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BRIDGING DATA GAPS IN URBAN CLIMATE STUDIES: THE POTENTIAL OF A LOW-COST METEOROLOGICAL SHELTER

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ABSTRACT

Climate change and rapid urbanization are altering urban ecosystems, intensifying phenomena such as Urban Heat Islands (UHI) and exacerbating challenges related to air quality, water availability, and public health. The replacement of natural surfaces with built infrastructure alters local climates dynamics, while global warming amplifies extreme events, increasing urban vulnerability. In line with Sustainable Development Goal (SDG) 11, which proposes to make cities inclusive, resilient, and sustainable, understanding urban microclimates is crucial for effective adaptation strategies. However, reliable meteorological data remain scarce in many developing countries due to limited monitoring networks, high costs, and infrastructure constraints. In response, this study developed and validated a low-cost meteorological shelter using accessible materials, in accordance with World Meteorological Organization (WMO) guidelines. Field tests conducted under real conditions confirmed their reliability in measuring near-surface air temperature. Its affordability and ease of replication make it a viable tool for institutions with limited resources, supporting the democratization of climate data. Beyond UHI research, the proposed solution has potential applications in agroclimatic assessments, hydrometeorological modeling, and environmental forecasting, with demonstrated suitability for tropical climates.

Keywords: Meteorological monitoring. Applied climatology. Microclimate analysis. Urban heat islands. Resilience.

PREENCHENDO LACUNAS DE DADOS EM ESTUDOS CLIMÁTICOS URBANOS: O POTENCIAL DE UM ABRIGO METEOROLÓGICO DE BAIXO CUSTO

RESUMO

As mudanças climáticas e a rápida urbanização estão intensificando fenômenos como as Ilhas de Calor Urbanas (ICUs) e agravando problemas relacionados à qualidade do ar, disponibilidade de água e saúde pública. A substituição por infraestrutura construída altera a dinâmica climática, enquanto o aquecimento global intensifica eventos extremos, aumentando a vulnerabilidade. Em consonância com o Objetivo do Desenvolvimento Sustentável (ODS) 11, que visa tornar as cidades inclusivas, resilientes e sustentáveis, compreender os microclimas urbanos é essencial para o desenvolvimento de estratégias eficazes de adaptação. Dados meteorológicos confiáveis são escassos em países em desenvolvimento, devido a redes de monitoramento limitadas, custos elevados e restrições de infraestrutura. Esse estudo desenvolveu e validou um abrigo meteorológico de baixo custo, utilizando materiais acessíveis e em conformidade com as diretrizes da Organização Meteorológica Mundial (OMM). Testes de campo realizados em condições reais confirmaram sua confiabilidade para medições de temperatura do ar próxima à superfície. Sua acessibilidade e facilidade de replicação o tornam uma solução viável para instituições com recursos limitados, contribuindo para a democratização dos dados climáticos. Além de aplicações em estudos de ICUs, a solução proposta apresenta potencial para uso em avaliações agroclimáticas, modelagem hidrometeorológica e previsão ambiental, com durabilidade adequada a climas tropicais.

Palavras-chaves: Monitoramento meteorológico. Climatologia aplicada. Análise de microclima. Ilha de calor urbano. Resiliência.

INTRODUCTION

Global climate change and rapid urban growth have significantly transformed urban ecosystems, posing complex challenges for climate research and management in cities (Angel *et al.*, 2010; Seto; Güneralp; Hutyra, 2012; United Nations, 2012). Urbanization, characterized by the replacement of natural surfaces with built infrastructure, alters local climate patterns (Amorim, 2020), intensifying phenomena like Urban Heat Islands (UHI) and affecting air quality, water resource availability, and public health (Oke, 1982; Stewart; Oke, 2012). These changes are further exacerbated by climate change, which increases the frequency and intensity of extreme weather events, such as heat waves, heavy rainfall, and prolonged droughts, thereby heightening urban vulnerability (IPCC, 2021). In this context, understanding urban microclimates and their impacts is crucial for developing effective public policies and implementing adaptation and mitigation strategies (Grimmond *et al.*, 2010; Vieira Zezzo *et al.*, 2024) that align with the Sustainable Development Goal (SDG) 11.

The interaction between urbanization and climate change is particularly evident in UHI formation, where urban temperatures can be up to 10°C higher than those in surrounding rural areas (Santamouris, 2015; Chapman *et al.*, 2017). This phenomenon is driven by the high concentration of impermeable surfaces, such as asphalt and concrete, which absorb and retain heat, alongside reduction of vegetation cover and emission of pollutants from vehicles and industries (Akbari *et al.*, 2016; Gohain *et al.*, 2023). In addition, urban morphology (geometry and density), such as street canyon configurations and building height–width ratios, affects heat storage and limits ventilation, while the thermal properties of materials (e.g., albedo, heat capacity, and conductivity) further intensify heat accumulation (Amorim *et al.*, 2024). Air pollution, exacerbated by human activities, interacts with climate patterns increasing public health risks such as respiratory and cardiovascular diseases (WHO, 2018; Lichtblau; Reimann; Piccari, 2024). These factors underscore the urgent need for detailed and continuous climate monitoring to provide reliable data for future scenario modeling, and implementation of sustainable urban planning measures (Lemonsu *et al.*, 2015; Murakami *et al.*, 2016).

Studies investigating UHI effects typically focus on three distinct scales: boundary UHI, canopy UHI, and surface UHI (Zhang; Odeh; Han, 2009). Boundary-layer UHI occurs in the atmospheric layer above urban surfaces and explores how urbanization affects heat distribution at the mesoscale (Voogt; Oke, 2003). This scale is examined using advanced technologies such as weather stations, radars, and balloon-borne sensors which generate vertical temperature profiles and insights into urban heat flux (Kim; Brown, 2021). Satellite-based remote sensing enhances these analyses by providing large-scale observations of land surface temperature (LST), which differ from near-surface air temperature measurements (Kim; Brown, 2021).

Canopy UHI refers to microclimate dynamics within the urban canopy, where interactions of buildings, vegetation, and streets significantly influence temperature patterns (Peng *et al.*, 2022). This scale is primarily studied using *in situ* measurements of air temperature, obtained from sensors installed at standardized heights within the urban canopy layer (Oke, 2006; WMO, 2023). While remote sensing can support the analysis by providing LST patterns and spatial variability, it does not directly measure air temperature, which is essential for characterizing canopy layer UHI and must therefore be obtained through *in situ* observations (Peng *et al.*, 2022). Surface UHI is the most visible manifestation of UHI effects, and refers to temperature differences at the Earth's surface between urban and rural areas. This scale is analyzed using data from the Landsat satellite, which provides extensive spatial and temporal coverage (Zhou *et al.*, 2011; Peng *et al.*, 2022). Complementary ground-based sensors, such as infrared thermometers, offer real-time localized temperature data enabling high-resolution urban heat mapping (Zhou *et al.*, 2011).

Among these scales, canopy UHI studies present unique challenges, as they require the direct collection of climate data (e.g., temperature and humidity) using instruments deployed at fixed or mobile locations (Kousis; Manni; Pisello, 2022). Ensuring consistent and reliable climate data, particularly from fixed locations, remains a significant hurdle, especially in the Global South (Karlsson; Srebotnjak; Gonzales, 2007; Pasgaard; Strange, 2013; Rojas; Gilete; Mazon, 2014; Zuniga, 2016; Rojas; Postigo, 2025). In these regions, meteorological monitoring infrastructure is often insufficient or inadequate, limiting the availability of high-quality urban climate data and hindering long-term climatological analyses (Domonkos; Tóth; Nyitrai, 2022).

Meteorological shelters play a critical role in ensuring the accuracy of climate measurements by protecting sensors from direct solar radiation, precipitation, and non-representative environmental influences (Lin; Hubbard; Meyer, 2001; WMO, 2018). The design, material properties, and placement of these shelters directly affect data quality, as inadequate shielding or ventilation can introduce systematic biases in temperature and humidity records (Hubbard; Lin; Baker, 2004; Stewart; Mills, 2021).

To ensure data comparability, the World Meteorological Organization (WMO) has established standardized guidelines for shelter construction and installation, including specifications related to ventilation, radiation shielding, and site exposure (WMO, 2023). These recommendations build upon earlier guidance on representative urban observations (Oke, 2006) and are fundamental for ensuring consistency in canopy-layer UHI studies.

Addressing climate study in countries with diverse climatic and regional conditions requires tailored strategies, particularly where financial constraints pose additional challenges to scientific research (Vieira Zezzo *et al.*, 2023). In Brazil, for example, the scarcity of meteorological stations in urban areas (Medeiros *et al.*, 2019) and the high costs associated with acquiring and maintaining standard equipment (Muller *et al.*, 2013) hinder researchers and policymakers from effectively addressing urban climate challenges (Marengo; Bernasconi, 2015). Moreover, the location of existing stations, often distant from urban centers or in non-representative areas, results in significant data gaps, impairing analysis accuracy (Hamdi *et al.*, 2020). These limitations are further compounded by the practical challenges of field data collection, including the high cost of deploying sensors across multiple sites and the operational constraints of automatic equipment, which may be prone to failures or inconsistencies in complex urban environments. As a result, obtaining continuous, reliable, and spatially representative measurements remains a major barrier for urban climate research. As highlighted by Stewart (2011), inconsistencies in measurement practices and insufficient documentation of observational conditions limit the comparability and robustness of UHI studies.

Compounding these challenges, research funding disparities in Brazil exacerbate the issue, as most state investment is concentrated in the Southeast, particularly in São Paulo (Silva, 2023). Due to local economic activity, prestigious universities, and higher public funding, the state accounted for over 70% of national research and development expenditures between 2017 and 2022 (Silva, 2023). In light of this scenario, developing accessible and innovative climate monitoring solutions is essential. Low-cost meteorological shelters constructed using readily available materials and simplified techniques have emerged as a viable alternative for democratizing climate data collection and expanding the spatial coverage of measurements (Rojas; Gilete; Mazon, 2014).

Developing and implementing accessible urban climate monitoring tools is closely aligned with SDG 11, which aims to make cities inclusive, safe, resilient, and sustainable. As urban areas continue to expand, often in unplanned and inequitable ways, climate-related risks disproportionately affect marginalized populations, who typically reside in poorly ventilated, high-density neighborhoods with limited access to green infrastructure (Kovats; Akhtar, 2008).

Enhancing climate data availability through low-cost monitoring technologies directly supports SDG 11 objectives, including the improvement of urban resilience to climate-related hazards (Target 11.5), the strengthening of participatory planning (Target 11.3), and reduction in the adverse per capita environmental impact of cities (Target 11.6) (United Nations, 2015). By providing accurate and localized climate information, these solutions might inform adaptive urban policies, promote equitable access to environmental data, and empower local communities in climate governance processes. Besides that, this approach is particularly critical in the Global South, where structural inequalities and underinvestment in monitoring infrastructure continue to hinder efforts to build sustainable and climate-resilient urban environments.

Within this framework, the central hypothesis of this study is that a low-cost meteorological shelter developed using accessible materials and simplified methods, can provide reliable measurements. From that, this study aims to develop, implement, and validate a low-cost meteorological shelter designed to support urban climate research. Rather than focusing on direct performance comparison with commercial instruments, the study emphasizes the feasibility of generating reliable field data through accessible, low-cost solutions, contributing to SDG 11 by supporting more inclusive, resilient, and data-informed urban environments. To achieve this overarching aim, we also want to describe the materials and methods employed in the construction of the meteorological shelter (i); evaluate the performance of the developed shelter under real field conditions, with attention to data consistency and reliability (ii), and assess the applicability of the shelter for urban climate studies, highlighting its potential to enable field data collection in data-scarce contexts (iii).

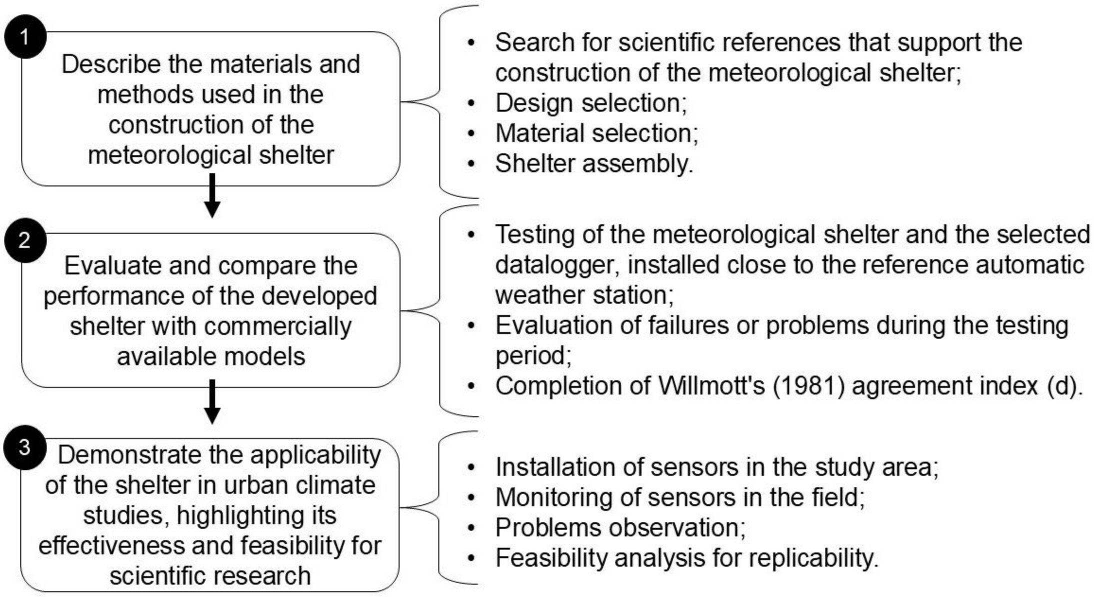
This solution has potential to facilitate detailed urban climate studies, particularly in regions with limited infrastructure, making it a valuable tool for climate research. Instead of proposing a novel conceptual approach, this study emphasizes a practical and context-sensitive methodological contribution, addressing the urgent need for precise and accessible climate measurements. Such an approach not only advances scientific knowledge but also contributes to addressing urban climate challenges in an inclusive and sustainable manner.

By democratizing access to reliable meteorological data, this initiative contributes not only to academic research but also to the operationalization of SDG 11, supporting cities in becoming more resilient and responsive to climate risks. Beyond UHI studies, the shelter can also be applied to agroclimatic assessments, hydrometeorological modeling, and environmental impact forecasting, broadening its relevance across multiple fields. Ultimately, this research underscores the importance of context-specific, low-cost technological innovations in bridging data gaps, especially in underserved regions. In doing so, it supports inclusive and evidence-based urban planning strategies that strengthen resilience and improve quality of life across the Global South.

METHODOLOGY

The methodology was divided into three stages, corresponding to the specific objectives (as shown in Figure 1):

Figure 1 - Presentation of the methodological steps taken to achieve the main objective of the research

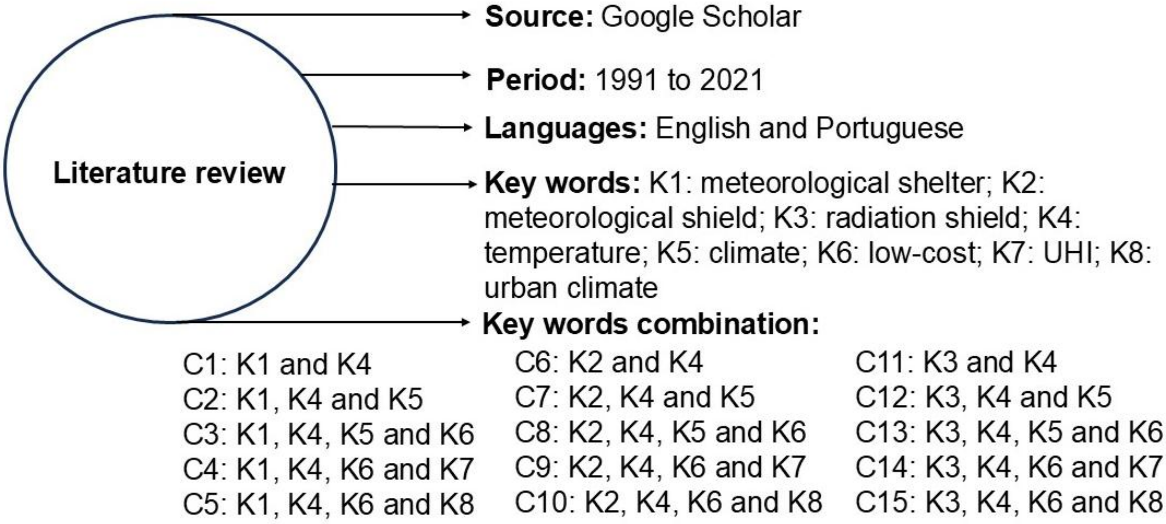


Source: Authors, 2025.

Methods from stage 1

The initial literature review was conducted using Google Scholar, a freely accessible web-based academic search engine (Google LLC, n.d.), as illustrated in Figure 2.

Figure 2 - Description of the method used for literature review



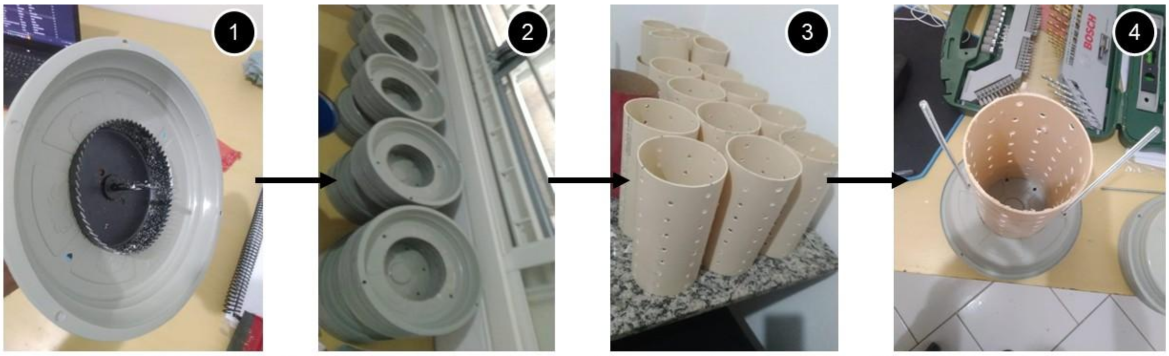
Source: Authors, 2025.

During the literature review, scientific studies were analyzed with a focus on two key aspects: the materials used in meteorological shelters and their practical application in field studies for climate monitoring. Based on insights from this review, the meteorological shelters were constructed in accordance with the best practices identified in literature.

The construction utilized accessible and cost-effective materials, including pine slats, polypropylene (PP) plastic, and polyvinyl chloride (PVC), which were used to support the sensor and form the shelter walls, respectively (Figure 3). In this sense, to ensure alignment with WMO (WMO, 2018) guidelines, the shelters were coated with white paint to reduce heat absorption and improve the accuracy of temperature measurements (Figure 4).

The selection of materials prioritized cost efficiency and durability considering Brazil’s climate conditions, which include high humidity and extreme high temperatures. The construction process followed standardized methods, utilizing basic tools such as drills and widely available accessories. This approach was designed to facilitate replication by educational and research institutions, even those with limited financial resources.

Figure 3 - Details of the weather shelters' construction process (part 1)



1. Approximately 10 plastic plates were used for each meteorological shelter. These plates, commonly used as plant supports, are available at gardening and construction material stores.

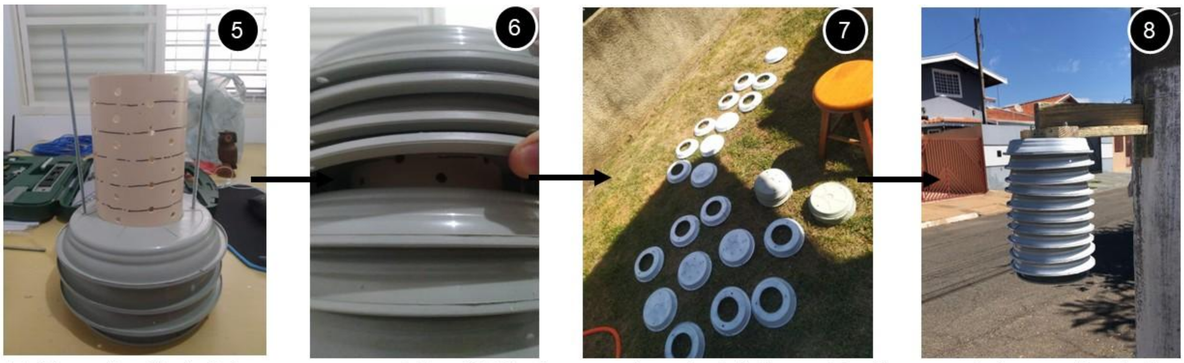
2. Eight out of the ten plates were drilled at the center and at two parallel points on their ends to facilitate assembly and stability.

3. Each sensor incorporated a 75mm PVC pipe, approximately 30cm in length, with multiple perforations to ensure proper air circulation.

4. The structure was assembled by placing a base plate, which was drilled only at two specific parallel points, allowing the insertion of two threaded steel rods measuring 5mm x 30cm, securing the entire setup.

Source: Authors, 2025.

Figure 4 - Details of the construction process of weather shelters (part 2)



5. Once the first plate was secured, the PVC pipe was inserted, followed by the remaining perforated plates being stacked in sequence.

6. The plates were spaced 2 cm apart, ensuring proper ventilation and heat dissipation.

7. After the pre-assembly was completed, all plates were removed and spray-painted white to reduce heat absorption and comply with meteorological standards.

8. Once the material had dried, the meteorological shelter was fully assembled. Nuts were fastened at both ends of the threaded bars to secure the plates and stabilize the structure. Finally, the datalogger was inserted through the bottom of the shelter, fitting into the PVC pipe space.

Source: Authors, 2025.

Methods from stage 2

A sensor unit consisting of a meteorological shelter and a datalogger (Instrutherm HT-900) was installed near an existing automatic weather station. This weather station has served as reference for the study region, continuously collecting meteorological data since 1989.

The Instrutherm datalogger (model HT-900) measures air temperature and relative humidity. The device operates within a temperature range of −30°C to 60°C, with resolution of 0.1 °C and accuracy of ±0.5°C between −30°C and 40°C, and ±1.0°C for higher temperatures. Relative humidity is measured over a range of 0% to 100% RH, with resolution of 0.1% RH and accuracy of ±3% RH (Instrutherm, n.d.).

The datalogger allows programmable sampling intervals ranging from 10 s to 18 h and has storage capacity of up to 32,000 readings. Data can be exported directly in CSV or PDF format via a USB connection, enabling efficient data retrieval and analysis. The device is powered by a 3 V lithium battery (CR2032), with approximate lifespan of 12 months under standard operating conditions (Instrutherm, n.d.).

Data reliability was assed using the Willmott (1981) agreement index (d), as defined in Equation (1). The index ranges from 0 to 1, with values closer to 1 indicating higher degree of agreement between the compared datasets.

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_1)^2}{\sum_{i=1}^{n}\left(|P_i - \overline{O}| + |O_i - \overline{O}|\right)^2} \quad (1)$$

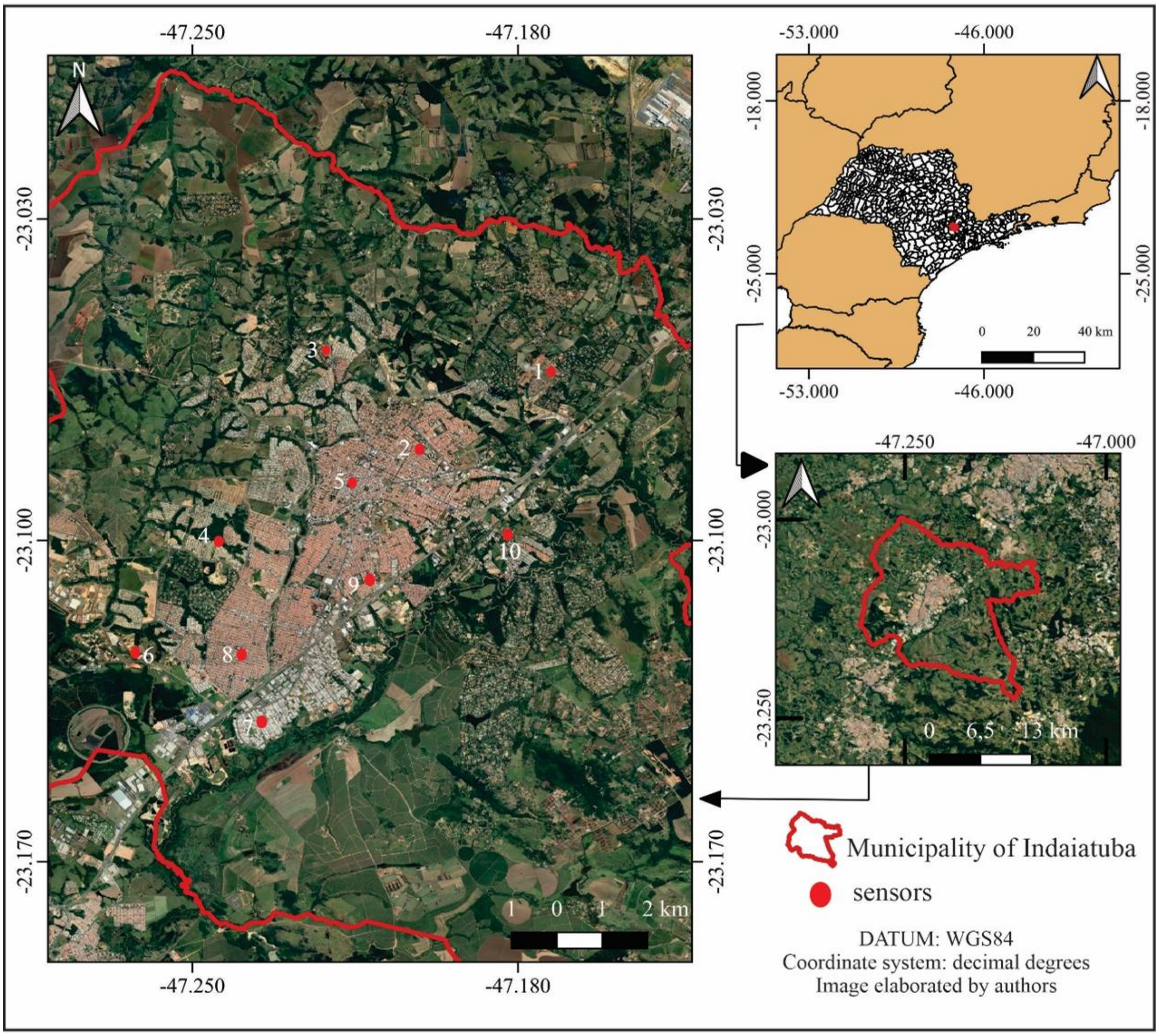
Where:
P_1: Predicted value at observation i.
O_i: Observed value at observation i.
$\overline{O}$: Mean of the observed values.
n: Number of observations.
$|P_i - \overline{O}|$: Absolute deviation of the predicted value from the mean of observed values.
$|O_i - \overline{O}|$: Absolute deviation of the observed value from the mean of observed values.

Methods from stage 3

Following the validation, the sensors were deployed in a tropical medium-sized city (Indaiatuba, São Paulo State, Brazil) (Figure 5). They were installed on existing urban infrastructure (electricity poles) belonging to São Paulo Power and Light Company (*Companhia Paulista de Força e Luz - CPFL Energia)*, at a height of 3.0 meters above ground level. The deployment began in December 2021, and the sensors remained operational in the field until February 2025.

The sensor units were installed across a set of sites selected to represent diverse urban and peri-urban conditions within the study area. Site selection considered variations in built density, land use, vegetation cover, and exposure characteristics, to capture different microclimatic contexts relevant to urban climate analysis. Each site was characterized based on its immediate surroundings within a 200 m radius, including the proportion of impervious surfaces, the presence of vegetation and trees, and the predominant urban morphology. Geographic information, including coordinates and altitude, was also recorded to support spatial analysis and ensure comparability across sites. A detailed description of the monitoring locations and their environmental characteristics is presented in Table 1.

Figure 5 - Location of the 10 sensors installed in the municipality of Indaiatuba, São Paulo



Source: Authors, 2025.

Table 1 - Characteristics of the locations where the sensors were installed, with regard to the study area

Sites	Urban Context	Built Density & Use	Vegetation Cover	Trees	Altitude (m)	Coordinates
1	High-income peri-urban residential	Low density, 1–2 floors	~20%	Yes	660	23° 03' 44.50" S 47° 10' 19.17" W
2	Residential (medium density)	Concrete housing, 1–2 floors	~5%	No	628	23° 04' 55.74" S 47° 12' 06.84" W
3	Peri-urban residential (farms)	Dispersed housing	~20%	Yes	641	23° 03' 28.29" S 47° 13' 22.16" W
4	Urban–green transition	Medium density, 1–2 floors	~50%	Yes	627	23° 06' 01.99" S

						47° 14' 44.05" W
5	City center (commercial)	High density, 1–3 floors	≤5%	No	582	23° 05' 14.71" S 47° 12' 35.01" W
6	Industrial expansion (periphery)	Low density, warehouses	<10%	No	580	23° 07' 25.38" S 47° 15' 50.02" W
7	Industrial zone	High density, industrial use	<5%	No	583	23° 08' 22.08" S 47° 13' 56.98" W
8	Dense residential (low-income)	High density, 1–2 floors	<5%	No	605	23° 07' 36.01" S 47° 14' 30.46" W
9	Dense residential (mixed use)	High density, 1–2 floors	~5%	No	619	23° 06' 27.77" S 47° 13' 13.47" W
10	Urban expansion (mixed use)	Medium density	~10%	No	606	23° 06' 06.22" S 47° 10' 57.01" W

Source: Authors, 2025.

RESULTS

The results will be presented according to the methodological sequence, detailing the findings from each stage of the study.

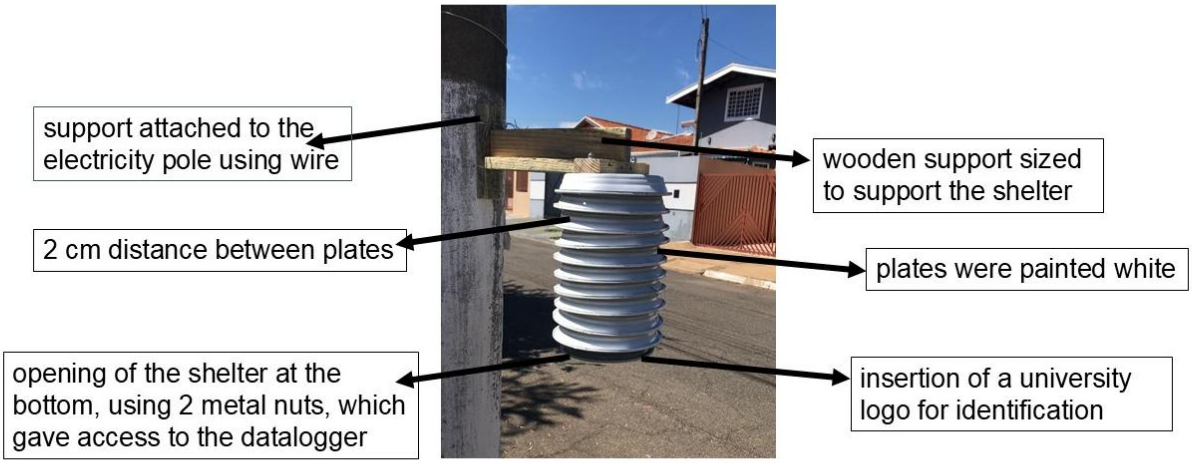
Results from stage 1

During the literature review on low-cost meteorological shelters, 80 articles were identified by reading title and abstract. Of these, 25 manuscripts were selected for full-text reading, with particular emphasis on the methodology sections, as they addressed the use of low-cost fixed sensors. However, only nine studies specifically discussed low-cost meteorological shelters. Among these, they all reported the materials used in shelter construction, but only seven included field testing, demonstrating their applicability in urban climate studies and alignment with WMO standards.

Notably, relatively few studies focused on the Global South (eight articles identified), with Júnior *et al.* (2016) and Freitas (2018) standing out. These studies not only detailed the materials used in shelter construction but also included field validation, making them key references for the present research. In our case, each meteorological shelter (Figure 6) was built at a cost of BRL 300 (updated to 2025 values). The Instrutherm HT-900 datalogger used in this study currently costs BRL 465. Thus, the total cost of each sensor unit was approximately BRL 765.

On the other hand, a standard meteorological shelter sold in a specialized store cost around BRL1200. This highlights the significant cost difference between conventional and low-cost solutions. Importantly, the meteorological shelters were relatively easy to assemble, requiring approximately one month to construct the ten units. An additional month was dedicated to testing and installing the sensors in the study area, ensuring their proper functionality before deployment.

Figure 6 - Finished weather shelter with description of important components that characterize it as a quality product, following WMO standards



Source: Authors, 2025.

Results from stage 2

The meteorological shelter installed near a reference automatic weather station remained fully operational throughout the testing period, with no reported issues. During this period, the datalogger recorded temperature measurements every 10 minutes. A comparative analysis between the reference station and the datalogger readings was performed using Willmott's (1981) agreement index (d), which yielded a value of 0.977. This high level of agreement indicates strong consistency between the datasets, supporting the reliability of the datalogger and the adequacy of the meteorological shelter for accurate temperature measurements in field conditions.

Results from stage 3

Given the promising results observed in stage 2, the sensors were deployed in the study area where they remained operational for one year, recording temperature data every 10 minutes. From the analysis period, a total of 52,560 data points were collected, with downloads performed every four months. This interval was chosen to prevent data loss, as the datalogger's memory holds approximately 20,000 measurements, and to allow for regular assessments of potential structural issues with the shelter or technical malfunctions in the datalogger.

No operational issues were reported during the monitoring period, confirming that low-cost weather shelters can serve as a reliable option for urban climate studies. The minimal material requirements, ease of assembly, and simple installation enhance their replicability, making them a valuable tool for expanding climate monitoring efforts, particularly in resource-limited settings.

DISCUSSIONS

A comprehensive literature review conducted for this study identified a significant gap in academic research on affordable climate measurement methods, particularly regarding standardized approaches for *in situ* observations in urban environments. Most existing studies focus on the use of low-cost display devices (LCDs) (Gluber *et al.*, 2021), including wireless sensor networks and Arduino-based systems for environmental monitoring (Hubbart, 2011; Antonini *et al.*, 2020; Khandelwal; Singhal, 2021). Additionally, some research explores mobile monitoring systems, such as urban transects and vehicle-mounted devices, to assess UHIs (Lima; Galvani, 2020). However, there is a notable lack of peer-reviewed studies specifically addressing the development of affordable and efficient meteorological shelters for long-term climate monitoring, particularly under standardized observational conditions as recommended by Oke (2006) and the WMO (WMO, 2023). This gap underscores the need for further research to support the establishment of cost-effective and reliable meteorological networks, particularly in resource-limited settings.

Notably, the most comprehensive studies on the development of meteorological shelters have been conducted by Brazilian researchers and published in national journals (Armani; Galvani, 2006) or as undergraduate theses without peer review (Júnior *et al.*, 2016; Freitas, 2018). A significant portion of the existing literature builds upon the foundational work of Armani and Galvani (2006), who developed a low-cost weather shelter inspired by the 410031-Plate Gill Radiation Shield model. In this sense, their study included a qualitative assessment of recorded data, concluding that the shelter functioned as a passive ventilation system suitable for remote environments and microclimate studies.

These findings reinforce broader critiques in urban climate research regarding methodological inconsistencies and limited comparability across studies (Stewart, 2011). In this context, the main contribution of the present study is not conceptual innovation, but rather a contextualized and applied methodological approach, demonstrating the feasibility of constructing and deploying a low-cost meteorological shelter capable of generating reliable field data under real urban conditions. Importantly, the data collected using this system was previously validated through statistical analysis and subsequently published in an international, peer-reviewed journal (Zezzo *et al.*, 2025), supporting the robustness and scientific credibility of the proposed approach. Furthermore, these data are publicly available in the Unicamp Research Data Repository (Zezzo; Coltri; Dubreuil, 2025).

Within this context, collecting long-term climate data (Domonkos *et al.*, 2022) in developing countries is hindered by substantial structural and financial challenges (Vieira Zezzo *et al.*, 2023). The lack of adequate infrastructure and limited funding for climate monitoring (Muller *et al.*, 2013) result in fragmented and outdated measurement networks (Marengo; Bernasconi, 2015). In contrast, developed countries benefit from extensive and technologically advanced monitoring systems, creating disparities in data availability and limiting environmental management and climate adaptation capacity in more vulnerable regions.

Climate data collection and analysis play a crucial role in understanding and mitigating UHI effects (Santamouris, 2015; Chapman *et al.*, 2017). Canopy-layer UHI studies require reliable *in situ* measurements of air temperature, obtained under controlled exposure conditions (WMO, 2023). A comprehensive understanding of local climate dynamics enables public authorities to implement effective adaptation strategies, for example, expanding green spaces, integrating reflective materials into urban infrastructure, and designing ventilation corridors (Lemonsu *et al.*, 2015; Murakami *et al.*, 2016). Consequently, high-quality meteorological data are fundamental for sustainable urban planning and climate adaptation.

Developing affordable and replicable meteorological shelters is therefore essential to democratizing access to climate data (Rojas, Gilete; Mazon, 2014). Low-cost solutions facilitate the expansion of climate monitoring networks in regions that would otherwise lack such infrastructure (Muller *et al.*, 2013). Compared to advanced and expensive meteorological systems, these solutions represent a viable alternative for research institutions, local governments, and communities that depend on accurate environmental data for decision-making.

Open access to meteorological data can further benefit multiple sectors by supporting inclusive and participatory climate governance. Democratizing access to environmental information enhances collaboration among academic institutions, government agencies, and civil society, contributing to improved climate resilience. This aligns directly with SDG 11, particularly targets 11.3 (inclusive and participatory planning), 11.5 (disaster risk reduction), and 11.6 (reducing environmental impact in cities) (United Nations, 2015).

Despite the promising performance of the proposed system, some limitations should be acknowledged. The proximity between the sensor and the supporting structure may represent a potential source of radiative interference, particularly under conditions of high solar exposure and low ventilation, as highlighted in previous studies (Stewart; Mills, 2021; WMO, 2023). Although efforts were made to minimize this effect through appropriate installation practices, such as ensuring ventilation, maintaining physical separation, and using a passively ventilated radiation shield, residual influences from adjacent surfaces cannot be entirely excluded. While the sensors were installed at a consistent height (3.0 meters), differences from standard reference configurations may influence comparability with other studies. Besides that, although the dataloggers demonstrated reliable performance during validation, low-cost sensors may present higher sensitivity to environmental conditions compared to high-precision instruments. The long-term durability of materials and sensor performance under extreme climatic conditions may also affect measurement stability over extended periods. Temporal constraints should also be considered, as the monitoring period, although representative, may not encompass long-term variability or extreme interannual events. Nevertheless, preliminary validation against a reference station demonstrated high level of agreement across datasets, indicating that any potential biases are unlikely to compromise the overall reliability of the measurements for the purposes of this study. Therefore, while acknowledging these constraints, the system remains suitable for urban climate monitoring applications, particularly in contexts where conventional instrumentation is not feasible.

It is also important to mention that significant challenges remain. Financial and logistical constraints continue to limit the expansion of monitoring networks, especially in remote or underserved areas (Marengo; Bernasconi, 2015). Additionally, the need for technical training and ongoing maintenance may affect data quality and continuity (Hamdi *et al.*, 2020). In this way, scientific collaboration and international partnerships are critical to overcome these barriers. The exchange of technologies, data, and methodologies across institutions can support the expansion of climate monitoring networks and enhance access to high-quality meteorological data, ultimately strengthening climate research and adaptation strategies across diverse socio-environmental contexts.

FINAL CONSIDERATIONS

The low-cost meteorological shelter developed in this study represents a practical and accessible solution for enhancing urban climate research, particularly in regions with limited infrastructure and financial resources. The results demonstrate that the shelter provides reliable temperature measurements, with performance levels comparable to those of standard commercial models under tested conditions. Its affordability, ease of assembly, and adaptability make it a valuable tool for expanding local climate monitoring networks and reducing data gaps in underrepresented areas, thereby advancing SDG 11, which proposes to make cities inclusive, safe, resilient, and sustainable. In particular, the shelter supports SDG 11.5 by enabling better preparedness and response to climate-related hazards, SDG 11.6 by informing urban strategies to reduce environmental impacts, and SDG 11.3 by promoting participatory and inclusive climate monitoring practices.

Beyond its scientific contributions, the shelter model also presents significant potential for education and community engagement. Its simplicity and low cost facilitate integration into school and university curricula, fostering hands-on learning experiences, enhancing scientific literacy, and encouraging youth involvement in environmental monitoring. These features position the shelter as a key resource for democratizing climate knowledge and promoting inclusive access to environmental data, in line with SDG 11's broader goals of empowering communities and strengthening urban resilience through informed participation.

However, this study also acknowledges certain limitations. Material durability and sensor performance under extreme weather conditions may affect long-term reliability, particularly in hot and humid environments. Further research is needed to evaluate the shelter's performance across diverse climatic zones, improve design robustness, and explore compatibility with additional meteorological sensors.

Ultimately, this work reinforces the role of low-cost technological solutions in addressing scientific and societal challenges. By bridging gaps in climate data availability and fostering collaboration of science, education, and society, the proposed shelter contributes to inclusive and sustainable responses to climate change. Future initiatives should continue to advance scalable, community-centered tools that support both research and resilience in vulnerable regions-core aspirations of SDG 11.

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REFERENCES

AKBARI, H. *et al.* Local climate change and urban heat island mitigation techniques: the state of the art. **Journal of Civil Engineering and Management**, v. 22, n. 1, p. 1-16, 2016. https://doi.org/10.3846/13923730.2015.1111934

AMORIM, M. C. C. T. Daily evolution of urban heat islands in a Brazilian tropical continental climate during dry and rainy periods. **Urban Climate**, v. 34, 100715, 2020. https://doi.org/10.1016/j.uclim.2020.100715

AMORIM, M. C. C. T. *et al.* Exceptional heat island intensities also occur in medium-sized cities. **Urban Climate**, v. 53, 101821, 2024. https://doi.org/10.1016/j.uclim.2024.101821

ANGEL, S. *et al.* The dimensions of global urban expansion: estimates and projections for all countries, 2000-2050. **Progress in Planning**, v. 75, n. 2, p. 53-107, 2011.https://doi.org/10.1016/j.progress.2011.04.001

ANTONINI, A. *et al.* Implementation of a low-cost weather station developed in design-based learning framework. In: IEEE International Conference on Sensing, Communication, and Networking, 2020. **Proceedings [...]**. Piscataway: IEEE, 2020. https://doi.org/10.1109/SECONWorkshops50264.2020.9149776

ARMANI, G.; GALVANI, E. Avaliação do desempenho de um abrigo meteorológico de baixo custo. **Revista Brasileira de Agrometeorologia**, v. 14, n. 1, p. 116-122, 2006. Available at: https://lcb.fflch.usp.br/sites/lcb.fflch.usp.br/files/upload/paginas/Avaliação do desempenho de um abrigo meteorológico de baixo custo.pdf Access: 02 February, 2025.

CHAPMAN, S. *et al.* The impact of urbanization and climate change on urban temperatures: a systematic review. **Landscape Ecology**, v. 32, p. 1921-1935, 2017. https://doi.org/10.1007/s10980-017-0561-4

DOMONKOS, P.; TÓTH, R.; NYITRAI, L. **Climate observations: data quality control and time series homogenization**. Amsterdam: Elsevier, 2022. 302 p.

FREITAS, M. **Caracterização de sensores e abrigos meteorológicos de baixo custo**. 2018. Trabalho de Conclusão de Curso (Instituto de Física) - Universidade Federal do Rio Grande do Sul, Porto Alegre, 2018. Available at: https://lume.ufrgs.br/handle/10183/180974 Access: 10 February, 2025.

GOOGLE LLC. Google Scholar. Available at: https://scholar.google.com Access: 07 May 2025.

GOHAIN, K. J. *et al.* Modelling relationship between land use land cover changes, land surface temperature and urban heat island in Indore city of central India. **Theoretical and Applied Climatology**, v. 151, p. 1981-2000, 2023. https://doi.org/10.1007/s00704-023-04371-x

GRIMMOND, S. *et al.* Climate and more sustainable cities: climate information for improved planning and management of cities (Producers/Capabilities Perspective). **Procedia Environmental Sciences**, v. 1, p. 247-274, 2010. https://doi.org/10.1016/j.proenv.2010.09.016

GUBLER, M. *et al.* Evaluation and application of a low-cost measurement network to study intra-urban temperature differences during summer 2018 in Bern, Switzerland. **Urban Climate**, v. 37, 100817, 2021. https://doi.org/10.1016/j.uclim.2021.100817

HAMDI, R. *et al.* The state-of-the-art of urban climate change modeling and observations. **Earth Systems and Environment**, v. 4, p. 631-646, 2020. https://doi.org/10.1007/s41748-020-00193-3

HUBBARD, K. G.; LIN, X.; BAKER, C. B. Air temperature comparison between the MMTS and the USCRN temperature systems. **Journal of Atmospheric and Oceanic Technology**, v. 21, n. 10, p. 1590-1597, 2004. Available at: https://journals.ametsoc.org/view/journals/atot/21/10/1520-0426_2004_021_1590_atcbtm_2_0_co_2.pdf Access: 30 January, 2025.

HUBBART, J. A. An inexpensive alternative solar radiation shield for ambient air temperature micro-sensors. **Journal of Natural & Environmental Sciences**, v. 2, n. 2, p. 9-14, 2011. Available at: https://www.asciencejournal.net/pdfs/214-1108-1-PB.pdf Access: 30 January, 2025.

INSTRUTHERM. **Manual de instruções: datalogger para medição de temperatura e umidade modelo HT-900**. São Paulo: Instrutherm, [s.d.]. Available at: https://www.instrutherm.com.br/media/hexaattachment/products/attachments/Manual_HT-900.pdf Access: 23 April, 2026.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). **Climate change 2021: the physical science basis**. Contribution of Working Group I to the Sixth Assessment Report of the

Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2021. Available at: https://www.ipcc.ch/report/ar6/wg1/ Access: 07 February, 2025.

JÚNIOR, M. O. V. *et al.* Análise da relação entre abrigos meteorológicos alternativos para pontos fixos e o comportamento de variáveis termo-higrométricas. **Revista Brasileira de Climatologia**, v. 18, p. 157-179, 2016. http://dx.doi.org/10.5380/abclima.v18i0.45146

KARLSSON, S.; SREBOTNJAK, T.; GONZALES, P. Understanding the North-South knowledge divide and its implications for policy: a quantitative analysis of the generation of scientific knowledge in the environmental sciences. **Environmental Science & Policy**, v. 10, n. 7-8, p. 668-684, 2007. https://doi.org/10.1016/j.envsci.2007.04.001

KHANDELWAL, D. D.; SINGHAL, M. Developing a low-cost weather monitoring system for data-sparse regions of the Himalayas. **Weather**, v. 76, n. 2, p. 48-52, 2021. https://doi.org/10.1002/wea.3647

KIM, S. W.; BROWN, R. D. Urban heat island (UHI) intensity and magnitude estimations: a systematic literature review. **Science of the Total Environment**, v. 779, 146389, 2021. https://doi.org/10.1016/j.scitotenv.2021.146389

KOVATS, S.; AKHTAR, R. Climate, climate change and human health in Asian cities. **Environment & Urbanization**, v. 20, n. 1, p. 165-175, 2008. https://doi.org/10.1177/0956247808089154

KOUSIS, I.; MANNI, M.; PISELLO, A. L. Environmental mobile monitoring of urban microclimates: a review. **Renewable and Sustainable Energy Reviews**, v. 169, 112847, 2022. https://doi.org/10.1016/j.rser.2022.112847

LEMONSU, A. *et al.* Vulnerability to heat waves: impact of urban expansion scenarios on urban heat island and heat stress in Paris (France). **Urban Climate**, v. 14, p. 586-605, 2015. https://doi.org/10.1016/j.uclim.2015.10.007

LICHTBLAU, M.; REIMANN, L.; PICCARI, L. Pulmonary vascular disease, environmental pollution, and climate change. **Pulmonary Circulation**, v. 14, n. 2, e12394, 2024. https://doi.org/10.1002/pul2.12394

LIMA, T. L.; GALVANI, E. Avaliação da ilha de calor urbana na zona norte de São Paulo: estudo de caso do bairro Jardim Peri. **Revista Brasileira de Climatologia**, v. 26, 2020. https://doi.org/10.5380/abclima.v26i0.69933

LIN, X.; HUBBARD, K. G.; MEYER, G. E. Airflow characteristics of commonly used temperature radiation shields. **Journal of Atmospheric and Oceanic Technology**, v. 18, n. 3, p. 329-339, 2001. https://doi.org/10.1175/1520-0426(2001)018

MARENGO, J. A.; BERNASCONI, M. Regional differences in aridity/drought conditions over Northeast Brazil: present state and future projections. **Climatic Change**, v. 129, n. 1-2, p. 103-115, 2015. https://doi.org/10.1007/s10584-014-1310-1

MEDEIROS, S. E. L. *et al.* Comparison between observed and estimated data to assess air temperature variability and trends in the Sertão Paraibano mesoregion (Brazil). **Environmental Monitoring and Assessment**, v. 191, 63, 2019. https://doi.org/10.1007/s10661-019-7207-8

MULLER, C. *et al.* Sensors and the city: a review of urban meteorological networks. **International Journal of Climatology**, v. 33, n. 7, p. 1585-1600, 2013. https://doi.org/10.1002/joc.3678

MURAKAMI, D. *et al.* Participatory sensing data tweets for micro-urban real-time resiliency monitoring and risk management. **IEEE Access**, v. 4, p. 347-372, 2016. https://doi.org/10.1109/ACCESS.2016.2516918

OKE, T. R. **Initial guidance to obtain representative meteorological observations at urban sites**. Geneva: World Meteorological Organization, 2006. Available at: https://urban-climate.org/wp-content/uploads/2023/10/Oke_2006_IOM-81-UrbanMetObs.pdf Access: 23 April, 2026

OKE, T. R. The energetic basis of the urban heat island. **Quarterly Journal of the Royal Meteorological Society**, v. 108, n. 455, p. 1-24, 1982. https://doi.org/10.1002/qj.49710845502

PASGAARD, M.; STRANGE, N. A quantitative analysis of the causes of the global climate change research distribution. **Global Environmental Change**, v. 23, n. 6, p. 1684-1693, 2013. https://doi.org/10.1016/j.gloenvcha.2013.08.013

PENG, W. *et al.* Surface and canopy urban heat islands: Does urban morphology result in the spatiotemporal differences? **Urban Climate**, v. 42, 101136, 2022. https://doi.org/10.1016/j.uclim.2022.101136

ROJAS, J.; GILETE, S. D.; MAZON, J. Development of a low-cost weather station to measure in situ essential climate variables. **Journal of Earth Science and Engineering**, v. 4, n. 8, p. 455-463, 2014. Available at: http://hdl.handle.net/2117/26929 Access: 28 January, 2025.

ROJAS, D. R.; POSTIGO, J. C. The cycle of underrepresentation: structural and institutional factors limiting the representation of Global South authors and knowledge in the IPCC. **Climatic Change**, v. 178, 19, 2025. https://doi.org/10.1007/s10584-025-03857-z

SANTAMOURIS, M. Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. **Science of the Total Environment**, v. 512-513, p. 582-598, 2015. https://doi.org/10.1016/j.scitotenv.2015.01.060

SETO, K. C.; GÜNERALP, B.; HUTYRA, L. R. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. **Proceedings of the National Academy of Sciences**, v. 109, n. 40, p. 16083-16088, 2012. https://doi.org/10.1073/pnas.1211658109

SILVA, L. D. A. **Políticas públicas municipais em ciência, tecnologia e inovação e o futuro das cidades**. 2023. Dissertação (Mestrado em Direito) - Faculdade de Direito, Universidade Estadual do Rio de Janeiro, Rio de Janeiro, 2023. Available at: https://www.bdtd.uerj.br:8443/handle/1/19658 Access: 30 January,2025.

STEWART, I. D. A systematic review and scientific critique of methodology in modern urban heat island literature. **International Journal of Climatology**, v. 31, n. 2, p. 200-217, 2011. https://doi.org/10.1002/joc.2141

STEWART, I. D.; MILLS, G. **The urban heat island: a guidebook.** Amsterdam: Elsevier, 2021. https://doi.org/10.1016/C2017-0-02872-0

STEWART, I. D.; OKE, T. R. Local climate zones for urban temperature studies. **Bulletin of the American Meteorological Society**, v. 93, n. 12, p. 1879-1900, 2012. https://doi.org/10.1175/BAMS-D-11-00019.1

UNITED NATIONS. **Transforming our world: the 2030 agenda for sustainable development**. New York: United Nations, 2015. Available at: https://sdgs.un.org/2030agenda Access: 12 February, 2025.

UNITED NATIONS. **World urbanization prospects: the 2011 revision**. New York: United Nations, 2012. Available at: http://esa.un.org/unpd/wup/index.htm Access: 12 February, 2025.

VIEIRA ZEZZO, L.; PEREIRA COLTRI, P.; DUBREUIL, V. Frequência e intensidade de ilhas de calor urbano em Indaiatuba (São Paulo). In: AMORIM, M. C. C. T.; DUBREUIL, V. (org.). **Cidades, clima e vegetação: modelagem e políticas ambientais públicas**. [S.l.]: TotalBooks, p. 105-123, 2024.

VIEIRA ZEZZO, L.; PEREIRA COLTRI, P.; DUBREUIL, V. Microscale models and urban heat island studies: a systematic review. **Environmental Monitoring and Assessment**, v. 195, 1284, 2023. https://doi.org/10.1007/s10661-023-11906-2

VOOGT, J. A.; OKE, T. R. Thermal remote sensing of urban climates. **Remote Sensing of Environment**, v. 86, n. 3, p. 370-384, 2003. https://doi.org/10.1016/S0034-4257(03)00079-8

WILLMOTT, C. J. On the validation of models. **Physical Geography**, v. 2, n. 2, p. 184-194, 1981. https://doi.org/10.1080/02723646.1981.10642213

WORLD HEALTH ORGANIZATION. **Ambient (outdoor) air pollution**. 2018. Available at: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health Access: 12 February, 2025.

WORLD METEOROLOGICAL ORGANIZATION. **Guidance on measuring, modelling and monitoring the canopy layer urban heat island (CL-UHI)**. Geneva: World Meteorological Organization, 2023. (WMO-No. 1292). Available at: https://urban-climate.org/wp-content/uploads/2024/06/1292_en.pdf Access: 23 Apri, 2026.

WORLD METEOROLOGICAL ORGANIZATION. **Guide to meteorological instruments and methods of observation (WMO-No. 8)**. Geneva: World Meteorological Organization, 2018. Available at: https://community.wmo.int/en/activity-areas/imop/wmo-no_8 Access: 10 February, 2025.

ZEZZO, L. V.; COLTRI, P. P.; DUBREUIL, V. **Dados de temperatura e umidade de Indaiatuba - ano 2022**. Versão 1. Campinas: Repositório de Dados de Pesquisa da Unicamp, 2025. https://doi.org/10.25824/redu/RMGPU1

ZEZZO, L. V. *et al.* Exploring the urban heat island phenomenon in a tropical medium-sized city: insights for sustainable urban development. **Environmental Monitoring and Assessment**, v. 197, 445, 2025. https://doi.org/10.1007/s10661-025-13890-1

ZHANG, Y.; ODEH, I. O. A.; HAN, C. Bi-temporal characterization of land surface temperature in relation to impervious surface area, NDVI and NDBI, using a sub-pixel image analysis. **International Journal of Applied Earth Observation and Geoinformation**, v. 11, p. 256–264, 2009. https://doi.org/10.1016/j.jag.2009.03.001

ZHOU, W.; HUANG, G.; CADENASSO, M. L. Does spatial configuration matter? Understanding the effects of land cover pattern on land surface temperature in urban landscapes. **Landscape Urban Plan**, v. 102, n. 1, p. 54–63, 2011. https://doi.org/10.1016/j.landurbplan.2011.03.009

ZUNIGA, P. **Innovation system in development: the case of Peru**. Maastricht: United Nations University - Maastricht Economic and Social Research Institute on Innovation and Technology, 2016. (UNU-MERIT Working Paper, n. 2016-058). Available at: https://unu-merit.nl/publications/wppdf/2016/wp2016-058.pdf Access: 03 February, 2025.

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