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ORIGINAL ARTICLE

Urban Climate InteracTable: towards an immersive contextual data analysis platform to visualize and explore urban heat

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Abstract

Extreme weather events, such as heat waves, are occurring more frequently and intensively, imposing new climate-adaptation demands on municipal planning. We conducted a design study across the domains of urban planning and urban climate research, and identified challenges regarding a lack of heat-related information in current planning processes, and the high complexity of effective climate data representation. To address these challenges, and so enhance the information flow between these domains, we developed *Urban Climate InteracTable*, an immersive interface that supports exploratory analysis of spatio-temporal climate simulation data integrated with an urban environment representation. We describe several use cases in which this interface can be utilized to assist with planning-related decision processes and to communicate heat-related phenomena. We present the feedback obtained from our collaborating domain experts and relevant external experts, and reflect on our experiences throughout the design study. From this, we offer insights for future research.

Keywords Immersive analytics · Urban analytics · Urban heat · Climate adaptation · Climate modelling · Visualization · Design study

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1 Introduction

Increased frequency and intensity of extreme weather events, such as heat waves, due to climate change cause severe risks to people's daily lives (Intergovernmental Panel on Climate Change 2022). Acute and/or extended heat exposure, e.g., experienced during hot summer periods, and its impact on public health and well-being have become an increasingly important concern to planners and policymakers on national, regional, and local levels (Benevolenza and DeRigne 2018), even in countries with historically cooler climates such as the Nordics (Opach et al 2022). In addition to climate change, related local phenomena require consideration as well, such as the Urban Heat Island (UHI) (Oke 1982; Prashad 2014; Hiemstra et al 2017), describing how built-up urban environments are more prone to higher temperatures and cool off less easily compared to green areas and suburban regions especially during the night, posing often overlooked heat-related health risks (Heaviside et al 2017). Climate adaptation, i.e., the process of adjusting to actual or expected climate change and its effects, requires awareness and the ability to make assessments to successfully plan, implement, and evaluate practical actions (Intergovernmental Panel on Climate Change 2022). While planners and policymakers appear aware and eager to implement measures, their ability to make evidence-based assessments by following often complex scientific data remains limited, not least because effectively communicating climate change, especially regarding "*invisible*" issues like heat or air quality, remains a major challenge (Moser 2010; Hawkins et al 2019; Larsson et al 2023). Although the adaptation to heat is becoming more urgent, more spatially detailed information is needed at neighborhood scale to support the development of local action plans that consider the effects of specific adaptation measures (André et al 2021).

Interactive visualization can be a valuable asset to explore and communicate scientific data (van Wijk 2005), but requires careful considerations based on existing user knowledge and needs (Hogräfer et al 2020; Goodwin et al 2021). Three-dimensional (3D) visualization can allow for better contextualization and spatial understanding in comparison to two-dimensional (2D) visualization, facilitating the ability to comprehend how complex urban data and phenomena interact in relation to the cityscape's geospatial composition (Miranda et al 2024). However, appropriately integrating data in such geospatial contexts remains challenging, e.g., based on spatial, temporal, and multivariate aspects and their respective visualization (Miranda et al 2024; Hogräfer et al 2020; Li et al 2016). The inherent 3D data context opens up promising synergies to Immersive Analytics (IA), a research area concerned with human-computer interfaces that support data understanding, analytical reasoning, and decision making through the utilization of immersive display and interaction technologies (Skarbez et al 2019; Marriott et al 2018; Klein et al 2022), e.g., large interactive tabletops (Ens et al. 2021b), dome theaters (Ynnerman et al 2020), Augmented Reality (Bressa et al 2022), or Virtual Reality (VR) (Reski et al 2024; Wagner et al 2024). Research indicates that IA can facilitate user engagement (Büschel et al 2018), support intuitive spatial understanding (Marriott et al 2018), deepen data understanding (Lee et al 2021), and enhance information presentation (Kraus et al 2021).

With the objective to support the integration and communication of climate insights into planning and decision-making processes and to better understand the challenges involved, we explored the visualization and interaction with urban climate data, particularly regarding urban heat and heat-related phenomena. We conducted a design study involving urban planners and urban climate researchers, aimed at facilitating the information pipeline between their domain contexts. The contributions of our work are threefold:

1. We conducted a contextual analysis across the two domains of urban planning and urban climate research, identifying four challenges in current practices regarding climate adaptation and urban heat.
2. We present *Urban Climate InteracTable*, an immersive contextual data analysis platform to visualize and interact with spatio-temporal urban climate data using a VR approach Fig. (1).
3. We evaluated the proposed platform in several expert feedback sessions and report on the results, reflect on the conducted design study, provide lessons learned and discuss considerations for future research.

2 Related work

Our work is related to (1) the visualization of urban data with a focus on urban heat and (2) the utilization of an Immersive Urban Analytics (IUA) approach. Despite recent advances in these areas, more research is needed to support practitioners within the context of urban climate adaptation.

2.1 Urban data/heat visualization

Miranda et al (2024) present foundational considerations of Visual Analytics (VA) for 3D urban data, arguing for the analysis of urban data in 3D due to their inherently 3D nature, and highlighting the importance of effective visualizations for urban planning, policy, and ecology. The authors identified approaches for the integration of physical

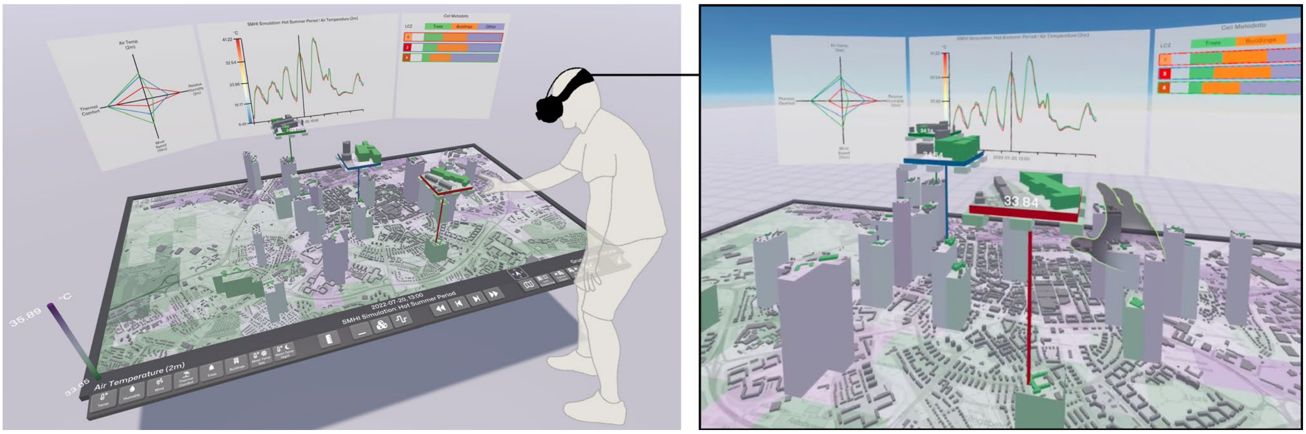

Fig. 1 The developed immersive contextual data analysis platform, *Urban Climate InteracTable*. Left: Following a virtual table metaphor with a data-driven miniature city representation, the interface supports various analysis tasks for the interactive exploration of spatio-temporal urban climate data via head-mounted display and 3D gestural input. Right: The immersed user's field of view

(urban environment) and thematic (related data layer) visualizations, i.e., superimposition (overlay), embedded views, linked views, interchangeable and juxtaposed layers, as well as different scopes for spatial data analysis, i.e., city, neighborhood, and building scale (Miranda et al 2024). In line with these, Deng et al (2023) identified various problem domains, including environment/climate and security-related issues, all requiring robust planning processes. Goodwin et al (2021) highlight important human-centered design considerations for creating urban data visualizations. Appropriate techniques, data choice, and visual literacy should empower users' data-enabled thinking, in turn facilitating data understanding and actions (Goodwin et al 2021). Hogräfer et al (2020) concur with these remarks, emphasizing that integrating abstract and geospatial data to facilitate data visualization remains a major challenge.

Air temperature, air quality, and storm water are commonly explored within the context of climate adaptation and urban VA, particularly regarding risk management (Miranda et al 2024; Deng et al 2023). The most common approach of visualizing urban air temperature data is to use 2D heat maps with additional representation of urban environment features (shapes, contours) as some type of overlay. The spatial context is essential for understanding the role of urban factors that potentially have contributing effects on air temperature (Hjort et al 2016; Miranda et al 2024). Christophe et al (2023) explored visualization approaches for air temperature simulations integrated in a 3D cityscape as horizontal and vertical planes, point clouds, and various morphological indicators, the latter visually encoding data directly in the features of the displayed urban environment. Their spatial data exploration interface facilitated discussion among meteorologists. It did not support temporal data. Opach et al (2022) built an interface to visualize local heat and flood vulnerabilities to support municipal planning and decision processes. Based on workshops to develop vulnerability indicators, their interface featured different 2D map representations (detailed, simplified, faded) for spatial context and interactive circular widgets, placed at vulnerable locations, for details-on-demand information (Opach et al 2022). Navarra et al (2021) describe a VA tool for climate-related experiences based on citizen-volunteered geographic information, following a linked views approach with established visualization techniques (map, scatter plot, line graph, image cloud, parallel coordinates, Sankey diagram). The authors reflect on the iterative design process, discussing interface needs and desired complexities based on anticipated user and analysis tasks (Navarra et al 2021). Interestingly, rather than visualizing the actual urban heat data, these works (Opach et al 2022; Navarra et al 2021) focus on human-centered aspects inherent from being part of the urban environment, aligned with the considerations brought forward by Goodwin et al (2021).

Few design studies have investigated VA for 3D urban data, none of which focused on urban climate (Miranda et al 2024). Furthermore, none of the presented interfaces utilized contextual data on a city scale, e.g., to support the user with focus on system-relevant areas and aspects.

2.2 Immersive urban analytics

Related to the work presented in Section 2.1, several efforts exist that explore IUA. Wagner et al (2024) built on the space-time cube concept to adapt a traditional VA tool to a VR modality, reflecting on its potential to support more focused analysis activities and higher user engagement while highlighting risks of oversimplifying or overcomplicating data exploration through interface limitations. The authors envision that integrating multiple data sources in 3D cityscape visualizations will be relevant for many applications (Wagner et al 2024). Bondakji et al (2019) present one such effort, integrating open source urban data about inhabitants, land use, and environment as an abstract visualization in an Immersive Virtual Reality Environment (IVRE), aiming to facilitate accessible discussions around urban complexities. Instead of exclusively relying on abstract visualization, Chen et al (2017) highlight opportunities by providing critical 3D context information. The authors explored a design space for IUA and, similar to the approaches of integrating physical and thematic visualizations identified by Miranda et al (2024), proposed a typology of linked, embedded, and mixed views (Chen et al 2017). Schrom-Feiertag et al (2020) developed an IVRE within an urban planning context that combines traffic simulations and participatory design. Professional planners valued the system's immersive features. The authors emphasize that utilizing scientifically validated simulation data was essential for accurately illustrating the urban environment. Schewenius and Wallhagen (2024) explored the application of immersive 360-degree video as a tool within a similar urban planning, design, and management context as Schrom-Feiertag et al (2020). Focusing on green and blue infrastructure, their evaluation results indicate increased understanding for complexities and relations in urban environments. Schewenius and Wallhagen (2024) conclude that applying immersive technologies can be a valuable supplement in addition to more traditional approaches, fostering communication between experts and non-experts, and enriching decision-making processes. Zhang et al (2022) built an IVRE to explore spatio-temporal energy data of buildings on a neighborhood scale, following a space-time cube concept similar to that applied by Wagner et al (2024). Their prototype provided various interactive analysis features (filter, compare, store, change perspective). The authors reflect on extending the IVRE through storytelling capabilities to support data presentation scenarios (Zhang et al 2022). The immersive visualization of extreme weather events (heavy rainfall, heat waves) was explored by Oyshi et al (2024). Their evaluation results indicate potential towards better risk mitigation through decision support for city planners. The authors reflect that the IVRE enabled effective data interpretation and communication, facilitating critical thinking and increasing awareness (Oyshi et al 2024). Çöltekin et al (2020) reflect on envisioning future cities with the aid of IVREs, including exploring urban planning what-if scenarios. The authors emphasize the need for careful integration of IVREs in established workflows and practices to avoid their disruption. Similarly, Larsson et al (2023) developed an IVRE as a communication tool to explore planning scenarios involving urban green spaces and air quality. While the implemented visualization approaches (volumetric particles, small heat map planes) were well received, the authors stressed the need to use appropriate color scales to avoid miscommunication (Larsson et al 2023). In the context of sustainable cities, Chandler et al (2018) developed an IVRE that visually superimposes a 3D urban city representation with flooding and heat stress data layers. The authors reflect on the potential of transformative narratives that immersive visualizations can encourage, similar to the storytelling remarks by Zhang et al (2022).

While IA systems can facilitate data analysis (Büschel et al 2018; Marriott et al 2018; Lee et al 2021; Kraus et al 2021), the complexity of their interaction, design space, evaluation, definition of application scenarios, and shift of analysis processes through immersion, are challenges that require further investigations (Friedl-Knirsch et al 2024; Ens et al. 2021a; Saffo et al 2024). The presented works provide useful considerations for the design of future IUA systems.

3 Design study methodology

Our methodological approach implemented several iterative stages of a design study framework (Sedlmair et al 2012). The case study area was Norrköping, a municipality in southern Sweden with about 145000 inhabitants. As Visualization (VIS) and Human-Computer Interaction (HCI) researchers, we actively collaborated with experts in the domains of urban planning and urban climate research. Our regular dialogue included dedicated meetings for obtaining feedback, requesting data, discussing progress, and sharing findings. Figure 2 illustrates a timeline with key events in the design study process.

After reviewing the literature for foundational background on urban climate adaptation (learn), we conducted two contextual inquiries, one with each domain group (discover). Our objective was to empirically gain insights to their respective domains, practices, and data contexts. We implemented a semi-structured interview approach with a prepared question catalogue and utilized audio recordings to capture the interviewees' responses. We performed a contextual analysis based on the processed and reviewed interview notes, defining current domain practices and characterizing challenges related to urban heat. We identified two domain-specific themes, each with two challenges (see Section 4). With these at hand, we revisited the literature for additional knowledge acquisition and considerations about the state-of-the-art (learn) of urban data and heat visualization as well as IUA (see Section 2).

The process of addressing the identified challenges, informed by the literature, led to *Urban Climate InteracTable* (design). A foundational aspect of the platform is the integration of multiple data layers (see Section 5.1)

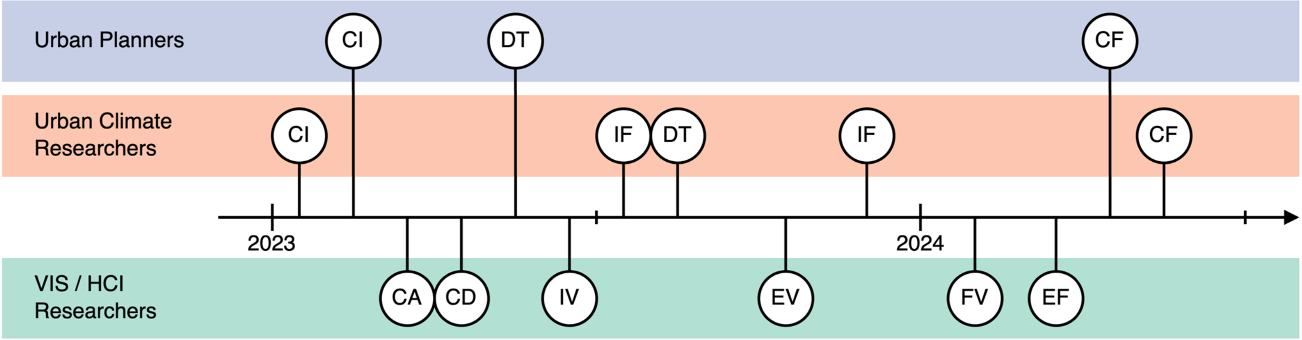

Fig. 2 Timeline with selected design study events. (CI) Contextual Inquiry. (CA) Contextual Analysis. (CD) Conceptual Design. (DT) Data Transmission. (IV, EV, FV) Initial, Extended, Final Version of *Urban Climate InteracTable*. (IF, EF, CF) Internal, Expert, Collaborator Feedback

in the same interface to examine urban climate and heat-related data under visual reference of an urban environment representation. The conceptual design includes relevant data analysis tasks to accommodate the prior identified challenges (see Section 5.2).

We followed a prototypical development approach for the implementation of *Urban Climate InteracTable* (implement). The *initial version* aimed to explore and validate the virtual table metaphor, the data processing workflow, and the choice of visual encoding. A major part of this version was the generation of a data-driven miniature representation of the urban environment in 3D. The *extended version* featured functionalities to support details-on-demand information display (Shneiderman 1996). This version also fully integrated the spatio-temporal urban climate simulation dataset. The *final version* focused on the immersive interface implementation, i.e., supporting head-mounted display (HMD) and 3D gestural input as interaction modalities (see Sections 5.3, 5.4, and 5.5). We describe how the interface can be utilized to address the prior identified challenges (see Section 6).

We obtained qualitative feedback from several evaluation sessions with our collaborating domain experts and relevant external experts (see Section 7), enabling us to offer reflections (see Section 8) on the design study process (reflect). The report of our work can provide inspiration and considerations for future research (write).

4 Contextual analysis

This section describes the domain situation and problem characterization for the two contexts of *urban planning* and *urban climate research*.

4.1 Urban planning

We conducted a two-hour semi-structured interview with four municipal representatives, holding relevant positions and responsibilities in urban planning and climate adaptation: one comprehensive planner, two detail planning architects, and one environment and climate strategist. The interview enabled us to gain a better understanding about the current municipal practices, workflows, and potential challenges, specifically with a focus on urban heat.

4.1.1 Domain situation

As a public entity, the municipality is responsible for strategic and sustainable planning of the urban environment (spatial composition, infrastructure, landscape). Two types of urban planners are commonly employed by a municipality to assume these responsibilities: *comprehensive planners* and *detail planning architects*.

Comprehensive planners are tasked to provide strategic orientation and input for sustainable development in the municipality at large. They keep an overview of the urban environment, identify areas that require development, and provide directions based on close collaboration with political actors and legal frameworks. For instance, comprehensive planners may identify areas that require the construction of health care and outdoor facilities.

Based on the directives received from the comprehensive planners, detail planning architects are tasked to make specific recommendations of how to develop an area, commonly encompassing one or few connected blocks, by conducting investigations and exploring alternatives. This may include height restrictions for newly constructed buildings or area allocations for specific purposes, such as urban green infrastructure (parks, trees, urban vegetation) (Amorim et al 2021).

Neither detail planning architects *nor* comprehensive planners are the final decision makers. Instead, they make informed recommendations that serve as decision support for politicians and governmental institutions. Presenting the motivations and rationales behind these recommendations is an essential part of their work. In response to more frequent and intense extreme weather events in recent years, specifically regarding heat and heat-related phenomena, the municipality is concerned with *climate adaptation* (Intergovernmental Panel on Climate Change 2022) through physical measures to appropriately adjust the cityscape.

4.1.2 Problem characterization

The dialogue with the municipal representatives revealed two *challenges* (C) in their current practice towards *Municipal Urban Heat Adaptation*.

Theme 1: Municipal Urban Heat Adaptation In the case of Norrköping, Sweden, the municipality began strategically addressing urban heat only in recent years in response to longer high-temperature periods, posing risks to resident health and well-being. Considering its location in the Nordics, urban heat had not previously been a particular issue. The comparatively early stage of explicitly addressing urban heat within municipal planning processes poses challenges.

C1.1: Lack of Urban Heat Information Data and meaningful insights about urban heat are at best sparsely and generically integrated into current municipal processes. There appears to be a lack of knowledge on urban heat exposure, and a lack of collected evidence (data sources) that can be incorporated and utilized within the planning processes.

C1.2: Challenging Insights Explanation Planners generally understand a lot about the various aspects relevant within the planning process. However, clearly presenting and communicating these aspects and their relevance to decision makers can be challenging. Comprehending heat-related issues is difficult as their impacts are “*invisible*” compared to matters of storm water and flooding (Moser 2010; Larsson et al 2023). There appears to be an attitude and tendency for prioritizing clearly quantifiable aspects over unclear ones. The lack of evidence-based data incorporated in the planning extends this issue (C1.1). This might result in a climate adaptation *deadlock*: if decision makers are not able to follow and comprehend the motivation and rationale behind the planners’ recommendations, there might be no action and no progress.

4.2 Urban climate research

We conducted a two-hour semi-structured interview with two researchers (urban climate and urban air quality) of the meteorological research unit at the national expert authority, the Swedish Meteorological and Hydrological Institute (SMHI). The interview enabled us to examine the researchers’ current workflows, the data they are working with, and potential challenges, all with a focus on urban heat.

4.2.1 Domain situation

Besides responsibility for weather and climate related public services, SMHI conducts research in the areas of climate, hydrology, meteorology, and oceanography. Recent challenges posed by climate change (Intergovernmental Panel on Climate Change 2022) increased the interest to investigate matters of urban climate, including urban green infrastructure and air quality (Amorim et al 2021), accurate real-world data collection (Li et al 2016), human comfort (Hiemstra et al 2017), and heat stress (Di Napoli et al 2018; Heaviside et al 2017).

To understand the current and possible future climates, climate researchers commonly work with *observations* and computational *simulations*, i.e., numerical models with varying degree of complexity. Urban climate-related factors are typically examined on comparatively small *spatial* scales, e.g., 1 km to 1 m, and of varying *temporal* granularity, e.g., daily or hourly. Challenges include the improvement of data collections, model simulations, evaluation, and analysis, as well as effectively disseminating information to the public, including municipal practitioners for climate adaptation.

4.2.2 Problem characterization

The dialogue with the climate researchers revealed two *challenges* (C) concerning *Urban Heat Insights Dissemination*.

Theme 2: Urban Heat Insights Dissemination Exploring and investigating urban heat-related phenomena is a complex scientific endeavor. Comprehensibly representing and communicating climate insights to non-climate experts is challenging, with research data visualizations commonly targeting scientific audiences instead of planners (C2.1), and due to the complexity of data and related terminology (C2.2).

C2.1: Appropriate Visualization for Non-Climate Experts The complexity of climate science requires special attention and efforts towards visual results presentation, particularly to accommodate non-climate experts (Moser 2010; Hawkins et al 2019; André et al 2021). The interviewees reflected that their visualizations typically focus on the “*scientific side*”, tending to appear “*daunting, boring, or not as beautiful as they could have been*,” preventing engagement and understanding by end-users of climate information. Insightful visualizations for non-climate experts require tailored solutions depending on the intended domain context and target audience. This takes time: a resource that is often lacking in practice.

C2.2: Challenging Data Understanding Investigating, analyzing, and presenting urban heat phenomena commonly involve a multitude of different data variables. Depending on the domain context, e.g., urban planning, it can be difficult for non-climate experts to comprehend and interpret climate science terminology (the meaning of specific data variables, their unit, impact, and comparison to other variables). This may have practical implications. Misinterpretation of data can lead to poor or inappropriate adaptation measures.

5 Urban Climate InteracTable

To address the identified challenges across both domain contexts (see Section 4), we conceptualized and implemented an IUA interface. In line with and informed by other works (Goodwin et al 2021; Miranda et al 2024; Chen et al 2017; Chandler et al 2018; Lee et al 2021; Deng et al 2023), we see potential for the visualization of urban geodata and climate data in context and relation. We anticipated that a suitable interface could aid the dissemination of and interaction with urban climate data (C1.1), in a manner that facilitates understanding and interpretation (C1.2, C2.2), supporting an engaging and insightful analysis (C1.2, C2.1). With a focus on urban heat and heat-related phenomena, we developed *Urban Climate InteracTable*, a data-driven *immersive contextual data analysis platform*. We defined the key components as follows:

- *immersive*: the utilization of immersive display and interaction technologies, i.e., a VR approach via HMD and 3D gestural input.
- *contextual*: the examination of urban geodata and urban climate data unified in a single visualization environment.
- *data analysis*: the provision of visualization and interaction features to support analytical tasks and data interpretation.
- *platform*: the application of a modular and extendable system architecture, incorporating data of different types and from different sources in the same visualization environment.

5.1 Data abstraction and datasets

Aligned with the two domains, the urban data context is likewise twofold: Geodata for describing the physical real-world environment, and climate-related data with spatial and temporal associations.

5.1.1 Urban geodata

Comprehensive planners and planning architects work with geographic information system (GIS) data, i.e., a *geometry* dataset type with *geospatial* positions (latitude, longitude, altitude) (Munzner 2014, Chapter 2). Dataset items may be *zero-dimensional points* (e.g., tree locations), *one-dimensional lines* and *curves* (e.g., traffic routes), or *two-dimensional surfaces* and *regions* (e.g., buildings or green areas). Individual items can be characterized by various multivariate attributes, including a *categorical* attribute indicating their *type* within the cityscape (water, greenery, building), a purpose identifier (*categorical*) for buildings, height attributes (*quantitative*) for buildings or trees, and crown radius (*quantitative*) for trees. Derived attributes can be generated on demand, e.g., computing the area of a surface (building, green area). From a visualization system perspective, GIS data can be considered *static* in terms of availability, i.e., all data is available at once.

Dataset: National Geodata The Swedish Mapping, Cadastral and Land Registration Authority (Lantmäteriet) provides a rich geodata corpus on a national level. Three datasets are of particular relevance for our work. First, 2D *map imagery* (GeoTIFF) visually illustrates geospatial area compositions. Second, *property maps* of built-up areas (Shapefile) provide detailed GIS information about all buildings, including location, layout, unique identifier, type, and generic purpose. Third, *light detection and ranging data* (LAZ) provides a remote aerial sensing point cloud that can be used to determine the real-world height of individual buildings.

Dataset: Municipal Geodata In addition to the available national geodata, the municipal GIS unit maintains more *detailed and contextual information* about the geospatial features in its area of responsibility. This information is publicly accessible,[1] featuring locations of various public service institutions (schools, health care) and public trees (height, crown diameter).

5.1.2 Urban climate data

The analysis of *spatio-temporal data* is integral in urban climate science. Climate simulation output can be classified as a *time-varying tensor field*, commonly composed of a *uniform grid* where all *cells* have the same spatial resolution (Munzner 2014, Chapter 2), similar to raster data. In addition to the geospatial real-world position and abstract location in the field, each cell holds *multivariate* data, i.e., attributes of varying types that represent its state at a given *time step*. Attribute type examples include *quantitative* data (air temperature, humidity, wind speed) and *categorical* data, such as a local climate zone (LCZ) classifier (Demuzere et al 2023). The multivariate data can be used to compute relevant indexes, such as the Universal Thermal

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[1] Norrköpingskartan: https://kartor.norrkoping.se/spatialmap

Climate Index (UTCI) (Di Napoli et al 2018). In terms of temporal granularity, the computation of climate simulations relies internally on comparatively high *sampling times* of a few seconds. The output is commonly aggregated into lower sampling times, e.g., hourly time steps, to make data storage, processing, and interpretation more efficient and comparable to observations.

Dataset: simulation – hot summer period Climate simulations (NetCDF) were produced by SMHI applying the pseudo-global-warming (PGW) approach (Brogli et al 2023), adopting a specific warming level (Bärring and Strandberg 2018) of 0.9°C, corresponding to a global temperature increase relative to preindustrial levels. The Surface Externalisée (SURFEX) (Masson et al 2013) Land Surface Model (LSM) was used to perform all simulations. SURFEX LSM contains various physical models and includes continental natural surfaces, sea, inland water, and urban areas (Masson et al 2013). Urban surfaces were modelled using the Town Energy Balance (TEB) (Masson 2000) scheme that is based on the Urban Canyon approach (Nunez and Oke 1977). Urban green areas were simulated by GARDEN (Lemonsu et al 2012) as part of the TEB scheme. Natural surfaces were parameterized using ISBA (Noilhan and Planton 1989), while inland water was simulated by the lake model FLake (Mironov et al 2012). SURFEX v8.1 was used, running at a spatial resolution of 300 m. The simulation period covers an entire summer (June–August). The simulation domain covers Norrköping and its surrounding areas, resulting in a field (grid) size of 565x565 cells. The atmospheric forcing data for SURFEX LSM was from hourly outputs of the HCLIM43-AROME model (Belušić et al 2020) at 3 km, nested within HCLIM43-AROME 12 km simulations driven by ERA5 reanalysis data (Hersbach et al 2024), and including a multitude of data variables (Wang et al 2023). Our study utilizes SURFEX outputs of 2 m (above ground) air temperature, 2 m relative humidity, 10 m wind speed, and perceived thermal comport (UTCI), all at 1 h temporal granularity. The UTCI is calculated from 2 m air temperature, 2 m water vapour pressure, 10 m wind speed, and mean radiant temperature (Bröde et al 2012; Redon et al 2020).

Dataset: Local Climate Zones To accurately simulate the fluxes between the complex urban surface and the overlying atmosphere, it is fundamental to rely on precise and sufficiently detailed *land cover description*. The physiography characterisation according to the ECOCLIMAP Second Generation (SG) (Bessardon et al 2024) global land cover map was used in the HCLIM and SURFEX simulations (from 12 km to 300 m resolution). The sand and clay dataset was obtained from the SoilGrids data at 250 m resolution. ECOCLIMAP-SG has 33 classes of land use covering ocean/sea, different water bodies, vegetation, and urban types (Druel et al 2022). For the urban land use types, ECOCLIMAP-SG followed the LCZ scheme (Demuzere et al 2023), a widely used 17-class research framework for the standardization of UHI studies (Stewart and Oke 2012). Ten urban LCZ classes are defined according to building height and density, vegetation coverage and type, human activities, and physical surface properties (roofs, walls, pavements), representing key urban canopy parameters critical to model atmospheric responses to urbanisation (Demuzere et al 2023).

5.2 Conceptual design

5.2.1 Data analysis tasks

Informed by the contextual analysis and available data, we derived four main data analysis *tasks* (T1–4) that the interface should support.

T1: Examine the spatial composition of the urban environment The interface should support the user to explore the urban environment from an analytical perspective, fostering the understanding of geospatial features and composition. The interface should support the user to examine characteristics and attributes of individual areas based on the processed geodata.

T2: Examine the urban environment in regard to spatio-temporal climate data variables Closely aligned with T1, the interface should support integrated visualization of urban heat-related data variables that enables contextual analysis from spatial and temporal perspectives.

T3: Visually identify data trends and patterns The interface should support the user to visually detect trends and patterns in the data, facilitating the identification of potential urban areas and/or time steps of interest for further examination. This should support the user with the identification of hot spot locations as well as areas with comparatively lower and/or higher data values.

T4: Compare different urban areas of interest The interface should support the simultaneous selection of multiple urban areas to compare their spatial composition and climate data, facilitating the identification of potential relations.

Data Analysis Task × Challenge Rationales Based on the identified domain challenges (see Sections 4.1.2 and 4.2.2), our rationales for the derived data analysis tasks are as follows. T1 serves as an important foundational task, supporting the user to obtain a visual and contextual reference of the real-world urban environment to facilitate their own understanding. This should aid explanations in close relation to any integrated data layers, aiming at addressing C1.2 and C2.2. The anticipated ability to examine spatio-temporal climate data integrated and visualized in the urban environment (T2) aims directly at addressing the current lack of urban heat-related information in the planners' tools and workflows (C1.1). The intention with T3 is to further facilitate such an integration of meaningful urban heat-related insights into the planners' processes (C1.1) through appropriate, engaging, and easily interpretable techniques that facilitate the understanding and communication of urban climate data to non-climate experts (C2.1). Enabling the user to compare multiple urban areas (T4) in regard to their location, physical composition, and urban climate characteristics, is intended to aid data understanding (C2.2). We anticipate that a planner's ability to explain insights (C1.2) is facilitated by first gaining a better understanding (C2.2).

5.2.2 Motivation for virtual reality approach

Immersive VR experiences are inherently interactive and engaging, two characteristics that are considered valuable for exploring and communicating complex scientific data (van Wijk 2005; Goodwin et al 2021; Büschel et al 2018). We see these characteristics as an opportunity to tackle some of the identified domain challenges.

Even though the urban climate simulation data contains geospatial location information, the data is not inherently three-dimensional and could be visualized utilizing 2D techniques and conventional non-immersive displays, e.g., as a 2D heat map on a desktop monitor. However, the urban environment context is inherently three-dimensional, with geodata describing its composition including building locations and heights. To integrate both climate and geodata in the same interface, we purposefully chose to follow a visualization approach that is situated in a 3D environment, motivated to support the user with better contextualization and spatial understanding of the urban environment (Miranda et al 2024; Marriott et al 2018).

Relevant research, such as by Lee et al (2021) and Kraus et al (2021), indicate that immersive visual analysis interfaces can support users with their data understanding and facilitate information presentation. Keeping in mind the identified domain challenges, we see potential to employ an IVRE within the scope of our design study.

Examining the rich corpus of related IUA works as described in Section 2.2, promising opportunities of using immersive interfaces to facilitate dissemination, discussion, and decision support around urban complexities can be identified (Bondakji et al 2019; Schrom-Feiertag et al 2020; Schewenius and Wallhagen 2024; Oyshi et al 2024; Larsson et al 2023).

5.2.3 Virtual table metaphor

We designed the interface around a *virtual table* metaphor (Wagner et al 2024; Zhang et al 2022). The idea is to visualize a data-driven miniature representation of the urban environment on a *table* placed in the *virtual environment*. The user can explore the rendered cityscape to obtain an overview of its spatial composition, and interact with the provided interface features by moving and acting naturally in the 3D VR space via HMD and gestural input (embodied interaction; see Fig. 1).

For simultaneous visual representation, we decided to integrate the urban geodata *on top* of the climate dataset. This approach effectively divides the cityscape in accordance to the individual cells (geospatial areas) as predetermined by the climate data.

Different visual mapping approaches can be considered to represent the field data, while aiming to retain a visual reference of the urban environment. We investigated three approaches to visually encode one individual data variable on the field as follows:

1. *Flat*: Application of color encoding, i.e., coloring the ground (cell) beneath a respective area in the city model in accordance to its data value (similar to 2D heat map).
2. *Extrusion*: Application of color and height encoding, i.e., coloring and vertically extruding the field cell in accordance of its data value, maintaining the respective area in the city model rendered on top of the extruded surface (similar to 3D histogram).
3. *Mesh Overlay*: Translation of the scalar field into a height map that is used to generate a semi-transparent color-coded 3D mesh as an overlay above the city model (similar to a 3D surface plot).

5.3 Immersive virtual reality environment

We employed a prototypical development approach to implement *Urban Climate InteracTable* from the ground up. This section describes the individual components, interface features, and design rationales. We outline the interaction workflow, and present the system architecture and utilized technologies. Figure 3 provides an interface overview. A video demonstration is available as supplemental material.[2]

Data-driven miniature city representation (T1) The *data-driven miniature city representation* (see Fig. 3) was created in several steps. First, grayscale map imagery was used as 2D textures to create a visual representation of the urban spatial composition, including transport networks and building locations. Second, polygon data was used to generate individual objects of all buildings, rendered as 3D prisms (extruded polygons) according to their layout and aligned to their geospatial position on top of the prior generated map textures. Each building object holds a unique identifier and

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[2] *Urban Climate InteracTable* video demonstration (2:20 min, no audio): see electronic supplementary material.

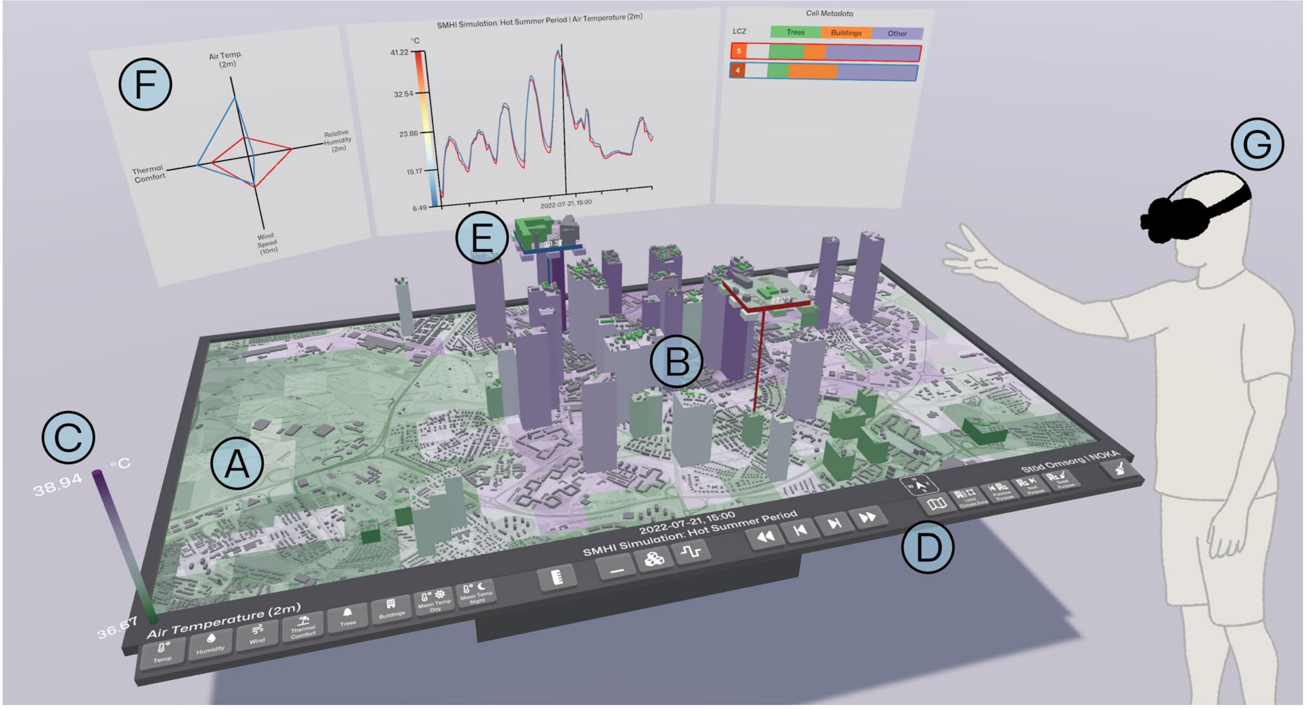

Fig. 3 Overview of *Urban Climate InteracTable* with annotations of its individual components/features. **A** Virtual Table Metaphor + Data-Driven Miniature City Representation. **B** Visualization Mode Extrusion + Contextual Area Highlight: *Support & Care* buildings. **C** 3D Reference Scale Widget. **D** Diegetic Interface: Buttons + Textual Labels. **E** Area Selection (100x100 m). **F** Details-on-Demand Information Panels (left to right: Climate Variables Radar Chart, Time-Series Line Chart, Characteristics Overview). **G** Immersed User: HMD + 3D Gestural Input

several attributes, e.g., a purpose such as residence, school, community function, culture, or industry. Third, the generated building polygons and LAZ data were preprocessed to generate a lookup table containing all unique building identifiers and their detected real-world ground and roof altitude values, enabling us to determine each building's height and extrude it appropriately as a 3D prism. Finally, we parsed the detailed municipal geodata to attach additional purpose attributes to the buildings.

Diegetic interface approach Aligned with the virtual table metaphor, we followed a diegetic interface approach (Salomoni et al 2017), integrating a variety of *virtual buttons* (with icons and/or text) directly as part of the table (see Fig. 3), providing the user with means to operate the interactive features. *Textual labels* at the table's lower edge provide current state information, e.g., which data variable, time step, and contextual area highlight are selected, and a compass for spatial orientation. In addition to the table-anchored buttons, we implemented a complementary *graphical hand menu* (see Fig. 6 top left). This menu follows the user's left hand and provides quick-access features (icon label indicating the displayed data variable, textual label describing the selected time step, visualization mode and time navigation buttons).

Visualization modes: flat and extrusion (T1, T2, T3) The underlying data visualization engine of *Urban Climate InteracTable* is based on a uniform grid, subdividing the geospatial urban environment into individual cells at 100x100 m resolution. Although the climate simulation data (see Section 5.1.2) is based on a spatial resolution of 300x300 m, we decided to support a higher spatial resolution. First, based on the feedback from the urban planners, 100x100 m areas are better for planning architects who tend to work at smaller scales. And second, some higher resolution urban data already exists or can be computed, including LCZs and tree/building coverage (see Fig. 6 bottom left and bottom right).

Based on the selected urban excerpt (downtown Norrköping) within our study, and in alignment with the urban climate data, we created a uniform reference grid with a 100x100 m spatial resolution, spanning across 31 rows and 59 columns, resulting in a total count of 1,829 cells.

Utilizing the reference grid, data values can be assigned to each individual cell, implementing the *flat* and *extrusion* visualization modes. To maintain the visibility of the reference urban imagery (textures and buildings), this is mapped to the top of the extruded cells. This implementation is facilitated by preprocessing of the geodata. The motivation of the *extrusion* mode is twofold: first, utilizing the additional height encoding counteracts potential occlusion caused by the superimposition of the city miniature in the *flat* mode. And second, following a *low–high* extrusion/value analogy in 3D, the user's data interpretation ability should be facilitated (see Fig. 4).

3D reference scale widget (T1, T2) We implemented an interactive *3D reference scale widget* to support the user with the data interpretation of color and height encoding. It is placed at the bottom left part of the table (see Fig. 3) in close proximity to the data variable buttons. The widget is purposefully shaped as a cylinder to avoid ambiguity from the cuboid-like extrusions that represent actual cell data. It is textured according to the applied color encoding, and scaled according to the height encoding. It features textual labels for the scale endpoints (minimum and maximum) and the unit of the currently displayed data variable. The widget is interactive insofar that the user can *grab & move it* freely over the field on the table, displaying the numerical value of its currently underlying cell at the top of the widget, functioning as a cell value measuring tool (see Fig. 6 top right).

Reference scale switch: time-series versus time step (T3) We chose to utilize a traditional *blue–yellow–red* color scale for mapping *low–high* values of the urban climate data following the feedback from the climate researchers. For this scale, the static minimum and maximum values of a data variable across the *time-series*,[3] are determined as endpoints. Examining *air temperature* across time, one can observe how the temperature objectively rises during the day (red → high) and cools at night (blue → low).

When examining color and height encoding for an hourly *time step*, it becomes difficult to identify the cell value variation across the spatial dimension of the data (see Fig. 4 top). While the value range of the climate data variables is comparatively *large* across the entire time-series, e.g., ranging between *many* degrees in temperature in the 7-day period, their value range at an individual time step is *small* in comparison, e.g., ranging only between *few* degrees in temperature at an individual hour. To facilitate visual pattern detection in the spatio-temporal dataset, we implemented an alternative scale that instead maps the minimum and maximum values of a data variable in the selected *time step* utilizing a *green–white–purple* color scale (see Fig. 4 bottom).

The distinctly different color scales are implemented for two reasons. First, we wanted to avoid potential data misinterpretation (Larsson et al 2023). Utilizing the *blue–yellow–red* color scale to represent hourly value ranges creates a risk for false interpretation. Envisioning a time step with an air temperature value range of 30–34°C, low-end values would still represent objectively high temperatures, but mapped to the blue-end of the scale could arguably provide a misleading visual representation. We anticipate that the *green–white–purple* color scale better supports the user to make the mental association of comparing cooler (green → lower) and hotter (purple → higher) temperature values in an objectively still high temperature range. Second, the utilization of distinctly different color scales can support the user to keep track of the current state of the visualization environment, i.e., whether the current focus is set on examining the entire time-series or a time step.

Visualization mode: mesh overlay (T1, T2, T3) A commonly examined urban heat-related phenomenon is the UHI (Oke 1982; Prashad 2014; Gupta et al 2022; Hiemstra et al

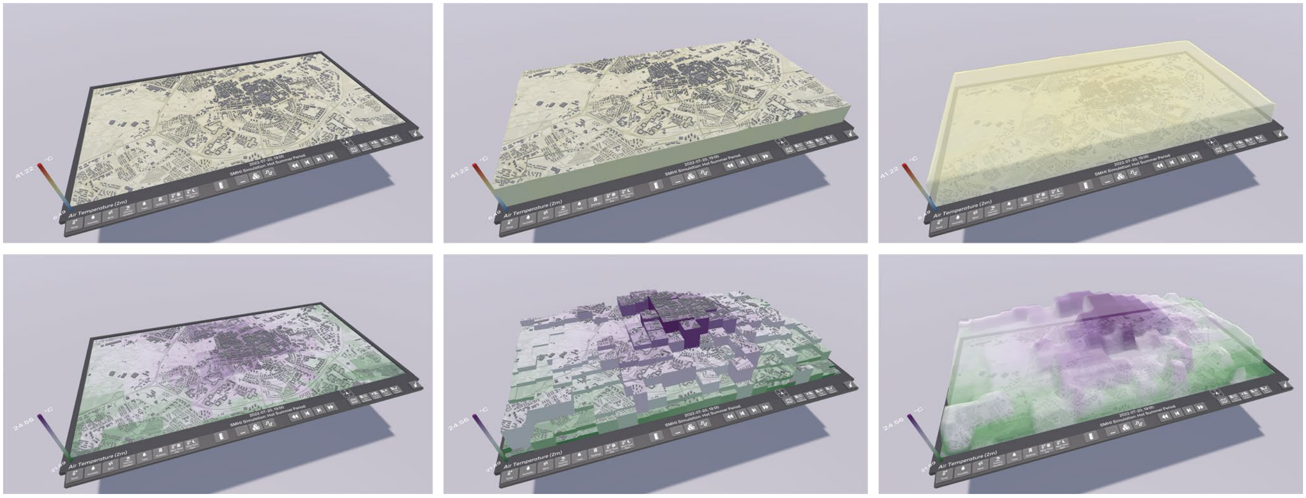

Fig. 4 Comparison of the Flat (left), Extrusion (center), and Mesh Overlay (right) visualization modes under utilization of the Time-Series (top) and Time Step (bottom) reference scales

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[3] We selected a 7-day hot summer period excerpt from the simulation dataset, representing a *heat event* i.e., a consecutive period with high air temperature.

2017; Heaviside et al 2017), describing how urban environments are more prone to higher temperatures and cool off less easily compared to green areas and suburban regions, especially at night.[4] To visually communicate this phenomenon, it is commonly illustrated as an air temperature line graph above representative urban areas (see Fig. 5 top). Drawing inspiration from this approach and utilizing a 3D heat map (Kraus et al 2020), we implemented a *mesh overlay* to create a data-based 3D visual representation of the UHI. Using the encoded height values for cell *extrusion*, we generated a color-coded, semi-transparent mesh as overlay above the otherwise flattened miniature city representation (see Fig. 4 right; Fig. 5 bottom left). The height pattern of the mesh overlay is the same as in the extrusion mode, but offers an alternative visualization technique.

Filter operation (T3) We implemented a *filter* feature to further facilitate spatial data analysis. The applied height encoding can be manipulated by interactively lowering/raising the mesh overlay. This mechanism creates a value threshold in the reference scale that needs to be surpassed to visually display a respective height encoding. The user can detect spatial areas that are above (mesh → visible) and below (mesh → hidden) a value threshold, effectively dividing the urban environment into low/high value areas. The user can perform a *grab & hold* of the mesh overlay using their hand, followed by a lowering/raising motion to adjust the applied value threshold. The 3D reference scale widget is synchronized, with the value threshold displayed as a label, and the filtered out, non-extruded segment of the scale displayed in 2D at the base of the widget (see Figs. 5 bottom right, and 10 right).

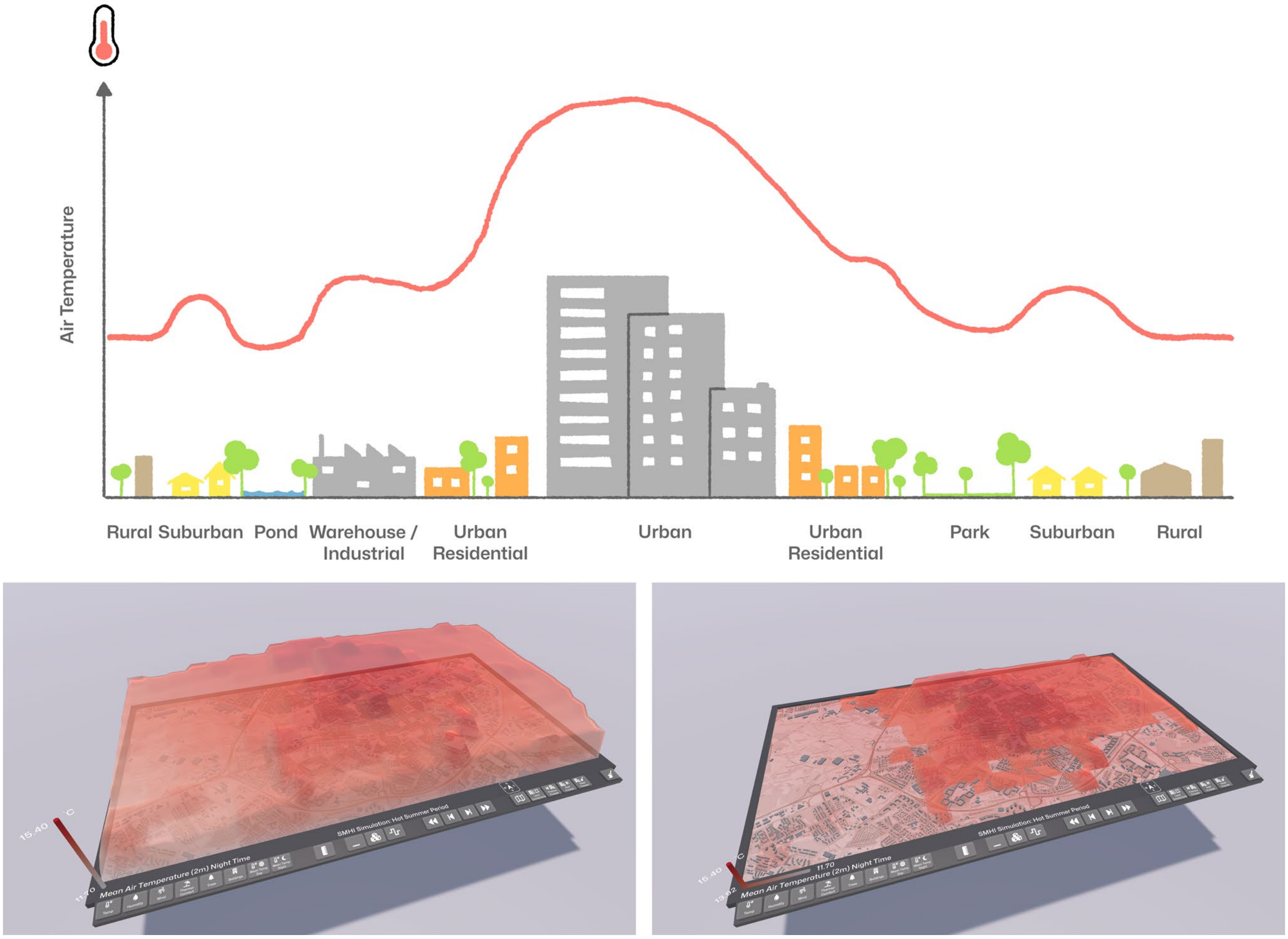

Fig. 5 Visualizations of the UHI phenomenon, under utilization of the derived *mean night time* air temperature at 300x300 m spatial resolution. Top: Conceptual illustration, adapted from Oke (1982); Prashad (2014); Gupta et al (2022). Bottom Left: Mesh Overlay visualization mode. Bottom Right: Mesh Overlay + Filter

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[4] The opposite of an UHI is referred to as a *park cool island* typically caused by urban green structures that issue cooling effects (Hiemstra et al 2017).

Contextual area highlight (T1, T4) We implemented a contextual query feature that highlights all field cells (urban areas) hosting buildings with specified purposes in the data-driven miniature city representation. Cells with one or more matched buildings will be extruded while all others remain flat (see Figs. 1 and 3). Additionally, matched buildings are temporarily colored green, instead of the grey default. This feature serves two purposes: first, it supports the identification of urban areas that host specific buildings, facilitating geospatial analysis, e.g, regarding infrastructure distribution. Second, it supports immediate data comparisons between highlighted areas. Aligned with municipal interests of taking particular care of vulnerable populations in urban heat-related scenarios (Benevolenza and DeRigne 2018; Opach et al 2022; Heaviside et al 2017), our interface features contextual query presets for different types of preschools, schools, and health care institutions.

Details-on-demand area selection (T1, T2, T3, T4) The features presented thus far focus on spatio-temporal data exploration by enabling the user to obtain, in various ways, an *overview first*. We implemented an *area selection* feature as a logical next step, supporting the user with retrieving *details-on-demand* (Shneiderman 1996) of one or multiple areas. The user can *point & touch* with their index finger an urban area for detailed examination, instantiating an enlarged copy above its miniature counterpart (see Figs. 1, 3, and 6 top left). The user can *grab & hold* this instance and move it freely around to examine its spatial composition. A *visual link* is drawn between the base of the enlarged copy and its location on the field to retain a geospatial reference. A *neighbour data frame* is placed at the base to provide visual indicators regarding the data of the cells in immediate proximity. It is composed of nine cuboids, each representing one of the area's neighbouring cells, and color-coded to reflect their data values. To remove a selected area, the user can *grab & hold* it, and move it below the table's surface, following an analogy of *putting the selected area back onto the table*.

A comprehensive data summary of each selected cell is displayed across three *information panels* (Wagner et al 2024; Bondakji et al 2019; Reski et al 2024), placed in juxtaposition to the table (see Figs. 1 and 3). The center panel displays a *line chart* visualizing the entire time-series of the currently displayed urban climate data variable, including a

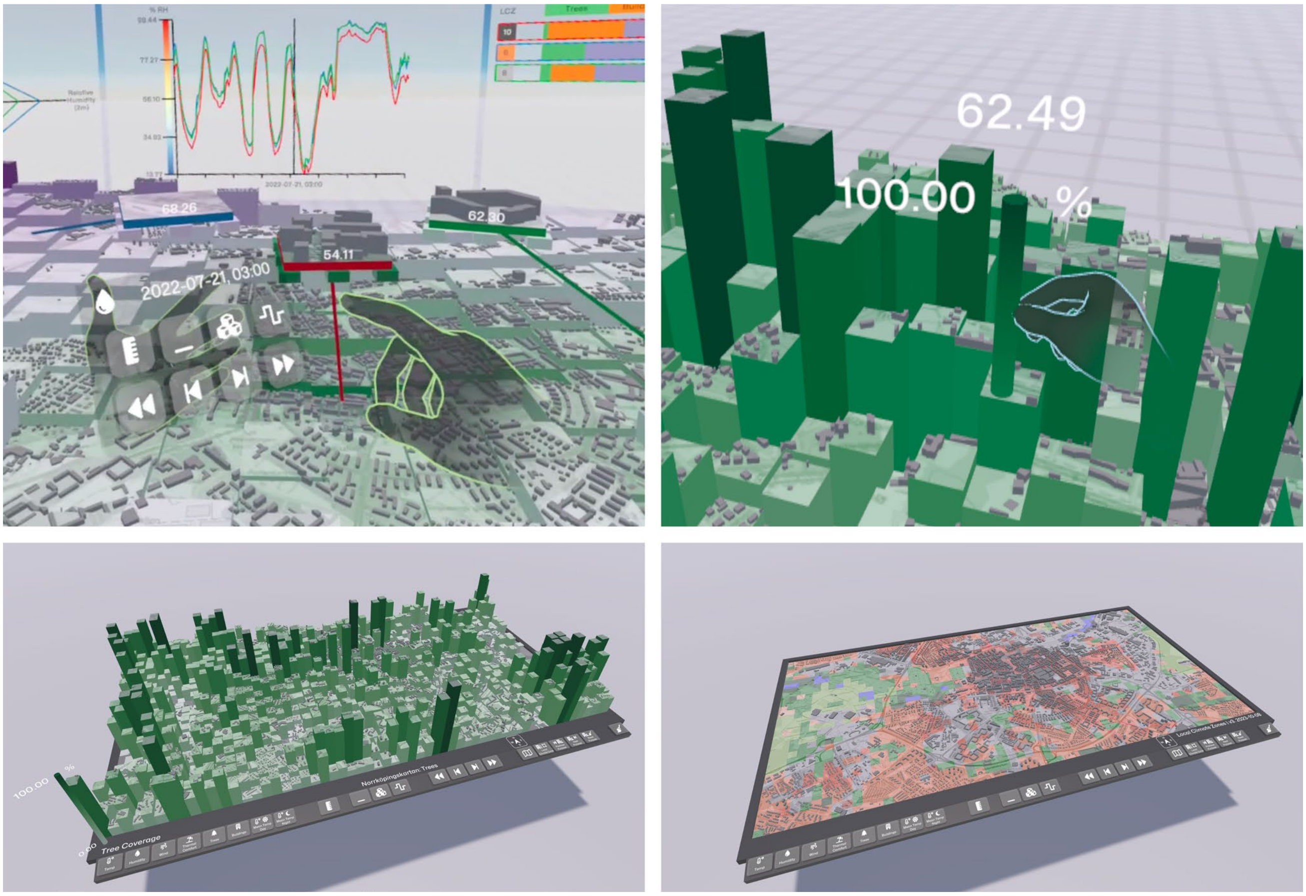

Fig. 6 Various impressions of *Urban Climate InteracTable.* Top Left: Graphical Hand Menu with quick-access buttons. Top Right: 3D Reference Scale Widget as measuring tool. Bottom Left: Tree coverage (characteristics) + Extrusion. Bottom Right: LCZ area categorization (characteristics) + Flat

visual indicator of the selected time step. The left panel displays a *radar chart* that outlines the values of all four urban climate data variables (air temperature, relative humidity, wind speed, UTCI) for the selected time step. The right panel displays an overview of the area's *characteristics* based on the available datasets (see Section 5.1). It features the LCZ identifier and a horizontal stacked bar chart that visualizes how much of a cell's 100x100 m area is covered by trees, buildings, and other (non-tree and non-buildings) components. The base of a selected area, its visual link, and its representation across the information panels are color-coded to allow respective identification and association.

5.4 Interaction and explorative analysis workflow

We envision *Urban Climate InteracTable* supporting two starting points for explorative analysis. First, if the user is interested in examining a particular time step, they start by selecting a climate data variable using the diegetic interface, followed by browsing to the desired time step. They may then utilize the visualization modes, reference scales, and filter capabilities to identify urban areas of interest for subsequent details-on-demand examination. This identification may be accompanied by iterating through the various climate data variables.

Second, if the user is already familiar with the cityscape, they could start by selecting one or multiple urban areas, displaying data summaries across the information panels. An arguably obvious choice could be the selection of a densely built-up area, and an area with high share of greenery, e.g., a park or forest, commonly located in more suburban areas. The user may toggle between displaying the normal (abstract) map imagery and the aerial orthophoto to obtain a real-world visual impression. Temporarily displaying the area characteristics, i.e., tree and building coverage, using the different visualization modes may guide the spatial area selection. With the data summaries displayed, the user can continue to explore the temporal dimension of the climate data associated to these areas. The inspection of the time-series line chart can guide the user to interesting time steps, e.g., those where values differ significantly.

5.5 Implementation

The system architecture of *Urban Climate InteracTable* is illustrated in Fig. 7. The IVRE was developed using Unity 2022 LTS. Using QGIS and Python, all datasets (see Section 5.1) were preprocessed based on their original format and transformed into GeoJSON or CSV data structures for import. 3dfier (Ledoux et al 2021) was utilized to derive height information for each individual building. A Meta Quest 2 HMD (1832x1920 pixel resolution per eye, 90 Hz refresh rate) with built-in hand tracking capabilities was utilized as VR interface. Meta XR Core SDK and Meta XR Interaction SDK, both in version 62.0, were utilized for the integration with Unity. A Windows 11 computer, in combination with the Meta Link cable to connect computer and HMD, were used to run the IVRE.

6 Use cases

Urban Climate InteracTable supports various investigations and workflows to explore urban geodata and climate data. We describe three use cases of how the developed interface can be utilized in practice.

6.1 Decision support concerning vulnerable populations

With a decreased need for preschool capacity during the summer period, municipalities commonly close the

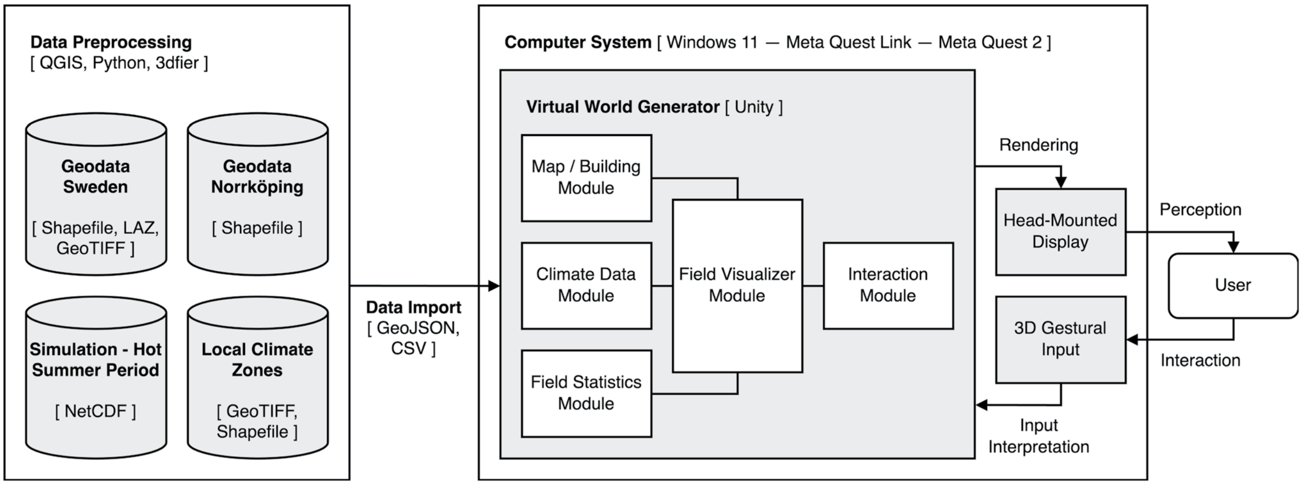

Fig. 7 System architecture overview

majority of preschools and merge remaining demands into a few selected ones that remain open. In regard to heat stress arising from higher temperatures or longer hot periods (Intergovernmental Panel on Climate Change 2022), the municipality's education office is particularly interested in appropriately selecting which preschools to keep open. Using *Urban Climate InteracTable*, the municipal planner starts by querying the contextual area preset for preschools, resulting in the visual highlighting of all respective buildings and their areas in the data-driven urban representation. To compare air temperature, or alternatively UTCI, the planner selects the respective data variable and navigates to a time step representative of expected opening hours. The time-series scale supports the visual interpretation of objectively hot time steps, while switching to the time step scale supports a focus on smaller temperature variations between the urban areas. Alternatively to the detailed step-wise (hourly) inspection, the planner may choose to display and examine the derived *mean day time* air temperature dataset[5] to identify cooler areas that are more suitable for keeping preschools open. With data variable and time step selected, only those urban areas that host a preschool are extruded, enabling the planner to visually detect differences and identify areas with lower (and higher) temperatures, facilitated through color and height encoding. The planner may choose to narrow down their selection process by displaying details-on-demand of identified candidates, for instance, examining tree coverage (possibly sun protection during outdoor activities). At this stage, the state of the interface is as illustrated in Fig. 8 and as part of Figs. 1 and 3.

6.2 Urban Heat Island depiction

To better understand the UHI phenomenon during day and night time, an analysis workflow could be structured as follows. The user starts by selecting the air temperature data variable to identify urban areas that are more prone to heat exposure and retention. Focusing on highlighting hourly differences, they switch to the time step reference scale. The user selects the mesh overlay visualization mode, and utilizes the filter operation to remove the lower 3/4 of air temperatures and just show the top 1/4 for the chosen time step. The user utilizes the quick-access buttons of their graphical hand menu (see Fig. 6 top left) to browse through the temporal dimension, enabling them to visually identify areas prone to urban heat as well as differences between day and night time. For instance, during night time, air temperature typically decreases radially outward from the city center, which retains the most heat (see Fig. 5 bottom right). This observation can be confirmed when examining the derived mean air temperature datasets for day time (3–6 pm) and night time (12–3 am), enabling even non-climate experts to gain a better understanding of the UHI phenomenon.

6.3 Simulation data quality control

An unexpected application of *Urban Climate InteracTable* emerged during collaboration with the climate researchers. When working with urban climate simulations (see Section 5.1.2), researchers commonly rely on static (non-interactive) plots to examine the generated data. The examination of complex multivariate data with spatial and temporal dimensions can be quite laborious. As part of the

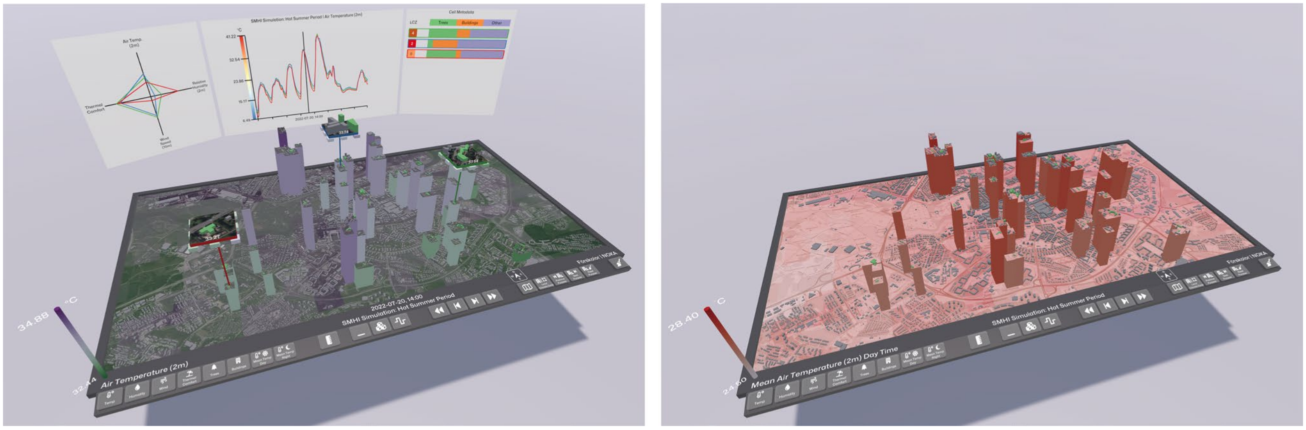

Fig. 8 Exploration of air temperature under utilization of the contextual area highlight for preschools. Left: Time Step scale + Aerial Orthophoto Map + Information Panels with three Area Selections. Right: *Mean day time* air temperature

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[5] The *mean day time* air temperature is computed based on the three hottest consecutive days in the 7-day sample period. We consider the period from 3 pm to 6 pm (local time) as representative of daytime conditions during the summer at this latitude (Norrköping, Sweden).

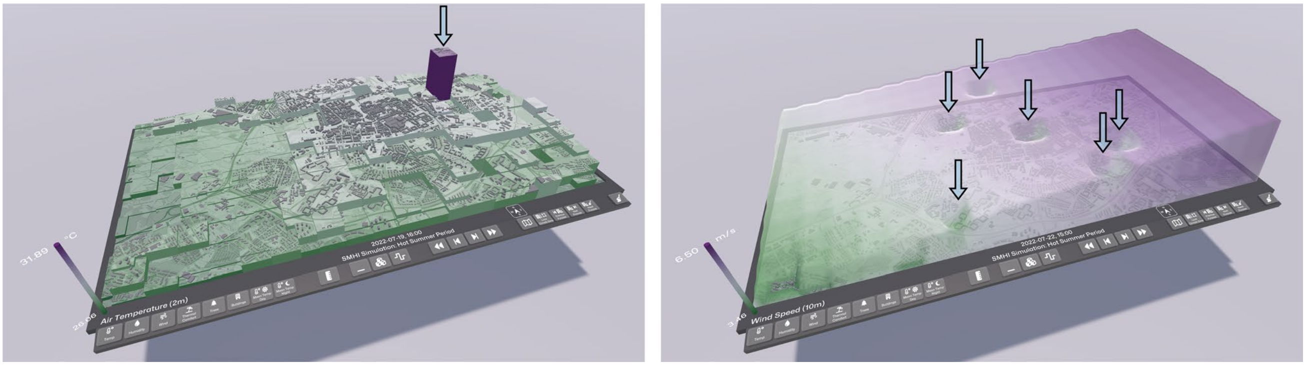

Fig. 9 A selection of two time steps with *anomalies* (annotated ⇓) discovered when interactively exploring the multivariate simulation dataset. Left: Air Temperature + Extrusion. Right: Wind Speed + Mesh Overlay

Table 1 Overview of the recruited seven collaborating domain (D) experts and four relevant external (E) experts, across four feedback sessions

No.	Role / expertise
Session 1: Urban planners	
D1	Detail planning architect
D2	Detail planning architect
D3	Landscape architect
D4	Environment and climate strategist
Session 2: Urban climate researchers	
D5	Climate modelling, Air quality, Human comfort; PhD
D6	High resolution climate modelling; PhD
D7	High resolution climate modelling; PhD
Session 3: Relevant external experts	
E1	IoT, Smart Cities, Digitization of urban environments; PhD
E2	Behavioral Science, Technology Education in Schools; PhD
Session 4: Relevant External Experts	
E3	Societal needs and applications for visualization
E4	Climate change/adaptation, heat exposure and health; PhD

prototypical development process, we engaged with the simulation data to ensure the accurate implementation of the various visualization modes. While utilizing the interface's features regarding visual pattern detection in the geospatial data context, and being able to quickly and interactively browse through the temporal dimension of the data, we stumbled across some rather "*odd*" looking patterns and seemingly "*drastic*" changes between some hourly time steps. A selection of such occurrences is illustrated in Fig. 9. Additional dialogues with the climate researchers led to a session where all researchers collaboratively used *Urban Climate InteracTable* to interactively browse through and discuss the simulation data. Our interface enabled the climate researchers in a novel and less-traditional way to identify spatio-temporal *anomalies* in the generated simulation data, serving as entry points to refine the simulation data.

7 Collaborator and expert feedback

To obtain qualitative feedback about *Urban Climate InteracTable*, we conducted four two-hour sessions with seven collaborating domain experts and four relevant external experts (see Table 1), employing a semi-structured interview approach that is commonly applied for IA evaluations (Friedl-Knirsch et al 2024). The collaborator sessions were conducted in-person and included a live hands-on test session, while the external expert sessions were performed online without a hands-on. All sessions were moderated by two researchers,[6] who began with a brief introduction, describing research context, purpose, and motivation. The moderators held an interface demonstration, walking through all major features and how these can be utilized to perform various analysis tasks. Afterwards, moderators and experts moved on to a group discussion, including hands-on and/or further demonstrations, discussing use cases and application scenarios, what they believe worked well, opportunities for improvements, and providing open-ended feedback on their overall impressions and experiences.

7.1 Visualization and interactivity

The multitude of data visualization approaches and interactive features were well received by all collaborators and external experts. D5 emphasized the ability to clearly and understandably observe the UHI effect during night time, which in their opinion is helpful to scientifically communicate this phenomenon (C1.2, C2.1). D7 reiterated that some of their workflows for comparing specific data across spatial and temporal dimensions can be quite tedious due to manually generating static plots. Therefore, D7 deemed the interface valuable as it helps to see a lot of information, interactively, in the same environment. E1 and E4 concurred with this assessment, expressing their excitement for such

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[6] One to two additional researchers were present and actively participated in the group discussions as part of the feedback sessions.

an interface that can quickly visualize data in an approachable manner (C2.1), allowing for potential impact in decision-making processes (C1.1).

D6 and D7 discussed using the interface as a quality control tool (see Section 6.3). The 3D extrusion (in addition to color) visually emphasizes anomalies, i.e., potential errors or glitches in the simulation that are worth examining. D6 and D7 elaborated that the climate data is directly related to the geospatial urban composition. Being able to visually examine these data layers in context is helpful to identify potential errors. Interestingly, while E2 found the height encoding explanatory, they cautioned for the careful introduction of such approaches, arguing that one is commonly used to seeing temperature just as colors (without extrusion).

While D1–D4 jointly emphasized that there are many factors that impact municipal decision making, not just climate-related, they all agreed that the presented interface can, due to its explanatory data visualization (C2.1), help to raise more awareness towards the topic of urban climate and to make heat-related matters more approachable (C2.2). Similarly, E2 and E3 valued the presented use case for decision support concerning vulnerable populations (see Section 6.1), hypothesizing that current decision makers may not even consider heat-related matters (C1.1).

D3 elaborated on having only a (subjective) feeling for extreme heat in their current planning processes, contemplating that data and tools can help to better understand and assess areas at risk, the underlying factors, and exposed entities. The contextual area highlight and filter functionalities of *Urban Climate InteracTable* could in their opinion provide starting points for areas that are worth looking into, particularly from the perspective of the comprehensive planners and the strategic urban environment development (C1.1), an argument that D1 and D2 agreed with. E1 acknowledged that tasks can be scenario-specific, which is in line with the intended purpose of explorative analysis using *Urban Climate InteracTable* and having the freedom to approach the analysis activity from different perspectives.

7.2 Immersive interface remarks

The collaborators had remarks based on their hands-on experiences with *Urban Climate InteracTable*. D5, a first-time VR user, appreciated the immersive capabilities and expressed that "*you really get into it*" due to all the (embodied) interactive capabilities, being able to grab things and move physically around. D5 highlighted the difference in experience compared to looking at the interface through an alternative 2D display. This remark was common throughout all the hands-on experiences by D1–D3 and D5–D6 as they engaged themselves with the stereoscopic 3D capabilities and various hand interaction mechanisms. We received comments (D2, D3, D5) regarding the static height of the virtual table itself: the collaborators would appreciate if the user themself could dynamically adjust the table height. D3 appreciated the 3D urban representation in the IVRE, stating that it is not just a top-down map that can be hard to understand at times when overlayed with data. Independently, the reflection of typically looking at maps from a top-down view was also made by E1 and E3. E1 envisioned that, in line with other research (Miranda et al 2024; Lee et al 2021), the 3D capabilities help with the geospatial understanding of the urban context. D5 suggested to add some distinct visual reference points for prominent landmarks (train station, hospital, city hall) to further facilitate the understanding of the urban context. E4 felt that the immersive interface was more interesting, understandable and user-friendly than more conventional approaches, in line with similar reflections by Schewenius and Wallhagen (2024).

7.3 Additional data layers

While *Urban Climate InteracTable* integrates comparatively rich data already (see Section 5.1), the majority of collaborators and external experts came up with ideas and suggestions for additional data layers. D5 and D6 explained that the generation of the climate simulation data relies on physiographic data, i.e., taking into account the real-world composition of an area, mapped as fractions of up to 33 different water, nature, and urban surface types (Druel et al 2022). It would be valuable to visualize these within the context of the urban environment, to potentially identify areas where the physiographic data is not (or no longer) consistent and representative of the actual real-world conditions. D3, a landscape architect, felt that it would be interesting to see additional data layers that focus on urban flora. While E1–E4 all deemed the interface useful for urban planners based on the existing climate data, they see a lot of potential through other urban-related data, e.g., indoor/outdoor thermal conditions, rain, air pollution, and traffic data, opening up such an interface to other potential target groups. E4 remarked that the included data is already fairly complex, but since the interface appears comprehensive and easy to use, adding and integrating additional data layers seems "*only natural*."

7.4 Request for comparative features

The request for additional comparative analysis features was issued across all sessions. D1–D3 described the value in seeing multiple data variables at the same time to identify potential dependencies and correlations. While the current

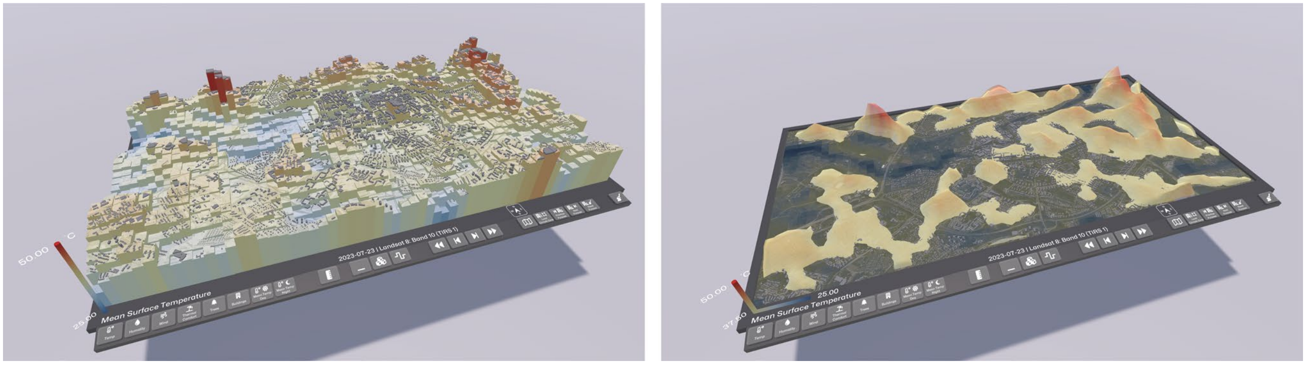

Fig. 10 Observation data, obtained from a Landsat 8 satellite (Band 10 – Thermal Infrared Sensor 1), for a hot summer day (2023-07-23), and on a 100 m spatial resolution, representing ground temperatures. Left: Extrusion. Right: Mesh Overlay + Filter + Aerial Orthophoto Map

interface supports the display of one data variable at a time, they would like to examine, e.g., both air temperature and tree coverage simultaneously. This was also remarked by D5–D7. D5 and D6 discussed possibilities to compare multiple climate simulation datasets. From their perspective, it could be valuable and informative to visually distinguish between different types of heat events (normal summer vs. typical heat wave vs. extreme heat wave) or global warming level scenarios (+0.9°C vs. +2°C vs. +3°C compared to preindustrial levels). Investigating green structures, it would be interesting to examine how forest areas compare with grassland. D2 and D3 remarked that it would be valuable to visually detect relations between cityscape characteristics and the urban climate. According to them, and particularly in discussions with decision makers, there is a difference between "*telling*" and actually "*seeing it for yourself*." Together with a moderator, D1–D3 discussed possibilities for additional contextual queries. In their opinion, and aligned with independent remarks by E4, this could assist with the data-driven identification of risk areas and vulnerabilities. A representative example query could be to display all areas than feature less than 30% tree coverage, more than 40% building coverage, and air temperature above 28°C. In a follow-up, D1–D3 remarked that there could even be an explicit sorting/ordering indicator based on the query results. E3 and E4 stated that it could be interesting to compare different cities using *Urban Climate InteracTable*.

8 Reflections

Finally, we present reflections on lessons learned from the conducted design study and describe some limitations of our work.

Connection to related work The state-of-the-art literature (see Section 2) served as the foundation when setting out to design our interface. The virtual table metaphor appeared to be a suitable approach for the interaction with maps and urban representations from a dynamic bird's-eye view (Wagner et al 2024; Zhang et al 2022). While many works display a 3D model of the cityscape to some extend, most of them appear to be static, providing only a visual reference. One counterexample focused on building interactions on a neighborhood scale, where buildings had some basic information attached (Zhang et al 2022). While not strictly comparable, *Urban Climate InteracTable* supports city scale interaction and instead utilizes building attributes for query purposes to highlight urban areas for further examination, which can be particularly relevant to municipal planners (Opach et al 2022). Prior research revealed promising performance results for lookup tasks in a 3D heat map visualization (Kraus et al 2020). Our mesh overlay visualization mode adapts this approach to directly represent conditions of interest, such as the UHI phenomenon (see Fig. 5). Examining related works (Hjort et al 2016; Oyshi et al 2024; Christophe et al 2023; Chen et al 2017; Larsson et al 2023), urban data are commonly integrated as superimposed visualizations on an otherwise static 3D urban representation. The extrusion visualization mode of our interface is unique as it retains each individual urban area representation on top of the *dynamically* extruded field cells. This supports the utilization of color and height as visual encoding modalities to explore the data while quickly obtaining an overview about an area's spatial composition. Based on our experience, we see value and opportunities in integrating urban environment presentations more dynamically in visual analysis interfaces.

Data complexity and synergies Similar to other works (Christophe et al 2023; Bondakji et al 2019; Larsson et al 2023), the objective of our interface was to contextualize and integrate urban geodata and climate data, aiming to facilitate data analysis and understanding. The interface utilizes a variety of complex data from multiple sources (see Section 5.1 and Fig. 7). Nevertheless, suggestions for the integration of even more data were made throughout all feedback sessions, indirectly indicating interest in similar related concepts, such as urban digital twins (Kuru 2023). The conceptualized *platform* aspect of the interface resulted in a modular and to a certain degree generalized implementation that already supports the import of new (or updated) data with minimal efforts. Figure 10 provides a climate-related example, displaying measured raw ground temperature based on satellite data, which has been identified as a contributing factor to UHIs (Gupta et al 2022; Hiemstra et al 2017). We identified three practical advantages of investing in a modular and data-agnostic system architecture. First, the interface can easily handle new (updated) climate simulation data. Second, we can display other non-climate data scenarios within the urban context, potentially opening up new research directions and collaborations. The integration of non-climate related data may be relevant in future iterations, as urban planners and decision makers often need to consider a multitude of aspects, with urban heat being one of many. And third, data-agnostic system capabilities, together with rapid prototyping, can support the reuse of previous implementation efforts in the future.

Educational scenarios One objective of our work was to design an appropriate visualization interface that facilitates the understanding and explainability of urban heat and heat-related phenomena, specifically by urban planners as non-climate experts. However, in line with the feedback obtained from external experts, we believe that the urban context can easily be related to by other audiences, such as residents. We see synergistic opportunities in using *Urban Climate InteracTable* to communicate urban climate data to target groups beyond municipal planners. One particular opportunity evolves around using the interface for educational purposes, aimed at increasing awareness of urban climate. Concepts such as *exploranation* (exploratory × explanatory visualization) and visual data stories could serve as an entry point to adapting the interface to support educational scenarios that communicate results from scientific data exploration (Ynnerman et al 2018; Mayer et al 2023). We envision distinct expert/non-expert user rules in a variety of scenarios: whether it is a climate researcher (expert) explaining to an urban planner (non-expert), an urban planner to a decision maker, a teacher to a student, or a public installation to a visitor.

Careful color encoding We purposefully implemented two reference scales for the spatio-temporal climate data variables, i.e., *blue-yellow-red* for *low-high* values throughout the time series, and *green-white-purple* for comparing *lower-higher* values at given (hourly) time steps. As described in Section 5.3, this was a result of intentionally avoiding visual miscommunication and misinterpretation of air temperature values. As a side effect of using distinct color scales for our two temporal contexts, we found that this helped users to retain awareness of their current analysis context. For interface coherence, we applied distinct color schemes also to other datasets, such as tree and building coverage (see Fig. 6 bottom left). Our approach and experiences are in line with the remarks by Larsson et al (2023), who reflect that miscommunication of data can occur if color scales are not carefully applied, with prior user knowledge and expectation being additional factors for consideration. Larsson et al (2023) allowed users to choose their own color scale preferences, but few users took this opportunity and accepted the default colors.

Unexpected use cases After becoming ourselves familiar with the urban climate data, we were eager to discuss discovered "*anomalies*" with our collaborating domain experts (see Section 6.3). According to the climate researchers, their data is commonly visualized as static plots. By interactively testing *Urban Climate InteracTable* together in group settings, typically by one user steering the IVRE while all others could follow the happenings on a large mirrored screen, interesting and often enthusiastic discussions evolved around the data. Addressing C2.1 with the urban planners in mind had the positive side effect of creating an interface that also supported a dedicated use case for the climate researchers, providing additional value (see Section 6.3).

Collaborative data exploration as discussion enabler By regularly presenting and testing *Urban Climate InteracTable*, many discussions emerged around the interface and the visualized data, also among our collaborators themselves, as described in the reflection on *Unexpected Use Cases*. These emerged despite the single-user centered characteristics of VR approaches (Skarbez et al 2019; Wagner et al 2024). We see unused potential for dedicated collaborative features to further support data exploration and discussions, either using the same visualization environment or through multimodal collaboration scenarios (Ens et al. 2021a; Fröhler et al 2022; Reski et al 2022). Within the context of insights dissemination, co-experience, co-exploration, and co-discovery can be valuable to build up shared knowledge and data understanding. We did not initially identify collaborative opportunities in our design study. As these might have been addressed early in our interface design process, we encourage future developers to consider hidden collaborative dimensions in workflows and interface design.

Immersive interface development While *Urban Climate InteracTable* was conceptualized as an IVRE, significant efforts were first spent on data processing and implementing the underlying visualization engine within the scope of the first two prototype versions (see Section 3). Only the final version implemented immersive capabilities.

This strategy was pragmatic. It enabled stepwise development of the system. The collaboration between data scientists, visualization experts, and interaction designers supported this process. While we were able to demonstrate regular interface advancements, the first opportunity for our collaborators to experience the immersive interface came comparatively late in the implementation. During the hands-on feedback sessions, all collaborators quickly familiarized themselves with the interface–even the first-time VR users. We feel that the choices of a virtual table metaphor and a diegetic interface were easily relatable, resulting in a shallow learning curve. However, collaborator experience of the IVRE earlier in the process would have meant greater familiarity and may have elicited additional, more-specific feedback. Other researchers who plan to conduct a design study that involves the use of immersive display and interaction technologies should carefully consider when, how, and how often to engage their collaborators in immersive interface feedback sessions.

Design study across multiple domain contexts Working with multiple collaborator groups across domain contexts is fulfilling from the VIS and HCI research perspective, learning a lot about their respective data, practices, and needs. However, the practical efforts required to enable successful collaboration across multiple domain contexts should not be underestimated. Based on our experience, such efforts include regular dialogue with two user groups (instead of one), two contextual inquiries that needed to be performed, and handling diverse sets of real-world data from multiple sources.

The contextual inquiries performed at the beginning of our study represent snapshots of the respective domain contexts at the time of inquiry. We experienced first hand changes in the contexts over time, such as new data, requests for new features, or other relevant considerations that emerge. One example late in our interface development was the emergence of the *3-30-300 rule* (Konijnendijk 2022). The rule acts as a guideline towards urban green infrastructure, describing that every resident should be able to see at least 3 trees from their home, live in a neighborhood with at least 30% tree canopy coverage, and have access to public green spaces in at least 300 m proximity. Closely related to urban climate and as an evidence-based assessment of urban green structures, the rule became of high interest to both urban planners and climate researchers. Implementing a query approach similar to our contextual area highlight (see Section 5.3), we see potential for the data-driven identification of areas where the conditions of this rule are not met.

Retrospectively, we also acknowledge the intermediary characteristics of our role as researchers throughout the design study process, which can be challenging when simultaneously working with experts from multiple domains. Considerable efforts have to be made to establish a common vocabulary. This is not a trivial task, as each domain context, including ours as VIS and HCI researchers, utilizes their own terminology that might overlap. The ambiguous term *model* is one example from the early stages of our study, referring context-dependent to either *city model* (3D visual representation of the urban environment) or *climate model* (an alternative description for simulation). To overcome such terminology-based challenges, it helped to utilize unambiguous descriptions instead, such as *city representation* and *climate simulation*–even if that demanded some efforts to readjust one's own vocabulary. Preventing misunderstandings and maintaining a clear communication between all parties (urban planners, climate researchers, VIS and HCI researchers) is fundamental for successful collaboration. In hindsight, we see value in creating a shared glossary to keep track of important terms across domain contexts.

Another challenge has been to navigate and align everyone's interests and motivations, likewise requiring intermediary actions. Although an overarching objective might exist (bridge the communication pipeline between urban planners and climate researchers), there are many constantly moving parts involved, especially over a longer period of time. We had to regularly review our development based on input from the domain experts. This was both challenging and rewarding, particularly as the climate researchers were, at the same time, advancing their research. We had to integrate updated or entirely new data throughout our interface development. Close communication and textual documentation was essential for a smooth process without major delays. We advise other design study researchers to be aware that multidisciplinary collaborations demand agility and flexibility in handling updated data and requirements.

Limitations Urban Climate InteracTable provides considerable functionality for analyzing heat-related data in an urban context. There are however also a number of limitations that require reflection. The reported findings should be interpreted as noteworthy considerations rather than definitive conclusions. The presented contextual analysis and the subsequent implementation are based on the case of Norrköping, Sweden. While we believe it to be representative to other similarly sized cities, particularly in the Nordics, it would be interesting to engage into dialogues with other municipalities, especially as climate-related matters are of timely interest (see Section 2). There are also some scalability limitations that may arise with the application of our approach to larger municipalities. The rendering of a larger city model may negatively impact system performance and thus user experience. The city model could be loaded only partially on-demand to address this, e.g., in the highlighted and selected areas. Moreover, the current size of the virtual table, and the respective physical real-world space required for embodied interaction, may be limiting for larger cities. This could be addressed by adjusting the size and/or scale of the map representation and/or the inclusion of functionality to look at the urban data at different detail levels, e.g., via zoom in/out feature. The potential interdependence of urban data layers requires consideration, specifically when integrating new data. Adding *a posteriori* a different data layer, e.g., could result in an erroneous interpretation of a relationship between a specific urban feature and the resulting effect on local climate, particularly if the new data is not (yet) incorporated in the climate simulations.

9 Conclusion

Interestingly, there exist only few design study papers within the context of VA for 3D urban data, and none of these appear to investigate urban climate-related matters (Miranda et al 2024). Based on two contextual inquiries, we identified a lack of heat-related climate information on the urban planner's side, while climate researchers encountered challenges to disseminate their insights through appropriate visualization to municipal practitioners. To address these challenges, we designed *Urban Climate InteracTable*, an immersive interface that supports data analysis tasks for spatio-temporal climate data exploration in an urban context through a variety of visualization modes and interactive features. We outlined several use cases of how we envision the interface can be used in practice. Urban planners could explore the spatial context and characteristics of urban areas in regard to climate simulations, and contextual query capabilities could assist with their ability to make assessments relating to planning and climate adaptation. Climate researchers could use the interface to interactively browse their generated simulation data for quality control, identifying potential anomalies that are worth investigating to improve future simulations. We conducted a semi-structured interview-based evaluation including interface hands-on with a mixture of collaborating domain experts and relevant external experts. They provided constructive feedback on several aspects of the interface, including aspects of visualization and interactivity, the immersive VR approach, data layers, and additional comparative features. Our various reflections may be useful and provide inspiration for similar future research.

Future Work We envision several directions for future work. We are interested in continuing our collaborations, particularly regarding a potential long-term deployment and evaluation with both the urban planners and climate researchers. While we collected valuable subjective data as feedback in our design study, performance-oriented user interaction studies may provide additional empirical insights about the interface (Samini and Palmerius 2017). There is potential for the integration of new data layers, either aligned with the climate context (air pollution, rain, green structures) or otherwise relevant to urban environments (traffic, energy infrastructure). The interface can be extended through the addition of comparative features, e.g., comparing two data variables at a given point in time, or comparing one data variable across multiple points in time, further developing existing approaches (Zhang et al 2022). We see high potential and implicit demand for supporting collaborative analysis scenarios, allowing two or more users to co-explore and discuss the data through dedicated interface features (Fröhler et al 2022; Reski et al 2022), which also appears to be underexplored (Miranda et al 2024; Ens et al. 2021a; Fonnet and Prié 2021). Some works support street-level exploration from the immersed user's field of view (Schrom-Feiertag et al 2020; Larsson et al 2023; Zhang et al 2022; Schewenius and Wallhagen 2024). It could be intriguing to implement a similar approach, e.g., within the scope of the details-on-demand exploration of individual urban areas. Finally, an adaption of the interface for science communication and use by the general public appears promising. This would raise public awareness of urban climate and heat issues.

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Data availability No datasets were generated or analysed during the current study.

Code availability We intend to publish selected modules of the developed data analysis platform in the future. Any further inquiries may be directed to the corresponding author.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential Conflict of interest.

Ethical approval We, the authors, acknowledge that any of our research addresses and follows ethical considerations for the work with human participants in general (Norwegian National Committee For Research Ethics in Science and Technology 2016; Swedish Research Council 2017). Ethical review and approval were not required for the study on human participants in accordance with the local legislation and institutional requirements.

Consent to participate The participants in data collection activities (contextual inquiry, collaborator and expert feedback) provided their written informed consent to participate in the design study.

Consent for publication The participants in data collection activities (contextual inquiry, collaborator and expert feedback) provided their written informed consent to allow the publication of any potentially identifiable images or data included in this article.

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