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Research Articles

Supporting urban planning with high-resolution climate data: development and testing of a new low-cost and user-oriented meteorological device (UrbanMobiClim) for mobile measurements and thermal comfort mapping

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ABSTRACT

Addressing urban heat and its impact on outdoor spaces and human well-being is critical for developing sustainable cities, particularly in the context of climate change, which is increasing both the frequency and severity of heatwaves. Traditional climate monitoring devices which are used to measure meteorological variables affecting thermal comfort are often expensive and require significant technical expertise to operate, limiting their accessibility. In response to these challenges, this study presents the development of UrbanMobiClim, a low-cost and user-oriented meteorological device, designed for mobile measurements of thermal comfort. Built on an Arduino platform microcontroller with low-cost sensors and guided by German standards for meteorological devices, UrbanMobiClim aims to empower urban planners and other stakeholders with accessible data to inform evidence-based urban adaptation strategies. UrbanMobiClim was statistically compared against two reputable high-end devices from the Dresden University of Technology's Chair of Meteorology and Arizona State University's Sensable Heatscapes and Digital Environments (SHaDE) lab, demonstrating its suitability for measuring thermal comfort in both stationary and mobile applications. This study presents the results of these comparisons, alongside a comprehensive technical framework for replicating the device. By establishing a baseline for future iterations, UrbanMobiClim contributes to the development of accessible, reliable, and easy-to-use tools that facilitate citizen science initiatives and support local stakeholders to make informed decisions for enhancing urban livability and sustainability.

Introduction

Urban areas are increasingly vulnerable to extreme heat, posing significant challenges to maintain the well-being of residents and the livability of cities [6]. As climate change intensifies, the frequency and severity of heatwaves are increasing, leading to heightened thermal stress and associated health risks in cities, particularly in densely populated urban environments [7,8].

Thermal comfort, defined as the state of mind whereby an individual expresses satisfaction with their thermal environment [9], is crucial for sustaining human health, productivity, and urban livability. In contrast, thermal stress refers to the physiological strain caused by excessive heat and represents a more acute threat to public health. In Germany, however, there is greater emphasis on improving outdoor thermal comfort, and urban planning and design are increasingly used as key instruments to create thermally comfortable cities [10–12].

High-resolution thermal comfort data at the hyperlocal scale (10–30 m) are critical for identifying fine spatial variations resulting from urban features, validating climate models, and informing targeted heat adaptation measures [13]. However, limited access to such data hinders stakeholders from making well-informed, climate-adapted planning decisions [14,15].

While stationary meteorological stations offer reliable time-series data, they lack the spatial granularity required for urban microclimate analysis [16,17]. Mobile monitoring approaches provide higher spatially resolved datasets, complementing the temporal resolution of stationary datasets. Devices can be mounted on various platforms – motorised (e.g. vans, cars) or non-motorised (bicycles, trailers,

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backpacks) – enabling flexible deployment in urban settings [17].

Pedestrian-operated mobile systems provide unique advantages. They can access narrow streets that may be inaccessible to bulkier equipment, and the sensor carrying height aligns with the perspective of the pedestrian as the primary end user of urban spaces. This contrasts with sensors mounted on lampposts, vehicles, or satellites, which fail to capture ground-level pedestrian conditions [18,19]. The slow movement of a pedestrian platform allows detailed mapping while balancing spatial and temporal resolution, making such systems particularly valuable for hyperlocal urban assessments.

However, many mobile devices are costly and require specialist knowledge, limiting their broader use [16,20]. Low-cost devices, especially when used in citizen science initiatives, can generate datasets with greater spatial and temporal resolution than those currently available, while engaging the public in climate awareness [15,21].

Microcontroller-based systems, such as those using Arduino or similar components, are steadily emerging as low-cost, open-source alternatives for environmental monitoring and outdoor thermal comfort assessment [16,22–26]. Recent developments include devices explicitly tailored to pedestrian-scale microclimate surveys and thermal comfort mapping, such as the Portable Low-cost Environmental Monitoring System (PLEMS) and related Arduino-based platforms, which integrate temperature, humidity, and radiation sensors in compact, wearable configurations [23]. While these systems demonstrate the potential of low-cost hardware for biometeorological applications, many are designed primarily for fixed-point or campaign-based scientific monitoring, or have only been validated against a limited set of reference measurements. Rigorous studies comparing these low-cost devices with high-end meteorological systems remain limited, hindering their widespread adoption [16]. Furthermore, many existing tools are general-purpose or lack the appropriate sensor suite for thermal comfort mapping, and few are optimised for mobile use. Questions remain concerning the accuracy and uncertainty of low-cost sensors under varying meteorological conditions and spatial contexts, and as a result the limits to their application are not yet well-defined.

In response, this study introduces UrbanMobiClim: a low-cost, and user-oriented device designed for mobile pedestrian thermal comfort mapping at the hyperlocal scale. Its development aims to supplement existing measurement networks and strategies while improving data accessibility for a broader range of users, particularly in urban-planning and citizen-science contexts.

Comparative experiments with two reputable high-end systems demonstrate UrbanMobiClim's performance and practicality: the Dresden University of Technology (TUD) backpack device [27,28] was used to validate individual sensors and UTCI under stationary and mobile conditions, and the MaRTy device from Arizona State University (ASU) [29] served as a radiative reference to benchmark RayMan-based mean radiant temperature (Tmrt). This study therefore focuses on the technical development and validation of UrbanMobiClim as a low-cost measurement platform; a companion study [30] provides a more detailed insight into how UrbanMobiClim data are combined with pedestrian surveys in a human-centered approach to support urban planning and citizen science. Its affordability and simplicity make UrbanMobiClim well-suited for citizen science and municipal applications, and this study provides a technical framework for future replication and improvement, thereby encouraging the progressive uptake of low-cost systems for thermal comfort mapping.

Materials and methods

Device design and components

UrbanMobiClim was designed following German standard guidelines [31] for sensor selection, while prioritising affordability to support wider accessibility (Fig. 1; Table 1). [4] provides a comprehensive "how-to" guide for assembling the device and datasheets for each component, encouraging replicability.

The total development cost was under 500 USD, significantly lower than high-end systems used for similar applications. Such systems are typically custom-built and not mass-produced, resulting in significant cost barriers, as the individual high-quality sensor prices add up linearly. For example, the MaRTy device costs approximately 20,000 USD due to

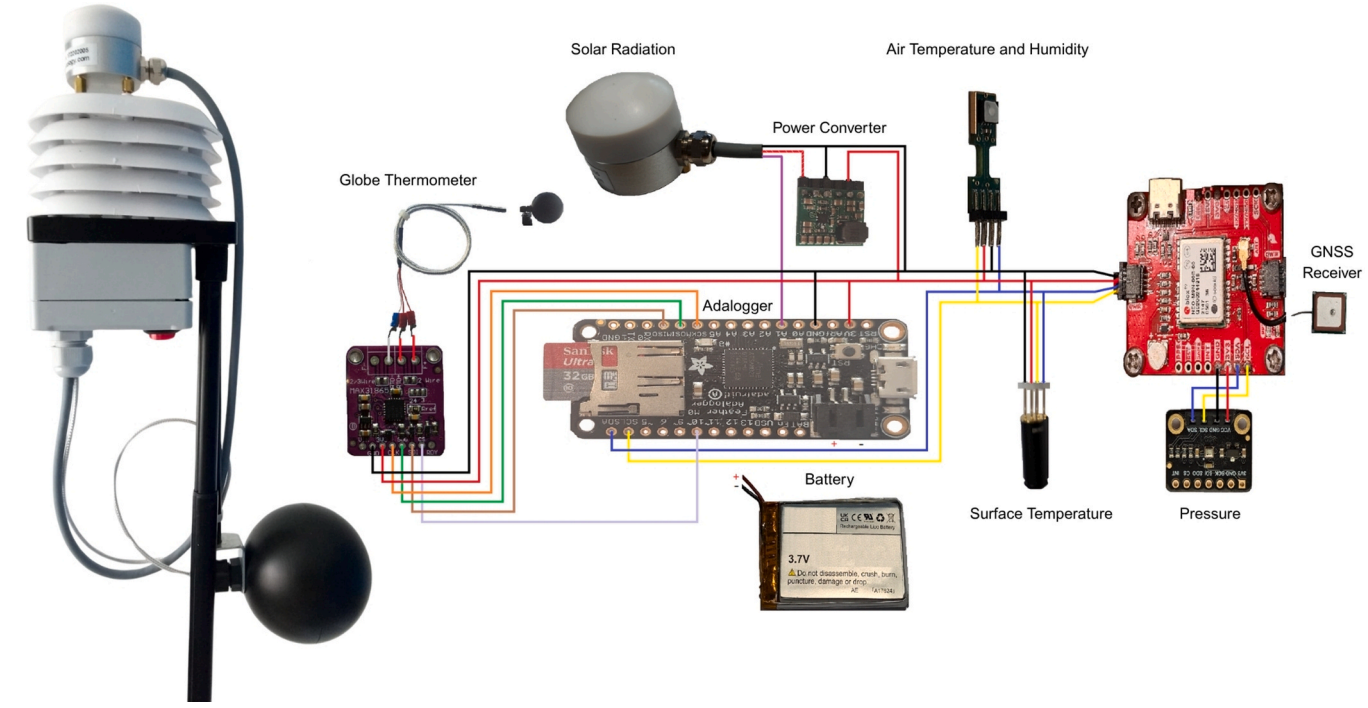


Fig. 1. Overview of the new low-cost mobile monitoring device, UrbanMobiClim, including: a picture of the device (left); device schematic (right), where red and black represent power lines, yellow and blue represent communication lines, other colours represent additional connections. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Specifications of the low-cost UrbanMobiClim's sensor components, manufacturer, and accuracy.

Sensor	Manufacturer	Variable	Accuracy	Approx. cost (USD)
SHT 85	Sensirion	Air temperature and Relative air humidity	+/- 0.1 °C +/- 1.5% RH	26
MLX90614 Infrared Sensor	Melexis	Surface temperature	0.3 °C	26
SR2AD pyranometer	PM Ecology	Solar irradiance	+/- 3%	207
Max 31865 Pt100 and black aluminium globe	Fuehler Systeme	Globe temperature	–	83
NEO-M9N	Sparkfun	Multi-constellation GNSS	2.0 m CEP	52

multiple net radiometers (~5,000 USD each), as precise measurements of Tmrt were prioritised without relying on model assumptions such as RayMan [32]. The total cost of the TUD backpack device components is around 8,500 USD, representing a reasonably priced backpack system. Table 1 and Supplementary file 1 outline the approximate costs of components for UrbanMobiClim and the TUD backpack device, respectively.

UrbanMobiClim uses an Adafruit Feather M0 Adalogger, powered by an ATSAMD21G18 ARM Cortex M0 processor. It measures the key meteorological variables of: air temperature and humidity (SHT 85 Sensirion), air pressure (BMP 390 Bosch), surface temperature (MLX90614 Melexis), solar irradiance (SR2AD PM Ecology), and globe temperature (Max 31865 Pt100 and black aluminium globe) – important inputs for calculating thermal comfort indices. The NEO-M9N Sparkfun Global Navigation Satellite System (GNSS) module provides spatial accuracy (~2.0 m CEP), preferred over GPS due to its broader satellite coverage in obstructed urban environments.

The sensors for air temperature, humidity, and pressure are housed within a Davis Vue Radiation Shield. Including a pressure sensor alongside the temperature sensor in the radiation shield enhances the accuracy of environmental readings by accounting for barometric changes and allowing for the calculation of absolute humidity. This setup helps cross-check sensor accuracy and data consistency, improving the robustness of the device. A wind sensor was omitted due to the challenges of capturing accurate wind speed measurements with mobile devices, and the minimal wind speed in the test circumstances during periods of high heat load [33]. In this study wind speed for UTCI and Tmrt calculations was therefore taken from co-deployed reference systems during the comparison campaigns; the latest UrbanMobiClim iteration now includes a cup anemometer to provide local wind measurements for future applications. The design remains modular for specific research requirements, with 20 General Purpose Input Output (GPIO) pins available for customisation.

The data logger has an integral 100 mA charger for the 3.7 V Lithium Polymer (LiPo) rechargeable battery. This setup ensures continuous operation of approximately six hours, aligning with the design objective for short mobile campaigns, and is compatible with portable power banks for extended use. The peak output limit of 500 mA has been more than adequate for the project as the logger and most sensors operate at a low voltage of 3.3 V. An exception is the pyranometer, which requires a higher voltage of 12 V DC; this is managed by converting the supply voltage from the logger.

The device supports three serial communications standards: a hardware serial used for the Universal Serial Bus (USB); Hardware Inter-Integrated Circuit (I2C) used for most sensor communications; Hardware Serial Peripheral Interface (SPI) specifically for the Max31865 and its Resistance Temperature Detector (RTD), and either Serial Data Interface at 1200 Baud (SDI-12) or a 0 to 5 V DC analog voltage reading for the pyranometer. To simplify the system, analog output is used, but this requires a potential divider circuit on the input of the logger's Analog to Digital Converter (ADC) to regulate voltages. Additionally, an analog input monitors the battery voltage, maintaining device efficiency and safety.

Data collection can be initiated or stopped using the red button located at the device's base. For ease of mobility the device is mounted onto a handheld GoPro stick and weighs approximately 0.9 kg in total (0.7 kg without mounting equipment). The aluminium globe, the heaviest component, contributes 0.45 kg to the total weight. The lightweight stick can easily be switched between hands, reducing operator fatigue over time. Initially, the device was developed to be worn on the carrier's back via a belt, but this introduced greater variability in height due to the operator's natural movement, compromising measurement consistency. In contrast, the handheld setup allows the operator to maintain a relatively consistent device height and positioning throughout the survey. Holding the device away from the body also reduces the influence of radiative heating from the operator. Additionally, this configuration gives a direct line of sight to the flashing indicator light that provides real-time confirmation of ongoing data logging and battery level. The modular design can accommodate alternative mounts, depending on the study's requirements.

Data acquisition and processing

The UrbanMobiClim device's user-friendly design helps to streamline data collection, processing, and mapping, ensuring that users can seamlessly retrieve and interpret the recorded meteorological data. Data are stored directly onto a microSD card within the data logger. The device's processing algorithms are programmed using the open-source Arduino Integrated Development Environment (IDE) software, primarily utilising libraries provided by the sensor manufacturers. For transparency and ease of replication, the code used for data collection is openly available [5].

Data are recorded at one-second intervals, with time stamps produced by the GNSS module. Following data collection, the microSD card can be removed from the device and inserted into a computer for analysis. The data are automatically structured into a CSV file with column formats compatible with RayMan Pro for the calculation of thermal comfort indices [34,35].

The output from RayMan is then formatted and imported into QGIS to create a georeferenced map [36]. These maps display thermal comfort index values as colour-coded points along the measurement route, which appears as a continuous line due to the high sampling frequency, highlighting the spatial variations in thermal comfort. Example maps produced by both the TUD backpack device and UrbanMobiClim during the mobile comparisons in Tharandt and Dresden's city centre are presented in Figs. 2 and 3. Gallacher & Boehnke [30] provide a detailed example of the data collection and mapping process for the case study of the city centre of Dresden, Germany, along with insights into how the results may be used to improve thermal conditions through evidence-based urban planning.

Device testing data collection

UrbanMobiClim was compared with two high-end mobile meteorological systems to evaluate the performance of individual sensors and overall accuracy for calculating key thermal comfort indicators, namely mean radiant temperature (Tmrt) and the Universal Thermal Climate Index (UTCI). The reference systems were: the backpack device from the Dresden University of Technology (TUD) Chair of Meteorology, Germany [27,28], and the MaRTy device developed by the Sensable Heatscapes and Digital Environments (SHaDE) lab at Arizona State

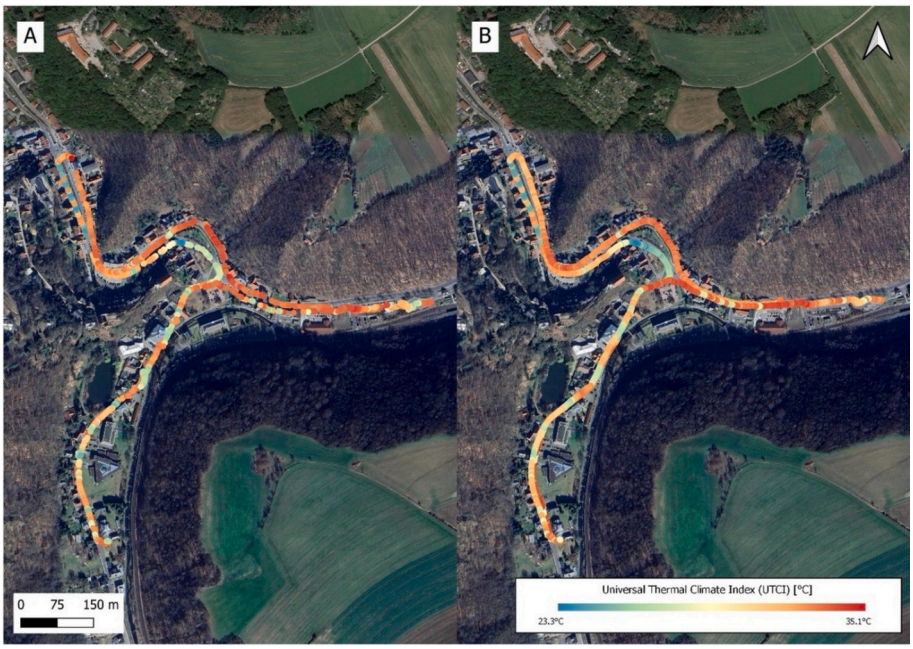


Fig. 2. Example mapping output from the TUD backpack device (A) and UrbanMobiClim (B) for the Tharandt mobile comparison on the 3rd of June 2022. Base Map source © 2025 Google, Airbus, Maxar Technologies, GeoBasis-DE/BKG (©2009).



Fig. 3. Example mapping output from the TUD backpack device (A) and UrbanMobiClim (B) for the Dresden mobile comparison on the 19th of July 2022. Base Map source © 2025 Google, Airbus, Maxar Technologies, GeoBasis-DE/BKG (©2009).

University, United States [29].

A side-by-side stationary comparison between the UrbanMobiClim device and the TUD backpack device was conducted at the TUD Chair of Meteorology's weather station in Tharandt (a small town south of Dresden, Germany) from the morning of June 1st to the afternoon of June 3rd, 2022 (Fig. 4A; Supplementary file 1). This comparison focused on air temperature and humidity sensors (SHT 85 vs. WXT520) and solar irradiance sensors (SR2AD vs. SKS 1110). UrbanMobiClim was connected to a low-voltage power source, while the battery pack for the TUD backpack device was changed at several points to ensure continuous operation. The stationary comparison provided valuable insights into the reliability of UrbanMobiClim under controlled conditions.

Two mobile comparison tests with the TUD backpack device were then conducted to evaluate UrbanMobiClim's performance and practicality under dynamic conditions, as its intended context. The first mobile test took place in Tharandt on the 3rd of June 2022, between 15:00 and 15:48 (CEST), along a 3.4 km route that began and ended at the TUD weather station site (Fig. 2; Fig. 4B). The second mobile test was conducted on the 19th of July 2022, in the densely built city centre of Dresden, along a 3.1 km route (Fig. 3). During both mobile comparisons, the UrbanMobiClim and TUD backpack devices were carried side-by-side, with care taken to avoid any mutual shading between the two

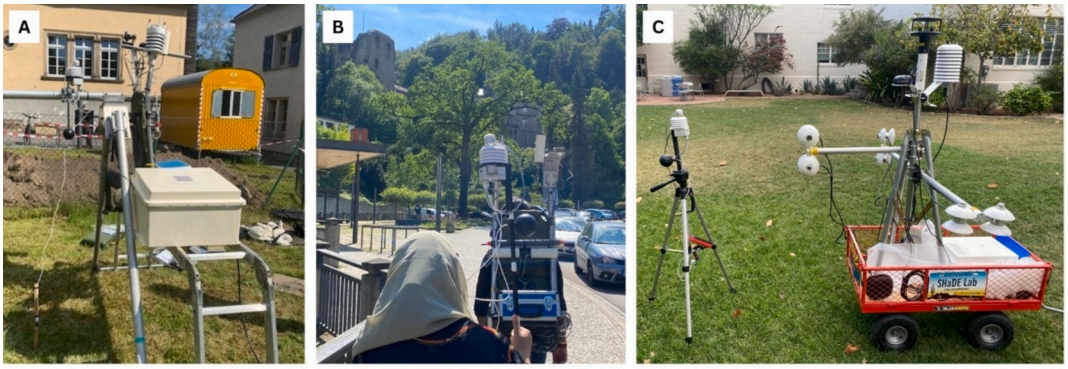


Fig. 4. Experimental set up for (A) Stationary comparison in Tharandt with UrbanMobiClim (left) and TUD backpack device (right) side by side (B) UrbanMobiClim (foreground) and TUD backpack device (background) being carried during the mobile comparison in Tharandt (C) Stationary comparison at Arizona State University courtyard location with UrbanMobiClim (left) and the MaRTy device (right) (Photos: Anonymous).

systems (Fig. 4B). These field tests, along with the stationary comparison in Tharandt, were carried out with the support of the TUD Chair of Meteorology and participating master's students from TUD [37].

On the 18th of May 2023, a stationary comparison between UrbanMobiClim and the MaRTy device was conducted in an outdoor courtyard on the campus of Arizona State University (Fig. 4C). Both devices were positioned side-by-side, ensuring similar exposure to environmental conditions. Data were collected from approximately 09:00 to 18:00 local time (GMT-7). This comparison aimed to directly assess UrbanMobiClim's accuracy in calculating mean radiant temperature (Tmrt) using the RayMan model, against MaRTy's benchmark six-directional radiometer measurements.

Analysis

For the stationary comparison conducted in Tharandt, temporal alignment was achieved by calculating 10-minute averages for both the UrbanMobiClim device and the TUD backpack device to match the resolution of the weather station. Averaging over this interval also reduced short-term fluctuations and random noise, improving data stability and yielding a more robust comparison of prevailing conditions.

For mobile comparisons, all data were aggregated into five-second averages, and data gaps in the TUD backpack dataset were removed from both datasets to ensure synchronised time steps. A five-second averaging interval was chosen as a practical compromise between capturing short-term variability in meteorological conditions and accounting for the slower response time of human thermal perception, which typically operates over several minutes.

Absolute humidity (g/m^3) was calculated from air temperature, air pressure and relative humidity to support a more robust comparison between datasets, as absolute humidity provides a direct measure of atmospheric water vapor content and is not temperature dependent like relative humidity [38]. For the reference weather station, which did not include air pressure measurements, the average air pressure recorded by the TUD backpack device was used to calculate absolute humidity.

For the mobile comparison, the UTCI was calculated using RayMan Pro [34,35], with inputs of air temperature, relative humidity, global irradiance, and surface temperature. Given the consistently low wind speeds observed during data collection and the challenges of accurately measuring wind speed in a mobile context, a constant wind speed of 0.5 m/s was assumed for UTCI calculations in this study. This assumption is supported by the wind speeds recorded by the TUD backpack while stationary during the Dresden city centre route, which averaged between 0.5 and 0.8 m/s. Similarly, in the Arizona comparison, wind was found to have a negligible effect on UTCI and PET during extreme heat events [29]. While absolute UTCI values are sensitive to wind speed, the spatial distribution of thermal comfort hotspots and relative rankings of locations remain consistent under uniformly low-wind conditions. For applications with higher or more variable wind speeds, however, local wind measurements from a dedicated sensor are required.

The choice of RayMan for the calculation of thermal indices is justified by the aim to create a user-oriented device and methodology. RayMan allows efficient dataset handling without requiring advanced prerequisite knowledge, making it accessible for non-scientists as the target user group of UrbanMobiClim. Given its ease of use, scientific validation, and established application in biometeorological research, RayMan Pro is a highly suitable tool for this study [39,40].

For the stationary comparison with the MaRTy device, which records data at two-second intervals, the MaRTy dataset was adjusted for temporal alignment and gaps were removed. For UrbanMobiClim, two approaches were tested to estimate Tmrt. The first approach followed the method described by Thorsson et al., [41], which estimates Tmrt using globe temperature and air temperature measurements, applied here in accordance with ISO 7243. However, this method showed limitations due to the slow response time of the black aluminium globe thermometer. To address these constraints, we adopted the more practical RayMan model, which calculates Tmrt using global solar radiation, air temperature, relative humidity, and environmental parameters (time, date, location). While the estimation of Tmrt using RayMan relies on certain model assumptions and simplifications, it is a practical and validated tool in cases where six-directional radiative flux measurements are unavailable [42].

Sensor performance was evaluated using the coefficient of determination (R^2), which quantified the proportion of variance explained by the low-cost sensors, and regression coefficients (slope and intercept), to assess systematic bias. Mean bias error (MBE) identified systematic deviations, while root mean square error (RMSE) assessed the overall magnitude of errors. These metrics were used to evaluate individual sensors and to assess the ability to predict UTCI in mobile conditions, as well as the estimation of Tmrt against the MaRTy reference device in stationary conditions.

Results and discussion

Stationary comparison to the Dresden University of Technology's backpack device and weather station

From the three-day stationary data collection period, the morning of the third day (03.06.2022 from 08:09 to 13:19) was selected for detailed analysis due to its optimal weather conditions, characterised by few clouds and minimal fluctuations in global irradiation. This period, from sunrise until noon, provided the greatest data spread, facilitating a check of the sensor's performance across a range of conditions.

The performance of the low-cost sensors for air temperature, humidity, and global irradiance was evaluated against the high-cost TUD

backpack device and the reference weather station. For global irradiance, direct comparison with the reference station was not optimal due to its placement on a rooftop approximately 20 m away, which exposed it to differing environmental influences such as building shading and varying cloud cover. Therefore, global irradiance comparisons were made only between the low-cost and high-cost mobile sensors. The results are summarised in Fig. 5 with the full dataset, also visualised as time series plots, are openly accessible in Gallacher et al. [1].

Air temperature measurements from UrbanMobiClim's low-cost SHT85 sensor were very strongly correlated with both the reference station and the TUD backpack device. However, the low-cost sensor had a consistent positive bias of approximately 1 K, most pronounced at lower temperatures. This suggests a systematic overestimation of air temperature, likely influenced by differences in shielding and sensor response characteristics.

Absolute humidity also showed high consistency between the low-cost and high-cost systems. The UrbanMobiClim slightly overestimated absolute humidity, particularly under more humid conditions, but overall agreement was strong. This indicates that the low-cost combination of temperature, humidity, and pressure sensors can reliably capture moisture variability for urban climate applications.

For global radiation, the two mobile systems showed a very strong correlation, confirming that the low-cost SR2AD pyranometer effectively captured overall radiation trends. However, a systematic underestimation was observed in the low-cost sensor, particularly during peak radiation times around midday.

Mobile comparisons to the Dresden University of Technology's backpack device

Results of the mobile comparisons are summarised in Table 2, with the full datasets available at [2]. The correlation between UrbanMobiClim and the TUD backpack device for air temperature was weak, reflecting the difficulty of synchronising temperature readings under mobile conditions, contributed to by sensor lag – including the thermal inertia of the temperature sensors – and rapid changes in environmental conditions [43,44]. Differences in airflow and ventilation through the radiation shields can also introduce measurement errors, particularly during transitions between sunlit and shaded areas. The lower correlation observed in Dresden city centre, compared to Tharandt, is also influenced by the more complex urban geometry which creates highly variable microclimatic conditions over short distances. Despite increased scatter in the Dresden data, UrbanMobiClim's SHT85 sensor consistently captured the main temperature trends, with a slight overall warm bias, as also seen in the stationary tests.

In the rural setting of Tharandt, absolute humidity measured by UrbanMobiClim aligned very closely with the TUD device. In the more complex urban environment of Dresden, the agreement in humidity readings weakened somewhat. The low-cost sensor again showed a tendency to slightly overestimate humidity levels. Even so, the humidity fluctuations and general patterns were similarly observed by both systems.

Global irradiation exhibited the strongest correlation between the devices, especially in Tharandt, indicating that the low-cost sensor (SR2AD) effectively captures variation in solar radiation. The higher correlation in Tharandt suggests more stable environmental conditions, compared to Dresden where urban shading effects, rapid transitions between sunlit and shaded areas create small-scale variability that is difficult to synchronise across both devices [43]. Additionally, inclination errors of the low-cost device during mobile use – particularly the dense urban environment of Dresden – contributed to the observed differences in measured radiation. Despite these effects, overall agreement remained high in both settings.

One of the most important findings was that UTCI calculations based on the low-cost device data inputs showed strong agreement with the UTCI calculated by the TUD backpack device's data, despite discrepancies in individual sensor measurements. This suggests that, under the specific conditions of our experiments, compensating effects among the input variables (in particular the close agreement in shortwave radiation) resulted in similar UTCI estimates, and that UTCI can be relatively robust to modest biases in individual sensors. A formal sensitivity analysis of UTCI with respect to each measured variable would be a valuable avenue for future work to identify which sensor improvements yield the largest gains in index reliability.

The higher correlation values in Tharandt compared to Dresden again highlights that the more complex urban structure of Dresden's city centre introduces additional sources of variability. Mean bias errors were −1.1 K in Tharandt and 0.1 K in Dresden, indicating that the low-cost device underestimated UTCI in the rural setting of Tharandt but provided nearly unbiased predictions of thermal comfort in the urban environment. The RMSE values were 1.9 K (Tharandt) and 1.5 K (Dresden), remaining within an acceptable range for pedestrian thermal comfort assessments. Despite these biases in individual sensors, UTCI remained a robust output of the low-cost device for the comparison campaigns, which can be explained by good agreement in radiative forcing (global solar radiation and derived Tmrt) and the relatively small discrepancies in air temperature and humidity under the clear-sky summer conditions considered.

Figs. 2 and 3 present the outdoor thermal comfort maps produced by both devices. Both maps show a similar spatial pattern of UTCI values, with visually coincident areas of higher thermal discomfort. The performance of the GPS of the high cost device was poorer than the GNSS of the low-cost device as can be seen in the visualisations, especially for the north of the route in Dresden while entering an urban canyon. However, the GoPro attachment on the high-cost device could be used to check the precise locations with reference to the time stamps.

Stationary comparison to Arizona State University's MaRTy device

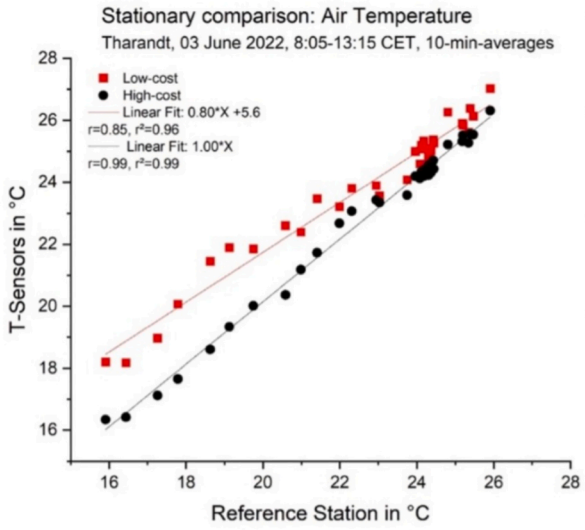
The primary objective of the comparison to the MaRTy device was to evaluate the assessment of mean radiant temperature (Tmrt) by the low-cost device against the MaRTy device's six-directional radiometer measurements, which are widely regarded as a reference standard.

Initial attempts to calculate Tmrt from the globe thermometer on UrbanMobiClim were unsuccessful, as the time series closely mirrored air temperature, indicating poor responsiveness to radiative flux. This result is consistent with the well-documented limitations of globe thermometers in outdoor environments, and in the context of mobile measurements the use of a globe thermometer becomes even more problematic due to sensor lag and calibration time [45–48]. By contrast, RayMan-derived Tmrt estimates from UrbanMobiClim demonstrated a strong correlation with MaRTy ($R^2 = 0.85$), indicating that the low-cost system effectively captured overall radiative trends (Table 3). Because Tmrt is a key input to UTCI, this agreement supports the use of RayMan-based Tmrt in conjunction with UrbanMobiClim for outdoor thermal comfort assessment. The mean bias of 0.2 K indicates a slight overall overestimation, and the RMSE of 3.2 K reflects some localised discrepancies, partly due to the spatial separation between the devices where shadows affected one device more than the other at specific times.

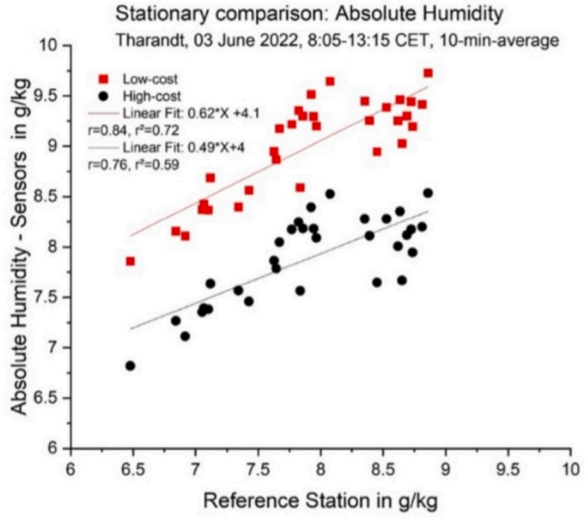
Air temperature and relative humidity from UrbanMobiClim also exhibited a strong agreement with MaRTy, though the low-cost sensor overestimated values. These trends were consistent with the stationary comparison in Tharandt. For transparency and replication, the full dataset for the stationary comparison with MaRTy is available in [3].

Sensor limitations and uncertainties

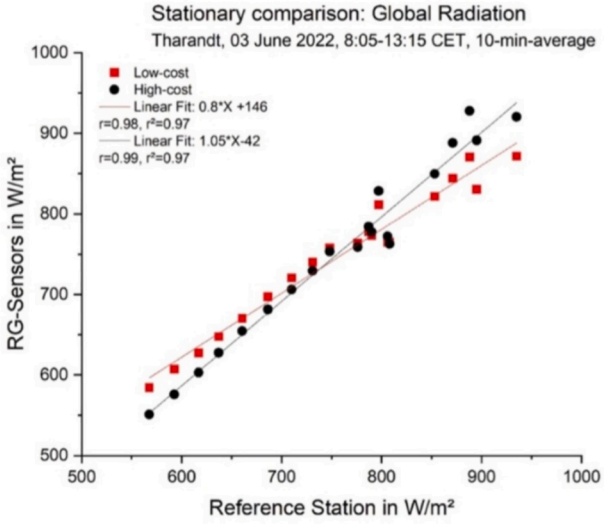
UrbanMobiClim demonstrates strong potential as an accessible, user-oriented tool for mapping pedestrian thermal comfort. Comparative tests with high-end devices from the Dresden University of Technology and Arizona State University confirmed that the system captures meaningful spatial and temporal microclimate variations. However,



	Low-cost vs. station	High-cost vs. station	Low-cost vs. high-cost
Mean bias	1.24	0.17	1.07
RMSE	1.42	0.29	1.29



	Low-cost vs. station	High-cost vs. station	Low-cost vs. high-cost
Mean bias	-0.02	1.08	-1.1
RMSE	1.14	0.43	1.1



	Low-cost vs. high-cost
Mean bias	-22.44
RMSE	45.38

Fig. 5. Statistical results for the stationary comparison of the low-cost UrbanMobiClim and high-cost TUD backpack sensors to the reference weather station in Tharandt on 03 June 2022 with results for R^2, mean bias, and RMSE.

Table 2
Mobile measurement results for R^2, Mean Bias and RMSE respectively in Tharandt (14:00 – 14:48; June 3rd, 2022) and Dresden city centre (14:28 – 16:04; July 19th, 2022), comparison of low-cost and high-cost sensor systems.

Variable	Tharandt			Dresden		
	R^2	Mean Bias	RMSE	R^2	Mean Bias	RMSE
Air temperature (°C)	0.36	0.28	0.57	0.29	0.29	0.64
Absolute humidity (g/m^3)	0.93	0.99	0.99	0.41	0.36	0.38
Global irradiation (W/m^2)	0.88	−9.37	100.97	0.74	−1.4	147.49
UTCI (°C)	0.84	−1.11	1.85	0.78	0.09	1.52

Table 3
Statistical results for the stationary comparison of UrbanMobiClim to the MaRTy device in Tempe, Arizona (08:59–17:56; May 18th, 2023) with results for R^2, Mean Bias, and RMSE respectively.

Variable	Low-cost vs. MaRTy device		
	R^2	Mean Bias	RMSE
Air temperature (°C)	0.95	0.69	0.85
Relative humidity (%)	0.98	1.84	2.04
Mean radiant temperature (°C)	0.85	0.19	3.2

biases in individual low-cost sensors highlight trade-offs between affordability and accuracy, underscoring the need for contextual interpretation.

The SHT85 sensor consistently overestimated air temperature, particularly at lower temperatures. Several factors likely contributed to these discrepancies, including the fundamental differences in the sensor type, data handling, and response time. While calibration may be required for precise applications, Pereira and Ramos [49] identified the SHT85 sensor as the most accurate among the low-cost sensors tested for air temperature and humidity, with deviations consistently below the recommended threshold.

Shortwave radiation sensors typically have fast response times and are less affected by airflow, which was reflected in both stationary and mobile tests. However, the SR2AD sensor underestimated solar radiation, during peak times. A critical limitation of the current device is the need for precise horizontal alignment of the pyranometer, as misalignment – especially under high solar angles – can introduce systematic errors. Incorporating a tilt sensor, as in the TUD backpack device, would provide real-time feedback to maintain proper alignment. Additional potential causes of underestimation include differences in sensor sensitivity to diffuse versus direct radiation, calibration discrepancies, or minor spectral response variations compared to the high-cost SKS1110 reference sensor. Nevertheless, our results support the use of the SR2AD sensor in thermal comfort assessments, provided that systematic underestimations are contextually interpreted and, if needed, corrected through calibration or post-processing.

Although the surface temperature sensor (MLX90614 Melexis) was not a primary focus of this study, its role as an input to UTCI calculations means that its performance merits attention. The spatial variability of surface temperatures recorded by the model used (MLX90614DCI) was implausibly low during mobile measurements, likely due to its narrow 5-degree field-of-view (FOV). Subsequent tests using a different model (MLX90614BAA) with a 90-degree FOV demonstrated significantly greater spatial variability, supporting this interpretation. The limited variability recorded by the surface temperature sensor likely contributed to some of the discrepancies in overall UTCI.

Current strengths and suitable applications

While individual low-cost sensors presented limitations, the high correlations observed in UTCI and the spatial consistency in identifying areas of higher thermal discomfort (Fig. 2), support the suitability of UrbanMobiClim for mobile thermal comfort mapping. Tmrt estimates from UrbanMobiClim and MaRTy were also strongly aligned when calculated using the RayMan model, supporting its utility despite known model simplifications and partial radiative input. RayMan may underestimate Tmrt in shaded or reflective environments due to missing sky-view and directional radiation data; future iterations could improve accuracy by integrating shortwave and longwave radiation measurements and incorporating sky-view factors [42].

Recent work has introduced other low-cost, microcontroller-based platforms for pedestrian-scale environmental monitoring, such as the Portable Low-cost Environmental Monitoring System (PLEMS) and related Arduino-based devices. These systems are primarily designed for scientific studies, and PLEMS namely for multi-environmental comfort. In contrast, UrbanMobiClim is explicitly optimised for outdoor thermal comfort mapping: it focuses on the variables required for indices such as UTCI and Tmrt, is benchmarked against high-end mobile and radiative reference systems, and integrates GNSS-based georeferencing with an open workflow for generating hyperlocal thermal comfort maps. UrbanMobiClim therefore complements PLEMS-type devices by targeting a different application niche – planning-oriented UTCI mapping rather than general multi-environmental comfort monitoring for scientific research.

The UrbanMobiClim approach offers a robust, user-friendly option for applications where relative differences in thermal conditions, rather than high-precision absolute values, are of primary interest. Our intended users are city planners, municipal practitioners and citizen-science groups who require interpretable UTCI maps to identify local hotspots and support climate-adaptation decisions. Local communities and citizen scientists can use the device to map thermal comfort in their neighbourhoods, raising awareness of heat risks and helping to translate scientific information into community-driven calls for action. City planners and environmental agencies can deploy UrbanMobiClim to collect fine-grained microclimate data that inform evidence-based decisions, including where to prioritise interventions such as tree planting, green facades, or shade structures. When combined with pedestrian surveys, these measurements ground thermal comfort maps in lived experience and support user-accepted adaptive urban design and policy [30]. Schools, universities, and NGOs may also integrate UrbanMobiClim into educational programs or community workshops, providing hands-on experience with climate data collection and fostering engagement with urban heat issues.

The device continues to be developed and optimised for use in evidence-based urban planning and citizen science applications. While well-suited for these purposes, it does not aim to replace comprehensive meteorological studies that require a broader sensor array and higher data accuracy; for such applications, correction for sensor lag and environmental effects remain necessary.

Beyond its technical performance, UrbanMobiClim offers several advantages over established high-cost alternatives. Its affordability and user-friendly design increase accessibility for lower-budget projects and for users without extensive technical expertise, broadening opportunities for long-term urban thermal comfort monitoring. Handheld portability facilitates access to pedestrian areas that may be inaccessible to stationary or bulky professional systems. Furthermore, the high temporal resolution during mobile measurements enables a correspondingly high spatial resolution, supported by the GNSS module. This capability allows for detailed mapping of thermal comfort conditions at the hyperlocal scale, which is particularly valuable for urban planning applications [13].

Future development and research needs

Recognising the importance of wind speed in calculating thermal comfort indices such as UTCI and PET, a cup-anemometer has since been

integrated to measure wind speed at stationary points [33,50]. For prospective survey applications, we envisage combining mobile transects with short stationary phases, during which the integrated anemometer can provide more representative local wind measurements. This addition improves the device's versatility for applications in case studies where wind speed variations are more pronounced and critical for accurate assessments. However, low-cost anemometers have well-known limitations at low wind speeds, particularly their starting thresholds of 0.5 m/s or greater, and must be carefully aligned horizontally to ensure accuracy. Alternative measurement methods such as hot-wire sensors or inertia-free sonic anemometers, for example the WXT 520 included in the TUD backpack device, avoid these issues but are currently too expensive for the low-cost, citizen-science focus of UrbanMobiClim.

Combining simultaneous stationary and mobile measurements could enable more comprehensive monitoring. Stationary data could serve as a correction reference for mobile transects, helping to distinguish changes attributable to urban form from those driven by diurnal variation. In addition, long-term stationary measurements would offer valuable insights into temporal patterns of thermal comfort and stress and enable evaluation of the long-term performance and durability of the UrbanMobiClim device.

Stationary setups would also facilitate the use of a more suitable globe thermometer. The poor performance of the black aluminium globe thermometer (SGT), used in this study, along with its known tendency to underestimate mean radiant temperature due to the time lag in adaptation to changing environmental conditions, and the influence of spatially inhomogeneous radiation, further discourages its use for mobile thermal comfort mapping applications [46]. Building directly on these findings, the SGT has been removed from the device; the next iteration of UrbanMobiClim will instead test an acrylic globe thermometer (AGT), which offers faster response times and a lower weight, thereby improving both measurement quality and portability [51]. Alternative globe designs proposed in the literature for outdoor applications (e.g., [41]) also provide promising options that we plan to explore.

Several additional hardware and usability improvements are planned. The current prototype, weighs just under 1 kg which operators found to be manageable for typical measurement sessions, although prolonged continuous use could be tiring. A carbon-fibre version of the carrying mount and a standardised, modular, lightweight mounting system, together with the replacement of the aluminium globe by a lighter acrylic alternative, will further reduce overall weight and physical strain during extended campaigns and offer flexibility for diverse study setups. Integrating a fisheye camera would further enhance the assessment of the surrounding thermal environment by enabling the calculation of the sky view factor (SVF), a key metric for understanding thermal comfort. It would also allow differentiation between the types of horizon obstructions, such as buildings or vegetation [52,53]. The camera could be used to check and correct the preciseness of GNSS measurements during mobile measurements, especially in complex urban environments where satellite signals are obstructed. The device would benefit from a small screen to display incoming live data and the current battery level. Alternatively, a WiFi or Bluetooth module could be integrated to stream data directly to a smartphone, maintaining the device's low-cost and user-friendly design.

The proposed changes are being integrated and tested with user feedback from German municipalities as the primary target end users of the device. Further research on the user experience, especially focusing on individuals with limited technical expertise, will inform further improvements in the device's design and usability and guide the development of user-friendly data analysis tools. At the same time, the core priority remains ensuring that sensors, installation, and measurement methods produce reliable data within acceptable uncertainty ranges. Providing clear, actionable guidelines on recommended use cases, operational limitations, and deployment considerations will be essential to ensure the device is applied effectively and its outputs are interpreted appropriately. This study, together with Gallacher & Boehnke [30], takes a first step in that direction.

Long-term comparisons with reference stations are needed to further assess UrbanMobiClim's accuracy and reliability. Longitudinal studies across a broader range of environmental conditions and urban forms, monitoring the device durability and performance over time, would provide valuable insights into UrbanMobiClim's lifecycle and consistency and validate its broader applicability. Collectively, these efforts will support the growing role of low-cost sensor systems such as UrbanMobiClim in urban climate research, enabling more extensive data collection at reduced cost while maintaining scientifically robust outputs.

Conclusions

This study advances the field of urban biometeorology through the development and testing of UrbanMobiClim, a novel low-cost and user-friendly meteorological device for mapping pedestrian thermal comfort. Comparisons with established high-cost devices from the Dresden University of Technology and Arizona State University demonstrated that UrbanMobiClim provides robust and reliable data across key meteorological variables essential for thermal comfort assessments.

In stationary tests, the low-cost sensors demonstrated strong statistical correlations for air temperature, absolute humidity, and global irradiance, confirming their reliability for urban climate studies. In mobile comparisons, variations in the UTCI showed strong agreement with the TUD backpack device's results. However, challenges such as systematic sensor biases, tilt/inclination errors, data linearity, and sensor lag were identified, highlighting the need for critical data interpretation and further refinement, particularly in calibration procedures and data processing.

UrbanMobiClim is under continuous development, with plans to address these limitations and further enhance the user experience. Longitudinal studies will be crucial for assessing its long-term performance, with further testing across diverse environmental conditions and geographical contexts to strengthen its applicability. Furthermore, developing user-friendly data analysis tools and clear usage guidelines will support wider adoption by researchers, urban planners, and non-specialists.

The findings of this study underscore the potential of low-cost meteorological devices to increase access to high-resolution thermal comfort data. By making robust data collection more affordable and scalable, such devices can empower a wider range of stakeholders, including local communities, citizen scientists and municipalities, to monitor and respond to heat stress – an increasingly urgent challenge in European cities in the context of climate change.

CRediT authorship contribution statement

Claire Gallacher: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paul Gallacher:** Writing – review & editing, Software, Methodology, Conceptualization. **Valeri Goldberg:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Astrid Ziemann:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.cacint.2026.100384.

Data availability

All datasets, code, and assembly instructions are openly available via Zenodo at the links listed below. Data availability: Gallacher et al. [1,2], Gallacher [3]. How to assemble the device and code: Gallacher [4,5].

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