

High-Resolution Urban Climate Visualization: A Dual-Screen Approach for Public Engagement

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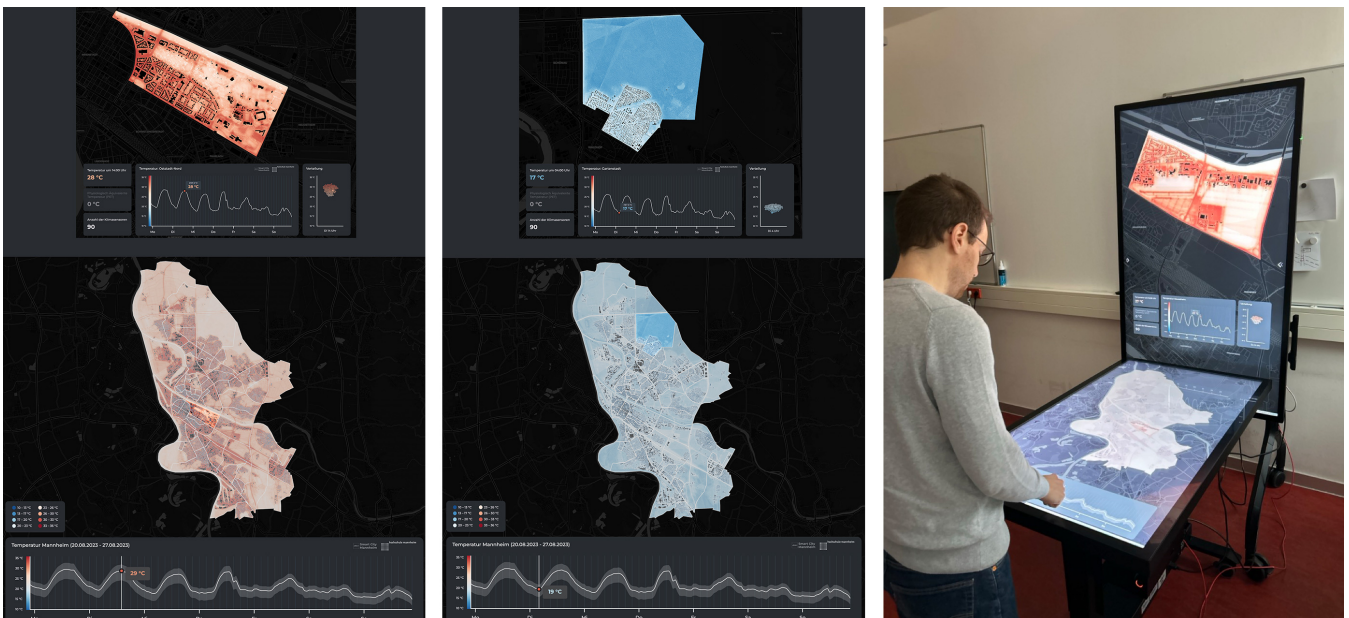


Figure 1: Example visualizations and installation setup. Left: a hot spot at 2 p.m. Middle: a warm spot at 4 a.m. Right: the interactive installation with a horizontal touchtable displaying the city-wide visualization, and a vertical screen showing the detailed view for a selected district. Users can select times and districts directly via the tabletop interface.

Abstract

Rising urban temperatures and climate variability increasingly affect city residents, yet accessible tools for understanding local climate dynamics remain scarce. This paper presents an interactive visualization of Mannheim's urban microclimate, designed primarily for citizens to explore climate patterns in their neighbourhood. The system is based on a high-resolution, AI-supported climate model that integrates real-time sensor data on temperature, perceived temperature, humidity, wind conditions, and global radiation. To provide intuitive access to climate variability, the visualization presents data for a full summer week, revealing diurnal patterns and variations across different weather conditions. The system aims to balance context and detail and is deployed on an interactive touch-table, complemented by an auxiliary screen in order to display the entire city for an overview, allowing users to focus on selected districts while maintaining comparability and contextualization. By mapping fine-scale climate variations onto familiar administrative units, the tool enables citizens to better understand microclimatic changes and their local implications. This work contributes to environmental visualization by combining geospatial modelling with intuitive visual representations to foster climate literacy and informed urban adaptation strategies. We discuss design choices, user engagement considerations, and the potential for extending the system to predictive modelling and scenario-based exploration.

1. Introduction

Climate change and the associated rise in temperatures will have a significant impact on the urban living environment in the coming years. To preserve livability and to make cities more sustainable, smart city initiatives are helping urban planning by providing real-time climate data [KS21]. In the context of the city of Mannheim, hundreds of climate sensors will be placed throughout the urban area to continuously provide measurement data for a fine-grained temperature model or grid. This data can be used to gather specific insights on urban heat, tropical nights or sealed surfaces [SMP*19, VMF*20]. These findings can be used, on the one hand, to plan the adaptation of urban areas to changing temperatures and, on the other hand, to communicate the changes to citizens. This will help to better inform and sensitize them to climate change [TCC22]. From a data visualization perspective, there are various systems for extracting insights from the collected data. These support both urban planning experts in-depth analysis and lay citizens without specific domain knowledge [MEP24]. The local relevance of the data and findings plays a particularly important role for citizens, enabling them to see in as much detail as possible how they are affected by the effects of temperature changes in their daily lives. During the corona crisis, data was typically published to the public at the state or county level, limiting citizens ability to understand local impacts [PSW23]. In addition, existing approaches often fall short in supporting temporal exploration because they typically rely on static representations or snapshots of selected points in time. To counteract the climate crisis, our approach presents a fine-granular grid of data aggregated at the neighbourhood level, enabling citizens to explore urban heat patterns in both spatial and temporal context, making climate data more tangible and personally more relevant.

2. Related Work

2.1. Climate Visualizations

Visualizations are widely used in climate science to understand data on how climate change is affecting our surrounding environments. Since everyone is affected, it targets different audiences [LSR22]. This range from climate scientists that want to create profound analysis, to policymakers and urban planners that need to plan and communicate decisions, to the public that needs to understand how they are affected by climate change and why policies are issued and how their surrounding is changing [MEP24, MEHD24]. The scope of the visualization ranges from global reports [CDK*23], national climate maps [LSR22], to locally relevant data stories [BPR24]. Topics vary widely and include communicating strategies to reduce greenhouse emissions generated through human activity [MEHD24], visualizing effects of climate change, such as extreme weather events (e.g., flooding of urban areas [VSOC22]), or the identification and understanding of heat islands within urban areas [SMP*19]. Our work focuses primarily on locally relevant urban microclimate data that can be explored at the neighbourhood level by a diverse set of users.

2.2. Visualizations for the Public

Visualizations for a broad public audience are typically designed for users without in-depth domain-specific knowledge. Their usage often centres on casual exploration rather than detailed analytical tasks [PSM07], which must be considered when selecting visualization techniques and designing interactions [TCC22]. Access is commonly provided as a web application, similar to dashboards or web-based geographic information system (GIS) [BFAR*23, MEP24]. Alternatively, visualizations are deployed on selected hardware, for example in public or semi-public spaces, sometimes with access constraints like admission or registration [VMH12]. These could be the Gallery, Archive, Library, Museum (GLAM) environment [WFS*19] or urban spaces [KT18]. In urban contexts, Hespanhol et al. emphasize the importance of situated placement within the spatial context of their referents, especially for sustainability-related topics [HFTM24]. Our installation is not intended to be deployed and situated directly in urban areas, leading to a higher spatial indirection between the data and the location [WJD17]. Instead, we focus on spatial and temporal exploration across the full urban area by placing it in more centralized locations, such as the GLAM environment.

2.3. Climate Visualizations for the Public

As climate change increasingly affects daily life, a wide array of climate visualizations for the public have emerged in recent years. Notable examples include the warming stripes [Gre24], diagrams in the IPCC summary reports [CDK*23], climate dashboards [BFAR*23], data journalism pieces [MEHD24] and non-digital data physicalizations [HNOW22]. In their review of climate change visualization tools, Lumley et al. found that these tools are increasingly designed for non-scientist audiences, and highlight the design opportunity to juxtapose related charts and maps for exploratory analysis [LSR22]. Projects like Orbacles demonstrate how large-scale physicalizations in public urban space can make climate change tangible [kee22], while hybrid approaches – such as those employed by Morini et al. [MEHD24] – allow climate maps to be integrated online and offline, enhancing public engagement through solution-oriented reporting. Additional, static, offline material such as posters can serve as supplements to interactive exploratory visualizations, by providing context and background information that supports interpretation, particularly in the context of addressing bias within the climate domain [CHRS20]. Despite these advancements, a gap remains in exploring how varying degrees of spatial situatedness affect the public's ability to interact with and understand high-resolution urban climate data. This gap invites further investigation into the trade-offs between localized contextualization and broader spatial and temporal exploration, paving the way for visualizations that are not only informative but also directly relevant to everyday urban experiences.

3. Design Process and Goals

3.1. Methodology

The design process was organized into multiple phases. First, a workshop with climate researchers, urban planners, and visualization experts was conducted to establish a common understanding

of the domain. Next, a session with visualization designers ensured that domain insights were effectively integrated into visual communication strategies. In parallel, exploratory data analysis was carried out to derive initial insights from the urban climate dataset, and relevant literature on climate visualization design was reviewed to further refine our design goals (as outlined in the next section).

Building upon these foundational steps, a series of individual charts was developed through an iterative design and implementation cycle. Ongoing feedback from climate experts and researchers in human-computer interaction and visualization guided successive refinements, culminating in a fully functional prototype.

The prototype described in this paper represents the first complete iteration of the system. Following its creation, we presented it to diverse audiences—including urban planners, computer science students, and visitors at a public event—to gather preliminary feedback. A laboratory study is planned as a next step to rigorously evaluate the system's effectiveness and usability.

3.2. Design Goals

To ensure that the urban climate visualization is both engaging and meaningful for citizens, we defined the following key design goals:

- **Inviting and Aesthetic (IA):** We aim to create a visually appealing and inviting interface that encourages users to explore climate data. By focusing on clear design, effective color choices, and an intuitive layout, we seek to lower the barrier to engagement and sustain user interest.
- **Local Relevance (LR):** The system should allow users to explore climate data in locations that matter to them, such as their home, workplace, or frequently visited areas. By anchoring the data in familiar places, we aim to enhance personal relevance and make climate insights more tangible.
- **Spatial and Temporal Variability (STV):** We aim to highlight both spatial and temporal variations in urban climate conditions. The visualization should make it easy to see how microclimates vary across different districts and how these patterns evolve throughout the day and under changing weather conditions.
- **Contextualization (CTX):** The system should help users interpret climate data in a meaningful way by providing comparative insights. Rather than presenting absolute values in isolation, the visualization should indicate whether a given temperature is typical, within an extreme range, or among the warmest or coolest areas of the city at that time.
- **Foster Discussion (FD):** The system should be designed to foster discussions on the data displayed and encourage joint exploration. Therefore, it must be possible for smaller groups of several people to look at the visualizations in parallel and somehow interact with the data.

Ultimately, the system is designed not just to display climate data, but to facilitate exploration and foster understanding. By providing an interactive environment where users can navigate, compare, and analyse temperature variations, the visualization supports curiosity-driven engagement and helps citizens make sense of complex urban microclimate patterns

4. The system

The interactive visualization system is designed to make urban microclimate data in Mannheim accessible and engaging for citizens. By integrating high-resolution climate modelling with intuitive visual representations, the system enables users to explore temperature variations across the city and gain a more profound understanding of local climate dynamics.

4.1. Data and Climate Model

At the core of the system lies a fine-granular climate model that calculates temperature distributions at a resolution of 5×5 meters. Technically, this model is a further development of the Fitnah-3D model, which is used in many municipalities in Germany and Switzerland [JLT*25]. This model integrates real-time sensor data [Lä24], along with spatial information such as terrain elevation, building outlines and land use classifications, which entails surface properties like sealed areas and green spaces [BGHB24]. The early model currently provides a continuous stream of hourly climate data covering an entire summer week, allowing users to observe how temperatures evolve over the course of the day and under varying weather conditions. Compared to earlier city climate analyses which focused on fewer or selected time points, this model takes advantage of both, high temporal and spatial resolution, thereby offering a more comprehensive and dynamic view of the urban climate [BGHB24].

4.2. Visualization Design

In the construction of the visualization, we followed a design approach that balances precision with accessibility. Temperature distributions across the city are represented using a blue-red color scale (Fig. 2 F) [Mor16], with cooler areas appearing in shades of blue and warmer areas in red. Buildings were colored black, similar to a figure-ground diagram because no temperature values are available for those grid cells from the dataset. Multiple color schemes from a related study were tested to optimize clarity [BPL23], ensuring that users can intuitively grasp temperature variations at a glance. Therefore, we used the guideline of Crameri et al. [CSH20], resulting in the blue-red scheme. The color scheme was also related to the publicly well-known Warming Stripes [O'C23]. Alternatively, a red-green color scheme was considered to emphasize that cool areas are primarily green areas. However, since this is not always the case and is therefore misleading, as well as for accessibility reasons, it was discarded. The colors were scaled to the minimum and maximum temperature values within a single summer week, allowing subtle spatial and temporal variations to become visually distinguishable. In contrast, applying a fixed scale for an entire seasonal cycle would have compressed the visual range, making short-term variances nearly imperceptible at the chosen hourly resolution.

The model provides temperature data at different levels of spatial granularity. While the high-resolution grid enables precise local analyses, the visualization also aggregates data at the level of statistical city districts. This approach helps citizens relate temperature patterns to familiar administrative units, making it easier for them to identify relevant information about their environments. We have

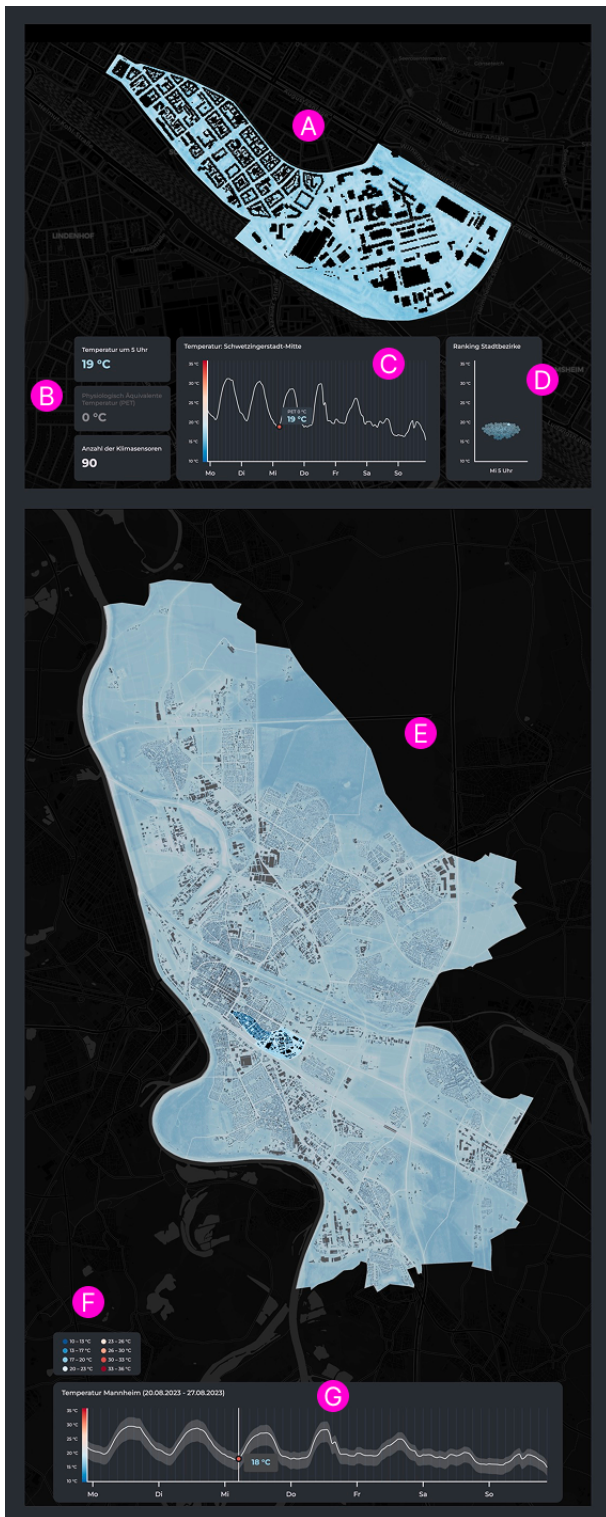


Figure 2: Visualization system, with the bottom screen showing the whole city, and the upper showing a selected district at the same point in time. (A) Detail map of the selected district. (B) Indicators at the selected point in time. (C) Temperature trend for the selected district. (D) Beeswarm plot with the ranking of the selected district compared to all other districts. (E) Overview map of the total urban area. (F) Color scheme for all maps and highlighted elements. (G)

chosen this familiarity over the disadvantages that arise from spatial aggregation of urban indicators [KLM15], e.g., the modifiable areal unit problem [Ope84].

In addition to the color-coded maps, temporal insights are supported through line charts that visualize temperature trends over one week. These visualizations allow users to see not only the current temperature at a given location, but also how it compares to other districts and how it fluctuates throughout the day. To avoid overwhelming users with excessive detail, the complexity of these representations has been carefully reduced, ensuring that key insights remain clear and interpretable.

4.3. Interaction and Display

The system is presented through a $2 \times 4K$ dual-screen setup designed to support exploration at different levels of detail (see Fig. 1). The primary interface is an interactive touch table that shows an overview of Mannheim's microclimate. A large, high-resolution map displays the city, with temperature variations visualized in 5×5 meter grid cells using the blue-red color scale. We opted for a portrait mode, as the city of Mannheim has a North-South orientation. While the focus is on the urban area, the surrounding regions are rendered in a darker base map, creating a visual separation that draws attention to the city proper (Fig. 2 A).

A timeline positioned at the bottom of the screen represents hourly temperature data over the course of the week (Fig. 2 B). It shows the mean temperature as a continuous line, while also indicating minimum and maximum variations as a shaded band. This interactive timeline allows users to scroll through different time points, making it possible to observe how temperatures change throughout the day. A legend accompanies the map, helping users quickly interpret the meaning of the color scale.

When a user selects a specific district on the touch table, the second screen, an upright display positioned at the far side of the table, provides a more detailed view of that area (Fig. 2 top). This screen presents a zoomed-in map of the selected district, maintaining the same 5×5 meter grid resolution and color scheme as the citywide view. Below the map, a district-specific timeline displays the temperature trends for that area over the course of the week, allowing for a direct comparison with the citywide patterns shown on the table.

To further contextualize the data, additional climate statistics for the selected district are presented in a dashboard-style format. At a glance, users can see key metrics such as the mean temperature at the selected time, the mean perceived temperature (physiological equivalent temperature, or: PET), and the number of climate sensors contributing to the data for that district. To provide a comparative perspective, a separate visualization on the right side of the screen displays a bee swarm plot representing the temperature distribution across all districts in Mannheim (Fig. 2 C). The selected district is highlighted within this plot, allowing users to immediately see how its temperature compares to other parts of the city at the chosen time.

4.4. Implementation

While using the large climate data described in section 4.1 the focus was on fluid direct exploration over time and space to support design goals **IA** and **STV** [EVMJ*11]. The visualization was implemented as a SvelteKit web application using open-source libraries D3.js for charts and Leaflet.js for maps [LSR22]. This architecture allows platform-independent deployment on common operating systems and browsers, which is relevant when the application is run on different third-party hardware for exhibitions or showrooms.

We also evaluated the Mosaic framework, which supports handling large datasets exceeding one billion rows [HM24, KMN23]. However, due to the substantial memory requirements of operating DuckDB as an in-memory database on local machines, this solution proved to be impractical. Instead, we opted to pre-render all map layers, enabling the application to run efficiently on common computer hardware without requiring specialized infrastructure.

To provide a clear view from a distance of what is presented on the displays, we used two screens to support our design goal **FD**. Synchronized communication between the windows on the two screens was established to coordinate all views across the selected space and time. This was implemented using the browsers local storage events, as both windows operate on the same machine. For remote communication across different machines, TUIO or web socket events would have been an option as well [KE18]. Given the use of varying hardware at different exhibition sites, we focused on the simplest possible configuration, consisting of one computer and two conventional screens connected via cable.

5. Deployment and Early Feedback

To obtain early qualitative feedback, the visualization prototype was presented to different audiences. We demonstrated the system to experts from urban planning and urban climate to gather feedback on legibility and sense-making. We also presented it to politicians and policy-makers at the city hall to understand how such systems might be used to communicate urban planning and climate adaptation policies to their electorate, and twice to lay audiences: citizens at a public exhibition with hundreds of visitors, and attendees at a semi-public university exhibition. The diverse groups appreciated the visualization's high aesthetic quality and fluid interaction [EVMJ*11], which aligns with our design goal **IA**. Overall, the system was well understood, except for the beeswarm plot, which many found rather complex. However, we observed that coordinating the charts across spatial and temporal dimensions (design goals **STV** and **CTX**) helped people interpret the visualization during interaction. The vertical alignment of the upper monitor ensured that visitors viewed the visualizations from all sides, supporting our design goal **FD**. Although the tabletop interactions were designed for single user engagement, multiple users interacted with the large map from different angles.

At the presentation with the city's planning experts, it was noticed that the statistical districts were used. This was criticized because the naming is not part of public communication for all areas. While individually selected locations from municipal were considered, this option was ultimately rejected to ensure comprehensive coverage of the entire urban area. This naming concern was not

raised during the public exhibition with non-experts, even though some had problems quickly identifying their neighborhoods.

6. Discussion and Outlook

Our current work is based on a dataset from a single city in Germany over a one-week period. To provide citizens with a richer contextual understanding, future work should facilitate comparisons with other cities offering climate data at a similar level of granularity [MOM*24]. Nonetheless, comparing neighbourhood-level across different cities remains challenging due to variations in district sizes and shapes [Sch19]. In the future, an additional view with a higher level of aggregation, such as a choropleth map, might help to make some comparisons easier.

During the public exhibition, it was observed that local users employed the map to search for places of personal interest, such as their homes and the surrounding area, often leading to comparative discussion (e.g. "but it's much cooler by the river"). Enhancing the brushing interaction could help users more precisely identify key locations, addressing feedback that many elements were only vaguely defined. State-of-the-art frameworks such as Mosaic would be one way of technically realizing this brushing interaction with the given data set while still enabling fluid interaction [HM24].

Others have even more focuses on individual locations by providing more situated visualization directly at the pedestrian level [BDPP23]. Technologies such as augmented reality can help them to explore specific, individually relevant places in situ in more detail [NHPH24]. Geospatial visualizations, on the other hand, provide an overview and enable comparisons across different location within the urban area [MOM*24].

As a next step, we intend to evaluate how this visualization setup can be integrated into public spaces. Drawing on insights from Hespánhol et al. [HFTM24] regarding the importance of the situated local context, our focus will be on adapting the prototype to enhance the local communication of the displayed data [JNL10].

7. Conclusion

In conclusion, by combining an interactive, citywide perspective with detailed local insights, the system engages citizens with urban climate data in an aesthetic and informative way. The integration of spatial visualization, temporal dynamics, and comparative statistics fosters climate awareness and encourages exploration of temperature variations across the city of Mannheim. Through this interactive approach, users can not only observe climate patterns in their city, but also better understand how these variations impact their daily lives and their neighborhoods. Future work will focus on refining these interactions further, expanding comparative analyses, and conducting controlled laboratory studies to evaluate effectiveness and usability.

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