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Short Communication

Indoor heat in Amsterdam: Comparing observed indoor air temperatures from a professional network and from a citizen science approach

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ABSTRACT

Ongoing climate change is increasing summertime temperatures, and frequency and intensity of heatwaves in Europe, which can threaten human health. Relatively little is known about how quickly outdoor heat penetrates into residences during heatwaves. Long-term and systematic networks recording indoor temperatures are challenging to install and maintain, and therefore scarce. We first report on crowdsourced indoor air temperature data in residences in Amsterdam (The Netherlands) during a heatwave event in September 2023. These data complement professional long-term indoor air temperature observations in 92 houses in Amsterdam. Second, we document the lessons learnt in the design and execution of this citizen science activity. 571 indoor temperature records were collected through the citizen science crowdsourcing approach, with a median value of 28.0 °C on the warmest day in the study period, while outdoor mean minimum and maximum temperatures reached 20.6 °C and 31.1 °C respectively. The results indicate that the crowdsourcing approach reports temperatures that are significantly higher than the professional approach, which supports the need for professional indoor networks. Finally, local media attention was critical in reaching a wide audience.

1. Introduction

The weather and climate in cities are different from the rural areas due to the modification of the surface energy and radiation balance of built-up areas. The typical urban canyon structure allows for efficient radiation absorption in both the shortwave and longwave bands, reduced wind speed, and efficient heat storage in the urban fabric. Moreover, anthropogenic heat sources enhance the urban atmospheric temperatures. The urban canyon heat island effect (UHI) is a well-known expression of the urban modification to the land surface (e.g. [26,16,14,15,34]).

Monitoring, understanding and forecasting outdoor air temperatures during heatwaves is important for estimating citizens' heat load (Molenaar et al. [25]), and to issue timely warnings (Gustin et al. [9], especially for specific vulnerable groups like children and the elderly [19,36,2,30]. Krelaus et al. [18] underlines that in understanding the UHI dynamics it is key that classification schemes should not be compared without considering the methodology, and that the UHI studies should consider the full continuum of its different times scales. In recent years, many urban meteorological networks have documented the spatiotemporal characteristics of outdoor urban air temperatures in multiple European cities [37,40,31,38,24]. These networks have recorded substantial UHI values and thermal load for pedestrians. Within the European context, e.g. Steeneveld et al. [35] reported a median daily maximum UHI effect of 2.3 °C across The Netherlands, while instantaneous UHI values can be substantially higher. Moreover, Gross [8] reports an instantaneous UHI of 6 °C for Hannover (Germany), while Top et al. [38] reported an hourly UHI of 8.7 °C during the record-breaking 2019 heatwave in Ghent (Belgium). Hidalgo et al. [11] found an UHI distribution for Toulouse (France) with daily maximum UHI values between 1–3 °C being most common, but values up to 7 °C appeared for the most extreme days. In addition, physiological apparent temperatures often exceed threshold values to ensure favourable health conditions (e.g. [17]).

While urban networks have delivered lots of insights in the dynamics of the outdoor urban atmosphere, relatively little is known about the indoor temperatures during heatwaves. This is surprising since urban dwellers spend 13.5 to 15.8 h/day indoors according to Schweizer et al. [33], while other studies report this to be 90 % of the time ([6], Mannan and Al-Ghamdi [22]; Kravchencko et al., 2023). While Aguilera et al. [1]

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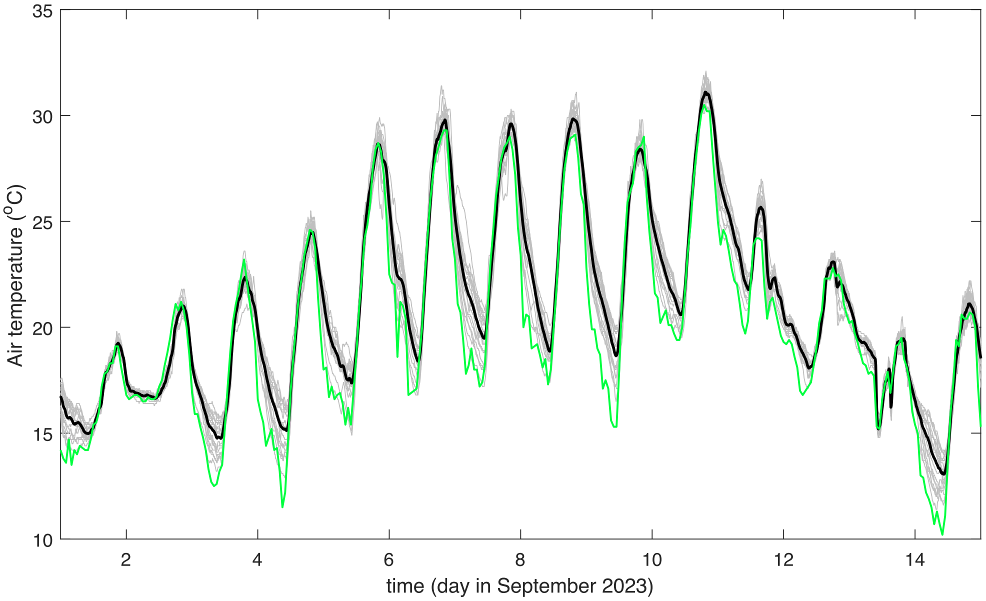

Fig. 1. Time series of observed outdoor air temperature by 24 weather stations across Amsterdam (grey lines) and the spatially mean temperature (black line), and Schiphol airport (green line) for the period 1–15 September 2023.

and Kravchencko et al. [42] report challenges in the modelling skill for high indoor air temperatures, they also report limited availability of indoor heat observations as observed in a real-world context (i.e. no controlled environment), and promote further development of field studies methodologies (Holzer [12]). On the other hand, Beckmann et al. [3] report that amongst others higher indoor temperature is a significant factor for subjective heat stress.

Since 2021 indoor heat assessments for new residences are required in The NetherlandsBouwbesluit [4]. These occur through numerical simulation to evaluate they constrain with the national heat regulations. Numerical model simulations that resolve the complete flow and temperature field are generally computationally costly (Salamanca et al. [32], Lomas and Porritt [21,29]), though still more efficient than indoor observations and surveys. Instead, model simulations often assume ideal

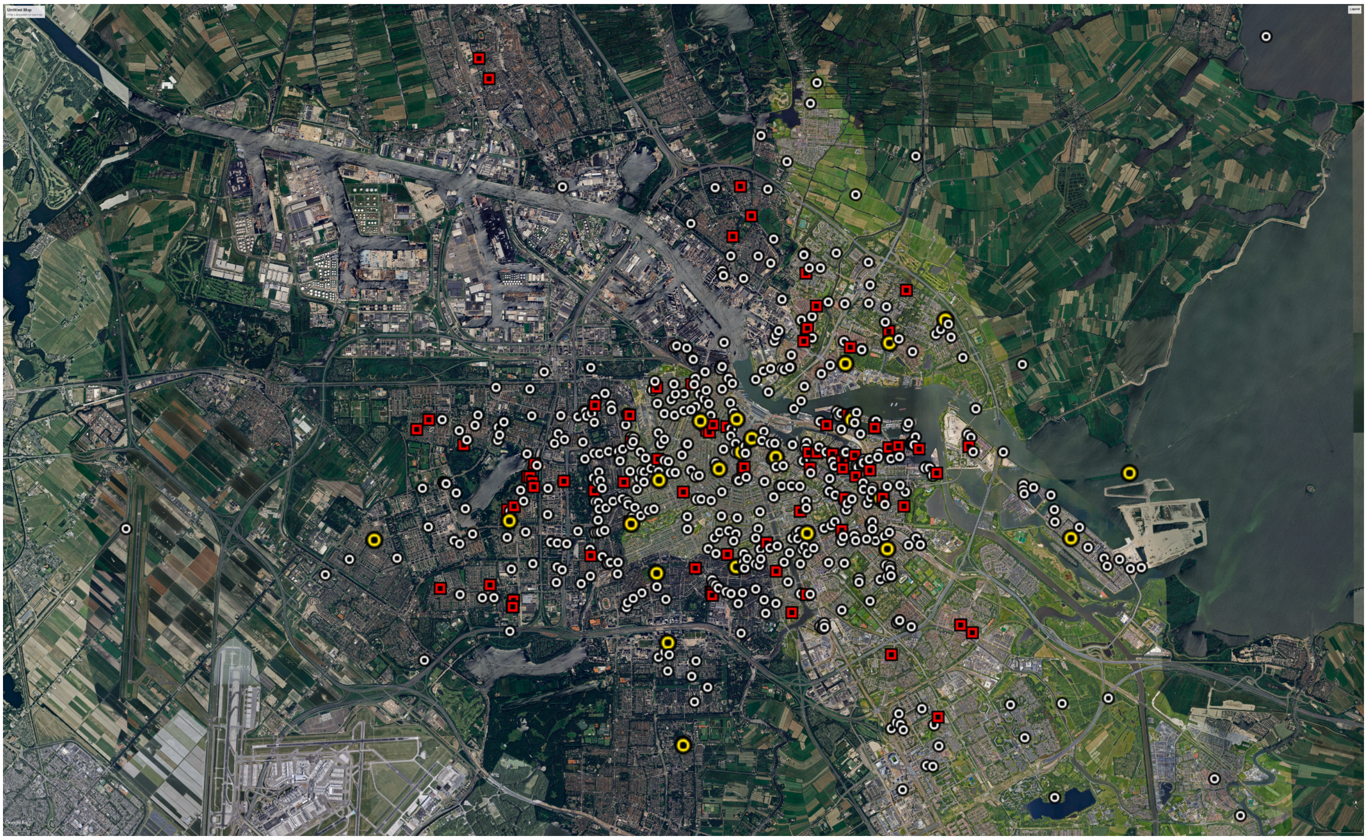

Fig. 2. Spatial overview of locations where temperatures have been reported. Yellow: AAMS station locations; Red: Netatmo indoor stations; White: SICSA observations.

conditions that exclude human behaviour, while intended and unintended human decisions on room ventilation and using sunscreens can be critical for the indoor temperature. Hence, their performance is relatively poor (Lomas and Porritt [21]).

While long-term indoor temperature recordings in a practical real-world setting are extremely valuable, their abundance is limited in space and time because their setup and maintenance are costly, time-consuming, and involve privacy issues of citizens hosting thermal sensors. Urban indoor temperature networks do exist, but often involve a limited number of sensors (~100 for Amsterdam, see [28], while a more general picture based on a wider number of temperature measurements would favour insights into human heat load and the ability to sleep at night.

To overcome this challenge, this study aims to collect indoor air temperatures from a citizen science approach during a heatwave in Amsterdam (The Netherlands), with the intention to collect a larger volume of data in a specifically relevant heatwave period than it would be possible with a modest professional network. Hence, this study presents the study design, infrastructure and results of this successful citizen science event. In this paper section 2 presents the methods and data, section 3 the results, and conclusions are drawn in section 4.

2. Methods and data

This section presents the design of the data platform used for the data collection, the communication strategy, and the meteorological datasets used.

a) Case study: Warm episode in Amsterdam during September 2023.

We have selected the period of 4–15 September 2023 in Amsterdam as a case study to collect indoor air temperature data. This case was one of the warmest periods in summer 2023, which also had maximum observational data availability. The synoptic situation was characterised by a persistent and approximately stationary high-pressure system located over Central Europe. The period was approximately cloud free, with relatively low 10-m wind speed (2.0 ms^{-1} at the Amsterdam airport) from east-south-easterly direction. These weather conditions are ideal to develop an UHI and to build up indoor heat load. Although the Dutch criterion for a heatwave (five consecutive days with T_{max} $\geq$25.0 °C of which three have a T_{max} $\geq$30.0 °C) was not met at the KNMI weather station in De Bilt (centre of The Netherlands) to qualify for a national heatwave, the heat wave criterion was met regionally. Outdoor air temperature observations reported for Amsterdam airport indicate that the maximum hourly temperatures increased from 25.4 °C on Sept 4th to 30.7 °C on September 10th, after which the warm period ended (Fig. 1).

b) Meteorological datasets.

This study uses two observational reference datasets, one for outdoor and one for the indoor air temperatures within the city of Amsterdam (see Fig. 2).

I. Amsterdam Atmospheric Monitoring Supersite (AAMS).

A network of 24 outdoor weather stations across the city of Amsterdam is present measuring air temperature, humidity, and wind speed. The weather stations are shielded and ventilated Decagon VP3 temperature and humidity sensors and have been mounted at 4 m height on lampposts, and report every 5 min. A more detailed description of the setup has been provided in Ronda et al. [31] and De Vos et al. [39]. Furthermore, we use weather observations from the routine national network operated by KNMI, especially the weather station at Amsterdam airport.

II. Long-term Citizen Science Indoor air temperature observations.

At the time of the citizen science event in September 2023, we also collected indoor temperatures in the living room and bedroom of the 92 households in Amsterdam as part of a long-lasting citizen science effort of the EU Green Deal I-CHANGE project (https://ichange-project.eu/). The I-CHANGE project follows a Living Lab approach and aims to study natural hazards through citizen science experiments, and to promote public awareness for natural hazards due to climate change. These observations are part of a long-term campaign running since summer 2022, in which residents voluntarily host an indoor weather station as a part of a living lab experiment [28]. The 92 households are reasonably well distributed over the city, though do not represent the complete building stock in Amsterdam (not shown). However, this is the first and so far, the only set of long-term indoor temperature data recorded in Amsterdam. For all households, we collected *meta*-information, e.g. building age, orientation, energy label, room volume. The *indoor* temperatures are observed with NetAtmo Weather stations, an instrument widely used in urban climate studies [23,7]. The instrument consists of two modules. The first module measures temperature (0–50 °C, accuracy 0.3 °C), relative humidity (0–100 %, accuracy 3 %), pressure (260–1160 hPa, accuracy 1 hPa, not used in this study), CO_2 concentration (0–5000 ppm) and sound (35–120 dB) and has been installed in bedrooms. The second module only measures air temperature and relative humidity (0–100 %, accuracy 3 %) and is located in the living room. Both sensors are shielded in a silver cylinder of 45×45×105 mm and 45×45×155 mm, respectively, and they report data in 5 min intervals. Citizens that host a NetAtmo have insight in the measurements via a mobile app and a website, which offers them a certain empowerment to adjust their living environment and behaviour in warm episodes. All stations have been installed by Wageningen University scientists to ensure sensors are not exposed to direct sunlight. Only temperature records are analysed here.

c) A citizen science campaign on crowdsourcing indoor temperatures.

Complementing the above introduced professional observations, we developed a Short Intensive Citizen Science Activity (SICSA) for a part of the study period, in which citizens were asked to report their indoor air temperatures during the heat event 6-12th September 2023 in Amsterdam (The Netherlands). More specifically, we apply the concept of volunteer geographic information which is a subset of citizen science that specifically focuses on crowdsourcing data with a geographic component [10].

For that purpose, firstly, we developed an online dashboard (https://citizens4climate.com) which is a WebGIS application that provides access to data, tools and applications developed within the I-CHANGE project. One of the components of the dashboard is the citizen science climate campaign tool which allows users to define subset of citizen science events for collecting a wide range of information from users. Each subset of citizen science events can have one or more attributes. For this study, a campaign (https://citizens4climate.com/crowdsourcing/campaigns/112/responses/add) was created with the following elements:

- Approximate location: latitude, longitude and/or street name (from a menu or with a mouse click on a map).
- Indoor temperature (°C): value input field.
- Heat perception: scale of 1–3 (traffic light system) “How difficult is it to deal with this temperature?”
- Photo proof: upload of photo of the thermometer recording the temperature indoors (optional).

Citizens were guided to the campaign through press releases and social media posts (see section d). The collected data can be visualized on a map and table interface, or it can be integrated in a GIS analysis. The data is stored in an object-relational database which allows the

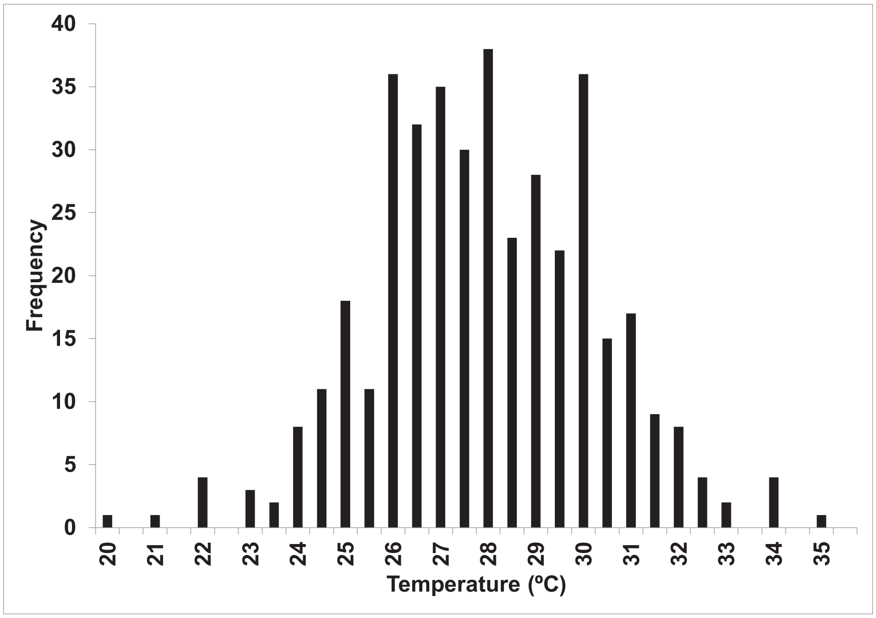

Fig. 3. Histogram of reported indoor air temperatures by citizens in the on September 11th of the SICSA period in the Amsterdam area. The mean and median of the reported air temperatures amounts to 27.8 °C and 28.0 °C respectively.

efficient storage and retrieval of the data. Moreover, the data is also exposed via the API (Application Programming Interface) which allows an easier integration of data into other systems or custom analytical workflows.

Citizens submitting data to the webform use temperature observations from regular in-house thermometers, e.g. analogue or digital thermometers that were already present in their homes for daily use, and they were not re-positioned for the research. Also, thermometers in central heating system devices were used. It is an obvious limitation that the precision and accuracy of these devices is not perfectly known. Moreover, a limited number of citizens, i.e. 269, uploaded photos of their thermometer as proof of their observation. Data recordings were manually screened on duplicates, i.e. records using the same address and temperature value within a time span of 5 min. Only 5 records were identified as duplicate and were excluded from the analysis. In addition to this limitation of crowdsourced information, the data reported by citizens in this study may be lacking information on the building or socio-economic and demographic aspects, and stratification of the records according to these variables is not possible. However, with the ambition to gather as much data as possible during the heatwave, it was decided on that the form for collecting information will be brief; thus, citizens are motivated to participate. Furthermore, this study aims to take a snapshot of the heatwave days and not derive a long-term perspective on the evolution of indoor temperatures for which a crowdsourcing campaign would not have been applicable.

d) Communication and dissemination strategy for the crowdsourcing campaign.

To reach a wide audience to collect environmental data in our SICSA, a communication strategy is critical. One of the major challenges of crowdsourcing is to actually recruit volunteers to contribute their data and information [13]. To reach a broad range of citizens, the SICSA was disseminated via various media channels and approaches. On the one hand, press releases were sent out by the scientific institutes in charge of the research (Wageningen University, AMS-Institute, and the EU I-CHANGE project office), and were posted on their websites. These announcements were shared through social media from these institutes including Twitter and LinkedIn, as well as through the personal accounts of the involved researchers. In total ~$5 \bullet 10^3$ reads were achieved on LinkedIn, and about $18 \bullet 10^3$ on Twitter. Consequently, the local TV station in Amsterdam, AT5, picked up the call for data and broadcasted a 1.5 min item in their early morning TV news on September 11th 2023.

After submitting data, citizens had the opportunity to explore the dashboard itself which offers information on indoor heat as a hazard, its impacts, and how to prevent or deal with indoor heat. This and other informative pages on hazards such as flooding, storms, heatwaves, and air pollution are available.

3. Results

We start summarizing the outdoor weather conditions during the selected heatwave. Fig. 1 shows the mean temperature in the outdoor AAMS network rising from 1st September and reaches maximum temperatures above 25 °C from 6 to 11 September 2023, after which the temperature rapidly drops. During this period the diurnal cycle is relatively large and amounts to ~10 °C. In addition, a substantial temperature difference between the city stations and Schiphol airport appears. This UHI is relatively small during the day, but increase substantially during the evening and night. Moreover, the variability between the individual AAMS stations is relatively small during the day (within ~1 °C), while it is larger at night (~4 °C). This is in good agreement with many earlier UHI studies (e.g. [26], and can be explained by relatively strong turbulence during the day, while at night winds and turbulence are relatively weak, which means the UHI effect increases. Also, these conditions allow for the development of spatially contrasting temperature patterns. Despite the heatwave occurred in late summer (September), the synoptic and near surface weather conditions are ideal for studying the urban heat island effects and the impact of heat penetration into houses.

Fig. 3 presents the histogram of the reported indoor air temperatures in the SICSA for 11 September 2023. Temperatures over a wide range between 20 and 35 °C have been reported. A Kolmogorov-Smirnov-test revealed the distribution is significantly different from a normal distribution ($p = 0.01195$), though with a low effect level ($D = 0.07966$), and as such we practically assume that the distribution behaves as a normal distribution. The distribution has a mean and median of 27.8 (±0.26)°C and 28.0 (±0.26) °C respectively. A Z-test revealed the data exceed the threshold of 26.5 °C at a 5 % significance level. This temperature threshold is now used in The Netherlands building decree for existing

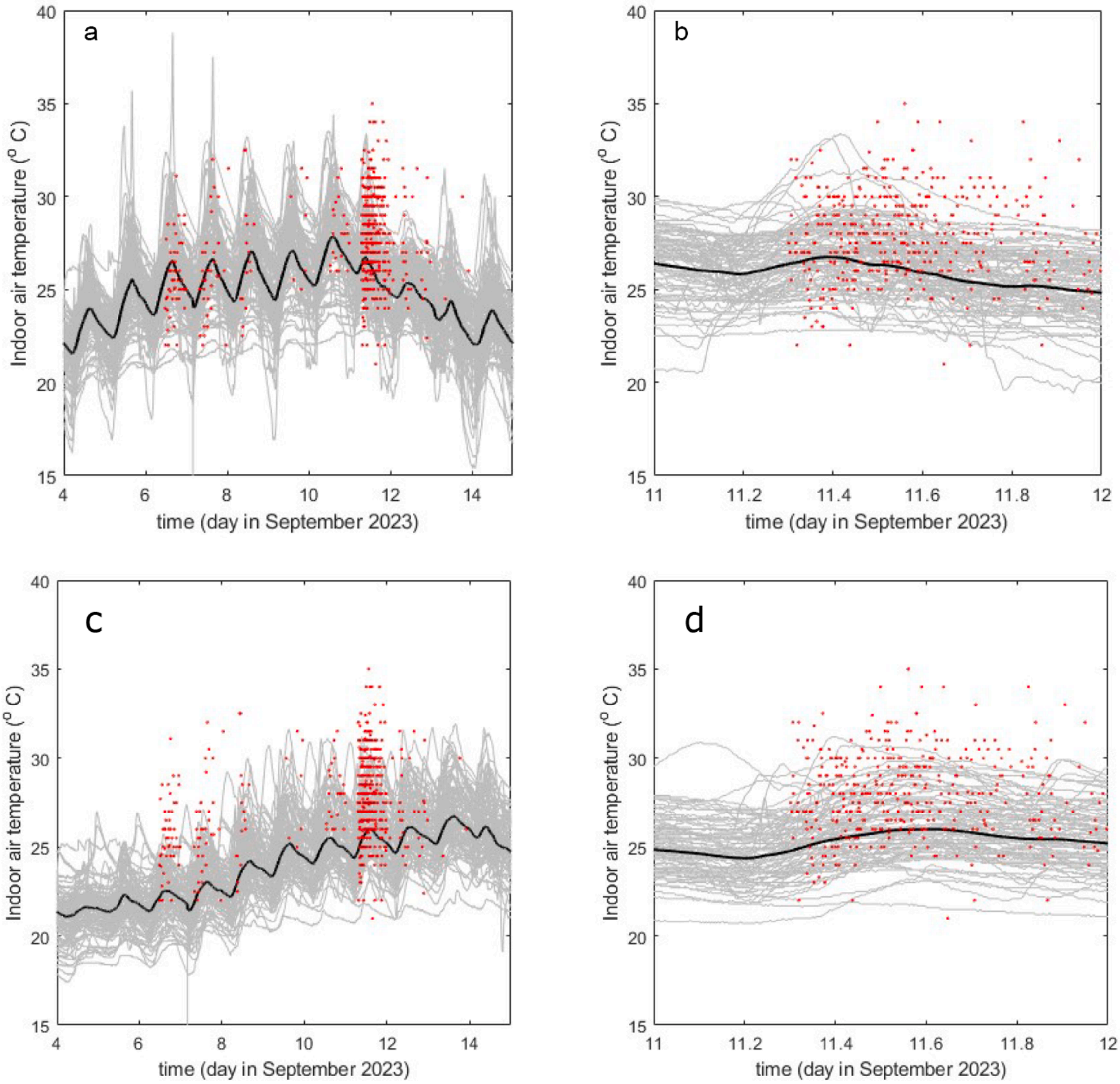

Fig. 4. Observed indoor air temperature (a: bedroom; b: living room) in a network of 92 indoor sensors in Amsterdam (grey lines) and their mean values (black line). The red markers indicate the temperature values submitted by the citizens science event.

building stock. In case 26.5 °C is exceeded for 300 h a year, a defect is confirmed according to the rental prices legislation.

Considering the time evolution of the bedroom temperatures, Fig. 4a shows that the average bedroom temperatures in the 92 houses rises from 22.1 °C on September 4th to 27.9 °C on September 10th. We also find a considerable spread amongst the houses available in the experiment. On the warmest day the lowest and highest indoor maximum temperature amounted to 22.7 °C and 34.4 °C respectively. The results show that the bed rooms become warmer than the living rooms, which is consistent with findings of Pathan et al. [27] for London but opposite of findings of Zuurbier et al. [41] for a set of about 100 homes in Arnhem and Groningen (both in The Netherlands). Moreover, we find that the increase of temperatures in the living room is delayed compared to the ones in the bedrooms, likely because they are more located in the interior of the building and the heat transport takes time to reach the living room. This could be due to the relatively large share (∼50 %) of row houses and (semi-)detached houses in the professional network, while this share amounts to 12.7 % for the total building stock in Amsterdam. Also because living rooms are generally larger than bedrooms, and therefore it takes more time to warm up and cool down. We also found that the bedroom temperatures start to decline from September 10th, the living room temperatures remain increasing till September 13th.

For comparing the temperature observations from the professional network of 92 sensors and the temperature obtained from the SICSA, we focus on September 11th when most data were submitted in the SICSA (red dots in Fig. 4). We find that the observed temperatures in the SICSA and the ones from the 92 sensors are in reasonable agreement for the bedrooms, while SICSA data are in general higher compared to the living rooms. A Student *t*-test and a Wilcoxon rank sum test revealed that for all 2-h blocks on September 11th the SICSA data are significantly warmer than the professional network observations at the 5 % significance level. Moreover, an F-test revealed the variances (e.g. temperature range) of the SICSA results and from the professional network are significantly different at the 5 % significance level.

In the short intensive citizen science activity, the 571 participants were also asked to rate how well they could cope with the heat through a traffic light (red, yellow, green) rating. We find 59 % of the respondents reported it be “very difficult” to handle the heat. That group reported a mean room temperature of 28.6 (±0.3) °C. Herein, the provided uncertainty estimate represents the estimated confidence interval assuming a t-distribution. As a comparison, Van Loenhout et al.[20] found that half of the respondents (elderly in their case) perceived their indoor climate as too warm during a warm week in The Netherlands.

The second cohort of 29.8 % reported a mean temperature of 26.3 (±0.3) °C and "It is okay" to handle the heat, while the third group of 11.2 % reported a mean indoor air temperature of 24.9 (±0.6) °C, and reported that coping with the heat was "Not difficult at all".

Finally, we discuss the temporal evolution of the number of responses in the online survey. Obviously, in the beginning of the campaign, the responses are relatively low. On the morning of 11th of September our citizen science event was a morning news item at AT5, the local TV channel of Amsterdam. This TV item was pre-recorded in the week before (on Sept 7th, when it was already substantially warm), and contained information about climate change, health effects on indoor heat, and tips and tricks to keep the house relatively cool in warm episodes. In addition, one of the hosts of the 92 professional sensors was interviewed at home, and in which he explained about the professional sensors used in the project. This visibility was crucial for the data collection, since within the following 24 h roughly 400 new records from unique residences were collected, which is about 75 % of the total dataset. As such we conclude that access to local mass media is crucial to collect large amount of data in such short-term and single-time crowdsourcing campaigns.

In this respect it is interesting to mention that Calhoun et al. [5] report a biased urban heat island effect measured by citizen scientists, since they are likely to be wealthier, making certain neighbourhoods better observed than others. Because urban heat islands are more prevalent in poorer neighbourhoods, they found heat extremes are less likely to be observed by citizen scientists.

4. Conclusions

This paper reports on a study that collected indoor air temperature observations during a warm episode in September 2023 in Amsterdam (The Netherlands). These indoor observations are complemented by observations from outdoor weather stations at 24 sites across the city. The indoor air temperatures are collected through a network of 92 long-term citizen science observations in the participating households' bedroom and living room. In addition, we performed a short intensive citizen science activity in which 571 citizens reported their indoor temperature through a crowdsourcing campaign and indicated their perception on coping with the indoor heat. A reasonable spatial representation of measurements over the city was achieved through these 571 observations. The results indicate that the indoor temperatures reported through the short intensive citizen science activity are statistically different (warmer) than in the professional indoor network. Also the variances differ significantly between these sampling methods. These results underline the need for professional indoor temperature networks. Despite the limitations of crowdsourced information, in terms of lacking information on the building or the socio-economic or demographic status of the inhabitants, or the difficulties in longer-term engagement in data collection, the crowdsourced data indicated several added values (compared to the other sensor measurements) such as the ability to collect information on heat perception, the abundancy of collected data in time and spatial context. Finally, we found that to achieve a high response in the short intensive citizen science activity, it was crucial to have local media attention to be successful in collecting large amounts of data.

CRediT authorship contribution statement

Esther Peerlings: Writing – review & editing, Investigation, Formal analysis, Conceptualization. **Saša Vranic:** Writing – review & editing, Visualization, Software, Methodology, Conceptualization. **Joy Ommer:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Milan Kalas:** Writing – review & editing, Methodology, Conceptualization. **Gert-Jan Steeneveld:** Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, 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.

Data availability

The data that has been used is confidential.

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