



From citizens to satellites to aircraft: What are emerging sources of data for urban climate adaptation?

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Abstract

Cities are increasingly vulnerable to the intensifying effects of climate change, particularly in the form of heatwaves and the phenomenon of urban heat islands. The CityCLIM project aims to address these risks by leveraging emerging data sources — citizen science, satellite-based Earth Observation (EO), and airborne-based EO — to collect, transform, and provide climate information. This accessible, actionable knowledge is a critical precondition for diverse stakeholders to identify priority areas and implement effective risk mitigation measures. Through citizen engagement, the project democratises climate data and sensors, while fostering collaborative strategies between citizens and city administration. The integration of satellite and airborne data further aids in decision-making, offering high-resolution land surface temperature (LST) maps that underpin urban planning and public health responses. Despite challenges such as data privacy concerns and the need for technical capacity among users, the project demonstrates the transformative potential of these emerging data sources in bridging knowledge gaps in climate action related knowledge that could be taken up by various stakeholders such as urban municipality and policymakers. Ultimately, CityCLIM not only addresses gaps in climate knowledge generation but also supports stakeholders to implement effective adaptation strategies, reinforcing the imperative for continual innovation in climate data methodologies to address the complexities of urban climate resilience.

Keywords Citizen science · Earth observation · Remote sensing · Emerging data sources · Urban heat island · Climate adaptation

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1 Introduction

Cities and their inhabitants will face significant challenges due to climate change. Factors such as natural disasters and extreme weather events (e.g. heatwaves) pose a greater threat to densely populated urban areas and their infrastructures compared to less populated regions (Haines et al. 2006; Possega et al. 2022; Unger et al. 2020). Simultaneously, cities contribute disproportionately to climate change, as urban activities such as transportation and building energy use account for approximately 75% of global CO₂ emissions (UNEP n.d.). Nevertheless, cities are also catalysts for change, equipped with the resources and capabilities to tackle complex climate issues. They are poised to play a crucial role in developing climate adaptation solutions, as demonstrated by major funding initiatives aimed at achieving climate neutrality and resilience in urban areas, such as the Horizon 2020-funded European Green Deal Calls. One such project in this call under the subtopic “Societal Challenges - Climate action, Environment, Resource Efficiency and Raw Materials” is the urban climate adaptation project CityCLIM.

The CityCLIM project, short for “Next Generation City Climate Services Using Advanced Weather Models and Emerging Data Sources”, was mainly funded to develop a cloud-based platform that provides various weather and climate services specifically for European metropolitan areas, which are experiencing a rising frequency of heatwaves as a consequence of climate change. Densely populated regions are particularly vulnerable to thermal stress (Unger et al. 2020), with heat persisting longer and nocturnal urban heat islands intensifying (Possega et al. 2022). Consequently, the health risks associated with extreme heat are markedly greater in urban environments compared to their surrounding rural areas (Haines et al. 2006; Patz et al. 2005; Unger et al. 2020). Thus, CityCLIM developed a weather forecast model tailored for large cities called the UltraHD model. The UltraHD model provides a significantly higher resolution of 100 m by 100 m, which contrasts traditional forecast models that typically operate at a resolution of several kilometres (Horn and Zimmer 2023).

Many of CityCLIM’s climate services (Citizen Climate Knowledge Services and City Administration Services) are underpinned by this UltraHD Model, which processes weather model outputs for real-time forecasting, simulation services, and early warnings. The model is novel from existing technology due to its high resolution, urban use suitability (high heterogeneity), and near-real-time simulations. Another key characteristic of the CityCLIM project is its use of novel in-situ data collection methods, as well as integration of space-based (e.g. Copernicus satellites) and airborne EO (earth observation). We define these collectively as emerging data sources, encompassing both novel collection methods and the innovative application of existing datasets not originally intended for their current context (Arribas-Bel 2014). For urban climate adaptation, this approach translates to utilising advanced, multi-source gathering methods to synthesise actionable climate information. Ultimately, the role of these sources is to address gaps arising from traditional data methods, for example providing the necessary detail required for urban investigations or a continuous flow of data needed for real-time monitoring (Arribas-Bel 2014). The EU Mission on Adaptation to Climate Change is explicitly designed to address key gaps by shifting from awareness to action and systemic transformation at the local and regional level (European Commission 2021). While high-level climate data exist, regions still lack the specific, usable knowledge required for local action, specifically in the form of downscaled, relevant climate data (e.g. for heatwaves) that are in the right resolution for urban planners

and local governments to use effectively. Emerging sources of data for climate adaptation leverage technological advancements and societal action to provide insights that traditional data sources may not fully capture and offers potential solutions for gathering fine-grained data suitable for urban use and understanding the dynamic climates of cities.

This research aims to explore a combination of three data collection streams seldom utilized together in urban climate adaptation: (1) Citizen Science, (2) Satellite-based EO, and (3) Airborne EO, and assess their collective value for bridging gaps in climate knowledge and informing adaptation strategies. These methods from the CityCLIM project illustrate that “emerging data sources” encompasses a broad spectrum of innovation. This spectrum ranges from innovative approaches to problem-solving and collection (Citizen Science), to novel applications of existing technologies and data (Satellite-based EO), and finally, to entirely new sensor systems (Airborne EO). As climate change continues to pose unprecedented challenges to urban areas and their inhabitants, the identification and use of emerging data sources are crucial for addressing the gaps in climate action related knowledge and promoting effective climate adaptation in cities. The findings of this research will provide valuable insights for city administration, policymakers, researchers, and companies seeking to incorporate emerging data sources into urban climate adaptation strategies.

2 CityCLIM case study regions and methods of data collection from emerging sources

2.1 Case study regions

The CityCLIM project was carried out in collaboration with four pilot cities located throughout Europe, showcasing climatic diversity across the continent and enabling project results to be validated in real environments. The four pilot cities are Karlsruhe (Germany), Valencia (Spain), Thessaloniki (Greece), and the city of Luxembourg. The CityCLIM case study regions experience the impacts of climate change in varied and distinct ways, though all of these effects pose a threat to the wellbeing of its citizens. Karlsruhe is located in the Rhine Valley, which experiences significantly higher heat exposure compared to other regions in Germany due to its orientation and flat terrain (Hundhausen et al. 2023). Valencia’s southern location, high humidity, and calm winds can combine to create dangerously high daytime temperatures. Furthermore, the absence of effective nocturnal cooling is driven by calm night events, higher sea temperatures, and crucially, high dew points that limit heat loss through radiative cooling (Lehoczky et al. 2017). Thessaloniki is densely populated with a deficit in green areas and its proximity to the Mediterranean Sea strongly influences climate. The city is projected to experience exacerbated urban heat island intensity that could increase mortality attributed to high temperatures (Parliari et al. 2023). In the city of Luxembourg, temperatures of 40.8 °C were recorded in July 2019 (according to the city’s weather sensor network), and there is an increasing incidence of “tropical nights” above 20 °C that affect inhabitants sleep quality and health (Junk et al. 2014). All case study regions experience intense heatwaves, increasing urban heat island effects, and temperatures higher than historically experienced (Fig. 1). This is a major threat to citizen wellbeing as increased temperatures are associated with a higher risk of mortality and deterioration of air quality leading to respiratory illnesses (Giannaros and Melas 2012). Further, cardiovascular issues

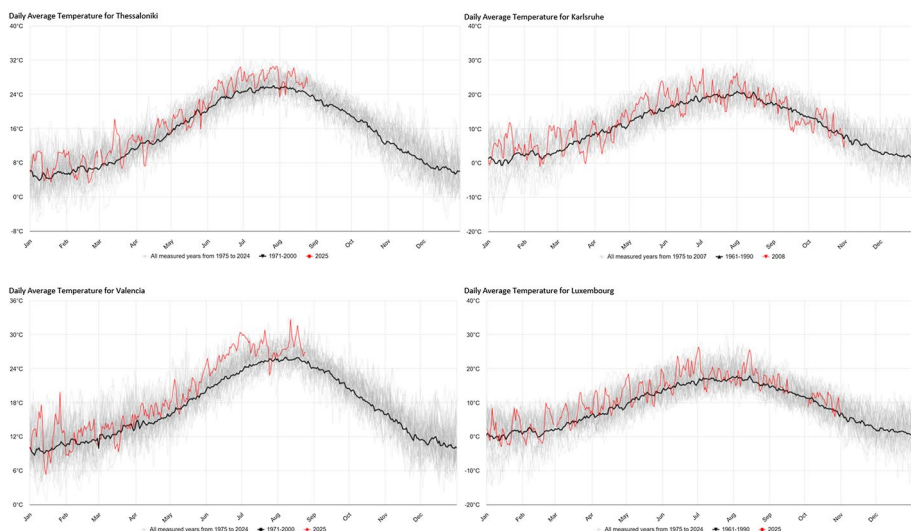


Fig. 1 Daily average temperature for the four case study regions from the CityCLIM Climate Portal, hosted by Meteologix (<https://meteologix.com/na/climate/stations>). Average temperatures are calculated from data acquired since 1975 from NOAA (with the exception of Karlsruhe, which uses DWD climate data as the data source)

can be triggered by heat and insufficient water intake, as well as heat strokes (Ebi et al. 2021).

Due to the varied climate conditions and factors of each region, the goals and activities that occurred in each city were different and tailored to meet their individual needs. Not all methods outlined below were implemented in every pilot city. In particular, the citizen science goals and activities implemented across the pilot cities varied significantly, a difference driven by the unique circumstances of each region. For example, Luxembourg presented a unique challenge: the local partner was a media company, not a city administration as in other case study sites. This organisational difference led to limited institutional capacity and a corresponding unwillingness to fully engage in the citizen science activities. As a media company, it could better contribute to the project by focussing resources to engage citizens through press releases and public announcements to “crowdsource” suitable locations for fixed professional weather sensors. In other pilot cities, certain activities or target audiences varied due to privacy concerns or existing networks. This divergence highlights the strong dependence of citizen science implementation on local conditions, which limits the direct transferability of the exact methodology but underscores the importance of flexible, context-specific adaptation pathways.

2.2 Citizen science activities

A major aspect of the CityCLIM project was collection of in-situ climate data using low-cost weather stations and mobile sensors for bicycles or cars, which can be used to validate other sensor systems in the project and ground-truth climate data. The citizen science data collection campaigns occurred only in the pilot cities Karlsruhe, Valencia and Thessalon-

iki. In Luxembourg city, the installation of fixed professional weather sensors provided in-situ and real-time environmental data that were assimilated into the UltraHD model. To secure a suitable location for the professional weather sensors, the local partner (a media company) “crowdsourced” potential sites by producing informational videos and issuing press releases. However, no citizen science activities using the mobile or stationary sensors occurred in this region due to lacking institutional involvement (as explained in Sect. 2.1), as well as the hilly terrain being unsuitable for cycling (Table 1).

While the broader CityCLIM citizen science framework relies on a comprehensive 12-step Standard Operating Procedure (SOP) previously published (Koedel et al. 2024a, b), this paper focuses strictly on the operational execution phases: participant recruitment and instruction and the subsequent measurement campaigns (visualized within the full workflow in Fig. 2). The foundational and preparatory phases of the SOP are documented in Koedel et al. (2024a, b) and accessible via a webtool (<https://www.ufz.de/index.php?en=51534>).

The recruitment of participants was designed to align with the unique needs of each pilot city and was conducted in close collaboration with local representatives from city administration. Recognising that effective outreach requires a tailored approach, we implemented distinct advertising strategies in each of the three pilot cities involved. This approach was

Table 1 Citizen science methods and data collection approaches across the four pilot cities

City	Mobile plat- forms: bike	Mobile plat- forms: car	Stationary weather stations	Remark
Karlsruhe	x	-	-	Opted out of deploying stationary weather stations due to localised citizen data protection concerns.
Valencia	x	x	x	Only city using car deployment because the city administration utilised their own municipal department vehicle fleets.
Thessaloniki	x	-	x	Recruitment heavily leveraged university students, who primarily utilised bicycles for mobile data collection.
Luxembourg	-	-	x	No institutional involvement of city administration; hilly terrain unsuited for bike-based collection during heat episodes.

The mobile platforms refer to the MeteoTracker sensor and the stationary weather stations refer to the National Geographic Weather Station, with the exception of Luxembourg where citizens were involved in selecting the location for professional stations

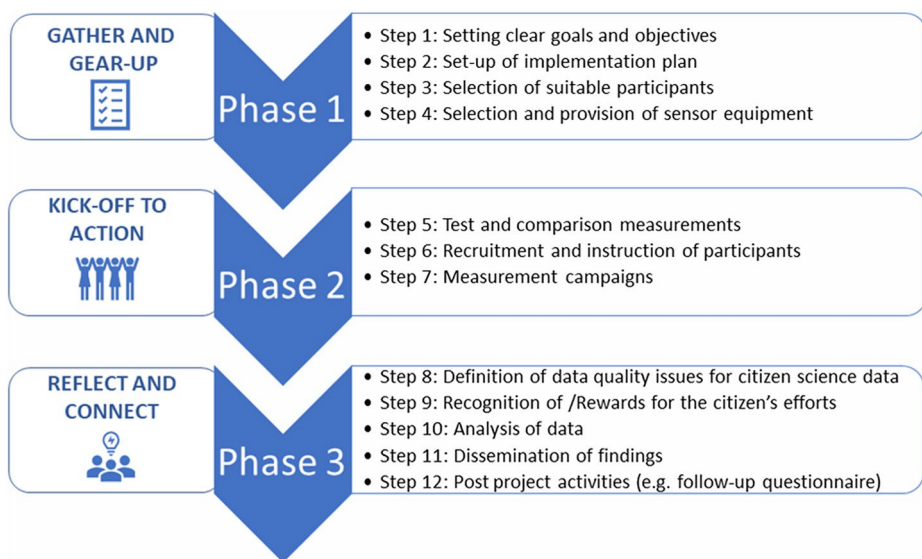


Fig. 2 Overview of the CityCLIM Citizen Science Standard Operating Procedure showing the 12 steps used to implement the citizen science data collection campaigns in the pilot cities

guided by regular meetings with the administration teams, a site visit to each pilot city, and ongoing dialogue with key stakeholders to identify any existing networks and the best way to reach citizen scientists based on local knowledge and experiences. The CityCLIM SOP recruitment strategy includes: an optimal advertisement strategy, selection of the most suitable participants, strategy for optimal instruction and training, strategy for optimal communication and considering ethical and privacy issues (Step 6, CityCLIM SOP; <https://www.ufz.de/index.php?en=51573>). According to the SOP, the most “suitable” participants for the CityCLIM citizen science activities were those with high motivation level, interest in the technical task, availability of required technologies (e.g. smart phone), length of commute (in order to capture the most data with the mobile sensors), frequency of use, and route of commuting (in order to capture diverse geographic data). The local administrative teams tailored their communication and outreach networks to identify and select participants meeting these target criteria, adapting the recruitment process to local municipal capacities.

In Karlsruhe, our primary focus was on utilising the city’s official website and channels as a platform for recruitment. This choice was informed by the understanding that residents frequently turn to their local administration’s online resources and social media channels for information and opportunities about climate information (e.g., the KA° climate platform: <https://klima.karlsruhe.de>), thus maximising visibility among potential participants. In addition, the city administration issued an official press release that garnered attention from local radio and television (e.g., Baden TV, Germany), which led to additional advertisement by word-of-mouth. Based on a stakeholder analysis that was performed before recruitment (Koedel et al. 2024b), we also used the Stadtradeln (City Cycling, a German campaign) network to spread the news. In Thessaloniki, we capitalised on the power of local media to generate interest and awareness about the CityCLIM project. By actively promoting the call for participation through various media outlets (such as TV and radio segments), we aimed

to reach a broader audience and engage citizens who may not have been as informed about the project through digital means alone. Another unique recruitment aspect for Thessaloniki was the involvement of students and educators from local public schools. This partnership was made possible since a meteorologist on the administration team already had strong ties with school programs in the area. In Valencia, the recruitment strategy targeted municipal employees directly from within the city administration. This approach was selected to optimise administrative resources, as coordinating an internal cohort allowed the project team to bypass the extensive public-outreach infrastructure required by the other pilots. This method created a distinct layer of institutional accountability: as public servants, these participants possessed a professional stake in properly representing their municipality and successfully executing the data collection campaigns. Furthermore, Valencia's recruitment within the city administration facilitated a streamlined communication process and high retention rate. The use of diverse recruitment methods across the pilot cities demonstrates that operational flexibility is essential in multi-city citizen science initiatives, requiring frameworks to proactively adapt to localised administrative structures and community demographics while working toward a shared climate adaptation goal.

The sensors used in the citizen science activities were selected for their functionality, affordability, and trustworthiness of the data (following in-house testing to compare sensors, or SOP Step 5 in Fig. 2). The mobile sensor selected for the project is called the MeteoTracker mobile weather network sensor, which is developed by IoTopon S.r.l. (Italy) (Fig. 3A). The MeteoTracker is simple to set up and operate, can be mounted on a vehicle or bicycle, and provides high spatial resolution temperature readings (among other parameters) that are geo-referenced with GPS and altitude data. To minimise solar radiation errors and ensure data validity through adequate sensor ventilation, the vehicle or bicycle must maintain a speed above 7 km/h during collection. The sensor connects to a smartphone via Bluetooth and sends readings to an interactive map via the free MeteoTracker app and data analysis of the measured data can be done directly in the MeteoTracker dashboard. A custom API as part of the CityCLIM In-Situ Data Processor (ISDP) was built to retrieve data from the MeteoTracker platform through collaboration with IoTopon developers. To maintain anonymity and prevent user location tracking, the first and last 20 data points from each recording session are immediately removed. Further analysis includes filtering for speed over 7 km/h, normalization, and grouping the measurements to specific collection time criteria (morning and afternoon). Although field tests were completed prior to the citizen science campaigns, the MeteoTracker data were further validated by comparing the data collected from the MeteoTrackers in Karlsruhe and comparing this to the temperature measured by local weather stations from the German Weather Service, just outside Karlsruhe (in rural areas). The comparison confirmed the anticipated trend of elevated temperatures within the city centre, contrasted with cooler temperatures observed in the surrounding rural areas outside the city.

The stationary sensor used by CityCLIM citizen scientists was the National Geographic 7-in-1 Weather Station with WIFI connectivity, which is developed by Bresser GmbH (Germany) (Fig. 3C). The device is WLAN-connected and capable of automatically uploading data to two community-driven weather observation platforms: The Weather Underground and Weathercloud. The sensors will continuously upload data to the Weather Underground servers and the CityCLIM ISDP will retrieve the data using a custom API in order to make the data available in the CityCLIM cloud platform. The ISDP queries the Weather Under-



Fig. 3 The sensors used in the CityCLIM citizen science activities. **A)** MeteoTracker mobile weather network sensor developed by IoTopon (source: www.meteotracker.com). **B)** The MeteoTracker is used by citizen scientists to collect temperature data while cycling, as shown on a participant's bicycle in Karlsruhe (outlined in white box). **C)** National Geographic 7-in-1 Weather Station with WIFI connectability developed by Bresser (source: www.bresser.com). **D)** The National Geographic 7-in-1 Weather Station is shown here mounted on a pole beside the building of a participating school in Thessaloniki (outlined in white box)

ground website every 10 min to retrieve the sensor updates. This high frequency is required to capture the rapid temporal variations in urban microclimates and provide near real-time data for the project's climate modelling framework.

The citizen science data collection campaigns were carried out in summer and fall of 2023 (Karlsruhe and Valencia) and in summer 2024 (Thessaloniki). Karlsruhe opted not to use stationary National Geographic Weather Stations due to citizen data protection concerns, as the fixed sensor locations could inadvertently reveal users' home addresses. In the participating pilot cities, 41 MeteoTracker mobile sensor participants were selected mainly based on their routes in order to ensure an even coverage of the collected data. The deployment of the National Geographic Weather Stations varied across cities, based solely on the administrative teams' existing engagement networks. In Valencia, 15 stations were installed in participants' backyards or on balconies and building roofs. Thessaloniki utilised its established relationship with local schools, resulting in 15 schools installing the stations on elevated poles near their buildings (Fig. 3D).

Following the completion of the recruitment phase and the establishment of the participant cohorts in each pilot city, we implemented a comprehensive series of interactive training events (both on-site and online) to prepare the participants for the measurement campaigns. These initiatives aimed to equip participants with the necessary skills to effec-

tively use the sensors and collaboratively analyse and interpret the data they gathered. Some events were unique to particular pilot cities. The events included:

- On-site meet-and-greet and distribution of mobile sensors: Coordinating schedules among a diverse group of participants can be challenging, making it difficult to gather everyone onsite simultaneously. To address this, we provided MeteoTrackers to each citizen scientist at a meeting time that was convenient for them. This approach not only facilitated participation but also allowed for meaningful face-to-face interactions, fostering an initial connection between the project members and the citizen scientists.
- Online kick-off and training sessions for instructions on how to operate mobile sensors: Our campaign kicked off with a warm welcome event, where participants were all brought together and introduced to the project and its objectives. This event was also intended to provide a training session on clear guidance on the operation of the MeteoTrackers. These sessions were designed to be accessible and informative, covering everything from basic operational instructions to troubleshooting common issues. Participants were encouraged to engage with the material, and comprehensive guidelines are readily available on the CityCLIM website for ongoing reference (https://www.cityclim.eu/_files/ugd/f44761_af8ca8c1a5794c9d9735e8e383eb5a99.pdf).
- On-site presentations about climate and weather station maintenance: We conducted on-site presentations tailored specifically for schools and students. These sessions focused on the fundamentals of heat islands, the importance of data collection, and a how-to on maintaining the National Geographic Weather Stations that become a fixture at their schools. By engaging with younger audiences, we aimed to inspire the next generation of climate advocates and scientists.
- Additional online workshops for citizen scientists: To further support our participants, we hosted additional online workshops that facilitated deeper discussions about the data collected. These sessions provided a platform for citizen scientists to share their findings, ask questions, and receive constructive feedback from both peers and experts in the field. This collaborative approach not only enhanced their understanding of the data but also fostered a sense of shared responsibility and community among participants.

To test the feasibility of integrating and assimilating these multi-source crowdsourced datasets into the UltraHD model, establishing reliable data quality was an essential first step. Because data quality in citizen science can vary due to participants lacking formal scientific training, the structured training events and feedback loops described above were designed to proactively minimise user error and improve data reliability for this proof-of-concept application. Aside from better positioning the data to be assimilated into the UltraHD model, the events also serve societal benefits: to empower citizen scientists, enhance their climate action knowledge, and promote a collective understanding of climate data and its implications.

2.3 Space-based earth observation

The Copernicus programme provides global, continuous, and autonomous earth and atmospheric observation data from satellites, which support and underpin numerous operational services (Cinquelpalmi and Piras 2023). The CityCLIM workflow processes Land Surface

Temperature (LST) data by fusing data from multiple thermal sensors across different Copernicus satellite products. Specifically, the CityCLIM Spaceborne Data Processor combines higher spatial resolution imagery with the higher temporal frequency observations. This fusion technique downscales the lower-resolution, high-frequency temporal data using the fine spatial structures captured in the high-resolution imagery, yielding an adjusted LST dataset that simultaneously optimises spatial detail and temporal coverage for urban area monitoring. The CityCLIM Spaceborne Data Processor combines raw satellite imagery from Sentinel-2, Sentinel-3, and Landsat 8/9 into three modules, which are also products of CityCLIM: the Spaceborne Data Preprocessor, the Thermal Sharpener, and the Index Calculator (<https://www.cityclim.eu/gccp>). The Spaceborne Data Preprocessor automates and harmonises data collection from different sources of satellite-based earth observation data:

- Sentinel-3 LST provides frequent imagery (2 to 4 images per day) but coarse (1 km resolution) LST data.
- Landsat 8 and 9 LST offers higher spatial resolution (30 m) but is less frequently available (every 16 days for each satellite).
- Sentinel-2 Optical Data are used to calculate the Normalized Difference Built-up Index (NDBI) and the Normalized Difference Vegetation Index (NDVI). Within the data-fusion workflow, these indices serve as dynamic surface covariates to preserve sharp thermal contrasts between urban built structures and vegetated areas.
- ESA Worldcover is a global land cover classification product provided annually on 10 m spatial resolution. This dataset is utilised independently from the optical indices to derive explicit land-cover masks and calculate spatial distance layers (e.g. distance-to-water and distance-to-vegetation boundaries) required for downscaling the model.
- Digital elevation models are information on a city's building topology (most often existing as proprietary datasets) and is used to derive indicators on the 3D urban morphology (e.g., building height index, building roof index).

The Thermal Sharpener fuses coarse but frequent LST (Land Surface Temperature) data from Sentinel-3 (2-4 images a day at 1 km resolution) with finer but less frequent data from Landsat 8 and 9 (every 16 days at 30 m resolution), which yields bi-daily LST outputs at a 30 m resolution, ~1 °C accuracy, and same-day validation. The sharpened LST outputs were validated against (i) an in-situ LST field campaign conducted across the city and (ii) airborne LWIR data from our 2024 Valencia flights (Sect. 2.4). The ESTARFM (Enhanced Spatial and Temporal Adaptive Reflectance Fusion Model) sharpening method is employed to fuse data from Sentinel-3 and Landsat 8/9 satellites, which integrates both spatial and temporal variability into the model. The Sentinel-2 Optical Data are used to calculate NDBI and NDVI, both of which contribute to the fusion process. The Index Calculator processes these data streams to generate key environmental indicators that characterise urban surface anomalies and human biometeorological discomfort:

- Urban Hot Spots (UHS) is an index that identifies areas with significantly higher LST linked to impervious surfaces and human activity.
- Surface Urban Heat Island (SUHI) is an index that measures LST differences between urban and rural areas, showing urbanization impacts.
- Urban Thermal Field Variance Index (UTFVI) is an index that assesses LST variability

within urban areas, indicating thermal heterogeneity.

- Urban Heat Island Intensity Index (UHII) is an index that measures intensity of the urban heat island effect by comparing LST between urban cores and rural areas.
- Discomfort Index (DI) is an index that combines surface temperature and relative humidity to quantify heat and humidity effects on comfort. Relative humidity is sourced from the ERA5 land reanalysis dataset and is used in combination with LST to calculate the DI. The ERA5-Land relative humidity data are used exclusively for calculating the DI. High precision for this variable is not essential, as an error of 10% in relative humidity is acceptable for DI computation as the formula is mathematically dominated by the temperature component and a $\pm 10\%$ variation in relative humidity results in a final index deviation that does not alter the qualitative heat stress classification thresholds.

The urban areas of interest for heat analysis and indices are calculated from WorldCover data on urban classes. Where needed, these were supplemented by custom geographic boundaries (rectangular coordinate frames or bounding boxes) that were manually defined by our municipal partners to ensure the analysis aligned with local administrative districts or specific areas of interest. An extensive field campaign was also undertaken to measure in-situ LST at various locations across the city. The field data were compared to satellite-derived LST in order to validate and enhance accuracy of satellite imagery. The resulting dataset of validated scenes along with their statistical accuracy metrics is publicly available as an open-access repository record (De la Fuente Daruich and Sobrino 2024; <https://zenodo.org/records/13693256>).

2.4 Airborne campaigns

Airborne thermal imaging occupies a niche between frequent but coarse spaceborne thermal sensors (e.g. ESA Sentinel-3: 1000 m, NASA Landsat-8/9: 100 m, future missions including ESA LSTM and commercial: 30–50 m) and sparse, highly localised in-situ measurements. Whereas spaceborne sensors excel at providing a consistent stream of data and cover large areas, they fail to resolve fine details of the urban environment. In contrast, in-situ measurements can provide highly specific, accurate, and time-resolved information at selected points of interest, but fail to deliver meaningful spatially resolved maps. Airborne thermal sensors provide LST measurements at resolutions suitable for resolving fine urban detail (modulated by operating altitude and sensor design) while covering larger spatial areas. Because they must be deployed specifically, they offer high spatial detail but limited temporal coverage, effectively providing thermal “snapshots” rather than continuous time series.

Accurate thermal remote sensing is challenging because thermal radiation is modulated by surface temperature and by surface properties (surface emissivity), requiring a method that can differentiate between these effects (Li et al. 2013). Appropriate methods, summarized as TES (Temperature Emissivity Separation) require either additional data or a multiband sensing principle (Wang et al. 2019). For the latter, commercial options are limited: existing airborne hyperspectral TIR systems, such as NASA's HyTES (Hook et al. 2013), remain primarily research instruments/prototypes with limited commercial availability. Due to their advanced operating principles, they are additionally incompatible with project limitations, both due to SWaP (size weight and power) requirements exceeding aircraft capabilities and also significant cost based on their niche applicability.

To circumvent these limitations, OHB Digital Connect (a partner in the CityCLIM project) developed RAVEN (Remote Airborne Variable Emissivity and Temperature SeNsor; Fig. 4B), a thermal sensor that considered SWaP, adopting a minimal multiband land surface -temperature sensing scheme based on commercial off-the-shelf components. The following campaign illustrates its application within CityCLIM, demonstrating how compact multiband thermal imaging can complement satellite and model datasets. RAVEN and the utilized measurement principles are described in greater detail in Appendix 1.

RAVEN as primary sensor was accompanied by a high-resolution RGB (red, green, blue) camera (PhaseOne ixm-100; www.phaseone.com; Fig. 4C) to provide natural imaging for enhanced interpretability of temperature data, as well as GNSS (Global Navigation Satellite System) and inertial measurement units to record aircraft pose and location, as required for geo-referencing of imagery and temperature data. Data were processed with the CityCLIM Airborne Data Processor, which applies standard radiometric and geometric corrections.

In the scope of CityCLIM, an airborne campaign was carried out in the pilot city Valencia in the summer of 2024 over two flight days (2024-09-10 and 2024-09-11). RAVEN was deployed on a lightweight motorized glider plane (Stemme S10 VT; Fig. 4A), which provides stable flight characteristics and lower fuel consumption in comparison to other aircraft, thus being well-suited for imaging tasks while at the same remaining environmentally-conscious. The three-kilometre altitude necessary to enable data collection covering a substantial area with a resolution near 4 m is too high for a drone, which is why planes are needed for this endeavour. Since the aircraft used for airborne campaigns is a glider, this inherently reduces noise during flights over residential areas, thereby minimizing disturbances for local residents, even at low altitudes.

The flight campaign was accompanied by a field campaign providing ground measurements used to validate both satellite- and airborne-based EO data. Land Surface Tempera-

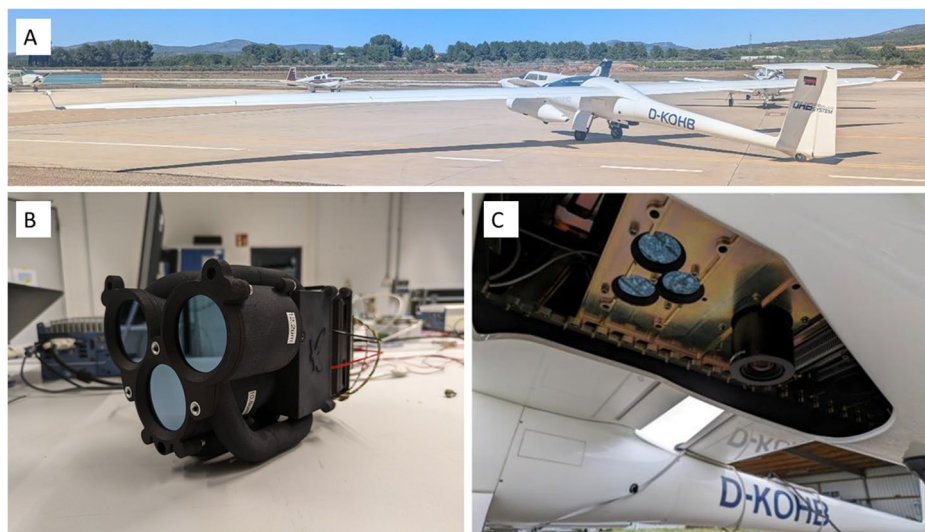


Fig. 4 The aircraft and sensor system used in the airborne campaign. **A)** the motorised glider aircraft prior to take-off for the Valencia campaign in Summer 2024. **B)** close-up of the RAVEN sensor before installation. **C)** the RAVEN sensor integrated into the aircraft beside a high-resolution RGB camera and secondary sensors for position and location

ture (LST) and spectral radiances in different bands (Appendix Fig. 1) were measured at various locations across the city, and surface types were classified for selected areas. The field data supported sensor calibration refinement and provided qualitative reference for assessing airborne retrieval consistency.

The main objectives of the campaign were (i) to verify the performance of the RAVEN system and associated data processor under real-world conditions, (ii) to demonstrate high-resolution mapping of intra-urban temperature variability, and (iii) to provide a high-resolution LST dataset for continued use, including verification of the UltraHD urban weather model and other purposes (for example as verification dataset or training target for LST downscaling methods).

3 Results

3.1 Citizen science

The CityCLIM citizen science data collection campaigns engaged a group of 1,080 citizen scientists. In Karlsruhe, 72 individuals expressed enthusiasm for participating in citizen science activities using a MeteoTracker mobile sensor. However, due to a limited number of available sensors, only 21 participants could be selected for this initiative. In Valencia, the response was equally promising, with 20 weather enthusiasts volunteering to install and maintain 15 National Geographic Weather Stations in their backyards or balconies during the campaign period. Participants also utilized 10 MeteoTracker mobile sensors, collecting temperature data as they travelled throughout the city by bicycle or car. Thessaloniki took a unique approach by engaging 15 local schools in hands-on activities centred around the National Geographic Weather Station, educating students about the phenomenon of urban heat islands. These interactive events attracted 1019 attendees, including students, educators, school directors, and community members. Additionally, 10 participants in Thessaloniki utilized the MeteoTracker to gather mobile temperature data, contributing further to the local climate knowledge base.

MeteoTracker data could be viewed by participants in real-time in the MeteoTracker dashboard, which has built-in data analysis and visualisation (Fig. 5A). The data were also able to be retrieved by the CityCLIM project partners for use in various other platforms, for example interactive maps for citizen scientists on the UFZ website and on the Karlsruhe city dashboard. The National Geographic Weather Station data could also be viewed in real-time by participants on the Weather Underground website (www.wunderground.com), which also has basic visualisation capabilities for current and past collected data (Fig. 5B). Visualisation of the temperature data across multiple platforms was intended to promote interaction from the citizen scientists with their collected data. In the follow-up online workshops for citizen scientists to share their findings, this presented qualitative evidence that interaction with the data analysis platforms deepened awareness for urban heat island knowledge. Workshop feedback and discussions indicated a shift from basic data understanding to recognising local and actionable implications.

The National Geographic Weather Stations are able to remain an educational tool within the participating schools in Thessaloniki, as they stay installed on school grounds and students are able to track their local weather in real-time. This enables ongoing engagement

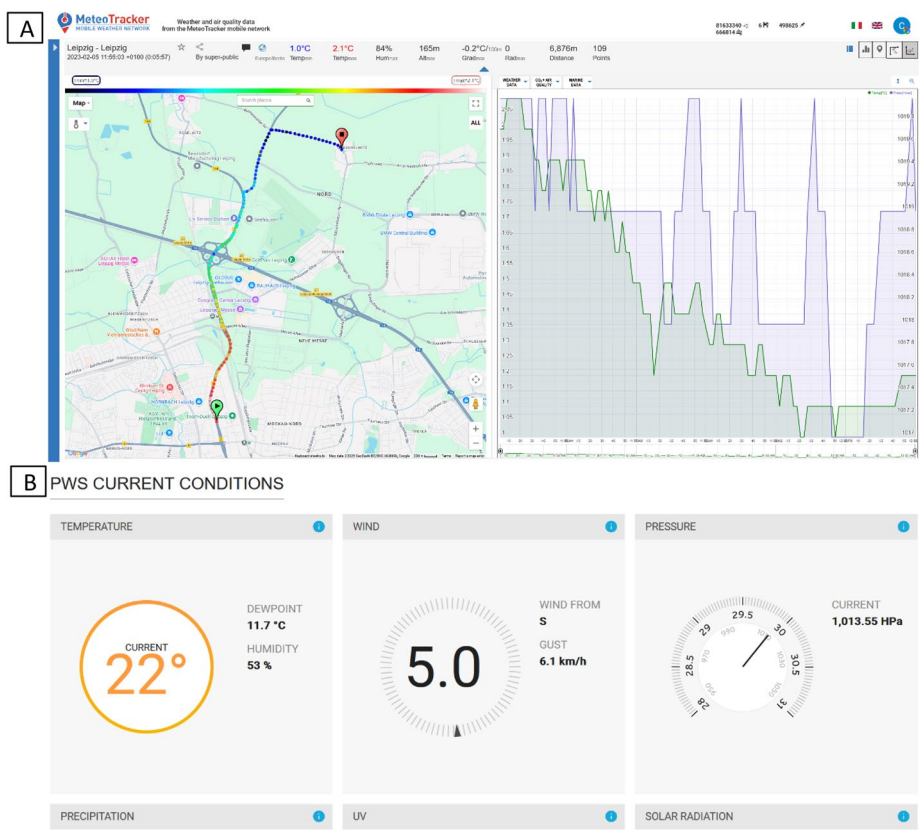


Fig. 5 MeteoTracker data can be viewed directly from the MeteoTracker dashboard (A), which shows a map of the points collected and a graph where the user can select various parameters to view (temperature, altitude, relative humidity, dew point, air pressure, solar radiation intensity). The National Geographic Weather Station data could also be viewed in real-time by participants on the Weather Underground website (B), which displays PWS (personal weather station) current conditions (as shown in the screenshot) as well as options to view data collected in the past by the weather station

with climate science and teachers are able to use the stations even after the CityCLIM project's end, for example to teach lessons on local climate analysis, weather pattern observation, and hands-on data literacy training. Crucially, all MeteoTrackers distributed to the pilot cities continue to play an active role in ongoing urban heat island research, utilized by city administrations and associated research institutions like the Karlsruhe Institute of Technology (KIT). Along with KIT researchers and students, the MeteoTracker data continue to be analysed and the results sent to city administration to support climate adaptation efforts (Fig. 6). A Pilot City Questionnaire following the campaigns revealed that citizen science data would be integrated in decision making through climate change adaptation planning and reporting. For instance, Thessaloniki's Regional Climate Change Adaptation Plans (RCCAP) outline a comprehensive set of measures and actions that stakeholders will undertake to address climate change impacts. The report will integrate data collected from citizens, alongside CityCLIM weather model simulations and satellite measurements, to provide high spatial resolution climatic information.

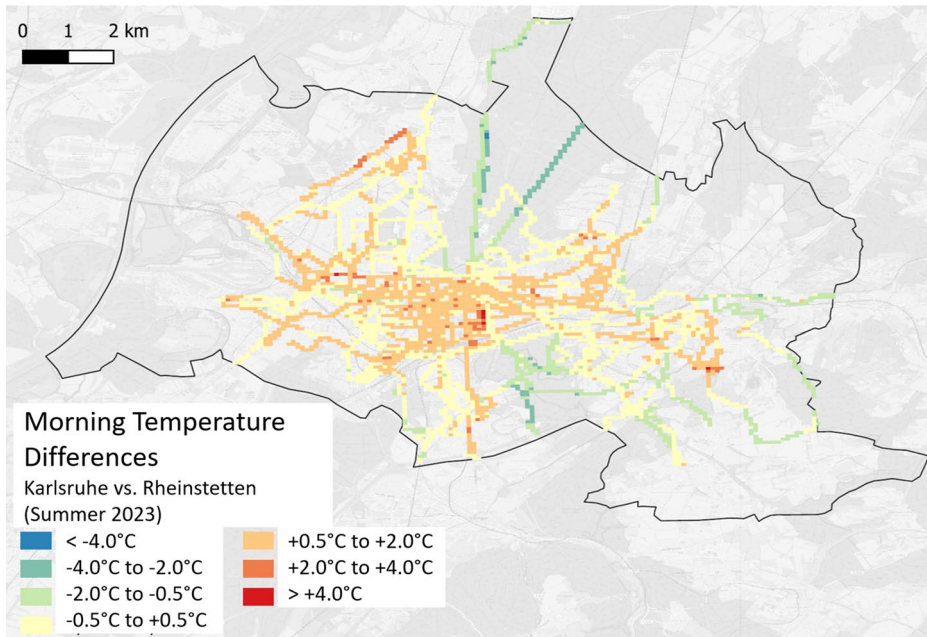


Fig. 6 MeteoTracker data collected by the citizen scientists were used by KIT scientists for student projects and to inform city administration. Preliminary results from KIT analyses are shown here, illustrating the temperature differences between Karlsruhe city (shown here within the black border; temperature measured by citizen scientists using MeteoTrackers) and a nearby rural town Rheinstetten, as measured by local weather stations from the German Weather Service. The city centre generally exhibits higher temperatures, although some areas display “microclimates” with cooler temperatures

The CityCLIM In-Situ Data Processor (ISDP) and custom-built API successfully retrieved data from both the MeteoTracker and National Geographic Weather Station by collecting data from the sensors via third-party servers and storing it on the CityCLIM cloud platform. The data could also be accessed by partners and downloaded as .json file format, in order to perform further analyses or visualisations for use by researchers or city planners. This served as proof-of-concept for data assimilation, demonstrating that the citizen science data could be technically integrated and processed by the UltraHD model. In theory, the additional fine-grained data collected by citizen scientists could help to improve the model by enhancing resolution. However, continuous measurements are required for the data to be useful for the model long-term, which is a challenge given the barriers to sustainability of citizen science activities. The data collection period of the citizen science campaigns was insufficient for the purposes of long-term data assimilation into the UltraHD model. If a long-term program was set-up with the intention of providing continuous data to the model, citizen science data could be integrated into the UltraHD model and resulting climate services.

3.2 Space-based earth observation

Based on the satellite-based earth observation data and the Spaceborne Data Processor, the EO-based Heat Island Identification service is now operational for the four case study

regions within CityCLIM. This service provides 30 m daily land surface temperature (LST) data from multiple thermal sensors onboard satellite platforms, reaching an accuracy of approximately 1 °C. After pre-processing the multiple satellite data sources, the resulting combined images from the Thermal Sharpener produce accurate, high resolution, LST products (Fig. 7).

The Index Calculator displays the sharpened LST data series with calculated indices that are understandable to users and provides insights for decision making and urban planning to reduce heat islands. For example, the surface urban heat island (SUHI) index maps generated for each pilot city illustrate the variations in surface temperatures between urban and surrounding rural areas, and could enable users to examine how various urban configurations impact the comfort of residents (Fig. 8).

The results demonstrate significant improvements in temperature data enhancement from original coarse images to resolution-enhanced images, particularly in regions with low cloud coverage. Evaluating reliability in urban heat analysis inherently requires satisfying the dual criteria of continuous spatial-temporal coverage and multi-tiered data validation. Because a contiguous, city-wide ground truth dataset is operationally unachievable, a possible reliable solution relies on multi-source data fusion where independent atmospheric and surface data streams systematically cross-verify one another.

3.3 Airborne earth observation

The Valencia pilot airborne campaign in conjunction with the accompanying ground campaign was carried out on two main flight days, with the second (2024-09-11) being partly clouded. Data analysis therefore focused on the first day (2024-09-10). Data were recorded in multiple consecutive flight lines, each covering a part of the city centre. Flight paths needed to be oriented in parallel to the approach of Valencia airport, which is located within the urban area. An overview of relevant acquired data is given in Fig. 9, showing an orthomosaic of flight lines covering the city centre. Additional flight lines covering surrounding suburban and rural areas were not considered for further processing.

The operational deployment of the Valencia pilot airborne campaign yielded a successful proof-of-concept data collection across two main flight days. While the second day (2024-09-11) was compromised by partial cloud cover, the campaign successfully generated a

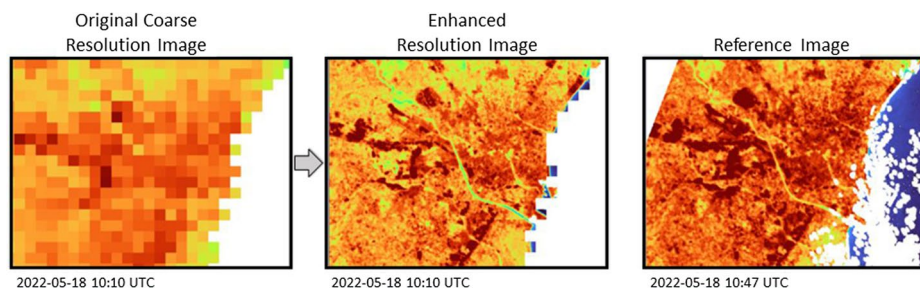


Fig. 7 A sharpened image of Valencia LST following enhancement from the Thermal Sharpener, and comparison of results to a reference image. The spatial resolution of the original image is 1 km while the spatial resolution of the reference image is 30 m (Landsat, natively acquired on 100 m, delivered on 30 m). The resolution of the enhanced image has been improved to match the reference image (20 m). The LST colour scale is the same for each image. The reference image displays slightly warmer (darker red) temperatures due to the later timing of the image acquisition

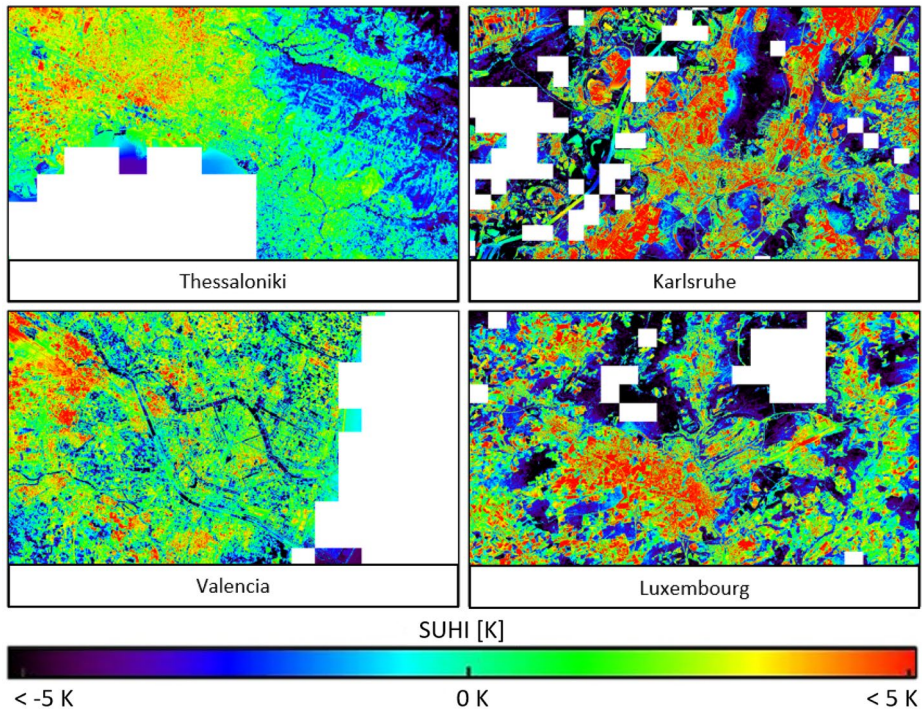


Fig. 8 Surface urban heat island (SUHI) index maps calculated for each of the pilot cities show cold areas (e.g. parks, rivers) are highlighted with blue colours, while impervious hot areas are highlighted in red. The white areas indicate the sea (Valencia, Thessaloniki) or cloud cover in one of the underlying datasets (Sentinel-3, Sentinel-2). The maps suggest that the SUHI effect is more pronounced in Karlsruhe and Luxembourg. However, the basis for the analysis (LST downscaling) are the Sentinel-3 data, which were acquired before midday. Thessaloniki and Valencia have not received as much solar warming by this time and is also cooled by the Mediterranean Sea

contiguous dataset on the first day (2024-09-10), which is therefore the focus of the data analysis. Navigating the complex airspace constraints of the nearby Valencia airport, the system successfully recorded multiple parallel flight lines covering the city centre. The primary visual output of this deployment is presented as a compiled orthomosaic in Fig. 9, demonstrating the sensor's capacity to map the city centre.

To provide more insight into the data compiled into the orthomosaic, two selected frames are displayed in Fig. 10, highlighting resolution of the data and alignment of thermal features with natural image features. Thermal features indicate the same characteristics and trends observable in lower-resolution spaceborne imagery. For instance, impervious built surfaces and barren areas generally exhibit higher temperatures, whereas vegetation and water bodies (natural or man-made) remain cool.

Although characteristics and trends are similar, the effect of higher resolution is also apparent and manifests primarily in the decreased presence of mixed pixels, leading to more well-defined delineations between regions of different land covers. Further, features that are lost at coarse resolution emerge. Examples for this are smaller parks or metal roofs. Whereas parks are naturally cool, metal roofs emit very little thermal radiation even when

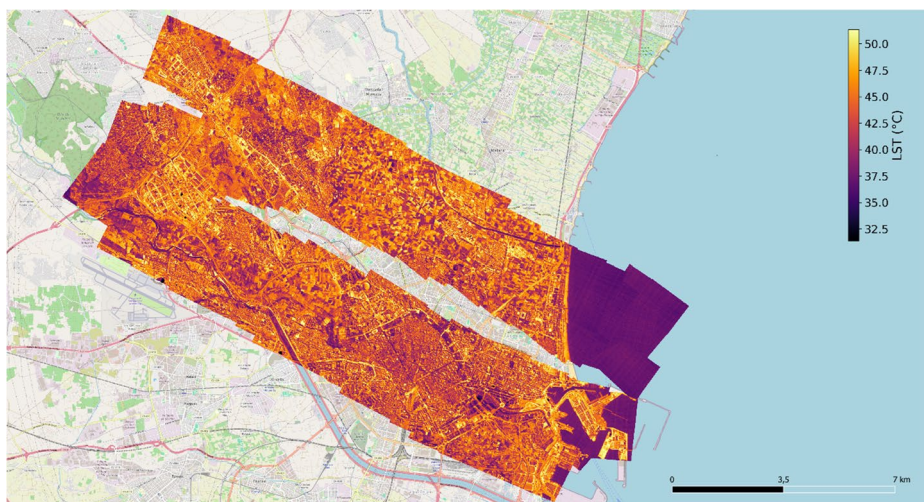


Fig. 9 Orthomosaic of airborne Land Surface Temperatures collected on 2024-09-10 and processed via the CityCLIM airborne data processor. To comply with aviation security, a central flight line in immediate proximity to the approach could not be executed as planned, leading to a data gap in the city centre. Basemap by openstreetmap (www.openstreetmap.org)

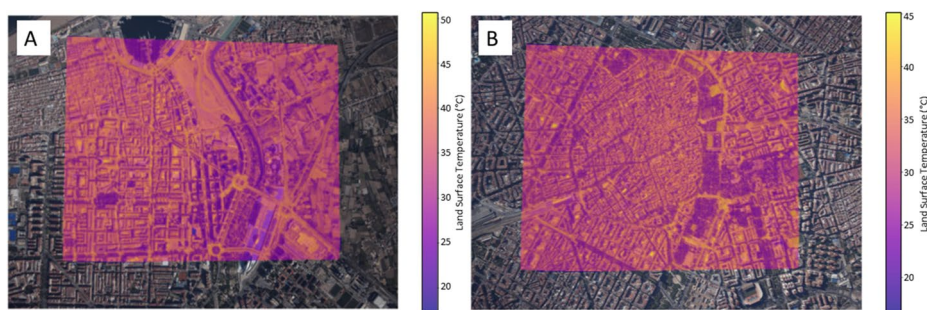


Fig. 10 Land surface temperature retrieved via airborne measurements overlaid onto accompanying RGB data. **A)** Near Valencia harbour, 2024-09-10 14:54 UTC. **B)** Valencia city center and Jardines del Real city park, 2024-09-10 15:30 UTC. Two locations were chosen to highlight resolution of the data and alignment of thermal features with natural image features (e.g. water bodies)

at high temperature due to their small emissivity, making them appear cool with improper high-resolution correction. Such surfaces are “overlooked” in lower-resolution imagery, highlighting the averaging effect of decreased resolution: while correct on a larger scale, for example for delineating urban heat islands, lower-resolution thermal imagery fails to correctly detect local extremes and underestimates gradients.

Beyond providing high-resolution maps, airborne measurements were also compared quantitatively to in-situ measurements for end-to-end verification of the data acquisition and processing system. This verification architecture was achieved as shown in Fig. 11. The framework successfully paired an in-situ measurement (e.g. a temperature measurement and a surface characterization, both for a sufficiently large, homogeneous surface), and the

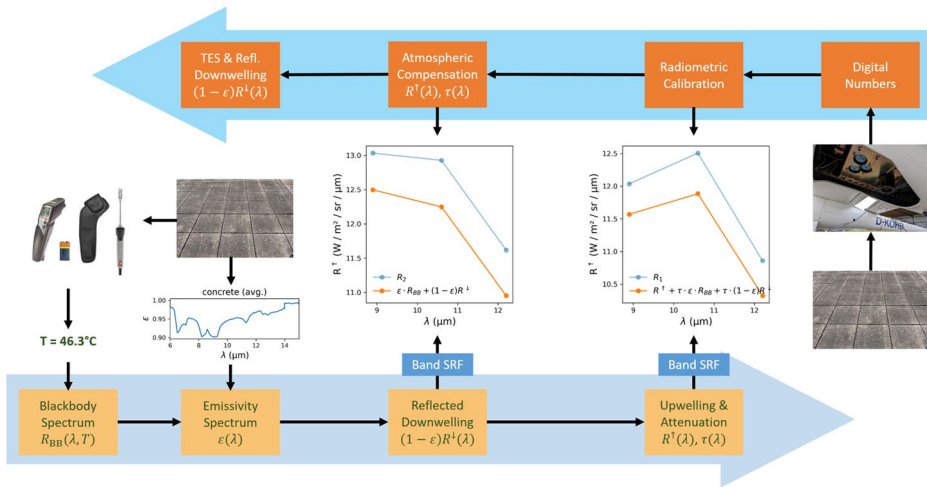


Fig. 11 End-to-end verification framework demonstrating the successful structural alignment and processing flow between airborne thermal data and empirical ground measurements

associated airborne measurement in close temporal proximity, demonstrating the system's operational capacity to link ground-truth data with remote sensing flights. By employing catalogued emissivity data and atmospheric parameters, both the magnitudes of emitted radiance (surface-leaving radiance, before atmospheric attenuation) and received radiance (at-sensor radiance) can be simulated. By following the inverse path, that is by starting with the associated airborne measurement after calibration (at-sensor radiance) and applying, consecutively, atmospheric correction followed by temperature emissivity separation, the same processing intermediates and end products can be created. This enables comparison at different stages of the processing pipeline. The example in Fig. 11 highlights this comparison and indicates a typical result: Radiances measured by the airborne system exceed simulated radiances. However, the effect manifests as a near-constant offset which is similar for all three bands, indicating that the error giving rise to this lies within a processing step applied to all bands in the same way. For a more detailed account of processing steps applied to airborne data, refer to Appendix 1.

Overall, the snapshot of results demonstrates that the RAVEN sensor system and City-CLIM Airborne Data Processor are successful in collecting, processing, and evaluating thermal infrared data. The georeferenced, high-resolution thermal imagery reproduces the overall structure, trends and characteristics of low-resolution data. However, it enables the identification of features lost in lower-resolution data and specifically excels at detecting local extremes and gradients, therefore promising significant improvements for specific tasks, while at the same time being suited for validation and verification activities involving other data sources.

Similarly to the issue of citizen science data, airborne data has limited potential for operational use as it is limited by the mode with which it is collected. Airborne campaigns are limited to specific points in time and are heavily influenced by external factors, including regulation and adverse weather conditions. Nevertheless, comparably lightweight thermal sensors employing advance measurement principles beyond broadband measurement show

potential, raising the possibility of future adaptation (e.g. on unmanned platforms for a more flexible on-demand deployment).

4 Discussion

In this article, we presented three diverse examples of emerging data sources for climate adaptation, which are distinct in terms of methodologies but demonstrate how the integration and combination of these evolving data streams can overcome traditional monitoring constraints. Our empirical results — ranging from the high-resolution RAVEN flight orthomosaics to the citizen science mobile measurements — demonstrate the practical utility of these platforms. Synthesising these findings within current geographic data science literature requires evaluating how these data streams are classified as “emerging” in relation to conventional monitoring. Citizen science in itself is an emerging methodology because it harnesses the collective efforts of the public to gather in-situ and real-time data that can complement traditional data sources (Haklay 2012). CityCLIM further applies the citizen science methodology in conjunction with mobile climate sensors connected to cellphone apps and WLAN-connected stationary weather sensors that are considered IoT (Internet of Things) devices. In this sense, the emerging concepts are a combination of crowdsourced data, mobile sensors, and IoT sensors (Zheng et al. 2018; Hsu et al. 2020). Another emerging source is Big Data, which are vast amounts of data that are generated in great volume from various sources (Arribas-Bel 2014). While satellite products have existed for some time, the full and free accessibility of Copernicus global observation data are relatively novel as open access to Copernicus data began in 2013 (Copernicus 2022). This qualifies satellite-based data as Big Data, or collectively as “Big EO Data”, one of the commonly considered subsets of emerging data sources (Hsu et al. 2020). Big EO Data make earth observation one of the most promising tools and fields of research that has emerged in recent decades for *widespread* use by urban planners, decision makers, and building designers in improving urban resilience in response to climate change (Cinquelpalmi and Piras 2023; Hsu et al. 2020). Furthermore, CityCLIM uses Copernicus data by fusing data from multiple thermal sensors on board satellite platforms in order to reach the higher accuracy of spatial patterns recorded by medium- and high-resolution thermal images to produce LST (Land Surface Temperature) data with improved temporal frequency and spatial resolution. Similarly to satellite EO applications, airborne data collection methods for environmental research are prevalent, from in-situ measurements of atmospheric constituents to Lidar (Light Detection and Ranging) scanning used to examine earth surface characteristics (Wendisch and Brenguier 2013). The CityCLIM project applies airborne data collection in conjunction with a custom-made thermal sensor to collect images not normally accessible with other remote sensing approaches. This approach reveals more fine-scale features and dynamics as compared to standard remote sensing methodologies. Having distinct types of emerging data sources for climate adaptation provides diverse perspectives and insights, allowing for a more comprehensive understanding of climate impacts and potential adaptation strategies.

The key stakeholders targeted by the CityCLIM project (city planners, city administration and officials) rely on a set of conventional data sources for climate adaptation planning. Conventional data sources include official meteorological stations, standard satellite imagery, and administrative records (e.g., land use maps), which are used to design plans to

mitigate climate change such as sustainability plans, spatial development plans, and emergency response plans (Reckien et al. 2018). However, the shortfall of conventional data sources often lies in the low resolution of the data in terms of spatial and temporal resolution (Arribas-Bel 2014). As introduced in this article, the main objective of the CityCLIM UltraHD model is to provide a high-resolution weather model (100 m by 100 m, as opposed to the resolution of several kilometres employed by official meteorological stations) in order to output data that are more usable and actionable by city planners and administration. Standard satellite imagery also has limited spatial and temporal resolution and administrative records are static and lacks real-time context. The methods presented in this paper were tested as a proof-of-concept to be technically assimilated into the UltraHD model as well as capability of generating fine-scale highly localised information on environmental data such as temperature measurements. In terms of these goals, the citizen science collected data were able to be technically assimilated into the UltraHD model and the sensors delivered real-time, highly localised information on weather conditions. This is demonstrated by the successful mapping of steep microclimate gradients, such as the morning temperature deviations between Karlsruhe city center and the rural reference station in Rheinstetten (Fig. 6). In addition, mobilising citizens to collect climate data expands observation networks to a larger extent and variety of spatial and temporal coverage beyond the existing professional weather stations that captured data for the UltraHD model. However, ultimately citizen science was not a suitable method in improving the model long-term as the data collection period was insufficient for the purposes of long-term data assimilation into the UltraHD model. Sustained data contribution to the model remains a challenge, primarily because the longevity and continuity of any citizen science project is inherently difficult to maintain, with barriers being attributed to lack of funding, dwindling volunteer enthusiasm/commitment, and absence of long-term communication (Cunha et al. 2017). The main barriers in the CityCLIM citizen science campaign were lack of capacity from the city administration (whose role in the project extended beyond solely coordinating the citizen science activities) and also the lack of funding, since partners were no longer obligated to organise data collection campaigns following the project's end. Although the CityCLIM citizen science data collection campaigns did not continue long enough to provide data to the UltraHD model, the data collected were used additionally by city administrators in sustainability plans (e.g., Thessaloniki's Regional Climate Change Adaptation Plans) and sensors remained in the pilot cities for use by schools and universities.

CityCLIM's generation of fused and sharpened satellite-based products also provided fine-scale data that are suitable for urban planners, city administration, and researchers interested in understanding and mitigating the effects of urban heat. These stakeholders would also be able to look at satellite-based LST maps in a more understandable and actionable way. For example, by identifying heat islands and hot spots on LST maps displaying the Surface Urban Heat Island (SUHI) index (Fig. 8), city planners can implement strategic interventions, such as enhancing green spaces or improving urban design, to effectively lower surface temperatures. This utility is evident in the sharpened imagery for Karlsruhe and Luxembourg, where distinct thermal signatures of localised built environments are isolated (Fig. 8). In the context of public health, the Discomfort Index identifies areas on the maps where extreme heat may pose a risk to human health, which could help guide public health responses during heatwaves. Airborne EO data are capable of bridging the gap between coarse but frequent satellite data and highly localized in-situ measurements by

providing high-resolution LST data that account for finer urban features. Our pilot campaign in Valencia proves this capability; the RAVEN sensor successfully revealed extreme local gradients and features that are entirely averaged out or overlooked in coarse satellite imagery, such as individual small urban parks (Fig. 10). The data can also be used as a layer of verification for model simulations, improving public confidence and trust in climate models – an essential factor in overcoming societal barriers to climate adaptation (Hargreaves and Annan 2014). Like the CityCLIM EO-based Heat Island Identification service, the high-resolution LST data gathered from airborne campaigns can be utilised to generate detailed heat maps. The maps offer valuable insights into local heat island effects, informing thermal comfort assessments that guide urban planning initiatives designed to mitigate extreme heat conditions. It is crucial to note, however, that the displayed LST is a key indicator but remains only a proxy for true thermal comfort. While each data source has value on its own, their combined use provides stakeholders with a more complete understanding of the “bigger picture”.

While the achievements of these emerging data sources in bridging climate action knowledge gaps have been presented thus far, it is equally important to address their inherent limitations and operational challenges. As mentioned above, a key operational challenge for citizen science activities is ensuring sustained data contribution due to common issues like funding shortages and declining volunteer commitment (Cunha et al. 2017). Further, one of the primary risks associated with the use of IoT-connected devices is the potential for data privacy and ethical concerns (Arribas-Bel 2014; Hsu et al. 2020). The collection of personal and geolocation data raises significant ethical questions about privacy and consent. For instance, the MeteoTracker sensor continuously monitors a user’s real-time location (provided they have opted to share their data publicly), thereby creating the risk of the user’s whereabouts being tracked. To address these issues, it is essential to implement strategies that safeguard individual rights during data collection. In the case of the MeteoTracker, measures have been taken to enhance user privacy by removing the first and last data points, thereby concealing users’ start and end locations, such as their home or workplace. Another challenge associated with IoT devices is connectivity issues. A delay in sensor response due to poor connectivity could affect the accuracy of temperature data collection, especially through city environments where many different microclimates could be found over a short distance. Localised spatial gaps where GPS errors and cellular lag temporarily disrupted real-time tracking is a common failure noted in mobile urban crowd-sensing (Overeem et al. 2013). The citizen science approach worked well for mapping of regional anomalies (such as the Karlsruhe-Rheinstetten temperature difference) but underperformed at trying to establish continuous, systematic baseline grids. Because volunteer routes were opportunistic rather than systematically planned, our dataset exhibited spatial-temporal sampling biases, which matches the crowdsourced data limitations documented by Meier et al. (2015). A main limitation of Big EO Data is the lack of technical capacity for stakeholders and decision makers to interact with this vast quantity of collected data, making it underutilised as a data source (Hsu et al. 2020). CityCLIM addresses this limitation by translating raw EO data into maps with useful heat indices, such as SUHI (Fig. 8), which are able to be more easily understood and used by planners and decision makers. However, when complex environmental information is simplified into actionable metrics such as calculated indices (like the SUHI), it creates an inherent risk of relying on proxies that may not be fully accurate. This challenge is particularly evident when relating physical measurements like surface or

air temperature to subjective human experiences, such as thermal comfort (Goldblatt et al. 2021). Our thermal downscaling algorithm succeeded most robustly in inland cities with high structural contrast (Karlsruhe and Luxembourg), but the approach faced challenges in coastal test sites (Thessaloniki and Valencia) due to maritime cooling, masking daytime satellite-derived SUHI intensity compared to inland counterparts as in Zhao et al. (2026). The airborne data collected in CityCLIM is obtained through a newly designed sensor (RAVEN sensor). As with any novel data source, this raises important questions about data quality and reliability. Therefore, it is recommended that any new data source undergo an initial research and validation period (as executed via our end-to-end ground-truth matching framework; Fig. 11) to thoroughly assess its reliability before being integrated into decision-making frameworks.

Ultimately, incorporating diverse data from citizen science to satellite and airborne observations into climate services and tools presents a multitude of advantages that enhance our understanding and response to climate change. These methods, as applied in the CityCLIM project, make climate action knowledge not only visible but also deeply rooted in local contexts. Together, these data sources allow for a holistic view of urban environments, capturing both physical and human dimensions of climate adaptation. They provide comprehensive, high-resolution insights that are useful for monitoring heat stress and informing decisions regarding urban heat management. These emerging data sources fulfil the essential criteria of accessibility, understandability, and actionability, catering to diverse types of stakeholders — from policymakers and researchers to community activists. The approaches support a diverse possibility of actions to reduce the impacts of heat on city environments and improve overall liveability for its residents. The advantages of emerging data sources presented in this research highlights the critical need for sustained innovation in data collection and analysis to keep pace with the rapidly evolving urban climate landscape. Future research pathways to bring emerging data sources to the forefront are development of longevity and scalability mechanisms (e.g., exploring non-grant funding streams like public-private partnerships for citizen science activities), interoperability mechanisms (e.g., making the data streams fully interoperable with established municipal planning systems), and integration with policy mandates (e.g., higher-resolution data especially for cities can be used to establish legally defined thresholds for urban heat mitigation efforts and measurable performance indicators). Integrating these future pathways into city planning faces multiple barriers, including: economic (absence of funding to renew old systems), institutional (limited capacity and competing priorities), and political (lack of political will to formally integrate non-traditional data into official decision-making frameworks).

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Data availability Exemplary datasets generated during and/or analysed during the current study are available in the Zenodo repository (<https://zenodo.org/records/10598570> and <https://zenodo.org/records/12742931> [citizen science data], <https://zenodo.org/records/13693256> [fused and sharpened satellite-based EO data], <https://zenodo.org/records/14204875> [airborne campaign data]). The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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