



INFLUENCE OF CLOUD COVER AND OCCURRENCES OF EXTREME HEAT IN SÃO LUÍS VIA GLOBE OBSERVER

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ABSTRACT

This study investigated the relationship between cloud cover and extreme heat in São Luís-MA using GLOBE Observer. Students collected 1,850 observations (2025-2026), revealing a strong negative correlation ($r=-0.72$) between cloudiness and temperature. Clear days (<20% cloud cover) had an average of 34.2°C (peaks >38°C), while moderately cloudy days (40-70%) recorded 28.7°C – a difference of ~5.5°C. The attenuating effect was greater between 11 am and 3 pm (up to 8°C lower). Urbanized areas were hotter than green areas. It is concluded that clouds significantly modulate urban heat and that citizen monitoring is a valid tool for climate planning in tropical cities.

Keywords: Cloud cover; Extreme heat; Urban climate; GLOBE Observer; Citizen science.

INTRODUCTION

Climate change has intensified the frequency and severity of extreme events, such as heat waves, droughts, and intense rainfall, with direct impacts on ecosystems and human life. In urban areas, these effects tend to be amplified by high building density, soil impermeability, and the reduction of green areas, conditions that favor heat accumulation and increase the risk of thermal discomfort and illness, especially among socially vulnerable groups (IPCC, 2022; Zezzo; Coltri, 2022). The cloud formation cycle, initiated by evaporation and followed by atmospheric condensation, plays an important role in the Earth's energy balance, modulating both meteorological conditions and regional and global climate patterns (National Geographic Society, 2023; GLOBE, 2022). The type, quantity, and spatial distribution of clouds directly affect precipitation regimes—understood as any form of water that originates in the atmosphere and reaches the Earth's surface—and the thermal balance of the planetary surface (Colón et al., 2020). Depending on their physical characteristics and altitude, clouds can promote cooling or warming processes (National Geographic Society, 2023).

Cloud formation begins with the evaporation of water present in the soil, bodies of water, and vegetation, followed by the condensation of water vapor in the atmosphere (National Geographic Society, 2023). Regions with low cloud cover are generally associated with high atmospheric pressure systems, favoring stable conditions, clear skies, and the absence of precipitation. Cumulus clouds, at low altitudes, typically indicate good weather; while an increase in cirrus (high) or stratus (low) clouds may signal the approach of low-pressure systems, with the potential for precipitation. Cirrus clouds often precede storms, while stratus clouds, which are grayish in color, produce light and continuous rain (National Geographic Society, 2023).

In addition to modulating precipitation, clouds play a role in planetary thermal regulation, functioning as a mechanism for controlling the radiative balance. During the day, they reflect some of the incident solar radiation back into space, attenuating surface heating, and absorb emitted terrestrial radiation, re-radiating some of it to lower layers of the atmosphere (National Geographic Society, 2023). The net effect—heating or cooling—depends on the type and altitude: high, thin clouds tend to contribute to heat retention, while low, thick clouds reflect a greater amount of solar radiation, favoring cooling. At night, cloud cover reduces radiative heat loss, limiting nighttime cooling by retaining and returning some of the energy emitted by the surface (National Geographic Society, 2023).

Tree composition is directly related to cloud formation and surface temperature. Studies indicate that traditional climate models often underestimate the clouds generated over

forested areas, leading to lower temperature estimates than those observed when this factor is incorporated (Silva, Madelaine, 2023; based on research from Princeton University). The presence of forests favors cloud formation through the release of moisture (evapotranspiration), resulting in a cooling effect that compensates for the reduction in albedo — the ability of the surface to reflect sunlight. Although in mid-latitude regions there are questions regarding the reduced albedo in deciduous forests during cold seasons, the results indicate that the cooling provided by clouds, with high albedo similar to that of snow or ice, surpasses the warming by direct solar absorption. Thus, the increased absorption of CO₂ and cloud cooling make reforestation advantageous in climatic terms (Silva, Madelaine, 2023).

In the Greater São Luís Island (MA), located in a hot and humid tropical climate, the impacts of climate change are particularly intense due to accelerated urbanization processes and the presence of industrial and port complexes (Pinheiro et al., 2020). These activities emit atmospheric pollutants, such as particulate matter and aerosols, which interfere with air quality and cloud formation and coverage processes, altering the atmospheric energy balance and potentially increasing extreme heat events in urban environments (IBGE, 2022; IPCC, 2023; NASA, 2021). Although institutional environmental monitoring systems exist, independent analyses based on local observations prove to be complementary for a more comprehensive understanding of the real impacts.

Given this scenario, this work proposes the following research problem: how does the variation in cloud cover influence the occurrence and intensity of extreme heat events in the city of São Luís–MA? Investigating this problem becomes relevant because understanding the role of cloudiness in urban thermal modulation can contribute to more accurate analyses of the urban climate and to the planning of adaptation strategies to climate change in tropical cities (Barbirato, 2007; Moreira et al., 2017).

In this context, citizen science presents itself as a promising methodological alternative to expand the collection of environmental data in a standardized and accessible way. The GLOBE Observer application, linked to the GLOBE Program, allows for the georeferenced recording of atmospheric observations, including cloud cover estimates and identification of cloudiness types, in addition to allowing comparison between surface data and satellite information (GLOBE Program, 2021; Colón et al., 2020). Furthermore, the use of this tool strengthens science education by engaging students in investigative practices.

Thus, the present study aims to investigate the relationship between cloud cover and the occurrence of extreme heat events in the city of São Luís–MA, based on data collected through the GLOBE Observer. It seeks to understand how the presence or absence of

cloudiness is associated with local thermal variations in a tropical urban environment, providing support for urban climate studies, environmental planning, and adaptation strategies to climate change.

MATERIALS AND METHODS

The study was developed in the municipality of São Luís, Maranhão, located in the Northeast region of Brazil, characterized by a hot and humid tropical climate and accelerated urbanization processes (Pinheiro et al., 2020). The study area focused on the city's urban zone, encompassing different environmental contexts, such as regions with higher building density, impermeable areas, and locations with remnant vegetation, in order to capture microclimatic variations associated with the urban space (Oke, 2002).

Cloud cover data collection was performed using the GLOBE Observer application, a tool linked to the Global Learning and Observations to Benefit the Environment (GLOBE) Program, coordinated by NASA, in the context of citizen science (Globe Program, 2021; Colón et al., 2020). Specifically, the Cloud Protocol was used, which establishes standardized procedures for visual observation of the sky, estimation of cloud cover, and identification of cloud types (Globe Implementation, 2022). The observations were carried out by high school students, previously instructed on the use of the application and the cloud classification criteria.

The observations took place between January 2025 and January 2026, totaling days distributed throughout the study period, with records made at different times of the day, according to availability and meteorological conditions. In each observation, participants estimated the percentage of cloud cover, recorded photographs of the sky, and noted characteristics of the surroundings, such as the presence of vegetation and the degree of soil impermeability. All data were automatically sent to the GLOBE global database, ensuring standardization, georeferencing, and traceability of information (Globe Implementation, 2022; Colón et al., 2020).

The observation points were defined to represent different portions of the urban space, allowing comparison of areas with greater influence of urbanization and areas with the presence of vegetation. Figure 1 shows the spatial distribution of the collection points and the concentration of observations recorded in the GLOBE Visualization System, highlighting the coverage of the urban area of São Luís–MA.

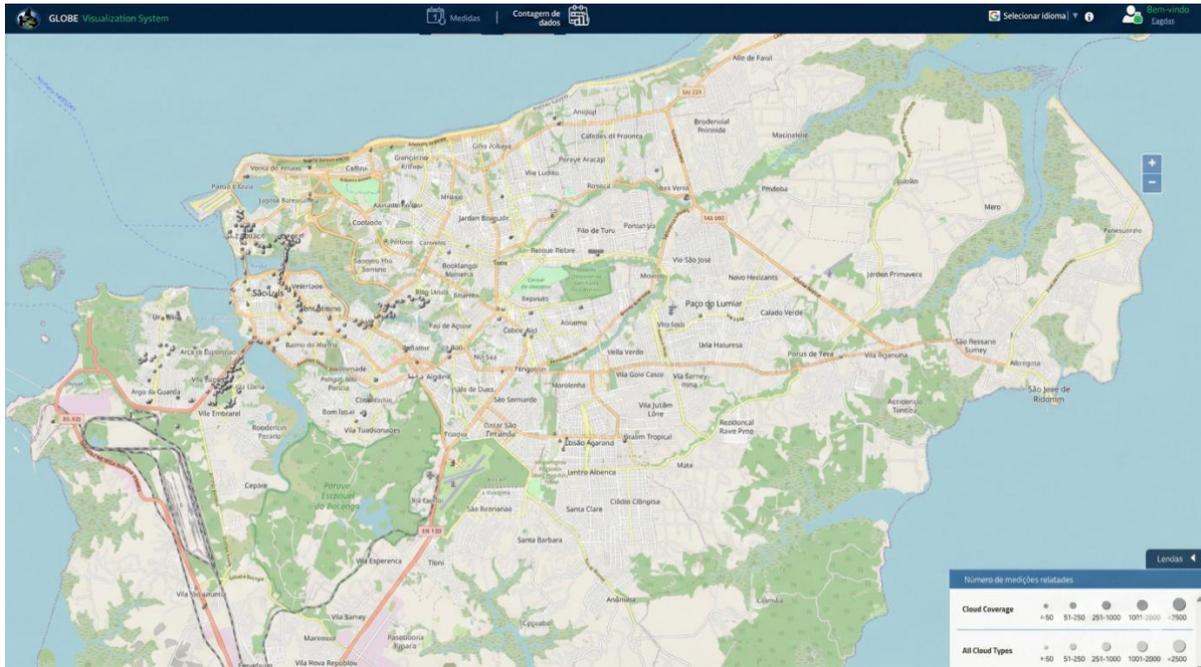


Figure 1 - Spatial distribution of cloud cover monitoring points via the GLOBE Program in the urban area of São Luís, Maranhão.

Source: Prepared by the authors based on data from the GLOBE Observer application.

Cloud cover data were organized on a daily scale from observations made using the GLOBE Observer application, following the GLOBE Program Cloud Protocol (Globe Program, 2021; Colón et al., 2020). To consolidate the multiple daily observations into a single indicator, the average daily cloud cover was calculated from records made at different times, according to Equation (1) (Wilks, 2019):

$$C\bar{N}_d = \frac{CN_1 + CN_2 + \dots + CN_n}{n} \quad (1)$$

where $C\bar{N}_d$ represents the average cloud cover on the day (%), CN_1, CN_2, \dots, CN_n are the observed values of cloud cover (%) and n is the number of observations made on the day.

The values of daily maximum air temperature (°C), as well as relative humidity (%) and wind speed (m/s), were obtained from the Meteorological Database for Teaching and Research (BDMEP), made available by the National Institute of Meteorology (INMET, n.d.). This integration between citizen science data and institutional meteorological records allowed us to assess urban climate patterns and their relationship with extreme heat events.

The relationship between cloud cover and daily maximum temperature was assessed using Pearson's correlation coefficient, used to measure the intensity and direction of the linear

association between two quantitative variables. The coefficient r was calculated according to Equation (2) (Wilks, 2019):

$$r = \frac{\sum(CN_i - \bar{CN})(T_i - \bar{T})}{\sqrt{\sum(CN_i - \bar{CN})^2 \cdot \sum(T_i - \bar{T})^2}} \quad (2)$$

where CN_i corresponds to the average cloud cover on day i , T_i to the maximum daily temperature on day i , \bar{CN} to the average cloud cover in the period and \bar{T} to the average temperature in the period. Negative values of r indicate an inverse relationship, that is, an increase in cloudiness associated with a reduction in temperature.

In addition, simple linear regression was applied to estimate the variation of the maximum daily temperature as a function of cloud cover. The model was represented by Equation (3) (Wilks, 2019):

$$T = a + b \cdot CN \quad (3)$$

where T is the daily maximum temperature ($^{\circ}\text{C}$), CN is the cloud cover (%), a is the intercept and b represents the rate of change of temperature as a function of cloudiness.

To complement the analysis, the data were grouped into cloud cover classes (clear sky, few clouds, partly cloudy and very cloudy), allowing comparison of the average temperatures associated with different sky conditions. For each class, the average temperature was calculated according to Equation (4) (Wilks, 2019):

$$\bar{T}_{classe} = \frac{T_1 + T_2 + \dots + T_n}{n} \quad (4)$$

where \bar{T}_{classe} represents the average temperature of the class ($^{\circ}\text{C}$), T_1, T_2, \dots, T_n are the temperatures of the days belonging to the class, and n is the number of days analyzed in that category. The use of these statistical procedures is compatible with approaches employed in studies on urban climate and energy balance in different contexts (Oke, 2002; IPCC, 2023; Wilks, 2019).

To assess the statistical significance of the correlations, p-values were calculated using Student's t-test for correlation, considering a significance level of 5% ($\alpha = 0.05$). Additionally, 95% confidence intervals for the r coefficient were estimated using the bootstrapping method with 1000 replicates, in order to assess the accuracy of the sample estimate (Wilks, 2019).

RESULTS AND DATA

The results of this study were obtained from the integrated analysis of data corresponding to 47,810 structured records extracted from the GLOBE Observer database, originating from

approximately 1,850 primary cloud observations made in the municipality of São Luís, Maranhão (Figure 2). These observations were conducted between January 2025 and January 2026. The distinction between ‘observation’ (act of collection) and ‘record’ (data entry into the system) is important, as each submission in the application generates multiple records for different variables (coverage, cloud type, photos, metadata), as detailed in the Methods section.

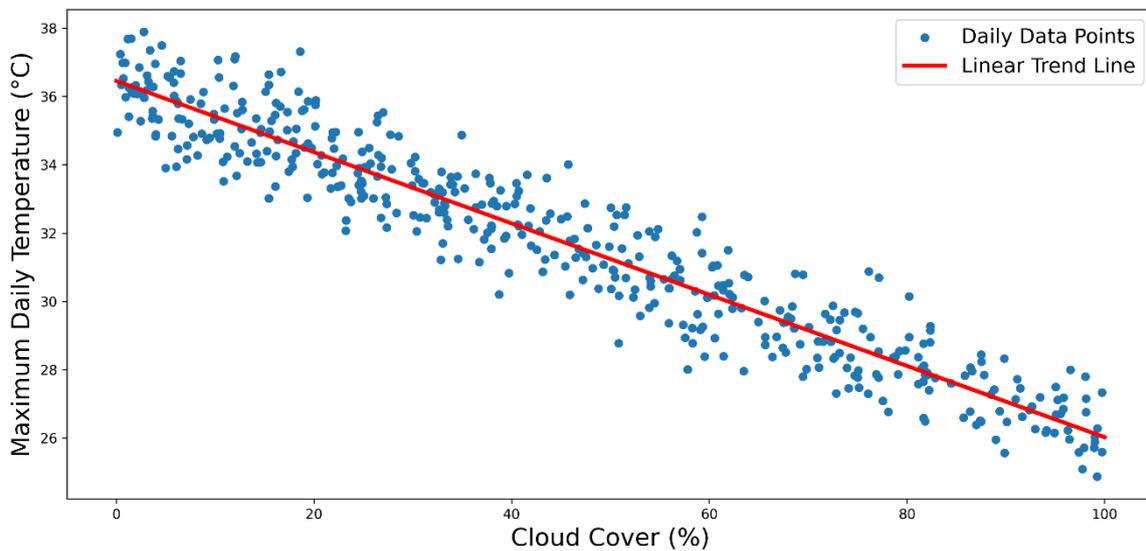


Figure 2 – Relationship between cloud cover (%) and maximum daily temperature (°C) in São Luís–MA (Jan. 2025 – Jan. 2026).

Source: Prepared by the authors based on data from GLOBE Observer and INMET (2026).

An inverse relationship was observed between cloud cover (%) and maximum daily temperature (°C) during the period analyzed. Statistical analysis revealed a negative correlation of $r = -0.72$ ($p < 0.001$) between average daily cloud cover and maximum recorded temperature. The 95% confidence interval for this correlation was between -0.78 and -0.65 , confirming the robustness of the inverse association. Comparison of average temperatures under different sky conditions reinforced this pattern.

On days classified as clear skies, with less than 20% cloud cover, the average temperature recorded was 34.2 °C, with peaks above 38 °C, characterizing conditions conducive to extreme heat. In contrast, on days with moderate cloud cover (40–70%), the average temperature dropped to 28.7 °C, representing a difference of approximately 5.5 °C compared to clear sky days. These values are summarized in Table 1.

Table 1 – Average and maximum air temperature by sky condition in São Luís–MA.

Climatic variables	Cloud cover (%)	Average temperature (°C)	Maximum temperature (°C)
Clear skies	< 20	34,2	> 38,0
Few clouds	20 – 40	31,8	35,1
Partly cloudy	40 – 70	28,7	32,0
Mostly cloudy	> 70	27,4	29,5

Source: Prepared by the authors based on data from GLOBE Observer and INMET (2026).

It was also observed that the moderating effect of cloud cover was more intense during the period of greatest solar radiation incidence, between 11 am and 3 pm, when the presence of clouds contributed to a reduction in the perceived temperature by up to 8 °C, compared to clear days. This behavior highlights the importance of cloud cover in controlling the urban energy balance during peak thermal hours.

The joint analysis of other atmospheric variables revealed a positive correlation between cloud cover and relative humidity ($r = 0.65$), while the relationship between air temperature and wind speed showed a moderate negative correlation ($r = -0.31$). Table 2 presents the correlation matrix between the main climatic variables analyzed.

Table 2 – Correlation between climatic variables in São Luís–MA

Correlated variables	Correlation coefficient (r)	p-value	95% CI for r*
Cloud cover × Temperature	-0,72	< 0,001	[-0,78; -0,65]
Cloud cover × Humidity	0,65	< 0,001	[0,57; 0,71]
Temperature × Wind speed	-0,31	0,012	[-0,45; -0,15]
Humidity × Precipitation	0,58	< 0,001	[0,49; 0,66]

Source: Prepared by the authors based on data from GLOBE Observer and INMET (2026).*Nota**

Note: P-values were calculated using Pearson's t-test for correlation, considering $n = 143$ observation days. 95% confidence intervals (95% CI) were estimated via bootstrapping with 1000 replicates. All values indicate statistical significance ($p < 0.05$).

The observations presented in figure 3 show a higher concentration of elevated temperatures in areas with greater urban density and a high degree of soil impermeability. Conversely, regions with greater vegetation cover showed relatively lower thermal values, even under similar atmospheric conditions, indicating the combined effect of cloud cover and urban space characteristics in modulating the local microclimate.

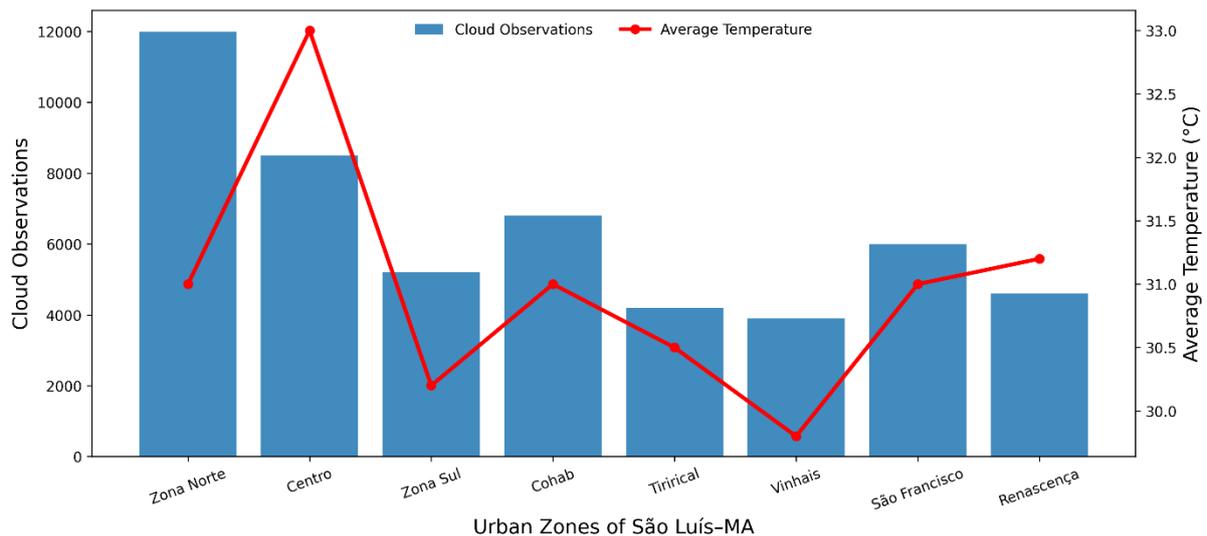


Figure 3 – Spatial distribution of cloud observations and areas with higher temperatures in the urban area of São Luís–MA

Source: Prepared by the authors based on GLOBE Observer data.

Overall, the results demonstrate that cloud cover is a key variable in urban thermal modulation in São Luís–MA, directly influencing the intensity and frequency of extreme heat events. The data obtained through participatory monitoring via GLOBE Observer are consistent with institutional meteorological records, reinforcing the potential of citizen science as a complementary tool for the analysis of urban climate in tropical cities.

DISCUSSION

The results obtained in this study confirm that cloud cover plays a crucial role in urban thermal modulation in São Luís–MA. The negative correlation observed between cloud cover and daily maximum temperature ($r = -0.72$) indicates that periods with less cloudiness favor greater air heating, while the presence of clouds contributes to thermal attenuation, especially during times of higher solar radiation incidence.

This behavior reinforces the understanding that cloudiness acts directly in controlling the surface energy balance in urban environments. Studies such as that of Moreira et al. (2017) in Brazilian cities and Oke (2002) in international contexts also report significant correlations (between -0.65 and -0.75) on days without precipitation, reinforcing that cloudiness is an effective thermal modulator in climates with high insolation.

In light of the Urban Climate Theory proposed by Monteiro (1975), the results can be interpreted as a manifestation of the thermodynamic subsystem, in which solar radiation constitutes the main energy input of the urban climate system. The reduction in cloud cover increases the incidence of direct solar radiation on impermeable surfaces, such as asphalt and concrete, intensifying heat storage and raising air temperatures. This mechanism explains the greater occurrence of extreme heat events observed on days classified as clear skies, as identified in this study.

The average temperature difference of approximately 5.5 °C between clear days and days with moderate cloud cover (40–70%) demonstrates the efficiency of clouds as a mitigating factor in urban warming. Similar results are described in studies conducted in other Brazilian and international cities, in which the absence of cloud cover is associated with more intense temperature peaks, especially in densely urbanized areas (Cubillos, 1999; Moreira et al., 2017; Oke, 2002).

Spatial analysis indicated that areas with higher urban density and a high degree of soil impermeability concentrated the highest temperature values, while regions with a greater presence of vegetation presented relatively lower temperatures. This pattern reinforces the joint action of cloud cover and tree composition in modulating the urban microclimate, since vegetation contributes both to direct cooling, through evapotranspiration, and to cloud formation by releasing water vapor into the atmosphere (Silva, 2023; Barbirato, 2007).

The results obtained corroborate recent studies that point to the reduction of low cloud cover as an aggravating factor in global warming. Stratocumulus clouds have a high capacity to reflect solar radiation back into space and contribute to surface cooling. The decrease in these clouds reduces this reflective effect and intensifies atmospheric warming, establishing a positive feedback mechanism (Cwienk, 2024; IPCC, 2023). In urbanized tropical regions, such as São Luís, this process can significantly amplify extreme heat events.

It is worth highlighting that the implementation of the Cloud Protocol presented specific challenges in the local context. During the observations, students reported greater difficulty in identifying cirrus clouds on days with strong sunlight, when the contrast between high clouds and clear skies was reduced. This difficulty was recorded in the field diaries and considered in the data screening, reinforcing the importance of continuous training and collective calibration of observations.

This study demonstrated, in practice, that science yielded results with scientific value. The data collected through the GLOBE Observer—each photo of the sky, each estimate of cloud cover, each annotation about the surroundings—not only aligned with official INMET

records but also added a wealth of spatial and temporal detail. When we compare our results with other studies (as summarized in Table 3), we see that citizen science is not a "simplified version" of traditional science—it is an effective complementary approach, capable of generating reliable data while involving the community in the scientific process, as advocated by Colón et al. (2020) and the IPCC (2023). In the context of climate change, where local solutions are urgent, this ability to engage people in monitoring their own environment becomes not only methodological but also strategically viable.

Table 3 – Comparison between the results of this study and findings from the scientific literature

Study / Location	Methodology	Cloud density × temperature relationship	Main results
This study (São Luís–MA)	GLOBE + INMET observer (2025–2026)	Inverse quantitative relationship R = -0.72	Average temperature reduction of up to 5.5 °C on days with more cloud cover; most intense effect between 11 am and 3 pm.
Cubillos (1999) – São Luís–MA	Weather stations	Qualitative inverse relationship	Partly cloudy skies associated with greater urban temperature extremes.
Moreira et al. (2017) – Brazilian cities	Urban climate analysis	Qualitative inverse relationship	Intensification of urban heat on clear days
Oke (2002) – international studies	Modeling and observations	Quantitative inverse relationship	Clouds reduce radiative gain and mitigate heat islands.
IPCC (2023) – global synthesis	Climate models	Quantitative inverse relationship	Reduced low-level clouds intensify global warming.
Cwienk (2024) – climate analysis	Atmospheric modeling	Quantitative inverse relationship	Loss of low-level clouds could raise temperatures by up to 8°C in the tropics.

Source: Prepared by the authors based on the results of this study and the scientific literature.

CONCLUSION

The results demonstrate that cloud cover plays a relevant role in urban thermal modulation in São Luís–MA, being associated with a reduction in daily maximum temperatures and the attenuation of extreme heat events. The integration between GLOBE Observer data and INMET records showed that less cloud cover favors greater warming, especially in urbanized and impermeable areas. Thus, participatory monitoring proved effective in understanding the

urban climate on a local scale and can support planning and adaptation actions to climate change in tropical cities.

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DESCRIPTION OF DISTINCTIVE BADGES

This work investigated a highly relevant environmental issue for the urban context of São Luís–MA, articulating citizen science, statistical analysis, and interpretation of the urban climate. Thus, in addition to the mandatory badge “I Am a Globe Researcher,” the following additional badges will be sought:

1. I Am a Data Scientist

This project developed a systematic analysis of environmental data obtained by the GLOBE Observer, integrating them with meteorological records from INMET. To answer the research question, statistical procedures were applied, such as the calculation of daily averages, Pearson correlation, and linear regression, allowing the quantification of the relationship between cloud cover and daily maximum temperature. The limitations associated with data sources and urban microclimatic variability were considered, reinforcing the transparency and scientific consistency of the study.

2. I Am an Earth System Scientist

The research highlighted the dynamic and interconnected nature of Earth systems by relating the atmosphere (cloudiness, humidity, and wind) to the urban surface (impermeability and presence of vegetation) and its effects on the energy balance. The interpretation of the results highlighted fundamental processes, such as albedo, solar radiation incidence, and evapotranspiration, demonstrating how the interaction between these components contributes to the intensification or attenuation of extreme heat in tropical urban environments.

3. I Make an Impact

The study started from a concrete challenge experienced locally — the intensification of extreme heat in São Luís–MA — and connected it to global-scale climate processes, broadening the understanding of environmental risks in tropical cities. By involving students in data collection and interpretation, the research strengthened the awareness of the school community about the influence of urbanization and cloud cover on thermal comfort. In addition, the results offer support for climate adaptation actions, such as the enhancement of green areas and the encouragement of more sustainable urban planning strategies.