

Components of urban climate analyses for the development of planning recommendation maps

Florian Reinwald^{a,*}, Sophie Thiel^a, Astrid Kainz^b, Claudia Hahn^b

^a University of Natural Resources and Life Sciences, Vienna, Department of Landscape, Spatial and Infrastructure Sciences, Institute of Landscape Planning, Peter-Jordan-Straße 65, 1180 Vienna, Austria

^b GeoSphere Austria, Vienna, Division Climate and Environment, Competence Unit Urban Climate, Hohe Warte 38, 1190 Vienna, Austria

ARTICLE INFO

Keywords:

Urban climate
Urban planning
Urban climatic map
Urban climate analysis
Planning recommendation map

ABSTRACT

Due to their high density and sealing, cities are vulnerable to more frequently occurring extreme weather events such as heat, heavy rainfall and storms. Urban planning needs to respond to these climate risks. Urban climate analysis maps are used to assess climate-related hazards. Subsequently, planning recommendation maps aim to inform urban planning processes and to derive effective measures for climate change adaptation planning. Taking the IPCC risk concept as a methodological framework, this paper assesses whether and how all three components of this concept – hazards, exposure and vulnerabilities – are considered in existing urban climate analyses and planning recommendation maps based on a comparison of 12 urban climate analyses from Switzerland, Germany and Austria. This comparative analysis highlights difficulties in the practical delineation of the components hazard, exposure and vulnerability in order to assess the risk of climate impacts on cities. The informativeness of planning recommendation maps depends on the depth of the analyses of the components and subsequently affects the quality of derived planning measures for urban climate adaptation and mitigation planning. The results confirm that there are basically two methodological approaches: those of climatopes and those of urban climate models. Increasingly, there are also mixed forms that combine the possibilities of both variants. Many additional analyses or components are needed to carry out a comprehensive risk analysis, to identify particularly affected areas and thus to provide spatially explicit indications for measures. We conclude from our comparison that urban climatic analyses must therefore include four components to enable spatial climate change adaptation: (1) urban climatic analysis related to the hazard component, (2) in depth social and spatial analysis related to exposure and vulnerability components, (3) adaptation options and thus (4) planning recommendations and planning recommendation maps as “guidance to reduce the risk”. To improve these analyses and provide a better basis for decision making and planning a (international) standardisation is recommended. A joint analysis of climate scenarios as well as socio-demographic and spatial developments can support a better analysis of (future) risks for cities. The effectiveness and implementation could be promoted if the analyses are linked to the cities’ “regular” planning instruments and the statutory planning instruments.

* Corresponding author at: University of Natural Resources and Life Sciences, Vienna, Department of Landscape, Spatial and Infrastructure Sciences, Institute of Landscape Planning, Peter-Jordan-Straße 65, 1180 Vienna, Austria.

E-mail address: florian.reinwald@boku.ac.at (F. Reinwald).

<https://doi.org/10.1016/j.uclim.2024.102090>

Received 23 January 2024; Received in revised form 5 July 2024; Accepted 31 July 2024

Available online 9 August 2024

2212-0955/© 2024 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

Cities are significantly affected by climate change due to the related health, environmental, social, and economic impacts (IPCC, 2014; IPCC, 2023; Kromp-Kolb et al., 2014). They are more vulnerable to extreme weather events such as heatwaves, heavy rainfall, storms, and hurricanes compared to less densely populated regions (Rawlins et al., 2015; Schütt et al., 2022; Labedens et al., 2018).

Urban areas can experience higher temperatures compared to their surrounding rural areas due to the urban heat island effect (UHI) (Oke, 1967). This is mainly caused by the concentration of buildings, roads, and other heat-absorbing surfaces, leading to increased temperatures (Lemonsu et al., 2015). Rising global temperatures due to climate change exacerbate this effect, making cities even hotter. The expected higher temperatures and more frequent heatwaves (Ulpiani et al., 2024) can lead to heat-related illnesses and exacerbate air quality issues, especially in densely populated urban areas (Tomlinson et al., 2011). Such changes have health impacts, lead to infrastructure damages and affect economic distributions (Heaviside et al., 2017; Martinich and Crimmins, 2019). Extreme weather events and temperature fluctuations can damage critical infrastructure such as roads, bridges, public transportation systems, and buildings (Markolf et al., 2019).

The changes in climate signals can also lead to an increased intensity of heavy rainfall events that can result in more frequent and severe flooding in urban areas, that can consequently lead to landslides, infrastructure damage, power outages, and disruptions in transportation and communication systems (e.g. Stoffel et al., 2014; Altvater et al., 2011). Climate change can alter precipitation and evapotranspiration patterns, leading to droughts and water scarcity in some regions – as it is the case in Central Europe (Haslinger et al., 2023). Climate-related hazards, such as heavy rainfall events, can disrupt economic activities, both directly through physical damage and indirectly through supply chain disruptions. Last but not least, urbanization and climate change can lead to habitat destruction and changes in ecosystems, resulting in a loss of biodiversity and ecosystem services within and around cities (Brunner and Cozens, 2013; Verbeeck et al., 2011).

To mitigate these impacts, cities are working on various strategies, such as implementing climate-resilient infrastructure, enhancing green spaces or developing emergency response plans and climate adaptation and mitigation action plans to deal with extreme weather events and to reduce the risk of adverse effects (e.g. Djedjig et al., 2015; Demuzere et al., 2014; Ulpiani et al., 2024; Aboagye and Sharifi, 2024).

The review of Aboagye and Sharifi (2024) pointed out that, among other potential deficiencies, “criteria related to implementation” of climate actions are often missing in current climate action plans. In addition, Ulpiani et al. (2024) mentioned that only about one quarter of the Global Covenant of Mayors climate action plans comprise a map of climate hazards (Ulpiani et al., 2024). They also state that “there is a noted deficiency in targeting specific vulnerable population” (Ulpiani et al., 2024). Both, however, are important to define appropriate adaptation options and to optimize the location of adaptation measures as essential part of recommendations for climate adaptation planning.

Ren et al. (2012) pointed out that urban climatic maps, consisting of an urban climatic analysis map and an urban climatic planning recommendation map, can help to bridge the gap between climate science and urban planning. Both, urban climatic analysis maps and planning recommendation maps, are therefore a valuable tool to enhance the urgently needed implementation of climate actions (IPCC, 2023). In recent years, many different urban climate analyses have been conducted around the world with the aim of providing planning recommendations for spatial development and to increase climate resilience (Ren et al., 2012, Ngamsiriudom and Tanaka, 2023, Xu et al., 2020, Guerra et al., 2023, Zhang et al., 2024). These were performed using different methods and tools (see chapter 1.2

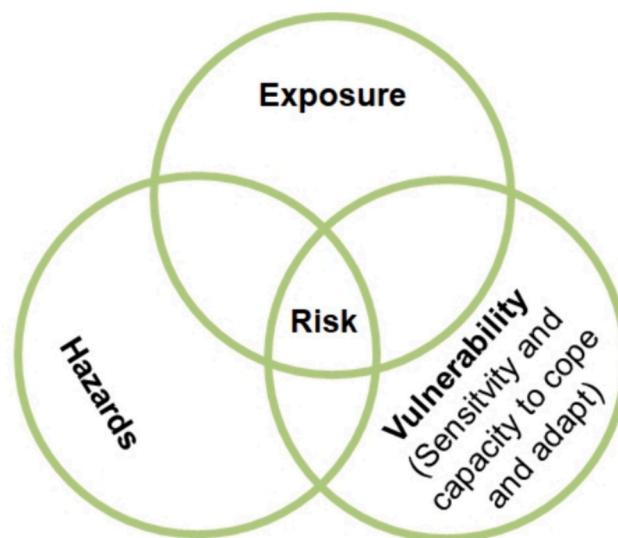


Fig. 1. Schematic showing the incorporation of hazards, exposure and vulnerability to determine risk as a basis for urban climate analysis (IPCC, 2014; Estoque et al., 2023).

and 3.1.1). Research and practice show that “pure” urban climate analyses are not sufficient for urban planning (Ren et al., 2012, Zhang et al., 2024, Ulpiani et al., 2024, Hidalgo et al., 2019). A comprehensive risk analysis and the identification of particularly affected areas, and thus spatially explicit indications for planning measures, require many additional analyses or components. In order to determine the consequences of climate change for cities and urban planning, the IPCC risk concept with the components hazard, exposure and vulnerability provides the theoretical framework.

1.1. Hazard, exposure and vulnerability – The IPCC framework as a basis for risk communication

In the context of climate change impacts, risks arise from the dynamic interactions between climate-related hazards and the exposure and vulnerability of the affected human or ecological system to those hazards. The concept of risk as depicted in the IPCC reports provides a useful framework for decision-makers to address negative impacts of climate change (IPCC, 2014). In the area of urban planning this helps to develop strategies to reduce the potential negative effects of urban climate change. To evaluate climate-related risks in urban areas, the determining factors should be assessed and embedded in urban climate analyses.

In the fifth Assessment Report (AR5) (IPCC, 2014) and the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) (IPCC, 2012), risk is expressed as a function of hazard, exposure and vulnerability. There has been a methodological shift towards a risk-centered approach compared to previous assessment reports (e.g. AR4), where vulnerability has been expressed as a function of exposure, sensitivity and adaptive capacity. In their review Estoque et al. (2023) found that misinterpretation and unawareness exist among researchers when addressing the revised concept. Here, we focus on the concept proposed in the AR5, thus considering the aspects of hazards, exposure and vulnerability together to support urban planning and decision making and to provide guidance to reduce the risk (see Fig. 1).

1.2. Adaptation to climate change in urban planning using urban climatic analysis

As a basis for climate change adaptation strategies, cities are commissioning urban climatic studies for strategy development and decision making. An important component of an urban climatic study is the production of urban climate analysis maps, which depict the local climatic conditions of an urban area (Baumüller, 2015).

Urban climate analyses have been conducted for several decades, with the emergence of urban climatology as a distinct field of study in the mid-20th century (Yoshino, 1990). However, the systematic examination of how urban environments influence local climate conditions dates back even further. As urbanization began to transform cities during the Industrial Revolution, observers noted temperature differences between urban and rural areas. One of the earliest recorded references to the urban heat island effect can be found in a publication by Luke Howard in the early 19th century (Howard, 1833). In Europe, the first urban climatic maps were developed in Germany in the 1970s (Matzarakis, 2005). At that time the mitigation of air pollution was in focus (Ren, 2015). Based on land use information and its climatic characteristics, the different urban climatic conditions were defined as climatopes – spatial units of the urban climatic maps (Ren, 2015) – which until today provide a central methodological approach to urban climate analyses (see a detailed description in chapter 1.2.1). In the 1990s several cities in Germany (e.g. Stuttgart, Berlin) continued to conduct climatic analyses leading to a set of ‘climatic atlases’ that informed urban planning decisions aiming at improved air exchange in these urban areas (Ren, 2015). Starting in the 1980s and with increasing awareness of environmental issues, urban climate analyses gained significance in the context of climate change and urban planning. Federal states and cities started to conduct detailed measurement campaigns to analyze urban climatic conditions. Thermal images, meteorological measurements, mobile measurements or vertical atmospheric soundings were used to evaluate the climatic situation within a city. Furthermore, researchers began using advanced computer modeling to simulate the spatial distribution of urban heat load and predict the effects of different urban designs and land use patterns (Sievers and Zdunkowski, 1986; Bruse and Fleer, 1998).

Similar to the climatopes, the urban climate zones (UCZ) are linking air temperature to land use/land cover classes surface properties and offer a generic typology for identifying areas in terms of their capacity to modify the local climate (Oke, 2006; Richard et al., 2018). Based on this approach, Stewart and Oke (2012) developed Local-Climate-Zones (LCZ) which are used worldwide due to offering an easily applicable global dataset (Richard et al., 2018; Guerra et al., 2023; Zhang et al., 2024; Lehnert et al., 2021).

According to Ren et al. (2011), urban climate analysis maps generally consist of three aspects: i) the dynamic component (e.g. local wind systems and cold air flows), ii) the thermal component, focusing on areas affected by heat stress and iii) air pollution. In current scientific literature, two primary methodologies are distinguished for evaluating settlement areas under bioclimatic stress: (1) climatopes and/or (2) urban climate models (Ren et al., 2011).

1.2.1. Urban climate analyses using climatopes

Climatopes are non-parcel-specific spatial units that represent areas with similar microclimatic characteristics (Baumüller, 2015). Meaning each climatope unit responds similarly to boundary layer forcing and represents a local (micro)climate (Mora, 2010). A boundary between two climatopes indicates the potential range of two neighboring urban climatic conditions (Ren, 2015) and is not a fixed entity in reality (Stanhill and Kalma, 1995). Climatopes are mainly distinguished by daily thermal variations, the surface structure and vertical roughness, topography as well as the type of land use and vegetation cover (Scherer et al., 1999; Baumüller, 2015). However, the development of climatopes is a qualitative process based on climatic expertise or prior knowledge of local topography and climatology and specialized to particular (urban) areas (Parlow, 1998; Scherer et al., 1996, 1999; Alcoforado et al., 2009; Ren, 2015). Consequently, each city exhibits a unique set of climatopes meaning that intercity comparisons or generalizations are of limited use (Stewart and Oke, 2015). The climatope approach was first used to differentiate urban areas according to their

climatic functions and characteristics, with the aim of reducing air pollution in the early second half of the 20th century in Germany (Ren, 2015). However, climatope maps are developed and used for other contexts as well, such as the climatic analysis of mountain areas (Mora, 2010).

The method of developing climatopes has been described in English and German by the Association of German Engineers (VDI)¹ in their standard “VDI 3787 Part 1” and studies not only in German-speaking countries used the climatope approach for generating urban climatic maps (see Ren et al., 2012 and Ren et al. 2015 for global examples). According to the VDI, climatopes are derived, classified and allocated from the latest digital, geo-referenced data (VDI – Verein Deutscher Ingenieure, 2015). This data consists of: land use data, topography (e.g. digital elevation model), data of building layer (including building height, building density and degree of sealing etc.), data of vegetation type and structure or aerial images with high spatial resolution (VDI – Verein Deutscher Ingenieure, 2015).

These data feed various GIS layers – e.g. building volume, ventilation paths, green areas, slopes, etc. – where climatopes can be delineated qualitatively. This classification of climatopes should then be further improved with information on the distribution of basic climatic parameters (e.g. air temperature, humidity, wind speed and direction, radiation), cold air drainage and thermally induced wind systems, as well as information on human-biometeorological conditions (VDI – Verein Deutscher Ingenieure, 2015). It is crucial to acknowledge that the VDI is a Germany based standard that is primarily designed for low-density urban settings (Ren, 2015). For high-density cities, which often have a diverse land-use composition, the climatope approach requires further refinement and expansion. In the case of urban climate analysis in Hong Kong, for example, not only were land use, topography, vegetation, and wind data employed to delineate climatopes, but further detailed urban morphology information, including building tower and podium data, was incorporated to calculate building volume and ground coverage, as well as proximity to openness (Ren, 2015).

1.2.2. Urban climate analyses using urban climate models

Climate analyses can also be based on numerical urban climate models for city-wide climate consideration, optionally supplemented with microclimate models to simulate detailed features such as building geometry and characteristics, vegetation, etc.

In recent years, several models (we mention some of them in chapter 3.1.1.) that cover a broad range regarding physical processes, spatial and temporal scales have been developed to provide urban climate information for different purposes (e.g. urban planning). Urban climate models are applied on city scale and take into account detailed information regarding land cover properties (e.g. buildings, soil, vegetation, water) to simulate interactions between built-up areas and natural surfaces within urban areas and surroundings. They can be used to simulate the spatial distribution of heat-related hazards and thus provide an important tool within the scope of urban climate analyses (e.g. Gross, 1994; Sievers, 2016; Maronga et al., 2020). By combining urban climate model results with regional climate projections using dynamical-statistical downscaling techniques, urban climate scenarios can be performed considering different greenhouse gas emission scenarios (Früh et al., 2011). Microscale models are used to simulate the effects of buildings and vegetation mainly on their immediate environment by considering detailed urban structures like building geometry, surface materials or different types of vegetation related to buildings (e.g. roof or façade greening). Due to their higher computational requirements, their spatial extent is limited to block or district areas, where they can be applied within the framework of detailed studies and (individual) urban development projects (Bruse and Fleer, 1998). Some models and tools were specifically designed to quantify radiation parameters like mean radiant temperature that provide the basis for the calculation of thermal indices like the physiological equivalent temperature (e.g. Matzarakis et al., 2010).

To consider important nocturnal cold air flows that provide natural ventilation and cooling of urban areas, cold air drainage models are often applied within the framework of urban climate analyses. As a result, parameters such as cold air layer height, wind speed and cold air volumetric flows are calculated (e.g. Lohmeyer and Schädler, 1998; Sievers 2005).

1.3. From urban climatic analysis to planning recommendation maps – Linking climatic and planning knowledge

In recent decades, with an improved understanding of urban climate dynamics, planning recommendation maps have gained significance as a crucial element of urban climate analysis and climate-resilient urban planning. The use of maps to inform urban planning decisions is a long-standing practice, though the methodical addition of climate-related recommendations to such maps has intensified in recent years, resulting in a limited amount of published scientific literature on the subject (Baumüller, 2015; Ren et al., 2011). As far as we know, the VDI directive 3787 Part 1 (2015) is presently the only methodological guideline for creating planning recommendation maps, although it is predominantly employed in German-speaking countries. In accordance with the directive and Baumüller (2015), the planning recommendation maps aim is to offer an integrated evaluation of climate analysis map results and supplementary analysis for the purpose of guiding cities on suitable adaptation and mitigation measures.

The derivation of planning recommendations from the analyses is a necessary step to “translate” the climatic knowledge for spatial planning and to inform subsequent urban planning and development processes. The transition from analysis to planning recommendations has gained traction in practice but not as much in research. There are currently limited methodological guidelines and

¹ VDI - which stands for “Verein Deutscher Ingenieure” and translates to “Association of German Engineers” - is a German network that publishes technical regulations in order to set quality standards in many areas of industry. Developed by engineers for engineers in an interactive process over several years, the VDI standards are practice-oriented and aim to reflect the state of the art - i.e. for urban climate analyses. As a result, VDI standards claim to be generally recognised technical rules that provide guidance, with the German version of these standards being binding (VDI, 2024; VDI – Verein Deutscher Ingenieure, 2015).

approaches for creating such recommendations. Analyses are developed both within research projects and on behalf of individual cities. In most cases, an own, individual method for the planning recommendation maps is developed.

1.4. Aims of the contribution and research questions

The aim of this paper is to compare different examples of urban climatic analysis in order to identify similarities and differences in their practical implementation, and to provide a basis for the development of a typology for urban climate analyses. Examples from cities in the DACH region (Germany, Austria, Switzerland) will serve as a basis.

The main research questions are: (1) How is the IPCC AR5 risk concept implemented in urban climate analyses and urban planning recommendation maps?, (2) How are the individual components – hazard, exposure and vulnerability – analyzed in practice for urban planning purposes?, (3) Which components must be included in an urban climate analysis in order to be able to make spatially explicit statements for the spatial development of a city (i.e. in the form of planning recommendation maps)?

2. Materials and methods

The development and implementation of urban climate analyses for planning recommendation maps requires a combination of climatic and urban planning expertise. The paper is based on a research project, where experts on urban climate, urban and landscape planning and planning practice cooperate and combine their approaches, knowledge and methods.

2.1. Selection of examples

The contribution is based on an analysis and comparison of practically implemented urban climate analyses from Austria, Germany and Switzerland (DACH region). Urban climate analyses are commissioned by cities and are therefore usually documented in the respective national language. In order to be able to organize an in-depth analysis and comparison, examples from German speaking countries were selected since all authors are native German speakers.

Initially, an online search was conducted focusing on the 25 most populated cities in Austria and Switzerland as well as the 30 most populated cities in Germany to determine whether they have an urban climate analysis. In Austria, five, in Switzerland six (additionally three analyses on the cantonal level) and in Germany, 27, cities were identified to have undertaken such analyses. Secondly, the examples were reviewed to determine whether they included planning recommendation maps (up till June 2023). This criterion reduced the number of examples to three Austrian, three Swiss² and 24 German examples. The next step involved evaluating whether the urban climate analyses were initiated by the respective municipalities – those initiated through research projects were eliminated in order to emphasize on the procedure of implementation in practice. Finally, the most diverse range of contractors of the examples was chosen, as we found that most of the examples in Switzerland and Germany were done by the same contracting company. Due to these exclusion criteria, the sample was reduced to a total of 12 cities, which were analyzed and compared in depth: Austria – Graz, Linz, Innsbruck; Switzerland – Zurich, Basel-Stadt, Winterthur; Germany – Berlin, Stuttgart, Leipzig, Essen, Gelsenkirchen, Aachen. For the comparison, the examples were anonymized by letters in brackets: (A) to (L). The materials used (the reports from the urban climate analyses as well as the main urban climate analysis maps and planning recommendation maps) to analyze our sample are documented in the appendix.

2.2. Qualitative content analysis and comparison by attributes

A qualitative content analysis (Mayring, 2019, Gläser and Laudel 2019) of the reports and maps was carried out for the analysis and subsequent serves as a basis for the comparison of the selected examples. A coding key based on the categories of the IPCC AR5 (2014) risk concept was developed for this purpose. The initial structure of the coding key consisted of the four main categories – hazard, exposure, vulnerability and (guidance to reduce the) risk – within which the different processing steps, methods and components were assigned. In order to understand the exact methodology, components and work steps for the production of planning recommendations maps, different forms of urban climate analyses and the corresponding planning recommendation maps were identified from the literature using a deductive approach. These served as a first categorization of codes for the processing steps, methods and components of urban climate analyses. Thereupon, the literature was searched for further differentiation attributes. In addition, individual attributes of the examples analyzed were inductively added. A total of 118 codes (65 codes for hazard in 10 categories, 11 codes in 4 categories for exposure and vulnerability, 11 codes in two categories for the adaptation options and 31 codes in 6 categories for the “guidance to reduce the risk”) were used for the analysis of the documents and plans from the examples (see Table 1 below and the complete table in the appendix).

After assigning the codes to the different methodologies, components and processing steps used in the examples analyzed the results were transferred in a table to compare differences and similarities and to develop first approaches for a typology. In order to

² Although the city of Basel lacks a “classic” planning recommendation map, our desire to have as many examples for comparison as possible meant that Basel’s heat-concept (their adaptation strategy to urban heat) was included in the sample. This is not seen as a big problem, since it followed on seamlessly from the climate analysis of the canton of Basel-Stadt and integrates the same workflow as stated in the VDI directive for planning recommendation maps and literature.

Table 1

Overview table of analyzed categories and attributes. The main categories were initially derived from the IPCC AR5 risk concept components and then revised to structure the results accordingly. Own table, 2024.

1) Hazard: Urban Climate Analysis and Analysis Maps
Method of urban climate analysis
Climate Analysis map(s) for daytime
Climate Analysis map(s) for nighttime
Climatope Map (with combined day- and nighttime thermal load)
Presentation of thermal and dynamic components within analysis map(s)
Differentiated climatopes as consolidated indicators (if applicable)
Consideration of climate change projections in hazard analysis
Additional urban climate change scenario maps depicting future periods
Measurement campaigns for data (climatope) generation or comparison with model results
Types of measurements
2) Exposure and Vulnerability: In-depth analyses
Identification of particularly affected areas (exposure analysis)
Analysis of sociodemographic Indicator (population density/distribution)
Identification and analysis of vulnerable groups (vuln. Group(s)/distribution)
Identification and analysis of vulnerable (social) Infrastructure
3) Adaptation Options
Identification and proposal of adaptation options
Fields of action for adaptation options identified
4) Guidance to reduce the Risk: Planning Recommendations and Planning Recommendation Maps (PRM)
Structure of Planning Recommendation Map (PRM)
Presentation of heat load in the built-up areas in PRM
Presentation of green/open spaces in PRM
Aspects of assessing the climate function of green/open space
Presentation of ventilation and cold air flow in PRM
Designation of traffic-related air pollution of Main roads

compare the examples, the processing steps, methods and components used in each case are marked with an “x” in the table.

The comparative method is often applied when looking for patterns of similarities and differences by comparing attributes. Such as, for example, different methods, input data, simulation tools or socio-demographic indicators used. This comparison leads to a typology of urban climate analyses with the aim of producing recommendation maps for urban planning. According to Mandara (2003), a typology is “a hierarchical system of categories used to organize objects according to their similarities and dissimilarities”. The construction of typologies is of central importance – mainly in qualitative social research – when complex realities have to be handled, understood and explained as far as possible. However, minimal methodological guidance has been developed so far to explain the process of a systematic and transparent type construction in detail. A typology is created by dividing an object field into groups (types) according to one or more attributes. In doing so, it is important to consider, that the elements within a type are as similar as possible (internal homogeneity on the “level of the type”) and, that the differences between the types are as great as possible (external heterogeneity on the “level of the typology”) (Mookerjee and Roy, 2023; Stapley et al., 2022).

Since there is no existing typology for urban climatic analysis, a progressive typification was carried out (Kluge, 1999). Starting from the individual attributes, those that are most similar are examined, based on the meaningful combinations of attributes. The results of this analysis and comparison are described in the following chapter.

3. Results – Components of an urban climate analysis for the development of planning recommendation maps

We distinguish the following components for the comparison of the attributes of the examples: (1) urban climatic analysis related to the hazard component, (2) in depth social and spatial analysis related to the exposure and vulnerability components, (3) adaptation options and thus (4) planning recommendations and planning recommendation maps as “guidance to reduce the risk”.

3.1. Comparison of the individual components of an urban climate analysis for the development of planning recommendation maps

We listed the above-mentioned four distinguished components (see chapter 3) in our table, which subsequently supported us in depicting and allocating many different attributes drawn from our sample of twelve examples during the comparative analysis. For better clarity and understanding we included a condensed version of this table for each component separated in the following (sub-) chapters (the complete table is in the appendix). Aside of the table we describe the differences and similarities found in the following sections.

3.1.1. Climate hazard analysis – Urban climatic analysis

In all twelve examples, urban heat load including cold air and/or ventilation paths were analyzed to represent the *thermal* and *dynamical* component of the urban climate analysis (See Table 2:). An additional analysis of air pollution was performed in seven examples (A), (G), (H), (I), (J), (K), (L), whereas two examples (G and H) additionally considered heavy rainfall. The results are summarized in the form of so-called urban climate analysis maps (for model-based analyses) or synthetic urban climatic maps (for

climatope-based analyses) to depict the climatic situation within a city and to delineate areas based on their climatic functions and their climate-ecological spatial structures. Furthermore, they provide the basis for in-depth analyses (see 3.1.2) and for deriving planning recommendation maps (see 3.2).

Our comparison has shown that the urban climate analyses and the delineation of affected areas provided by each city are based on numerical simulations or on climatopes, using different tools and techniques. When analyzing hazards on city or microscale, it is important to consider detailed city-specific structures as they strongly influence the characteristics of extreme weather events. Individual weather stations are not sufficient to depict the climatic situation in detail. Numerical models, GIS analyses or additional meteorological measurements are therefore used to locate spatially areas prone to a certain hazard. The input data used for performing the urban climate analysis strongly depend on the applied models or tools and their requirements. The following datasets are commonly used within the scope of urban climate analyses and were included by a majority of the studies: a digital elevation model, land use classification scheme or zoning plan, vegetation data, building data and degree of soil sealing. Some analyses include elaborate urban climatic observational assessments representing meteorological and climatological conditions regarding near-surface temperature, relative humidity, wind field or cold air paths. The topic of air quality was considered in seven examples by providing

Table 2

Summary of the indicators found for depicting the thermal and dynamic aspect of the urban climate analyses and to characterize the hazard. This table is a condensed version of the comparative analysis of attributes allocated to the hazard component (the full/complete table is in the appendix). Key: x = applicable. Own table, 2024.

Example Codes		D	E	F	G	I	C	B	H	A	J	K	L
1) Hazard: Urban Climate Analysis and Analysis Maps													
Method of urban climate analysis													
	Model-based approach	x	x	x	x	x							
	Climatope-based approach									x	x	x	x
	Mixed form approach						x	x	x				
Climate Analysis map(s) for daytime		x	x	x	x	x							
Climate Analysis map(s) for nighttime		x	x	x	x	x							
Climatope Map (with combined day- and nighttime thermal load)							x	x	x	x	x	x	x
Presentation of thermal and dynamic components within (consolidated) urban climate analysis map(s) or climatope map													
	PET - Physiological Equivalent Temperature (day)	x	x	x		x							
	2 m air temperature (night)	x	x	x		x							
	Urban heat island effect (night)	x	x	x	x	x							
	Climatopes						x	x	x	x	x	x	x
	Nocturnal wind field	x	x	x		x							
	Wind field changes				x		x	x			x		
	Wind rose						x	x	x				
	Cold air volume flow	x	x	x		x							
	Cold-air paths		x		x	x	x	x	x		x	x	x
	Cold air production areas (implicit or explicit)		x			x	x	x	x	x	x	x	x
	Cold air impact areas		x		x	x							
	Ventilation paths				x	x	x	x	x	x	x	x	
Differentiated climatopes as consolidated indicators of combined day- and nighttime thermal load as well as dynamic components (only applicable for climatope map examples)													
Consideration of climate change projections in hazard analysis		x	x	x	x	x	x	x				x	
Additional urban climate change scenario maps depicting future periods		x	x	x		x	x	x					
Measurement campaigns for data (climatope) generation or comparison with model results													
	for thermal component (heat)					x	x	x	x	x	x	x	x
	for dynamic component (wind/ventilation/ cold air)						x	x	x	x	x	x	x
	no additional measurements	x	x	x	x								
Types of measurements													
	Station measurement campaigns to determine meteorological parameters such as air temperature, wind, relative humidity						x	x	x	x	x	x	x
	Mobile measurements (vehicles) to assess air temperature and urban heat island effects					x	x			x	x	x	x
	Thermal airborne measurements to determine radiation and surface temperatures					x			x	x			x
	Trace gas measurements to determine cold air flows											x	x
	Vertical soundings to analyze vertical profiles of temperature, relative humidity and wind									x			x

additional data and maps regarding pollutant emissions and their value exceedances (e.g. CO, PM10 or NOx emissions).

The mesoscale model FITNAH-3D (Flow over Irregular Terrain with Natural and Anthropogenic Heat Sources) (Gross et al. 1994) was applied in all model-based studies investigated here. It is a three-dimensional numerical model developed at the Meteorological Institute of the University of Darmstadt, Germany, and has since been further refined and enhanced by the private company GEO-NET Umweltconsulting GmbH. It has been employed in many cities across Germany and Switzerland to investigate urban climatic patterns by analyzing small-scale temperature distribution, thermal load, cold air dynamics and flow conditions during representative fair weather conditions. In particular, the physiological equivalent temperature PET at 14:00 Central European Summer Time (CEST) was used to characterize thermal stress during daytime. For the nighttime, the 2 m near-surface temperature (and the subsequently derived nocturnal urban heat island effect) as well as wind field and cold air volume flow at 04:00 CEST were used to indicate areas prone to nocturnal overheating, to investigate processes of nocturnal air exchange and to depict important cold air and ventilation paths.

In the case of the climatope-based and mixed-form analyses, the results were merged and summarized into one synthetic urban climate analysis map by delineating areas based on their microclimatic properties. The number and type of climatope classes strongly differs among the analyzed examples and ranges from 9 to 30 (see appendix table for detailed differentiation of climatopes found in the sample). For two examples (C and B) it was mentioned that some climatopes are only implicitly included and have been taken into account, even if they are not visible on the map. Cold air drainage models, such as KLAM_21 (Sievers 2005) or KALM (Lohmeyer, 1998), were frequently applied to simulate nocturnal cold air paths and to identify cold air volume flow or thickness of cold air. In most cases, the delineation of the climatopes is not solely based on static data. Some analyses (A, H, J, K, L) combine comprehensive available meteorological observational datasets from measurement campaigns, air quality data or aerial images with topographic and land use data to assess the climatic and air hygiene situation and to define the climatopes. The measurement campaigns include temporary installed climate monitoring stations, vehicle-based measurements, airborne multispectral scanners or vertical soundings, aiming to identify local characteristics and spatial differences within the city. In certain climatope-based studies, human-biometeorological conditions were integrated into the analysis. One example explicitly mentions the RayMan Pro model (Matzarakis et al., 2010) to determine PET at selected stations. Other studies state that PET served as a basis for the characterization of the climatopes.

Regarding the future development of heat-related hazards, the effects of climate change in the respective areas were additionally analyzed by many studies, with examples (B), (C), (D), (E), (F) and (I) explicitly providing urban climate change scenario maps based on the results of the hazard analysis in combination with regional climate projections. For instance, heat-related climate indicators (e. g. the mean annual number of hot days, summer days, tropical nights or PET exceedance days) were evaluated for current and future 30-year periods, considering different representative concentration pathways (RCP). One example (E) presented daytime and nighttime scenarios for the year 2030 by taking into account future climatic conditions and projected land-use changes. Examples (B) and (C) analyzed the potential impact of hypothetical urban development scenarios in the context of climate change.

3.1.2. Exposure and vulnerability – In depth social and spatial analysis

In addition to the climate hazard analysis, in-depth analyses were found to identify urban areas that are particularly exposed and/or vulnerable to climatic changes (See Table 3:). Subsequently, particular socio-spatial vulnerabilities can be derived from these in-depth exposure analyses. The in-depth analyses were based on the areas of a city with high thermal load as identified and located in the hazard analyses. The extent to which individual areas of the city are particularly exposed depends, primarily, on the time of the day. Therefore, the distinction in daytime and nighttime heat load, based on the same distinction of the hazard analysis, was made in all five examples using simulation tools to determine the hazard. Our findings further reveal that such in-depth analyses of socio-spatial exposure and vulnerability were lacking in all of the climatope- or mixed-form-examples. Those cases that conducted in-depth analyses were presenting these aspects mostly in the written reports or in additional maps, sometimes as part of subsequently written climate change adaptation strategies.

Population density can indicate the areas where many people are exposed to the urban heat island effect, especially at night. Areas with an above-average number of inhabitants (compared to the overall urban population density) were considered. This differentiation by daytime and nighttime heat load was then overlaid with different socio-demographic and spatial criteria. The overlaying socio-

Table 3
Summary of the aspects and indicators found to characterize the exposure and vulnerability component. This table is a condensed version of the comparative analysis of attributes allocated to the exposure and vulnerability components (the full/complete table is in the appendix). Key: x = applicable. Own table, 2024.

2) Exposure and Vulnerability: In-depth analyses									
Identification of particularly affected areas (exposure analysis)									
No particularly affected areas identified									
Particularly affected areas: Daytime					x	x	x	x	x
Particularly affected areas: Nighttime					x	x	x	x	x
Built-up areas with green space deficit									
Analysis of sociodemographic Indicator (population density/distribution)					x		x		x
Identification and analysis of vulnerable groups (vuln. Group(s)/distribution)						x		x	x
Identification and analysis of vulnerable (social) Infrastructure						x		x	x

demographic indicators were the 90th percentile of the overall population density in example (D) and (F), or the upper quartile in example (I). The examples (I) and (G) added the distinction of vulnerable population groups, which were in both cases particularly young or elderly people. Example (I) used the upper quartile to distinguish the additional social vulnerability, while example (G) just stated “above average” occurrence of these vulnerable groups for outlining a further (socio-spatial) vulnerability to heat in these respective spatial blocks.

These indicator groups for social vulnerability were also used to define the vulnerable (social) infrastructure that was considered in two in-depth analyses carried out by our examples. In (I) these were health-care facilities, retirement and nursing homes, childcare facilities and educational buildings including after-school care for children; and in (G) the same vulnerable infrastructure was considered plus additionally: libraries, playgrounds and sport facilities.

The areas of high thermal exposure during the day are used to delineate the areas of bioclimatic stress at the places of stay. These places of stay can be further differentiated by spatial units - for example by (i) built-up areas – mostly residential, (ii) green and open spaces and (iii) public street spaces (G). The distance to green and cooler areas was used to delineate areas with a lack of access to cool and green spaces) and/or ii) built-up areas with a lack of (compensating) green space availability within walking distance (G).

3.1.3. Adaptation options

In addition to the urban hazard analyses and in-depth analyses, the selection and assessment of climate adaptation measures play a crucial role within the framework of planning recommendation maps (See Table 4:). Their consideration however differs strongly among the studies and some studies do not consider them at all. In our sample, measures were not proposed by: (B), (H), (K), (L). Applying adaptation options is often related to a modification of certain physical microclimatic parameters that affect the associated hazard level and/or a modification of the exposure of elements at risk or their vulnerability, implying a variation in the risk.

Adaptation strategies and recommendations are often provided in the form of a catalog, listing several adaptation options relevant for the respective study site. In some studies, the measures were spatially located and prioritized: (A), (C), (E), (G), (I). The identification and evaluation of adaptation options supports stakeholders and decision-makers in gaining a more detailed understanding of the availability, efficiency and feasibility of different measures with regard to the local requirements.

All examples mentioned similar fields of action for adaptation, which include: additional greening, shading (reduction of radiation input), increase in albedo, unsealing, water areas for evaporative cooling, preventing densification at the expense of green areas, improvement of ventilation/flow-through, climate sensitive spatial structures, reduction of emissions or emission control.

To assess the efficiency of these measures, some studies applied different types of models to carry out sensitivity simulations for an entire city as well as individual project sites, either considering new development areas or already developed areas. Usually, for each study area, the current condition is simulated based on a three-dimensional microclimate model and subsequently, a climate-optimized situation is simulated by considering selected adaptation measures like unsealing of surfaces, increasing albedo or implementing new green infrastructure (mostly hypothetical measures without considering their feasibility). The effects of these measures on near-surface temperature or bioclimatic indicators like PET are then evaluated.

3.2. Planning recommendations and planning recommendation maps - guidance to reduce the risk

The multi-layered results of the urban climate analysis map and the various analyses are synthesized in planning recommendations and in a planning recommendation map in order to provide the technical basis for consideration in urban planning and development processes (See Table 5:).

The basis of almost all the examples studied was a spatial delineation by areas with thermal load (built-up areas) and by areas with relevance for cooling as compensation areas (green spaces). We found that three out of four climatope-based examples, as well as one mixed-form example, (H), were structuring their planning recommendation maps mostly according to the VDI: three classes for green-

Table 4

The aspects found to characterize and define adaptation options. This table depicts the full component of adaptation options that could be derived from the comparative analysis. Key: x = applicable. Own table, 2024.

3) Adaptation Options													
Identification and proposal of adaptation options													
No concrete options proposed/Recommendation to develop a catalog of options (toolbox)													
Individual proposed options not or partially spatially allocated													
Catalog of options (toolbox) proposed, partly spatial allocation or explicitly located within city													
Fields of action for adaptation options identified													
Additional greening													
Shading (reduction of radiation)													
Albedo increase													
Unsealing / Specify max. Sealing Degree													
Water surfaces for evaporative cooling													
Preventing redensification													
Improvement of ventilation/flow-through (consideration of cold and fresh air flows)													
Emission reduction / immission control													

Table 5

The aspects found to characterize and define the component of planning recommendations and planning recommendation maps. This table depicts the full component. Key: x = applicable, (x) = implicitly applicable. Own table, 2024.

4) Guidance to reduce the Risk: Plannig Recommendations and Planning Recommendation Maps (PRM)												
Structure of Planning Recommendation Map (PRM)												
One map with with destinction of heat load areas (built-up space) and compensation areas (green space)												
+ information on air exchange and linear designations for roads as ground-level emitters										x	x	x
One map with destination between heat-load areas (built-up and street space) and compensation areas,												
(without planning designations for traffic-related air pollution)												
										x	x	x
Two maps: Additional differentiation in daytime and nighttime situation												
										x	x	x
Special case (One map divided in 29 zones by building density, land use, slope and ventilation and fresh air function; some of the zones have emission control restrictions)												
											x	
Presentation of heat load in the built-up areas in PRM												
Categories based on PET (day)												
										x	x	x
Categories based on air temperature (night)												
										x	x	x
Categories combining day- and nighttime load (thermal-bioclimate load and/or immission-climate load)												
											x	x
Special case (heat load or cold air production implicit in or explicitly mentioned for 29 zones)												
											x	
Presentation of green/open spaces in PRM												
Regarding functionality/bioclimate significance												
										x	x	x
Regarding need of protection												
											x	
Regarding quality of stay (day)												
										x	x	x
Special case (some of the 29 zones are green and open space zones)												
											x	
Aspects of assessing the climate function of green/open space												
Part of ventilation path												
										x	x	x
High cold air volume flow or cold air discharge												
										x	x	x
Proximity to built-up areas with high heat-load												
										x	x	x
Proximity to green space underserved blocks												
										x	x	x
Size of the green open space												
										x	x	x
Microclimate diversity												
											x	
high share of adjacent sensitive population												
											x	
close to sensitive Infrastructure												
											x	
Type = forest												
										x	x	x
Presentation of ventilation and cold air flow in PRM												
Cold air paths												
										x	x	x
Ventilation paths												
										x	x	x
Cold air productivity (high)												
										x	(x)	(x)
Cold air impact area												
										x	x	x
Cold air volume flow												
										x	x	x
Average wind direction and wind speed												
										x	x	x
Special case (implicit or explicitly described for 29 zones)												
											x	
Designation of traffic-related air pollution of Main roads												
No designation of air pollution												
										x	x	x
Implicit integration of air pollution												
											x	
Explicit presentation of air pollution												
										x	x	x

and open spaces (compensation areas) and three to five classes of built-up areas with different bioclimatic loads. Additionally, main traffic axes are depicted in the maps as ground-level pollutant emitters (VDI). One simulation-based example, (G), was additionally depicting the thermal load of streetscapes as a third category by another four classes. Three other simulation-based examples were depicting the thermal load of streetscapes as a third category as well. However, they did not include ground-level pollutants in their planning recommendation maps.

In two of these examples, we found a differentiation between day- and nighttime in two different maps instead of a combination of both. These simulation-based examples used the PET to differentiate between the different areas with bioclimatic load for the daytime, and air temperature to delineate areas for the nighttime.

There were also two special cases: one of example (A) even though being a climate-based example – did not depict a planning recommendation map according to the VDI, but made a differentiation between 29 different zones. The thermal as well as the dynamic components and the air pollution were implicitly included in the classification of these 29 zones. The second special case was (E), which did not process the results from the hazard, exposure and vulnerability analyses into a planning recommendation map. However, as explained in the materials section, we integrated their urban climate (heat) concept maps for our analysis.

4. Discussion

Our comparison of existing urban climate analyses and planning recommendation maps from the DACH region confirms, that urban climate analyses that result in planning recommendation maps, have different components that can be linked to the three components

of the IPCC AR5 risk concept: i) hazard, ii) exposure and iii) vulnerability (including the sub-components sensitivity and capacity to cope and adapt) (IPCC, 2014).

4.1. Components of urban climate analyses

One of the guiding questions was: How are the individual components - hazard, exposure and vulnerability - analyzed practically for planning? This will be answered for each component in the following sub-chapters.

4.1.1. Hazards

The analysis confirms previous research by Ren et al. (2011) and Baumüller (2015) regarding two approaches in urban climatic analysis for planning recommendation maps: climatopes and urban climate models. Our analysis showed that this basic approach in the analysis of hazards also affects the further possible processing steps. It was also shown based on the comparison that there are also mixed forms that combine the possibilities of both variants and that the delineation and definition of the climatopes strongly differ. Especially for the determination of cold air paths, simulation tools (cold air drainage models) are frequently used in climatope-based approaches. Furthermore, numerical simulations can serve as a basis to delineate the climatopes (similar to the use of measurement data for defining the climatopes). Apart from the models used in the analyzed examples (mentioned in chapter 3.1.1.), there are as well other models to analyze the local climate. An advanced development of urban climate models that enable turbulence-resolving urban climate analyses at high resolution at city-wide level has recently gained significant importance also in terms of their practicability within the scope of urban planning. State-of-the-art urban climate models are designed to take into account relevant components with respect to environmental and meteorological issues. They should be able to carry out building resolving simulations and include aspects with regard to air pollution or cold air flows (e.g. Maronga et al., 2020). In addition, there are now various approaches that use statistical regression and machine learning techniques to model urban temperatures (e.g. Alonso and Renard, 2020). The analysis of thermal components require the use of different meteorological or climatological indicators to analyze urban heat load (near-surface temperature, physiological equivalent temperature, surface temperature, number of summer days, hot days, tropical nights or PET exceedance days). In our analyzed examples, PET was mainly used to depict thermal comfort during the day. However, a set of bioclimatic indicators exists to assess the thermal perception of a human being (e.g. Jendritzky et al., 1979, Höppe, 1999, Jendritzky et al., 2011). Paranunzio et al. (2021), for example, used the UTCI to generate a hazard index and subsequently to determine heat-related risks in the city of Dublin. A comparison between PET and UTCI showed that both parameters are useful for a general analysis and that for extreme conditions is recommended to use more than one index (Matzarakis et al., 2014).

Besides the advanced methods described above, the concept of local climate zones (LCZ), which was developed by (Stewart and Oke, 2012), has also been used worldwide to evaluate the thermal load (Guerra et al., 2023, Zhang et al., 2024, Lehnert et al., 2021). It could be used as a first screening of the thermal load for cities that have no climate analysis so far. A global dataset is also available (Demuzere et al., 2022), with all the limitations that come with it (Bechtel et al., 2019). While the use of LCZs can help to assess the thermal load and to place adaptation measures that in the short term reduce the burden, it is not sufficient to advice local planning that tries to counteract the increasing thermal load due to climate change at an urban scale, where, among other aspects, the regional influences e.g. caused by topography and dynamic components (wind) need to be considered as well (Ren et al., 2012).

In our examples, for the analysis of the dynamical component, the near-surface wind field and cold air flows based on models or data from meteorological measurements are used in the climatope-based and model-based approaches.

As a result, one or more thematic analysis maps (sometimes distinguished between day and night time) are generated that provide the basis for in-depth analyses. This approach also enables different loads to be represented during the day and at night. Other than the information about the current climatic situation, only a few examples include future urban heat load in combination with planned urban developments.

The spatial resolution of analyses plays an important role within the scope of urban planning purposes. Even though from a climatological point of view, the consideration of overlapping or transition zones might be beneficial or at least a more realistic depiction of the natural gradation of the thermal load, the demarcation of “hard boundaries” as with the climatope (and the LCZ) approach is more useful for subsequent urban planning processes.

4.1.2. Exposure and vulnerability analyses help to identify appropriate adaptation options

Our findings revealed that many urban climate analyses lack in-depth analyses of socio-spatial exposure and vulnerability which are two main and equally important components of the IPCC risk concept (IPCC, 2014; IPCC, 2023). This lack is a deficiency that can – and, according to Ulpiani et al. (2024), does – lead to a further gap in the consideration of these aspects in deriving adaptation options and defining appropriate planning responses in practice. Since the AR6, the IPCC (2023) places emphasis on these “responses to climate change”, stressing the need to avoid maladaptation, since this affects the marginalized and most vulnerable populations adversely (Amorim-Maia et al., 2022; IPCC, 2023). This, in turn, means that a thorough analysis of the exposure and vulnerability components, which creates knowledge about highly exposed and vulnerable infrastructure and populations, is needed to avoid reproducing and exacerbating urban vulnerabilities and social marginalization in the process of developing adaptation options (based on the respective urban climate analysis) (Amorim-Maia et al., 2022,).

Vulnerability and exposure are difficult to determine in practice since they are dependent on capacities to cope and adapt (IPCC, 2014; IPCC, 2023; Laranjeira et al., 2021). The identification and effectiveness of adaptation options in the spatial domain were, if at all, only considered in simulation-based approaches that simulated the effect of spatial adaptation measures either for the city as a whole or for particular areas of the city. Neither capacities to cope and adapt of different social groups nor more general future

population developments were considered in the determination of vulnerability in the examples studied, even though research points to the need of including these (Birkmann et al., 2021; IPCC, 2023). Unfortunately, this is a common shortcoming in the context of working towards urban resilience where social justice is key (Calderón-Argelech et al., 2023; Ziervogel et al., 2017; Amorim-Maia et al., 2022).

All of the examples studied that did perform in-depth analyses of the exposure and vulnerability component, have been using population densities as well as certain indicator groups (children and elderly with different age group cut-offs) to determine “social” exposure and vulnerability which is in line with the ongoing urbanization coupled with an ageing trend of the population in Europe (Baccini et al., 2008; Hajat et al., 2014) and is therefore the minimum of what should be considered in social exposure and vulnerability analyses. Recently, urban climatic map studies, as highlighted by Ng (2015) and Parsaee et al. (2019), have repeatedly urged for an increased emphasis on the “human-dimension” within the socio-physical urban environment in urban climate analyses. Our sample shows that five out of seven urban climate analyses carried out in 2015 or later contained some form of (social) vulnerability analysis, including assessment of particular sensitive infrastructure and vulnerable age groups. However, the state of the art of vulnerability research points to the need of a more context-dependent and intersectional approach to which aspects of social vulnerabilities need to be incorporated (Thomas et al., 2018; Ergas et al., 2021; Laranjeira et al., 2021; Amorim-Maia et al., 2022; Ulpiani et al., 2024). Therefore, we can conclude that a shortcoming in all examples in our sample is the limited consideration of the (social) vulnerability component.

Another important aspect for both, exposure and vulnerability assessments, is to distinguish between daytime and nighttime thermal loads in order to demonstrate the combined exposure and to identify areas with significant exposure at both times for further assessments. The possibility to differentiate between daytime and nighttime exposure enables differentiated analyses of, for example, the working population or the residential population (Chen et al., 2022). This increases the informational value for planning, since the different load can be delineated and adaptation options (e.g., promotion of nighttime ventilation) can have bigger positive impacts. This differentiation could facilitate crucial comprehensive analyses of social and socio-spatial vulnerability arising from the temporal variations of where different groups or people stay – for example considering the place of residency and the place of work (Chen et al., 2022). Some Swiss cities, were taking the density of work places into account in their further heat mitigation and adaptation strategies, but not for the analyses leading to the planning recommendation map (Bau- und Verkehrsdepartement des Kantons Basel-Stadt (ed.), 2021; Stadt Zürich (Hrsg.), 2020).

The “spatial” exposure analyses focusing on the assessment of diverse sensitive infrastructure is in line with the necessity of safeguarding all forms of critical infrastructure as fundamental elements of a functioning society by adaptation and mitigation measures (McEvoy et al., 2012; Huddleston et al., 2022).

In addition to considering spatial adaptation options for the vulnerability assessment, the temporal component is also important, since (average) temperatures will, after all, change in the future. The projection of future (socio-spatial) developments and the use of these in simulation tools enables the analysis of an additional component in order to be able to take future vulnerabilities into account (Sheridan and Dixon, 2017; Ho et al., 2018). The simultaneous consideration of future socio-spatial and climatic developments in simulations did not take place in the examples examined. This is an area where further development and research is needed.

The adaptation options identified in our sample are also comparable with the international case studies: (1) promoting ventilation through appropriate building design and adapting the urban fabric in combination with the local urban morphology and the development of climate-resilient urban structures, (2) maintaining and establishing urban green and blue infrastructure as well as measures in the area of albedo and surfaces to reduce the heat load (Acero et al., 2013; Ren et al., 2013). The variation in location accounts for the differences among the measures, as they hinge upon the particular city and its structures. According to Acero et al. (2013), the integration of the measures into the planning processes also varies according to the relevant planning instruments or level. The measures, moreover, are contingent not only on the spatial and climatic conditions of a city, but also on its goals and possibilities.

4.1.3. Planning recommendation maps

The process from the analysis of the individual components to the planning recommendation map is the methodologically weakest and most ambiguously documented in the examples studied. This is also evident when analyzing international studies and literature. The step from analysis to planning is usually only described on the basis of a specific city or a specific case study and with individually developed methods and approaches (e.g. Alcoforado et al. 2009; Acero et al., 2013). This is unfortunate given that the literature states that the “translation” of the climate analyses to a language that planners understand is crucial for successful implementation in subsequent planning procedures for urban climate adaptation planning (VDI – Verein Deutscher Ingenieure, 2015; Ren, 2015; Burghardt et al., 2010; He et al., 2015).

The analyzed examples demonstrate that planning recommendation maps are a result of the synthesis of climate analysis maps. These maps always encompass subjective assessments, for example the precise demarcation of climatopes. Schau-Noppel et al. (2020) and others (e.g. Fallmann and Emeis, 2020) have already described that the co-creation of planning recommendation maps through the cooperation of climate experts, planning experts and municipal agencies is a challenging but crucial step. This is also discussed and confirmed in many local case studies - mainly from the Asian region with its rapidly growing cities but also cities from Southern Europe. Authors such as Ren et al., 2013 using the example of Kaohsiung (Taiwan), Alcoforado et al. (2009) on the example of Lisbon (Portugal) or Acero et al. (2013) on the example of Basque County (Spain) describe similar approaches as found in our examples. In addition, authors such as Parsaee et al. (2019) point out that local communities and stakeholders must also be involved in this step.

Numerous international case studies support the approach of synthesizing the analyses and combining them with concrete plans and measures to create planning recommendation maps (Ren et al., 2013; He et al., 2015). Our investigation aligns with specific international studies in terms of the recommendations developed: reducing thermal load and improving urban ventilation hold

significant importance.

4.2. The implementation of the IPCC risk concept in urban climate analyses

Our analysis indicates that it is possible to implement the IPCC risk concept in the development of planning recommendation maps, as demonstrated by some of the analyzed examples where the necessary processing steps are already in use. The incorporation of all three components - hazard, exposure, and vulnerability - that determine the risk can be achieved through the use of existing approaches and methods during the mapping process. Nevertheless, it should be noted that not all urban climate analyses take into account all three components. In many cases, the analysis relies heavily on hazard analysis, which has been criticized as a shortcoming in other studies (Ahmed et al., 2023; Parsaee, 2019).

In the discussion of the implementation of the IPCC risk concept, however, it has also become apparent that there are allocation difficulties or overlaps of the components – hazard, exposure, vulnerability as well as adaptation options – in practice. This could be attributed to the reconceptualization and changes in terminology over time within the climate research community, as exemplified by revisions to the concept and assessment of vulnerability (IPCC, 2014; IPCC, 2023; Estoque et al., 2023).

The studies were evaluated with a focus on the individual components of the risk assessment according to IPCC AR5. Further analysis and weighting of the various components is required to assess the actual risk (as the combination of hazard, exposure and vulnerability). Paranunzio et al. (2021) emphasize the importance of risk assessments also with regard to urban planning projects. In their study, the authors employed the AR5 risk concept to analyze urban heat risk, based on a heat risk index, in Dublin for past and future climate periods. They utilized the UHCI index to characterize heat hazards and applied a principal component analysis to assess vulnerability. Räsänen et al. (2019) highlight the influence of weighting and zoning, as well as indicator selection and visualization, on the outcome of map production. They also stress the necessity of addressing uncertainties when providing maps for adaptation planning.

A differentiation between exposure and vulnerability turned out to be particularly difficult. Exposure means “*the presence of people, livelihoods, species or ecosystems, environmental functions, services and resources, infrastructure [...] in places and settings that could be adversely affected*” (IPCC, 2014). According to this definition, the whole system “city”, and/or the population of the city and/or solely particular population groups could be included in the component exposure (by definition of their “*presence in places and settings that could be adversely affected*”).

It was difficult to decide whether individual population groups (for example particular age groups) and individual infrastructures (such as particular social infrastructure) should also be included in the ‘exposure’ component or not. However, as vulnerability “*encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt*” (IPCC, 2014), we tended to treat these distinctive groups as well as the mentioned infrastructure as part of the vulnerability component, but due to uncertainty we still decided to keep these aspects in one chapter combining exposure and vulnerability for the discussion.

The terminology used in our sample mostly referred to “vulnerable groups” or “vulnerable infrastructure”, sometimes to “sensitive” groups or infrastructure which was another indicator for them to belong to the component of vulnerability. However, there are numerous other terms used for in-depth analyses in our sample (e.g. vulnerability, sensitivity, affectedness). This evidence points to difficulty to differentiate between these terms in practice. Additionally, variations in the usage of these terms depending on the country context (Switzerland vs. Germany vs. Austria) may also have an impact.

We faced a comparable challenge in determining whether to assign the adaptation options to the vulnerability component or not. Adaptation options target particular microclimatic variables (e.g. albedo, vegetation) to mitigate hazards (e.g. decreasing air temperature, PET). These principles can also be applied to adjust the exposure of elements at risk or modify the vulnerability function of an element at risk, such as enhancing the thermal efficiency of buildings.

However, these findings reveal a general difficulty to apply the IPCC risk concept and its components for urban climatic analyses to inform climate responsive planning. In addition, there is a need for greater clarification and distinction of the terms *exposure* and *vulnerability* especially for (applied) planning sciences. The IPCC AR6 (2023) with its updated risk-concept including a fourth component called “responses”, offers a novel perspective to allocating adaptation options as well as planning recommendations within the risk concept. Still, the difficulties of differentiating between exposure and vulnerability components prevail.

4.3. Types of urban climatic analysis

Our analysis has revealed both similarities and differences among the examples examined, and thus among the methodologies used. The differentiation of types is based on a selection of attributes, including an attempt to provide an interpretation of these various attributes through an attributive classification. As with any classification system, these attributes may be subject to interpretation and modification based on new information or perspectives (Flett and Vernau, 2011). All the urban climatic analyses considered have dealt with (at least parts of) the risk approach. Urban climatic analyses must therefore basically fulfill these four components: (1) urban climatic analysis related to the hazard component, (2) in depth social and spatial analysis related to exposure and vulnerability components, (3) adaptation options and thus (4) planning recommendations and planning recommendation maps as “guidance to reduce the risk”.

Within the individual components, however, there were (sometimes large) differences: Three formations can be distinguished according to our first typology: those that rely on numerical simulations, those that depend on the climatope approach, and mixed forms that incorporate simulations as a supplementary information layer for identifying climatopes in hazard analysis. This mixed form has not yet been delineated as a third approach in the previous (few) papers on this topic (e.g. Ren et al., 2011; Baumüller, 2015).

Within the formation of model-based approaches, a much higher number of different forms of analysis is visible. The formations of mixed forms or climatope-based approaches are much more homogeneous - because there is a corresponding methodological specification. It is surprising that in the area of exposure and vulnerability analysis, no vulnerability analyses are carried out in the formation of mixed forms or climatope-based approaches. In principle, these would be possible, since the climatopes are also differentiated according to the stress level of urban overheating. The same applies to the area of adaptive capacities: here, too, a sensitivity analysis would be possible for the mixed forms as for the model-based ones.

However, current developments in the field of these analyses are evident. In one of our analyzed examples, a risk map has recently been generated that includes results of urban climate analyses and planning recommendation maps, combined with sociodemographic data and vulnerable groups. The map indicates areas with elevated heat risks and identifies regions where enhanced action is required to implement adaptation measures.

The “picture” is most heterogeneous for the planning recommendation maps. This is also an indication of the central methodological challenge in this processing step: linking climatic information with spatial information (and planning intentions) (Baumüller, 2015). This is where the examples differ the most, as (qualitative) information is also considered in this step by involving local experts and thus city-tailored maps are developed. At the level of planning recommendation maps, one of the key advantages of the climatope (and also the LCZ) approach becomes apparent: since the analysis is already divided into clearly spatially delimited areas, the planning recommendation map can make use of these areas. In contrast, simulation-based approaches require the climatopes to be “re-engineered” in this step in order to achieve the hard delineation necessary for planning and the subsequent anchoring of measures by sub-areas. Simulation-based approaches may not use clear spatial delimitations, which can hinder the link with downstream planning instruments and the implementation of measures.

Other European examples of urban climate analyses outside the analyzed DACH region that contain planning recommendation maps, such as Acero et al. (2013) for Bilbao (Spain), show that a climatope-based approach was also used in the analysis here - they also refer to the VDI. In the UC-ReMap, the grid-based climatopes are presented together with the ventilation pathways and planning information is provided. Comparable approaches can also be found worldwide: The urban climate analysis map for Beijing (He et al., 2015) combines the analysis of fresh air ventilation paths and specific wind situations with the thermal load in order to obtain a delineation of sub-areas - referred to here as “a set of hierarchical urban climatic classifications”. In the planning recommendation map, “planning zones” are specified and planning information is provided for these. Liu et al. (2017) describe another comparable approach using the example of the City of Xiamen (China): here, too, an urban climatic analysis map is created from the combination of heat load, wind systems (and here also air pollution). However, in contrast to the two other examples described above, the climatopes are not shown in grid form but on the basis of the delimitation of land uses. The planning recommendation map then distinguishes between nine zones and provides planning information for each. The planning recommendation map for Xi'an, China, described by Xu et al. (2020) is also based on a climate analysis map in which a block-based demarcation of climatopes - here called urban climate classification - is carried out and this is shown in combination with the wind system. The planning recommendation map based on this then differentiates five sub-areas called “Urban Planning Action”, which are linked to measures.

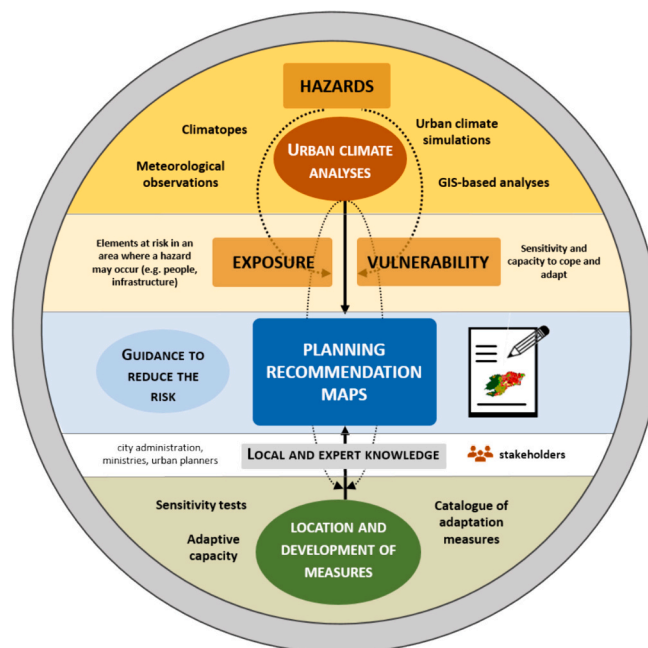


Fig. 2. Framework for urban climate analyses aiming for planning recommendation maps while considering the IPCC risk concepts (own representation; visualization based on World Bank, 2020).

These examples show that there are also internationally comparable approaches for deriving planning recommendation maps from climate analyses, which also supports the derivation and international transferability of the proposed “Framework for urban climate analyses aiming for planning recommendation maps” (see Fig. 2). At the same time, it is clear that there is a need for further research at the interface or the transfer of the analysis into planning recommendation maps because there are these different approaches with their individual advantages and disadvantages for planning.

4.4. Recommendations and research gaps derived from the comparison

As the comparison of the examples has shown, standards and specifications naturally have an impact on the content and statements of the analyses and the planning recommendation maps. Standardisation has the potential to support both planners and political decision-makers as they can fall back on “standardised” specifications and there is also greater certainty with regard to the methods (and their validity). Analyses could also be implemented more quickly, as no methodology needs to be developed (which can also potentially reduce costs). However, these specifications must manage a “balancing act” between standardised specifications and the ability to respond to local challenges. Due to the different local climates but also the different local building traditions, flexibility must be ensured. The few studies that exist on the need for standardisation of analyses from the perspective of the cities also show that this is necessary, as it offers the advantages described above (e. g. [de Jong et al., 2018](#)). However, the comparison has also shown that it is not necessary to favour individual methods or individual indicators.

In the examples considered, the future climatic development is analyzed in some cases on the basis of the IPCC scenarios. What is usually missing, however, is the simulation of the effects of land use changes due to urban development and redensification but also the future development of the population. This is crucial for planning as a forward-looking science. Particularly due to the urban heat island effect, which is increased by urban growth (in the absence of adaptation measures), future climatic and structural-spatial developments must be considered and included in the analyses at the same time.

What is also striking is that the analyses mainly refer to the urban overheating caused by rising temperatures. However, changes in other climate signals are given comparatively less consideration. In relation to the increase in heavy rainfall events, aspects of fluvial flooding are sometimes considered (as a “classic” element of natural hazard management), but pluvial flooding is hardly taken into account (which is an increasing challenge for cities). The same applies to the issue of drought. However, as the changes in climate signals have mutual interactions and measures can simultaneously contribute to different areas of adaptation (heat, drought and heavy rainfall), there is a need for further research here, as there may be conflicts of objectives but there are also synergies (especially in the area of nature-based solutions).

What is usually missing in practice is the connection, the anchoring or integration into existing planning instruments at local level ([Eum et al., 2013](#)). Both the planning recommendation maps and the adaptation options must be linked to the statutory planning instruments ([Reinwald et al., 2024](#); [Acero et al., 2013](#)). Only in combination with (legally binding) planning instruments broad implementation is possible and the necessary rapid adaptation can take place. This is an area in which there is still much need for research.

5. Conclusion

Planning recommendation maps are an essential part of urban climate adaptation. The analysis of our sample of practical examples commissioned by various cities to support their climate adaptation efforts has revealed a broad range of approaches, methods, and procedures employed in such analyses. The research shows that the Intergovernmental Panel on Climate Change (IPCC) concept of risk, which considers hazard, exposure and vulnerability, can be and is being used in the development of planning recommendation maps. All three elements for assessing the risk and creating planning recommendation maps can be analyzed by existing methods and approaches and incorporated in the mapping process. Nevertheless, the practical implementation has revealed challenges in the allocation and overlapping of these elements.

Individual examples show that in-depth analyses are not necessary for the preparation of the planning recommendation map. However, the more detailed the in-depth analyses are, the more precise and locally located measures can be developed and serve as a better aid for planning as well as for a more accurate assessment of the future impacts of climate hazards and the effects of adaptation measures. From this, we conclude that all components should be analyzed in order to create a robust and scientific-driven basis for spatial and urban planning. The precision of these analyses facilitates the planning process, especially if it comes to justifying planning decisions and providing the necessary basis for interventions in the course of many adaptation options.

Based on the comparative analysis we recommend the following framework (see Fig. 2) for urban climatic analysis aiming for planning recommendation maps that take into account the IPCC risk concept as well as the allocation difficulties or overlaps of the three analysis components in practice. This framework can support practice and research in the further development of climate-sensitive urban and spatial planning.

Potentials and recommendations for the further development of urban climate analyses aiming for planning recommendation maps can also be derived from the comparison. To increase reliability and efficiency a (international) standardisation is recommended.

In future, climate scenarios as well as socio-demographic and spatial development should also be simulated and analyzed together in these analyses. A joint analysis of these three developments is the only way to comprehensively assess the future risk for cities. A further improvement could also be offered by the joint consideration of changes in climate signals (primarily heat, drought and heavy rainfall events) and their spatial consequences, as these are closely linked and at the same time the adaptation options (especially in the area of nature-based solutions) have synergies in the adaptation services they provide. Finally, effectiveness and implementation can

be promoted if the analyses are linked to the cities' "regular" planning instruments and the statutory planning instruments.

Although this paper thoroughly compared and analyzed different examples of urban climate analysis maps as well as planning recommendation maps and their diverse methods used, this paper only examined examples from German-speaking countries which may restrict the generalizability of the findings to other regions. However, as far as we know, this is the first attempt to develop a typification of urban climate analysis aiming for planning recommendation maps. Therefore, future scholars could explore further contributions to put this typology on a broader basis and to verify it. There is also a clear need for research regarding the step from the analysis to the planning recommendation map as this has not yet been methodologically very well developed or scientifically analyzed.

Funding

The research was conducted as part of the project "GreenAdaptation – Adaptive capacities and resilience in urban and landscape planning", funded by the Austrian Climate Research Program and conducted within the program "ACRP – 14th Call" (KR21KB0K00001).

CRediT authorship contribution statement

Florian Reinwald: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Conceptualization. **Sophie Thiel:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Astrid Kainz:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Claudia Hahn:** Writing – review & editing, Investigation.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.uclim.2024.102090>.

References

- Aboagye, P.D., Sharifi, A., 2024. Urban climate adaptation and mitigation action plans: a critical review, renew. Sustain. Energy Rev. 189, 113886 <https://doi.org/10.1016/j.rser.2023.113886>.
- Acero, J., Arrizabalaga, J., Kupski, S., Katschnner, L., 2013. Deriving an urban climate map in coastal areas with complex terrain in the Basque Country (Spain). Urban Clim. 4, 35–60. ISSN 2212–0955. <https://doi.org/10.1016/j.uclim.2013.02.002>.
- Ahmed, I., van Esch, M., van der Hoeven, F., 2023. Heatwave vulnerability across different spatial scales: insights from the Dutch built environment. Urban Clim. 51 (1) <https://doi.org/10.1016/j.uclim.2023.101614>.
- Alcoforado, M.J., Andrade, H., Lopes, A., Vasconcelos, J., 2009. Application of climatic guidelines to urban planning: the example of Lisbon (Portugal). Landsc. Urban Plan. 90, 56–65. <https://doi.org/10.1016/j.landurbplan.2008.10.006>.
- Alonso, L., Renard, F., 2020. A new approach for understanding urban microclimate by integrating complementary predictors at different scales in regression and machine learning models. Remote Sens. (Basel) 12 (15), 2434.
- Altvater, S., van de Sandt, K., Marinova, N., de Block, D., Klostermann, J., Swart, R., Bouwma, I., McCallum, S., Dworak, T., Osbergerhaus, D., 2011. Assessment of the Most Significant Threats to the EU Posed by the Changing Climate in the Short, Medium and Long Term—Task 1 Report. Ecologic, Berlin.
- Amorim-Maia, A.T., Anguelovski, I., Chu, E., Connolly, J., 2022. Intersectional climate justice: a conceptual pathway for bridging adaptation planning, transformative action, and social equity. Urban Clim. 41 <https://doi.org/10.1016/j.uclim.2021.101053>.
- Baccini, M., et al., 2008. Heat effects on mortality in 15 European cities. Epidemiology 19 (5), 711–719. <https://doi.org/10.1097/EDE.0b013e318176bfcd>.
- Bau- und Verkehrsdepartement des Kantons Basel-Stadt (ed.), 2021. Stadtklimakonzept zur klimaangepassten Siedlungsentwicklung im Kanton Basel-Stadt. In: Urban climate concept for climate-adapted settlement development in the canton of Basel-Stadt.
- Baumüller, J., 2015. A summary of key methodologies. In: Ng, E., Ren, C. (Eds.), The Urban Climatic Map for Sustainable Urban Planning. Routledge, London and New York, pp. 35–44.
- Bechtel, B., Alexander, P.J., Beck, C., Böhner, J., Brousse, O., Ching, J., Demuzere, M., Fonte, C., Gál, T., Hidalgo, J., Hoffmann, P., Middel, A., Mills, G., Ren, C., See, L., Sismanidis, P., Verdonck, M.-L., Xu, G., Xu, Y., 2019. Generating WUDAPT level 0 data – current status of production and evaluation. Urban Clim. 27, 24–45. <https://doi.org/10.1016/j.uclim.2018.10.001>.
- Birkmann, J., et al., 2021. New methods for local vulnerability scenarios to heat stress to inform urban planning—case study City of Ludwigsburg/Germany. Clim. Change 165 (1–2), 193. <https://doi.org/10.1007/s10584-021-03005-3>.
- Brunner, J., Cozens, P., 2013. Where have all the trees gone? Urban consolidation and the demise of urban vegetation: a case study from Western Australia. Planning Practice Res. 28 (2), 231–255.
- Bruse, M., Fleer, H., 1998. Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. Environ. Model. Software 13 (3–4), 373–384. [https://doi.org/10.1016/S1364-8152\(98\)00042-5](https://doi.org/10.1016/S1364-8152(98)00042-5).
- Burghardt, R., Katschnner, L., Kupski, S., 2010. Urban climatic map of Arnhem City. Online: https://www.researchgate.net/publication/267300384_Urban_Climatic_Map_of_Arnhem_City.

- Calderón-Angelich, A., Anguelovski, I., Connolly, J.J.T., Baró, F., 2023. Greening plans as (re)presentation of the city: toward an inclusive and gender-sensitive approach to urban greenspaces. *Urban For. Urban Green.* 86 (1979), 127984 <https://doi.org/10.1016/j.ufug.2023.127984>.
- Chen, B., Xie, M., Feng, Q., Wu, R., Jiang, L., 2022. Diurnal heat exposure risk mapping and related governance zoning: a case study of Beijing, China. *Sustain. Cities Soc.* 81, 103831.
- de Jong, M., de Buck, A., Balder, M., Bogen, M., 2018. RESIN deliverable 5.1/2.2: standardization in urban climate adaptation. Available at: <https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5bed462af&appId=PPGMS>.
- Demuzere, M., et al., 2014. Mitigating and adapting to climate change: multi-functional and multi-scale assessment of green urban infrastructure. *J. Environ. Manage.* 146, 107–115. <https://doi.org/10.1016/j.jenvman.2014.07.025>.
- Demuzere, M.; Kittner, J.; Martilli, A.; Mills, G.; Moede, C.; Stewart, I.D.; van Vliet, J. & Bechtel, B. (2022) 'Global map of local climate zones (1.0.0)' [data set]. Zenodo. <https://doi.org/https://doi.org/10.5281/zenodo.6364594>.
- Djedjig, R., Bozonnet, E., Belarbi, R., 2015. Experimental study of the urban microclimate mitigation potential of green roofs and green walls in street canyons. *Int. J. Low Carbon Technol* 10 (1), 34–44. <https://doi.org/10.1093/ijlct/ctt019>.
- Ergas, C., McKinney, L., Bell, S.E., 2021. Intersectionality and the Environment.' In: Schaefer Caniglia. In: Jorgenson, et al. (Eds.), 2021 – Handbook of Environmental Sociology. https://doi.org/10.1007/978-3-030-77712-8_2.
- Estoque, R.C., Ishitake, A., Parajuli, J., et al., 2023. Has the IPCC's revised vulnerability concept been well adopted? *Ambio* 52, 376–389 doi:10.1007.
- Eum, J., Dieter Scherer, S., Fehrenbach, U., Köppel, J., Woo, J. (2013) Integrating urban climate into urban master plans using spatially distributed information—the Seoul example, *Land Use Policy*, Volume 34, 223–232, doi:<https://doi.org/10.1016/j.landusepol.2013.03.016>.
- Fallmann, J., Emeis, S., 2020. 'How to bring urban and global climate studies together with urban planning and architecture?', *Developments in the. Built Environ.* 4, 100023 <https://doi.org/10.1016/j.dibe.2020.100023>.
- Flett, A., Vernau, J., 2011. Applied taxonomy frameworks. *Bus. Inf. Rev.* 28 (4), 226–235. <https://doi.org/10.1177/0266382111429208>.
- Früh, B., et al., 2011. Estimation of climate-change impacts on the urban heat load using an urban climate model and regional climate projections. *J. Appl. Meteorol. Climatol.* 50 (1), 167–184. <https://doi.org/10.1175/2010JAMC2377.1>.
- Gross, G., 1994. Project WIND numerical simulations with FITNAH. In: *Mesoscale Modeling of the Atmosphere*. American Meteorological Society, Boston, MA, pp. 73–80.
- Guerra, P.S., Trigo, O.P., Espinosa, P.S., Felipe Thomas Cabrera, F.T., Meseguer-Ruiz, O., 2023. Climate-sensitive planning. Opportunities through the study of LCZs in Chile. *Building and Environment* 242. <https://doi.org/10.1016/j.buildenv.2023.110444>.
- Hajat, S., Vardoulakis, S., Heaviside, C., Eggen, B., 2014. Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. *J. Epidemiol. Community Health* 68 (7), 641–648. <https://doi.org/10.1136/jech-2013-202449>.
- Haslinger, K., Schöner, W., Abermann, J., Laaha, G., Andre, K., Olefs, M., Koch, R., 2023. Apparent contradiction in the projected climatic water balance for Austria: wetter conditions on average versus higher probability of meteorological droughts. *Nat. Hazards Earth Syst. Sci.* 23, 2749–2768. <https://doi.org/10.5194/nhess-23-2749-2023>.
- He, X., Shen, S., Miao, S., Dou, J., Zhang, Y., 2015. Quantitative detection of urban climate resources and the establishment of an urban climate map (UCMap) system in Beijing. *Build. Environ.* 92, 668–678. ISSN 0360-1323. <https://doi.org/10.1016/j.buildenv.2015.05.044>.
- Heaviside, C., Macintyre, H., Vardoulakis, S., 2017. (2017) 'the urban Heat Island: implications for health in a changing environment'. *Curr. Environ. Health Rep.* 4, 296–305.
- Hidalgo, J., Lemonsu, A., Masson, V., 2019. Between progress and obstacles in urban climate interdisciplinary studies and knowledge transfer to society. *Ann. N. Y. Acad. Sci.* 1436 (1), 5–18. <https://doi.org/10.1111/nyas.13986>.
- Ho, H.C., Knudby, A., Chi, G., Aminipouri, M., Yuk-FoLai, D., 2018. Spatiotemporal analysis of regional socio-economic vulnerability change associated with heat risks in Canada. *Appl. Geography* (Sevenoaks, England) 95, 61–70. <https://doi.org/10.1016/j.apgeog.2018.04.015>.
- Höppe, P., 1999. The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. *Int. J. Biometeorol.* 43, 71–75. <https://doi.org/10.1007/s004840050118>.
- Howard, L., 1833. The climate of London: deduced from meteorological observations made in the metropolis and at various places around it' (Vol. 3). Harvey and Darton, J. and A. arch, Longman, Hatchard, S. Highley [and] R. Hunter.
- Huddleston, P., Smith, T., White, I., Elrick-Barr, C., 2022. Adapting critical infrastructure to climate change: a scoping review. *Environ. Sci. Policy* 135, 67–76.
- IPCC, 2012. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P. M. (Eds.), *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. Available at: <https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/>. Accessed: 23 October 2023.
- IPCC, 2014. In: Pachauri, R.K., Meyer, L.A. (Eds.), *Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change*. IPCC, Geneva, Switzerland, p. 151. Core writing team.
- IPCC, 2023. In: Lee, H., Romero, J. (Eds.), *Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change*. IPCC, Geneva, Switzerland, p. 184. <https://doi.org/10.59327/IPCC/AR6-9789291691647>. Core writing team.
- Jendritzky, G., Sönning, W., Swantes, H.J., 1979. Ein objectives Bewertungsverfahren zur Beschreibung des thermischen Milieus in der Stadt- und Landschaftsplanung "Klima-Michel-Modell".
- Jendritzky, Gerd, de Dear, Richard, Havenith, George, 2011. UTCI-why another thermal index? *Int. J. Biometeorol.* 56, 421–428. <https://doi.org/10.1007/s00484-011-0513-7>.
- Kluge, S., 1999. *Empirisch begründete Typenbildung. Zur Konstruktion von Typen und Typologien in der qualitativen Sozialforschung*. Leske + Budrich Verlag, Opladen.
- Kromp-Kolb, H., Nakicenovic, N., Steininger, K., Gobiet, A., Formayer, H., Köppl, A., Pretenthaler, F., Stötter, J., Schneider, J., 2014. *Österreichischer Sachstandsbericht Klimawandel 2014*. Verlag der Österreichischen Akademie der Wissenschaften, Vienna.
- Labeledens, S., Scartezini, J., Mauree, D., 2018. Modeling the effects of future urban planning scenarios on the urban Heat Island in a complex region. *Urban Clim.* 1–41 <https://doi.org/10.31223/OSF.IO%2FC8MZB>.
- Laranjeira, K., Götsche, F., Birkmann, J., Garschagen, M., 2021. Heat vulnerability and adaptive capacities: findings of a household survey in Ludwigsburg, BW, Germany. *Clim. Change* 166 (1–2), 335. <https://doi.org/10.1007/s10584-021-03103-2>.
- Lehnert, M., Savić, S., Milošević, D., Dunjić, J., Geletić, J., 2021. Mapping local climate zones and their applications in European urban environments: a systematic literature review and future development trends. *ISPRS Int. J. Geo Inf.* 10 (4), 260. <https://doi.org/10.3390/ijgi10040260>.
- Lemonsu, A., Viguié, V., Daniel, M., Masson, V., 2015. Vulnerability to heat waves: impact of urban expansion scenarios on urban heat island and heat stress in Paris (France). *Urban Clim.* 14, 586–605.
- Liu, S., Song, D., Yu, B., 2017. The objective and methodology of urban climate map for the City of Xiamen. *Procedia Engineering* 180, 462–470. <https://doi.org/10.1016/j.proeng.2017.04.205>.
- Lohmeyer, A., Schädler, G., 1998. *Description of the Drainage Flow Model KALM*. Lohmeyer engineers.
- Mandara, J., 2003. 'The typological approach in child and family psychology: a review of theory, methods, and research'. *Clin. Child Fam. Psychol. Rev.* 6, 129–146. <https://doi.org/10.1023/A:1023734627624>.
- Markolf, S., Hoehne, C., Fraser, A., Chester, M., Underwood, S., 2019. Transportation resilience to climate change and extreme weather events – beyond risk and robustness. *Transp. Policy* 74, 174–186. <https://doi.org/10.1016/j.tranpol.2018.11.003>.
- Maronga, B., et al., 2020. Overview of the PALM model system 6.0. *Geosci. Model Dev.* 13 (3), 1335–1372.
- Martinich, J., Crimmins, A., 2019. Climate damages and adaptation potential across diverse sectors of the United States. *Nat. Clim. Chang.* 9, 397–404. <https://doi.org/10.1038/s41558-019-0444-6>.

- Matzarakis, A., 2005. Country report: Urban Climate Research in Germany, 11. IAUC Newsletter, pp. 4–6. Available at: https://www.urbanclimate.net/matzarakis/papers/UCRE_de_IAUC011.pdf. Accessed: 23 October 2023.
- Matzarakis, A., Rutz, F., Mayer, H., 2010. Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. *Int. J. Biometeorol.* 54, 131–139.
- Matzarakis, Andreas, Muthers, Stefan, Rutz, Frank, 2014. Application and comparison of UTCI and PET in temperate climate conditions. *Finisterra* 48, 21–31. <https://doi.org/10.18055/Finis6453>.
- Mayring, P., 2019. Qualitative content analysis: demarcation, varieties, developments. *Forum qualitative Sozialforschung forum: qualitative Soc. Res.* 20 (3) <https://doi.org/10.17169/fqs-20.3.3343>.
- McEvoy, D., Ahmed, I., Mullett, J., 2023. The impact of the 2009 heat wave on Melbourne's critical infrastructure [Online]. Available at: <https://www.tandfonline.com/doi/epdf/10.1080/13549839.2012.678320?src=getfr>. Accessed 1 December 2023.
- Mookerjee, D., Roy, S., 2023. 'A typology of the sources of mental health precarity among migrant workers in India during the COVID-19 lockdown'. *Frontiers Commun.* 7 <https://doi.org/10.3389/fcomm.2022.969879>.
- Mora, C., 2010. A synthetic map of the climatopes of the Serra da Estrela (Portugal). *J. Maps* 6 (1), 591–608. <https://doi.org/10.4113/jom.2010.1112>.
- Ng, E., 2015. 'Postscript'. In: Ng, E., Ren, C. (Eds.), *The Urban Climatic Map for Sustainable Urban Planning*. Routledge, London and New York, pp. 454–455. <https://doi.org/10.4324/9781315717616>.
- Ngamsirudom, T., Tanaka, T., 2023. Making an urban environmental climate map of the Bangkok metropolitan region, Thailand: analysis of air temperature, wind distributions, and spatial environmental factors. *World Dev. Sustain.* 3 <https://doi.org/10.1016/j.wds.2023.100105>.
- Oke, T.R., 1967. City size and the urban heat island. *Atmos. Environ.* 7 (8), 769–779. ISSN 0004-6981(73)90140-6, 1973.
- Oke, T.R., 2006. Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites. In: *World Meteorological Organization, Instruments and Observing Methods (Report No.)* 81.
- Paranunzio, R., Dwyer, E., Fittion, J.M., Alexander, P.J., O'Dwyer, B., 2021. Assessing current and future heat risk in Dublin city, Ireland. *Urban Clim.* 40, 100983.
- Parsaee, M., Joybari, M.M., Mirzaei, P.A., Haghighat, F., 2019. Urban heat island, urban climate maps and urban development policies and action plans. *Environ. Technol. Innov.* 14 (3), 100341.
- Räsänen, A., Heikkinen, K., Piila, N., Juhola, S., 2019. Zoning and weighting in urban heat island vulnerability and risk mapping in Helsinki, Finland. *Reg. Environ. Chang.* 19, 1481–1493.
- Rawlins, B.G., Harris, J., Price, S., Bartlett, M., 2015. A review of climate change impacts on urban soil functions with examples and policy insights from England, UK. *Soil Use Manage.* 31, 46–61. <https://doi.org/10.1111/sum.12079>.
- Reinwald, F., Weichselbaumer, R., Schindelegger, A., Damyanovic, D., 2024. From strategy to implementation: mainstreaming urban green infrastructure in Austria's spatial planning instruments for climate change adaptation. *Urban Forestry Urban Greening* 94. <https://doi.org/10.1016/j.ufug.2024.128232>.
- Ren, C., 2015. A review of the historical development of urban climatic map study. In: Ng, E., Ren, C. (Eds.), *The Urban Climatic Map for Sustainable Urban Planning*. Routledge, Oxfordshire and New York, pp. 10–34.
- Ren, C., Ng, E., Katschner, L., 2011. Urban climatic map studies: a review. *Int. J. Climatol.* 31, 2213–2233.
- Ren, C., Spit, T., Lenholzer, S., Yim, H.L.S., Heusinkveld, B., van Hove, B., Chen, L., Kupski, S., Burghardt, R., Katschner, L., 2012. Urban climate map system for Dutch spatial planning. *Int. J. Appl. Earth Obs. Geoinf.* 18, 207–221. <https://doi.org/10.1016/j.jag.2012.01.026>.
- Ren, C.; Lau, K.L.; Yiu, K.P. and Ng, E. (2013) 'The application of urban climatic mapping to the urban planning of high-density cities: the case of Kaohsiung, Taiwan.' *Cities*, Volume 31, Pages 1–16, doi:<https://doi.org/10.1016/j.cities.2012.12.005>.
- Richard, Y., Emery, J., Dudek, J., Pergaud, J., Chateau-Smith, C., Zito, S., Vaire, T., Castel, T., Thévenin, T., Pohl, B., 2018. How relevant are local climate zones and urban climate zones for urban climate research? Dijon (France) as a case study. *Urban Clim.* 26, 258–274. <https://doi.org/10.1016/j.uclim.2018.10.002>.
- Schau-Noppel, H., Kossmann, M., Buchholz, S., 2020. Meteorological information for climate-proof urban planning - the example of KLIMPRAX. *Urban Clim.* 32, 100614 <https://doi.org/10.1016/j.uclim.2020.100614>.
- Scherer, D., Fehrenbach, U., Parlow, E., Beha, H.-D., 1996. Determination of aggregated aerial types from a Landsat-TM and ERS-1 based land-use classification for the agglomeration of Basel/Switzerland. *Progress Environ. Remote Sensing Appl.* 197–200.
- Scherer, D., Fehrenbach, U., Beha, H.-D., Parlow, E., 1999. Improved concepts and methods in analysis and evaluation of the urban climate for optimizing urban planning process. *Atmos. Environ.* 33, 4185–4193.
- Schütt, A., Becker, J.N., Gröngroft, A., Schaaf-Titel, S., Eschenbach, A., 2022. Soil water stress at young urban street-tree sites in response to meteorology and site parameters. *Urban Forestry Urban Greening* 75, 127692. <https://doi.org/10.1016/j.ufug.2022.127692>.
- Sheridan, S.C., Dixon, P.G., 2017. Spatiotemporal trends in human vulnerability and adaptation to heat across the United States. *Anthropocene* 20 (2), 61–73. <https://doi.org/10.1016/j.anucene.2016.10.001>.
- Sievers, U., 2005. Theoretische Grundlagen, Anwendung und Handhabung des PC-Modells. *Berichte des Deutschen Wetterdienstes Nr 227*, 101. Seiten, ISBN 978-3-88148-407-7. Available at: https://www.dwd.de/DE/leistungen/pbfb_verlag_berichte/archiv/archiv_berichte.html;jsessionid=0AFEB90C8DABA14F9D8C559C988C03D9.live31092?nn=16102.
- Sievers, U., 2016. Das kleinskalige Strömungsmodell MUKLIMO_3. Teil 2: Thermodynamische Erweiterungen.
- Sievers, V., Zdunkowski, W.G., 1986. A microscale urban climate model. *Beitr. Phys. Atmos.* 59 (1), 13–40.
- Stadt Zürich (Hrsg.), 2020. 'Fachplanung Hitzeminderung'. Zürich.
- Stanhill, G., Kalma, J.D., 1995. Solar dimming and urban heating at Hong Kong. *Int. J. Climatol.* 15, 933–941. <https://doi.org/10.1002/joc.3370150807>.
- Stapley, E., O'Keefe, S., Midgley, N., 2022. Developing typologies in qualitative research: the use of ideal-type analysis. *Int. J. Qual. Methods* 21. <https://doi.org/10.1177/16094069221100633>.
- Stewart, I.D., Oke, T.R., 2012. Local climate zones for urban temperature studies. *Bull. Am. Meteorol. Soc.* 93, 1879–1900. <https://doi.org/10.1175/BAMS-D-11-00019.1>.
- Stewart, I.D., Oke, T.R., 2015. Local climate zones and urban climatic mapping. In: Ng, E., Ren, C. (Eds.), *The Urban Climatic Map for Sustainable Urban Planning*. Routledge, Oxfordshire and New York, pp. 397–401.
- Stoffel, M., Tiranti, D., Huggel, C., 2014. (2014) 'climate change impacts on mass movements—case studies from the European Alps'. *Sci. Total Environ.* 493, 1255–1266.
- Thomas, K., Hardy, R.D., Lazrus, H., Mendez, M., Orlove, B., Rivera-Collazo, I., Roberts, J.T., Rockman, M., Warner, B.P., Winthrop, R., 2018. Explaining differential vulnerability to climate change: a social science review. *Wiley interdisciplinary Reviews. Climate change* 10 (2), e565. <https://doi.org/10.1002/wcc.565>.
- Tomlinson, C.J., Chapman, L., Thornes, J.E., Baker, C.J., 2011. Including the urban heat island in spatial heat health risk assessment strategies: a case study for Birmingham, UK. *Int. J. Health Geogr.* 10, 42.
- Ulpiani, G., Treville, A., Bertoldi, P., Vettors, N., Barbosa, P., Feyen, L., Naumann, G., Santamouris, M., 2024. Are cities taking action against urban overheating? Insights from over 7,500 local climate actions. *One Earth*. <https://doi.org/10.1016/j.oneear.2024.04.010>.
- VDI - Verein Deutscher Ingenieure, 2024. VDI-Richtlinien: Standards setzen - auf dem aktuellen Stand der Technik. Available at: <https://www.vdi.de/richtlinien/seite/2#richtlinien>. Accessed 13 May 2024.
- VDI - Verein Deutscher Ingenieure, 2015. 3787 Part 1. *Environmental meteorology: Climate and air pollution maps for cities and regions*. In: ICS 07.060, 13.040.20. Beuth Verlag GmbH, Berlin.
- Verbeeck, K., Van Orshoven, J., Hermij, M., 2011. Measuring extent, location and change of imperviousness in urban domestic gardens in collective housing projects. *Landscape Urban Planning* 100 (1–2), 57–66. ISSN 0169–2046. <https://doi.org/10.1016/j.landurbplan.2010.09.007>.
- World Bank, 2020. *Analysis of heat waves and urban Heat Island effects in central European cities and implications for urban planning*.
- Xu, D., Zhou, D., Wang, Y., Meng, X., Chen, W., Yang, Y., 2020. Temporal and spatial variations of urban climate and derivation of an urban climate map for Xi'an, China. *Sustain. Cities Soc.* 52, 101850 <https://doi.org/10.1016/j.scs.2019.101850>, 2020.

- Yoshino, M., 1990. Development of urban climatology and problems today. *Energ. Buildings* 15 (1–2), 1–10.
- Zhang, H., Bai, J., Zhao, J., Guo, F., Zhu, P., Dong, J., Cai, J., 2024. Application and future of local climate zone system in urban climate assessment and planning—Bibliometrics and meta-analysis. *Cities* 150, 104999. <https://doi.org/10.1016/j.cities.2024.104999>.
- Ziervogel, G., et al., 2017. Inserting rights and justice into urban resilience: a focus on everyday risk. *Environ. Urban.* 29 (1), 123–138. <https://doi.org/10.1177/0956247816686905>.