. A notable difference in average temperatures was observed between areas with varying levels of urban densification. For instance, Piracicaba recorded an average temperature of approximately 43.8°C, whereas São Pedro, a less urbanized city, registered an average of about 39.0°C, resulting in a difference of approximately 4.8°C.

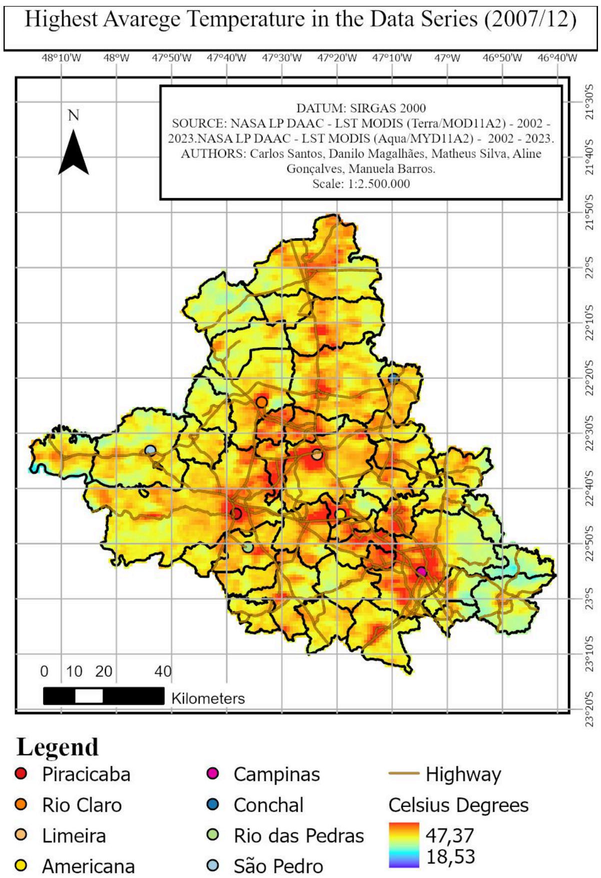

Figure 2. The maximum temperature recorded across the historical series

Areas with higher temperatures generally correspond to the urban footprints of the most densely populated municipalities, underscoring the direct impact of urbanization on thermal variation. Additionally, localized hotspots are observed along major road corridors connecting municipalities, where surrounding land use is predominantly sugarcane monoculture, which tends to contribute to higher surface temperatures. In contrast, regions characterized by milder temperatures are primarily composed of native vegetation, steep slopes, and water bodies. The presence of the Piracicaba River contributes to lower temperatures in the western portion of the study area. Similarly, the Basaltic Cuestas—a stepped relief formed by alternating layers of volcanic basalt and sedimentary sandstone—result in milder temperatures along the northwestern boundary. Additionally, a strip of remnant natural vegetation surrounding the municipality of Itatiba in the southeastern portion, along with its proximity to the Serra da Cantareira, also contributes to milder temperatures in this area.

Analysis of the time series indicates that municipalities experiencing more intense urbanization, population densification, and conurbation generally exhibited higher average land surface temperatures (Figure 3). This thermal pattern illustrates the direct impact of anthropogenic changes on the local energy balance, resulting in increased heat absorption and retention, particularly in densely builtt environments with limited vegetation. Notably, these municipalities were already significantly urbanized and industrialized by the early 2000s, supporting the observation of elevated temperatures throughout the time series.

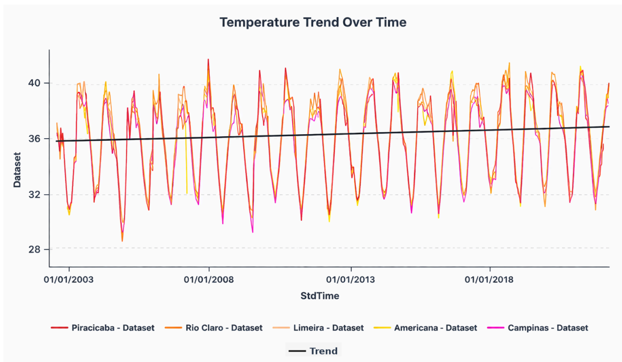

Figure 3. Temporal temperature profiles for municipalities characterized by higher urban density.

In contrast, less populous municipalities situated in more peripheral areas exhibit distinct patterns. These municipalities initially experienced milder average temperatures but displayed a more pronounced warming trend compared to the first group (Figure 4). This difference appears to be directly associated with changes in land use and land cover during the study period. While municipalities in the first group were already characterized by dense urbanization and industrialization at the start of the millennium, those in the second group underwent more substantial transformations, including increased building density and significant loss of vegetation cover (Figure 5). These findings support the conclusion that population densification, intensive urbanization, industrialization, and the removal of vegetation cover contribute to increased surface temperatures.

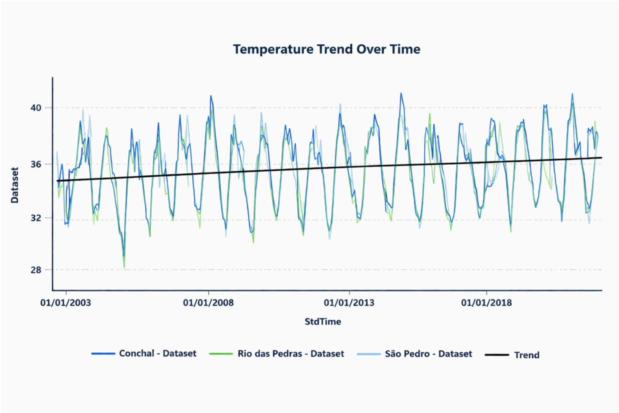

Figure 4. Predicted future temperatures in municipalities characterized by lower urban density.

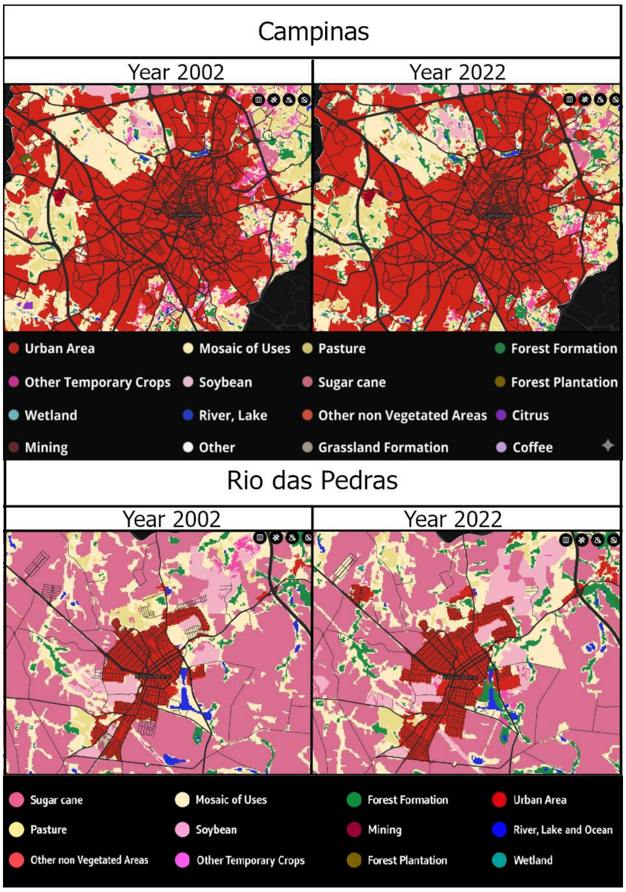

Figure 5. LULC changes between 2002 and 2022 in Campinas and Rio das Pedras municipalities. Source: MapBiomas Collection 10.1

Analysis of the time series indicates that both maximum and minimum average temperatures exhibited a gradual increase, consistent with the global warming trend. These findings strengthen the established association between urban expansion and rising surface temperatures, a phenomenon extensively documented in the literature and linked to the intensification of urban heat islands.

Future temperature projections for the study area were developed using the observed trend data and the harmonic model. These projections generated new temporal temperature profiles for future scenarios, as shown in Figures 6 and 7. The historical trend of consistent and gradual warming suggests that this process is likely to continue, with forecasts indicating that the average temperature may increase by up to approximately 1°C by the end of 2033 if current warming factors persist. Although this scenario is based on a relatively simple model that relies solely on historical temperature series and does not explicitly account for explanatory variables such as vegetation cover, surface materials, or emissions, it remains noteworthy. A more detailed assessment of urban heat island dynamics, particularly the thermal contrast between urban and surrounding rural areas at finer temporal scales, would require higher-frequency observations and dedicated analyses beyond the scope of this study. Research on the urban heat island phenomenon reveals an intensification of minimum and average temperatures in urbanized areas, linked to urban expansion, surface sealing, and vegetation reduction (Ullah et al., 2023). Recent evidence further indicates that the intensity of the surface urban heat island has been increasing globally at a rate of approximately 0.02°C per year in analyzed cities, reflecting both the direct effects of urbanization and broader climate warming (Yuan et al., 2025).

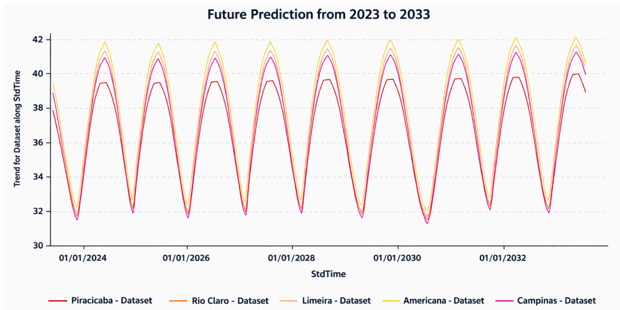

Figure 6. Future temperature prediction for municipalities with higher urban density.

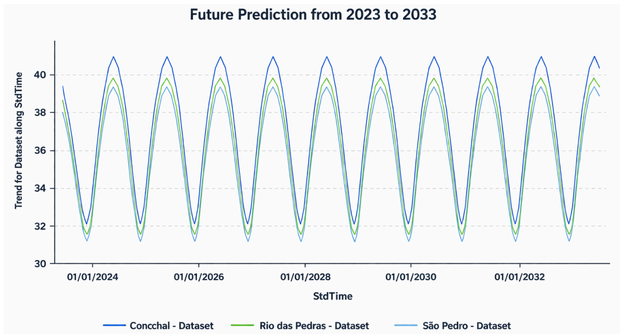

Figure 7. Future temperature prediction for municipalities with lower urban density.

The projected average temperature increase of approximately 1°C by 2033 constitutes a significant risk indicator for the local context. The cumulative effects of warming, intensified heat waves, and rising nighttime minimum temperatures are likely to exacerbate human vulnerability, increase energy demand, and negatively impact thermal comfort and public health, particularly among the most vulnerable populations. These findings underscore the need for public managers to plan and implement mitigation measures, such as restoring vegetation cover, utilizing permeable materials, and enhancing urban albedo strategies, which have been identified in the literature as effective approaches to attenuating urban heat islands (Ahmed et al., 2025).

In summary, although the adopted methodology does not account for all explanatory factors and uncertainties, the projection indicates that, if current conditions persist, the studied territory is likely to experience additional warming by 2033. These results should be interpreted as a warning and incorporated into territorial action plans that address both surface dynamics and future land-use and land-cover scenarios. The curves presented in the graph illustrate the region's characteristic thermal seasonality, characterized by hotter summers and milder winters, reflecting the humid subtropical climate with a dry winter (Cwa) that predominates in the MRC and MRP.

Analysis of the time series confirms that January consistently exhibits the highest annual average temperatures. Accordingly, estimated temperatures for January were examined for the period from 2023 to 2033, as shown in Table 1. Given the projected trend of continuous warming, comparing January 2023 and January 2033 provides an estimate of the expected temperature increase over the ten-year interval.

A comparative analysis of temperatures between 2023 and 2033 indicates a consistent trend of thermal elevation across all evaluated municipalities. The largest projected temperature increases, 0.6°C and 1.0°C, are observed in less populous municipalities that initially exhibited milder temperatures at the start of the historical series. These municipalities, characterized by smaller and less densely populated urban areas with greater intra-urban vegetation in 2002, underwent significant transformations in land use and land cover by 2022. Over the analysis period, urban areas in these municipalities expanded, became more densely occupied, and lost vegetation cover, contributing to a more pronounced increase in average temperature. This trend is further supported by the slope of the trend line generated for these municipalities using the harmonic model.

Cities	Years		Variation
	Jan/23	Jan/33	
Piracicaba	40.9 ° C	41.4 ° C	0.5 ° C
Limeira	40.9 ° C	41.3 ° C	0.4 ° C
Americana	40.2 ° C	40.7 ° C	0.5 ° C
Rio Claro	40.3 ° C	40.9 ° C	0.6 ° C
Campinas	39.7 ° C	40.2 ° C	0.5 ° C
Conchal	37.9 ° C	38.9 ° C	1.0 ° C
Rio das Pedras	37.6 ° C	38.4 ° C	0.8 ° C
São Pedro	38.5 ° C	39.1 ° C	0.6 ° C

Table 1. Predicted average temperature from January 2023 to January 2033.

In contrast, municipalities that were already consolidated from an urban perspective experienced less significant changes in land use during the period, which resulted in relatively lower rates of warming. Nevertheless, due to a sustained high degree of densification and urbanization since the start of the time series, these municipalities recorded higher temperatures throughout the entire analyzed period. This comparison suggests that municipalities with lower urban density retain opportunities to strategically plan land use and occupation, thereby mitigating future warming and enhancing thermal comfort conditions.

4. Conclusion

The findings of this study suggest that combining MODIS time series data with multidimensional analysis tools in ArcGIS Pro offers an effective approach for analyzing temperature patterns and projecting future scenarios in metropolitan regions undergoing rapid territorial change. Integrating the MOD11A1 (Terra) and MYD11A1 (Aqua) products reduced data gaps, increased spatial coverage across urban areas, and enabled the creation of a consistent monthly database spanning the period from 2002 to 2022.

The analysis revealed that municipalities characterized by higher population density, extensive conurbation, and a predominance of impermeable surfaces consistently exhibit elevated surface temperatures compared to smaller municipalities with greater vegetation cover. The near 5°C temperature difference observed between Piracicaba and São Pedro in December 2007 exemplifies this pattern and supports existing literature on urban heat islands and the tropicalization of urban environments in Brazil (Monteiro, 1976; Mendonça, 2011).

Projections for the period 2023 to 2033 suggest a persistent warming trend, which may significantly exacerbate thermal discomfort if these trends are realized. Additionally, increasing temperatures are likely to drive higher household energy consumption and place additional strain on public health systems, particularly during heatwave events. Therefore, these results can inform policy development aimed at maintaining and expanding green areas, revising urban planning parameters, and implementing green and blue infrastructure.

Although the results are consistent and align with established trends in the urban climate literature, several methodological limitations must be acknowledged. The 1 km resolution of MODIS products smooths highly localized thermal contrasts, thereby failing to capture the intra-urban heterogeneity characteristic of complex urban environments. Additionally, the image acquisition times (10:30 a.m. and 01:30 p.m.) yield elevated monthly average temperatures, as they record data only during periods of peak heat and omit the naturally lower nighttime values. The harmonic model implemented in ArcGIS Pro also presumes seasonal regularity, which may be disrupted by global or regional climatic phenomena such as El Niño, La Niña, or regional wildfire events. Therefore, the projections should be regarded as indicative trends rather than deterministic outcomes.

In the context of metropolitan planning, these results provide a means to distinguish between the effects of regional climate and those arising directly from local land use decisions. This distinction is essential for enabling master plans, urban afforestation policies, and climate adaptation programs to prioritize the most sensitive areas, particularly where increased impervious surfaces and vertical development have occurred without sufficient compensation through green spaces or shading.

Integrating these findings with socioeconomic data from the Census and public health information can identify areas of heightened climate vulnerability, where elevated temperatures coincide with lower income levels, inadequate housing, or a high proportion of elderly residents. In these instances, remote sensing evolves from a tool for physical diagnosis to a foundation for urban climate justice policies, facilitating the allocation of resources to areas where they yield the greatest social benefit.

A follow-up study is necessary to empirically validate the predictions generated by the harmonic model. Since predictions have been available since January 2023, the current time frame (up to 2025) allows for a comparison between predicted and observed values, thereby enabling an assessment of model performance. This process involves collecting actual surface temperature data and cross-referencing these series to calculate error metrics such as RMSE, MAE, and bias. It also enables the identification of months in which the model overestimates or underestimates temperature, and, if necessary, allows for recalibration or the inclusion of additional variables, such as humidity, cloud cover, or ENSO anomalies. This methodological step is crucial for transforming projections from a purely statistical exercise into actionable information for territorial planning and urban climate risk management.

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