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Linking science and practice in participatory future-oriented assessment and planning of human heat stress vulnerability in Bonn, Germany

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The juxtaposition of climate change and development changes is vital for understanding the future impacts of heat stress in urban areas. However, an approach that considers the relationship between climatic factors and socio-economic vulnerability in a forward-looking and stakeholder-involved manner is challenging. This article demonstrates the application of a future-oriented vulnerability scenarios approach to address human heat stress in Bonn, Germany, in 2035. The study highlights the interplays between climate trajectories and heat exposure associated with urban development scenario corridors. Moreover, this method allows for changing combinations of intersections and conditionalities of projected individual socio-economic vulnerability indicators in response to social and climate governance. However, this study found that a conventional structure within city departments might limit this integrative approach in practice. Thus, the theoretical background and the concept of alternative futures and uncertainties should be the focus of communication with practitioners to maximize the utilization of the results.

Keywords: parallel modeling approach; human heat stress; scenario planning; vulnerability analysis; urban planning; Bonn; Germany

1. Introduction

Looking at the practice of urban planning and development in terms of climate change adaptation, inconsistencies become evident: Although climate change scenarios are standard in climate change impact assessments and adaptation strategies, social vulnerability and its future changes are largely ignored in local climate change impact assessments. Building resilience toward climate change and climate change adaptation cannot rely exclusively on climate projections, nor solely on qualitative scenarios. An innovative approach combining quantitative and qualitative risk-informed planning instruments is needed to layout possible futures that enable robust decision-making on human heat stress (Mahlkow *et al.* 2016) and address equity and social justice issues.

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It has been recognized that climate change is a factor increasing uncertainties in urban planning and decision-making (e. g. Hallegatte 2009; Fierman, Field, and Aldrich 2012; Berke and Lyles 2013). This is related to the fact that climate change processes are complex and future changes are not very predictable. Thus, a well-accepted approach to dealing with climate change is developing scenarios that show corridors of possible future developments. Scenarios can be defined as "descriptions of potential future conditions developed to inform decision making under uncertainty" (Parson 2008, 1).

At the global scale, the analysis of climate change was initially based on scenarios of physical climate-related parameters (IPCC [Intergovernmental Panel on Climate Change] 1992) without considering socio-economic factors. Subsequently, these socio-economic factors were integrated into the assessment scenarios (IPCC 2000, 2001) until the idea of combining socio-economic scenarios (based on Shared Socio-economic Pathways, SSP) with climate projections (based on Representative Concentration Pathways, RCP) was introduced in the IPCC's Fifth Assessment Report (IPCC 2014b) to provide a useful integrative frame for climate impact and policy analysis (Moss *et al.* 2010; Kriegler *et al.* 2012). More recently, it has been discussed to extend the policy framework by including Shared climate Policy Assumptions (SPA) (Kriegler *et al.* 2014; Kebede *et al.* 2018).

For adaptation to heat stress, policymakers and planners need small-scale information on people's current and future exposure and vulnerability to heat. Information and projections about the physical factors of human heat stress need to be supplemented by socio-economic information about those potentially affected: where do the most vulnerable groups live today and which neighborhoods will most likely be vulnerable to future heat stress? In order to shape adaptation policies adequately, several requirements regarding the assessment of human heat stress exist: consideration of recent and future climate hazards, recent and future vulnerability, as well as recent and future exposure. Further, the analysis has to be in high resolution to enable the planning and implementation of locally tailored, adequate and effective adaptation measures. Thus, it is beneficial if the assessment is linked with storylines that describe the development toward a (desired) future, ideally with stakeholders and public participation. These requirements are addressed by several studies. A review of 24 peer-reviewed studies from the last decade (2011–2021), however, shows that—although single requirements are addressed in several of the listed studies—only one of them (Birkmann *et al.* 2021) covers all of these requirements (see Table 1).

Concepts for adaptation to potential impacts of climate change, e. g., human heat stress, at the local level often still focus on urban heat islands. A comparison of the practices of such human heat stress analyses shows that different degrees of inadequacies exist (Birkmann *et al.* 2015; Schulze-Dieckhoff *et al.* 2018):

- In many cases, human heat stress assessments show hotspots and related impacts throughout the city only for the present situation, i. e. for the current climate and against the background of today's urban structure and society.
- More differentiated approaches also include future changes in climate parameters and map the city's heat stress situation for a certain year. This approach provides additional information for decision-makers, e.g. by showing that today's hotspots will become the norm in the future, illustrating the severity of the problem in the future.
- There are very few examples where—apart from the changing climate—socio-economic trajectories are also included in analyzing human heat stress.

Table 1. Requirements of future-oriented assessments of human vulnerability to human heat stress.

Requirements	Studies
Integration of physical (climatic, urban fabric) as well as socio-economic (social vulnerability) factors in the assessment	e. g., Weber *et al.* 2015; Karimi *et al.,* 2018; Rohat, Flacke, and Dao 2017; Yiannakou and Salata 2017; Asefi-Najafabady *et al.* 2018; Macintyre *et al.* 2018; He *et al.* 2019; Ho *et al.* 2018; Lapola *et al.* 2019; Jagarnath, Thambiran, and Gebreslasie 2020; Maragno, Fontana, and Musco 2020; Paranunzio *et al.* 2021; Birkmann *et al.* 2021
Integration of current vulnerability and exposition data and estimations, projections or scenarios of future vulnerability and or exposure in the assessment	e. g., Georgescu, 2015; Koomen and Diogo 2017; Asefi-Najafabady *et al.* 2018; De Groot-Reichwein *et al.* 2018; Lipiec *et al.* 2018; Rohat, Flacke, and Dao 2017; Paranunzio *et al.* 2021; Birkmann *et al.* 2021
Use of data or downscaling approaches that provide high resolution/small-scale information to inform urban planners and policy makers	e. g., Karimi *et al.,* 2018; Koomen and Diogo 2017; Yiannakou and Salata 2017; De Groot-Reichwein *et al.* 2018; He *et al.* 2019; Ho *et al.* 2018; Lapola *et al.* 2019; Jagarnath, Thambiran, and Gebreslasie 2020; Kazak 2018; Lipiec *et al.* 2018; Macintyre *et al.* 2018; Maragno, Fontana, and Musco 2020; Sabrin *et al.* 2020; Paranunzio *et al.* 2021; Birkmann *et al.* 2021
Development of storylines or (positive) scenarios for achieving future sustainability and climate change adaptation or resilience	e. g., Robinson *et al.* 2011; Sheppard *et al.* 2011; Lipiec *et al.* 2018; McPhearson, Iwaniec, and Bai 2016; Iwaniec *et al.* 2020a, 2020b; Birkmann *et al.* 2021
Involvement of stakeholders and the public in the research design and scenario development	e. g., Robinson *et al.* 2011; Sheppard *et al.* 2011; De Groot-Reichwein *et al.* 2018; Lipiec *et al.* 2018; Newell, Picketts, and Dale 2020; Wilk *et al.* 2018; Iwaniec *et al.* 2020a, 2020b; Maragno, Fontana, and Musco 2020; Birkmann *et al.* 2021

Approaches that meet the requirements of parallel modeling of climate and socio-economic scenarios (Moss *et al.* 2008; Kriegler *et al.* 2012; Bullock *et al.* 2015; Greiving *et al.* 2017) are still the exception, especially at the regional and local level (Birkmann *et al.* 2015). It is not only a question of data availability or open conceptual questions—as the various approaches to socio-spatial analysis or the assessment of environmental justice show—but it is instead the lack of an integrated perspective on environmental and social change that hampers the application of necessary integrative approaches (Greiving and Fleischhauer 2020).

In this respect, the research project ZURES[1] aimed at innovations by linking social vulnerability to heat stress for the two German cities Bonn and Ludwigsburg (Birkmann *et al.* 2020a, 2020b, 2021). The consideration of social vulnerability and its possible changes in the future was embedded in a participatory scenario development—taking into account institutions and actor constellations—and based on a medium- and long-term socio-economic trend analysis.

This paper is organized as follows: Section 2 outlines the participatory scenario approach that integrates climate and socio-economic vulnerability scenarios to articulate future human heat stress at the neighborhood level. Section 3 presents multi-facets of combinations of single indicators and clustering human heat stress vulnerability indicators for the city of Bonn, and Section 4 discusses and reflects on the nexus between science and planning practice. Finally, lessons learned and recommendations from participatory scenario planning are extracted and concluded in Section 5.

2. Methodology

2.1. Scenario approaches in Bonn

The development of human heat stress vulnerability scenarios at the local level presented in this study contains an urban climatic-physical and a socio-economic component. The link between these components is reflected not only in the type, intensity, and changes in land use, which have a considerable influence on the urban climate (heat storage, ventilation, open spaces), but also on socio-economic factors with which socio-spatial vulnerabilities can be described (location of housing and workspaces, segregation processes, access to open space).

As a growing medium-sized city, the city of Bonn has about 330,000 inhabitants (Bundesstadt Bonn Statistikstelle 2018) and consists of four municipal districts (Stadtbezirk) and 65 statistical districts (Statistische Bezirke).[2] The small-scale vulnerability scenarios developed for the city of Bonn were embedded in a series of participatory scenarios and co-produced in workshops with researchers and representatives of the city's administrative departments. The participatory scenario development followed common steps (Stiens 1998, 131; Avin and Dembner 2001; Scholles 2001, 206 ff.; Hagemeier-Klose *et al.* 2013, 418 f.) and aimed to identify variations of future development of Bonn that served as a broad and consistent framework to derive urban land use scenarios as well as socio-economic scenarios. Following an approach developed by Garschagen and Birkmann (2014), participatory scenario workshops were conducted with key stakeholders of Bonn's city administration. In these workshops, participants discussed the spatial and content-related orientation of the framework scenarios and determined the two axes that stretch out the scenario variations. They further identified key factors relevant to heat stress and adaptation in the city. These factors were clustered and ranked according to their perceived relevance. Four scenario variations (I-IV) were developed and interpreted along the content axes that determined the scenarios based on the workshop results. In cooperation with the city administration, these four scenarios were summarized in narrative storylines, representing four potential urban development paths:

- Scenario I: The City of Bonn does not pursue an active growth policy but follows a climate-adapted urban development as a guiding principle
- Scenario II: Bonn pursues an active growth policy as well as climate-adapted urban development
- Scenario III: Bonn pursues an active growth policy in which climate-adapted urban development plays a secondary role

- Scenario IV: Bonn neither pursues an active growth policy nor actively promotes climate-adapted urban development

Because the city expects overall growth in the future according to population forecasts (BBSR [Bundesinstitut für Bau-, Stadt- und Raumforschung] 2012; Bertelsmann Stiftung 2015), the city administration selected to proceed with scenarios II and III, which pursue an active growth policy and variations of climate change adaptation policies.

2.2. *Integrating future socio-economic vulnerability and bio-climatic conditions*

This section focuses on the integration of scenarios of bio-climatic conditions with scenarios of local vulnerability, providing a new understanding of the intersection and conditionality of individual socio-economic vulnerability indicators.

2.2.1. *Scenarios of local bio-climatic conditions*

Under the ZURES umbrella, the research consortium established future scenarios of the local bio-climatic conditions (Bueter *et al.* 2019). The projections of human-biometeorological situations—which describe the local bio-climatic conditions—are based on downscaling EURO-CORDEX data by using a FITNAH-3D model (Flow over Irregular Terrain with Natural and Anthropogenic Heat sources) with a 10 m × 10 m resolution under RCP 2.6 ($\Delta + 0.5$) and RCP 8.5 ($\Delta + 2.0$)[3] while considering land use changes in the city according to planned urban growth. The simulation takes into account the sealing degree and the structure and height of buildings and vegetation. The methodology used for downscaling climate data is based on guidelines of an expert commission of federal and state institutions in Germany (Birkmann *et al.* 2020a). The future human-biometeorological situation (describing the local bio-climatic conditions) is characterized through the physiological equivalent temperature (PET) (Mayer and Höppe 1987). The PET values aggregated on the statistical district level were normalized in five scales from ’very favourable’ to ’very unfavorable’. Following the understanding of climate risk defined by IPCC AR5 (IPCC 2014a), this study marks the PET value of different RCPs represented as Hazard (H) (human-biometeorological situations). RCP 2.6 represents a low level of the climate signal (human-biometeorological situation) scenario and RCP 8.5 represents a high level of the climate signal (human-biometeorological situation). The data on the different degrees of the human-biometeorological situation are shown with geographical reference representing exposure (E) of all statistical districts.

2.2.2. *Scenarios of local socio-economic vulnerability*

In this study, vulnerability describes the multidimensional causal factors that shape the ability of a society or system to deal with hazards and extreme events and how the society or system can recover from impacts (Wisner *et al.* 2004). The development of the local vulnerability scenarios was based on two intertwined pillars: firstly, the participatory framework scenario development as described in Section 2.1 (to provide basic qualitative storylines on potential urban futures) and secondly, a long-term transformation analysis based on physical, demographic, and economic indicators (20-to-30-year global perspective for the city as a whole and eight-year detailed perspective at the statistical district level).

Among a wide range of indicators that contribute to human heat vulnerability, the most frequently cited are pre-existing physical conditions (such as cardio-vascular and cerebrovascular conditions and diabetes) or those related to mental health (such as depression) potentially leading to mortality and morbidity, age (particularly children and the elderly) followed by economic status and social capital (such as household income, poverty, unemployment, social isolation, social cohesion, household structure, gender, education attainment, language proficiency, race, house-ownership and more) (Medina-Ramón *et al.* 2006; Johnson *et al.* 2012; Reid *et al.* 2012; Scherer *et al.* 2013; Bao, Li, and Yu 2015; Hatvani-Kovacs *et al.* 2016; Laranjeira *et al.* 2021; Paranunzio *et al.* 2021). Furthermore, urban environment and building structure play a vital role in determining the vulnerability of urban populations to heat stress, such as access to vegetation and green space, development intensity, living on a high floor of multi-storey buildings, building materials, land cover and housing density (Krüger *et al.* 2013; Lemonsu *et al.* 2015; Mitchell and Chakraborty 2015; Inostroza, Palme, and De La Barrera 2016; Nayak *et al.* 2018; Méndez-Lázaro *et al.* 2018; Voelkel *et al.* 2018; EEA 2018; Lee, Mayer, and Kuttler 2020; Maragno, Fontana, and Musco 2020; Laranjeira *et al.* 2021; Paranunzio *et al.* 2021). However, it must be distinguished that factors such as age and health status influence a person's sensitivity, while other indicators may promote or reduce one's coping and adaptive capacity and access to resources. In the context of resources, several studies include the provision of air conditioning, increasing urban vegetation, accessibility to medical services and insurance, and accessibility to nearby public heat refuges as crucial (Kovats and Hajat 2008; Weber *et al.* 2015; Inostroza, Palme, and De La Barrera 2016; Méndez-Lázaro *et al.* 2018; Voelkel *et al.* 2018; Laranjeira *et al.* 2021). Although many factors influence human vulnerability to heat, the indicators ultimately selected for vulnerability assessments often depend on data availability and resolution. The indicators selected for this study's analysis met three key requirements: they needed to be able to serve as proxy indicators that represent some of those detailed indicator categories mentioned before (see also core indicators described below), they needed to be available for both pilot cities, Bonn and Ludwigsburg (under the context of the ZURES project), and finally, their spatial resolution needed to be compatible. Based on further dialogues with Bonn's city administration, three factors were assigned as core indicators of vulnerability (V): population density, the elderly population (65 and older), and economic status represented by social welfare recipients (or SGB II).[4]

2.2.2.1. Socio-economic vulnerability core indicators.

Population density. The study used the ratio of inhabitants to residential area as one of the socio-economic core indicators. With a forward-looking perspective, this study downscaled the population growth scenario to the statistical district level through two approaches, statistical estimation and the future development objectives of the preparatory land use plan (Flächennutzungsplan, FNP)[5] of the city (Figure 1). The first estimation assumed that Bonn's population would grow by at least 0.3% (per year) until 2035, according to the minimum population growth rate between 2011 and 2018. The second estimation was based on the number of future residents on the FNP. The FNP defines the specific location of new housing stock and determines the spatial distribution for calculating a potential population in response to the number of new housing units proposed, taking into account the average household size in the respective statistical district.

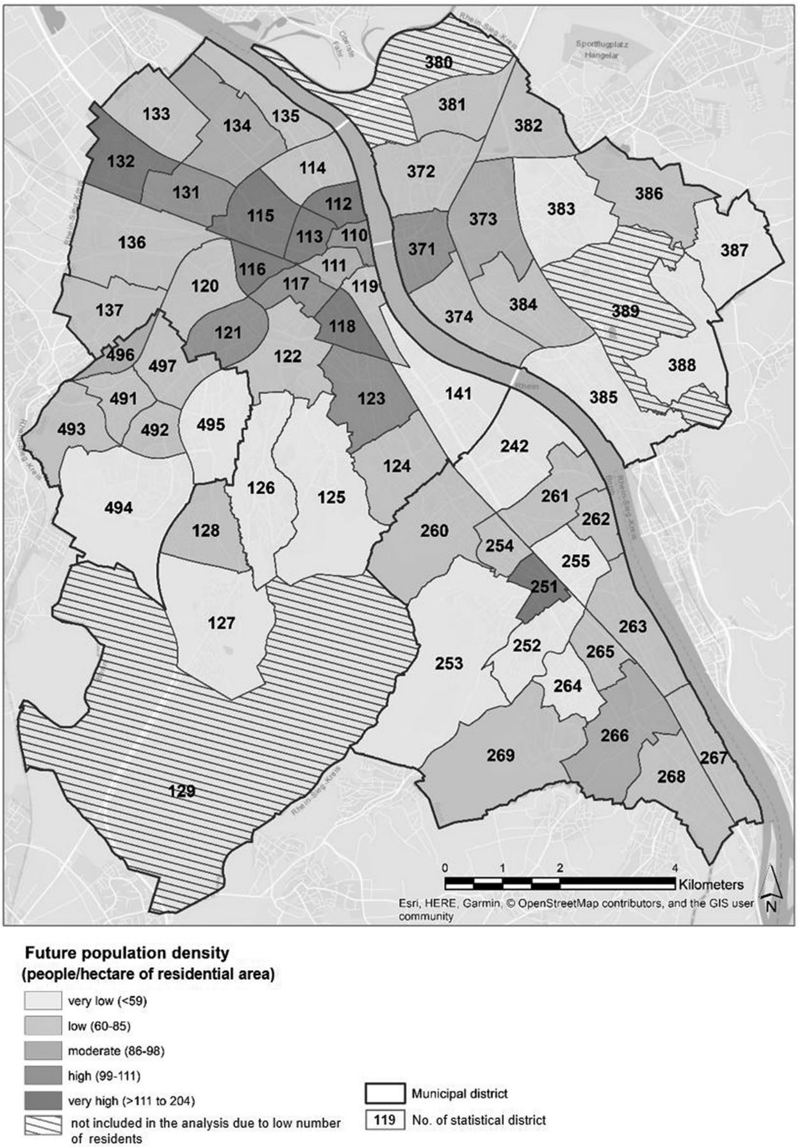

Figure 1. Future land use of Bonn. The light gray polygons represent the residential areas of Bonn in 2016, while the dark polygons show the potential new residential areas by the year 2030, based on the preparatory land use plan of the City of Bonn.

Population 65-year-old and older. The approximate percentage of each statistical district's future elderly population (65-year-old and older) was used to represent socio-demographic related heat vulnerability. Using the mortality rate, the number of people alive in 2016 expected to be alive in 2035 was calculated to portray the share of the elderly population in the future. It was assumed that the population aged 49–65 years in 2016 would still be alive in 2035, as well as no or neutral relocation.

Social welfare recipients. The ratio of social welfare recipients to 1,000 of the employable population was applied to represent local low-income groups with economic disadvantages and thus have lower adaptation capacity during extreme heat situations. Estimating the future state of this core indicator in each statistical district is highly complex. However, the scenario approach allows the assumption of local interventions or market instruments that can directly or indirectly influence the spatial distribution of low-income groups. Based on Bonn's social welfare recipients trend (2009–2016), this research sheds light on the variable implications of social integration through housing policy orientations (residential milieu and equal distribution)

The core indicator values aggregated on the statistical district level were normalized in five scales from 'very low' to 'very high', which allow the combination with climate scenario in the later stage. With regard to the selected storylines II and III from the general scenarios, this study focuses on two fundamental questions: What happens if the city fails or makes little effort to provide affordable housing in response to increasing demands (scenario storyline II)? Furthermore, what happens if the city intervenes in the rental and land market to reduce the extent of socio-economic segregation (scenario storyline III)? Hence, the study addresses these variations through the core indicator of the social welfare recipients.

2.2.3. Coupling scenarios of local socio-economic vulnerability and bio-climatic conditions

Figure 2 shows the overall conceptual framework for integrating future socio-economic vulnerability and climate scenarios. The 2×2 matrix framed the potential impact of heat stress based on different vulnerability profiles and the degree of climate signals as follows:

- Residential milieu-oriented policy and low climate signal (heat) (RCP 2.6)
- Equal distribution-oriented policy and low climate signal (heat) (RCP 2.6)
- Residential milieu-oriented policy and high climate signal (heat) (RCP 8.5)
- Equal distribution-oriented policy and high climate signal (heat) (RCP 8.5)

According to risk definitions (see IPCC 2014a), hazard, exposure, and vulnerability are treated as a non-compensable geometric aggregation of normalized variables. The resulting human heat stress-related impact value could range between 0–1; see Equation (1). This study does not consider the probability element in the analysis; thus, the analytical result represented 'potential impact' rather than 'risk'. The visualization of the conceptual framework on scenario-based potential impact analysis of this study is shown in Figure 3.

$$\text{Potential Impact} = \text{Hazard} * \text{Exposure} * \text{Vulnerability} \tag{1}$$

In addition to the overall integration of human heat stress vulnerability, practitioners and local experts expressed their desire to see the different combinations of core indicators overlaid with climate scenarios, especially the most extreme climate scenario. Therefore, this study illustrates a variety of core indicators as clusters that represent multi-faceted views on socio-economic human heat stress vulnerability in the context of the extremely warm climate scenario (RCP 8.5) as follows:

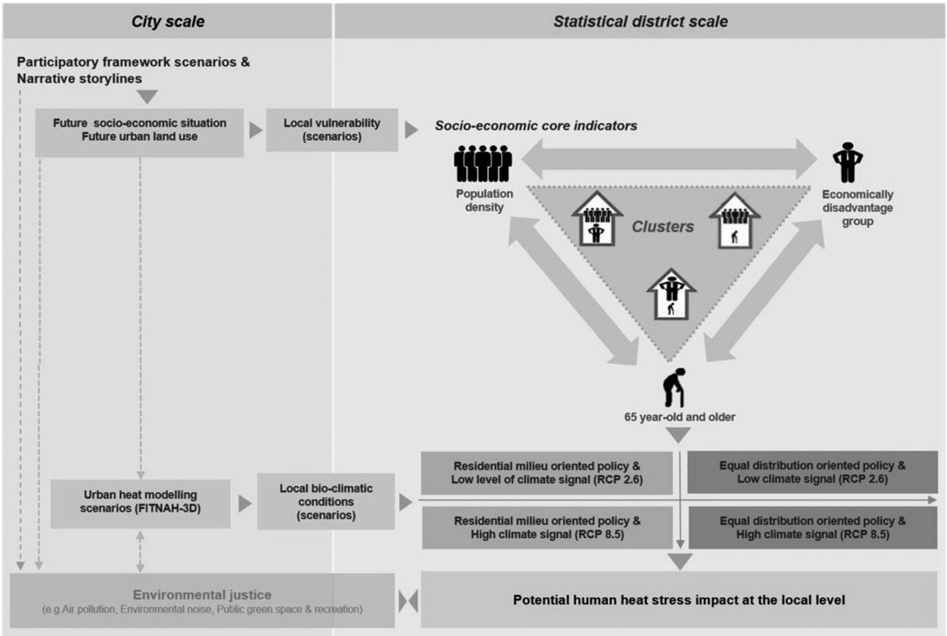

Figure 2. Conceptual framework for integrating future socio-economic vulnerability and climate scenarios. The diagram shows the interlinkage between city-wide (left) and statistical district level (right) on climate and socio-economic vulnerability perspectives. The upper right shows the relationship among the selected core indicators and a combination of clusters. The lower right exhibits 2×2 matrix of socio-economic vulnerability and climate signal scenarios. The lower left shows opportunities for inserting environmental justice layers into the analysis (was done within the ZURES project but is not addressed in this article).

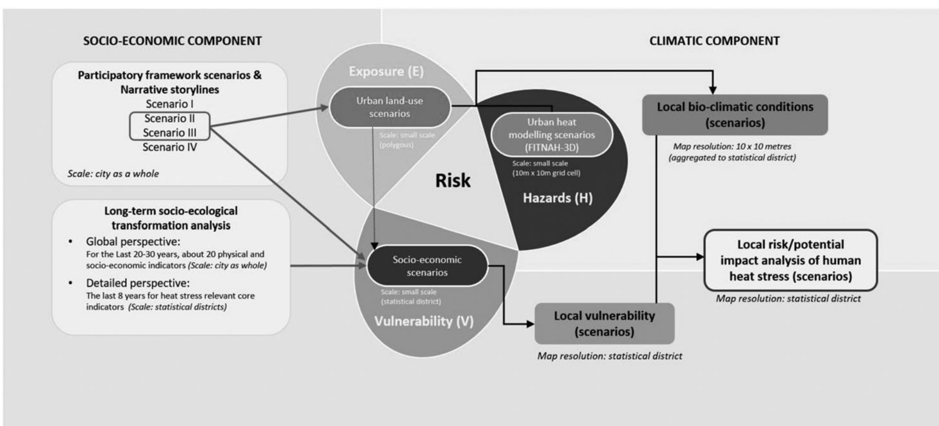

Figure 3. Framework of scenario-based potential impact analysis of human heat stress. The diagram presents the integration of participatory scenario development in the IPCC climate risk framework in the context of human heat stress within an urban setting.
Source: Adapted from Oppenheimer et al., 2014.

- Cluster 1 (social welfare recipients and people 65 and older): This cluster highlights those statistical districts where poverty and age coincide and could be exacerbated under extreme heat conditions. The analysis of this cluster could further

investigate the impact of human heat stress on low-income households with elderly family members in need of care. In this cluster, a high level of the social welfare recipients factor was assigned as a prerequisite in the calculation.
- Cluster 2 (population density and social welfare recipients): This cluster emphasizes that low-income groups in dense agglomeration are more vulnerable and should be prioritized to improve the urban structure and social benefits. A high population density in a residential area was assigned as a prerequisite factor in the calculation.
- Cluster 3 (population density and people 65 and older): This cluster underlines the statistical districts where the aged population lives in dense agglomerated areas with (often) inadequate heat refuge facilities and large vegetation space accessibility.

3. Results

Based on the cross combination of the socio-economic vulnerability and bio-climatic conditions at the level of statistical districts, Figure 4 shows the spatial extent of the potential impact of human heat stress in 2035 for Bonn. The upper section of the quadrant shows the low climate (heat) signal scenario (RCP 2.6) combined with different socio-economic vulnerability scenarios. Meanwhile, the lower section of the quadrant illustrates the high climate signal (heat) scenario (RCP 8.5) combined with different socio-economic vulnerability scenarios.

Considering the climatic factor, the spatial distribution of hotspots is defined by the urban fabric, especially in the city center, which tends to have a high thermal environment, roughness, impermeability, and low vegetation (Oke *et al.* 2017). Thus, city centers are more likely to have a higher heat exposure level than peripheral rural areas. From a socio-economic vulnerability perspective, most emerging hotspots are dominated by population density and social welfare recipients (see Figure 4). The cluster analysis also confirms that the combination of population density and unemployment (cluster 2) exhibits the highest degree of human heat stress vulnerability compared to other clusters. Cluster 1 highlights the areas along the four edges of the city, especially the northern part, where the local government should pay attention to households in which families receive social welfare and also care for the elderly, which therefore tend to be more sensitive and have less coping capacity during heatwaves. Nevertheless, the analysis also unveils that most of the elderly population live in low heat exposure areas, even in the extreme climate scenario (RCP 8.5).

Figure 5 demonstrates why adaptation strategies should be tailor-made by focusing on four statistical districts, i.e. Ellerviertel (no. 115); Bonn-Gueterbahnhof (no. 116); Alt-Tannenbusch (no. 131) and Neu-Tannenbusch (no. 132). Ellerviertel (no. 115) and Bonn-Gueterbahnhof (no. 116) showed a higher density of inhabitants in the residential area (and less vegetation), contributing to the relatively higher thermal environment. However, both areas have a substantially less physically vulnerable population (elderly). In contrast, Tannenbusch (no. 131) and Neu-Tannenbusch (no. 132) have lower population densities (surrounded by a substantial green environment) but a higher number of social welfare recipients. Hence, potential action needs to be undertaken in Ellerviertel (no. 115) and Bonn-Gueterbahnhof (no. 116) is to improve the urban fabric and physical environment. Meanwhile, in Tannenbusch (no. 131) and Neu-

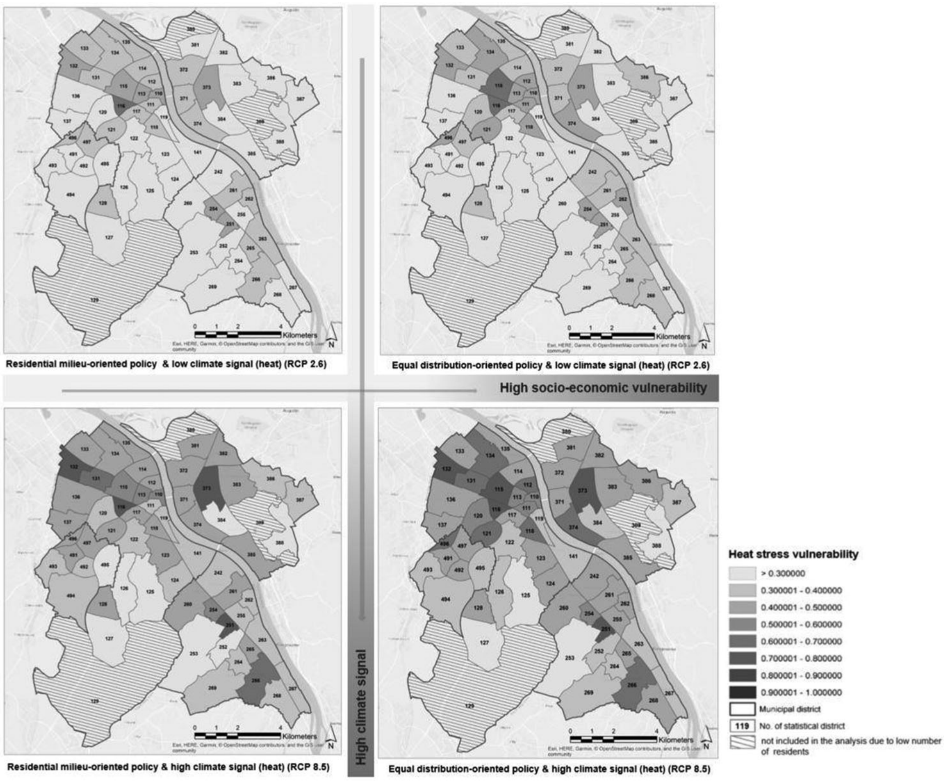

Figure 4. Integrated future heat vulnerability in statistical district level of Bonn in 2035. The figure shows four human heat stress vulnerability scenarios based on different combinations of socio-economic vulnerability profiles and the degree of climate signals.

Tannenbusch (no. 132), the focus should be more on enhancing households' socio-economic capacity to cope with and adapt to extreme heat.

4. Discussion

4.1. Advanced vulnerability assessment approach enabling robust decision making

Besides highlighting future scenarios of heat exposure in relation to the physical changes according to development pathways (Kazak 2018) or fixing the perspective of socio-economic vulnerability with the present situation (Paranunzio *et al.* 2021), this study demonstrated an advanced human-heat stress vulnerability assessment approach by considering both climate changes and socio-economic changes. This approach not only enhances co-production between academia and practitioners in climate resilient strategy development, but also encompasses robust decision-making. Different climate signal scenarios significantly influence the variation of an overall magnitude of human heat stress. However, the socio-economic core indicators mainly explain the heterogeneity in the spatial distribution of heat vulnerability hotspots. Interestingly, the city-wide spatial distribution patterns do not differ dramatically between heat stress vulnerability scenarios. This similar pattern of overall vulnerability among the four scenarios shows that heat-related risk reduction strategies could potentially contribute to robust

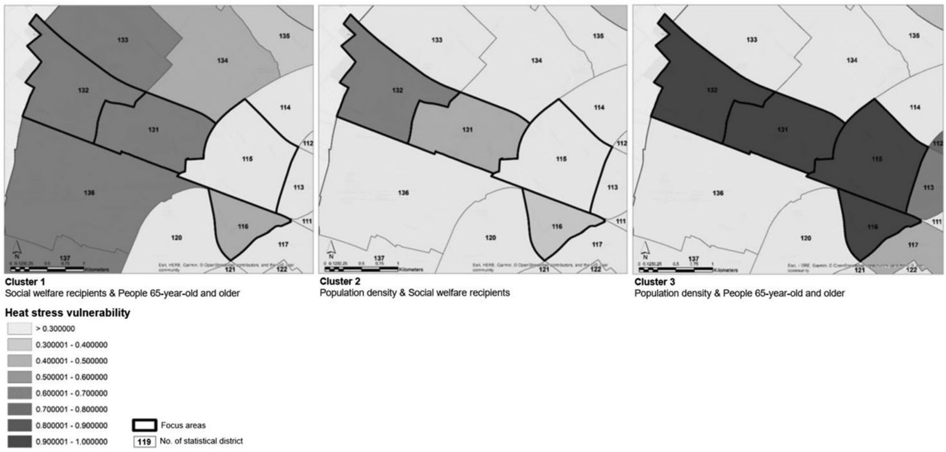

Figure 5. Cluster-based analysis of future human heat stress vulnerability in statistical district level of Bonn in 2035. The figure highlights cluster analysis of human heat stress vulnerability of four focused statistical districts under the high climate scenario (RCP 8.5).

decision-making under any unfavorable thermal situation in the future. The cluster analysis also identifies multifaceted perspectives of the problems that help planners to adapt heat stress-related risk reduction strategies to be relevant and appropriate for area-based socio-economic vulnerability profiles and their degree of heat stress. Improving the urban fabric and enhancing the coping and adaptive capacity of vulnerable groups contributes to urban heat resilient and no-regret measures investment, which at the same time have co-benefits in mitigating social inequality and addressing environmental justice issues. In addition, visualizing the results of this advanced vulnerability assessment helps practitioners and policymakers set priorities, precautionary models, and warning systems. It also supports identifying criteria for heat-resilient locations for sensitive social infrastructure (e.g. new hospitals, nurseries, and retirement homes) and developing blue and green infrastructures.

4.2. Science and planning practice nexus in the planning process for future-oriented human heat stress vulnerability scenarios

In linking science and practice in the context of a planning process for future-oriented human heat-stress scenarios, both methodological and implementation aspects are discussed and reflected as takeaway messages from the city of Bonn for other cities in the following.

4.2.1. Appropriate data resolution for risk-informed planning and decision making on future human heat stress

It is challenging to define the data representing the factors that nexus physical and socio-economic characteristics of the human-heat stress at the urban scale (Ellena *et al.* 2020). The practitioners (representatives from several departments in the City of Bonn) found the analysis of the human-biometeorological situations that produced 10 m × 10 m resolution urban climate maps (potential hazard and exposure) and the transfer of these results into planning advice maps to be useful. However, the intersection of the high-resolution urban climate map with the socio-economic vulnerability indicators at a statistical district level caused methodological objections and was perceived as a challenge for risk communication and decision-making. A methodologically consistent intersection of urban climate and vulnerability data would require a high resolution of socio-economic data, usually not published due to data protection requirements. To identify vulnerable population groups, the building block or neighborhood level would be preferable to support decision-making. The lack of high-resolution socio-economic vulnerability data revealed a dilemma: on the one hand, the research teams could not use high-resolution vulnerability data. On the other hand, the acceptance of the results and their use for decision-making was regarded low, mainly because of the low resolution of results.

Nevertheless, the statistical district-scale offers the opportunity to identify hotspots that can prioritize particular areas or issues. Data on this scale would generally work for the city development strategy that addresses large-scale development patterns and medium-term development perspectives. This resolution of information can be the basis for identifying areas within the city eligible for urban renewal funding. However, for detailed analysis within one specific ward, data resolution at the statistical district level is too broad.

It must be emphasized that statistical boundaries are invisible for people in their daily lives and that their interaction and mobility throughout the city are not bound to the place they live. Therefore, examining the areas based on statistical districts' census data might be insufficient to reflect reality. In addition, heat exposure of inhabitants differs throughout daytime and nighttime depending on their activities, which in turn often differ according to age groups, occupations, or culture. Even though heat stress is a primarily nocturnal phenomenon, people are more exposed to heat during the daytime. The availability or development of datasets on nighttime and daytime activities could enhance the scope of the analysis and design heat stress mitigation measures according to inhabitants' collective behaviors and their exposure to heat (Kazak 2018) and other types of environmental justice concerns, especially for vulnerable population groups (e. g. Schläpfer *et al.* 2021).

4.2.2. Focused communication in participatory scenario planning

Despite long-term record data availability and confidentiality reasons, the three selected core indicators cannot fully capture the population's coping capacity, perceptions, and individual or community resources (Wilhelmi and Hayden 2010). Nevertheless, they help identify areas where adaptation measures can be regarded as especially effective by addressing those areas with the highest need for support due to the combination of unfavorable bio-climatic conditions and high social vulnerability. However, perceptions regarding the relevance and need for vulnerability information differed (from approval to reluctance, e.g. avoiding a competing or similar product based on research done with the own departmental policies) among relevant city departments with competing interests and responsibilities. Moreover, although some practitioners preferred quantitative analyses such as indicators and maps over qualitative narrative storylines, combining climate change and vulnerability scenarios revealed competing interests within the city administration.

Thinking in scenarios with an open-ended discussion of potential development paths beyond well-known boundaries still seemed unfamiliar for practitioners. Yet, their conventional planning routines are determined by limited resources and political boundaries. Even though this study attempted to ensure early involvement of stakeholders, more intensive and especially more bilateral communication would have helped identify different perceptions of the intermediate results at an earlier stage and increase the overall acceptance of the results. Thus, examining further discrepancies between the research community's and the practitioners' points of view is essential to generate valuable results.

5. Conclusions

This article highlights the integration of downscaled climate scenarios with localized socio-economic vulnerability scenarios. It offers an advanced understanding of the intersection and conditionality of individual socio-economic vulnerability indicators (cluster analysis) of the city of Bonn. The result shows that different climate scenarios significantly influence the variation of an overall magnitude of human heat stress. However, the three socio-economic core indicators (population density, the elderly population [65 and older], and social welfare recipients) mainly explain the heterogeneity in the spatial distribution of heat vulnerability hotspots. A similar pattern of overall vulnerability among the scenarios shows that heat-related risk reduction strategies could potentially contribute to robust decision-making under any unfavorable thermal situation in the future.

In the nexus between the research and practice point of view, this research approach and findings presented provide new insights into human heat vulnerability and ways to assess vulnerabilities more holistically. The results presented can be used to support urban adaptation planning and strategic urban development planning. Nevertheless, the indicator-based scenario assessment helps to simplify the complexity of human heat vulnerability to a manageable level. It is vital to ensure the early involvement of relevant city departments to discourse on their joint interests and encompass a mutual understanding of a wide range of uncertainties and the possibility of alternative futures. Strong involvement and streamlining of competing interests of the departments are crucial to maximize the utilization of the results and promote risk-informed planning.

Furthermore, the case of Bonn also reveals opportunities for further research on human heat stress at a higher resolution that is not bound by administrative boundary and reflects reality and spatio-temporal (day and nighttime) dynamics of inhabitants' collective behaviors in correlation to their exposure to heat and other types of environmental stresses. Yet, the convergence between human heat stress vulnerability and other environmental justice concerns emerges as an exacerbating impact on human health that shall be profoundly analyzed. Therefore, we propose to explore the potential integration between future-oriented human heat stress vulnerability and environmental justice elements through the integration of model simulation analysis.

Notes

1. The research project 'Vulnerability and risk analysis as an instrument for the advancement of resilience of cities and urban infrastructure (ZURES)' during 2016–2019, project website: https://www.project.uni-stuttgart.de/zures/en/).
2. There are three statistical districts with a very small number of inhabitants, therefore, the data is not included in the report, i.e. Kottenforst, Siegaue, and Ennert.

3. RCP2.6: One pathway where radiative forcing peaks at approximately 3 W m^{-2} before 2100 and then declines; RCP8.5: One high pathway for which radiative forcing reaches greater than 8.5 W m^{-2} by 2100 and continues to rise for some amount of time (IPCC 2014c: 126–7).
4. The definition of social welfare in this paper refers to the second book of the German Social Code (SGB II). It combines unemployment support and social assistance to form a uniform basic income support scheme for those capable of work but in need of support (Grundsicherung für erwerbsfähige Hilfebedürftige) (IAB 2020)
5. Even though the timeframe of the preparatory land use plan is 2030, the time horizon of the climate trajectories is 2035. Considering the great uncertainty of future climate change, 2035 was selected as the end point for the scenarios analysis.

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