Assessing and Mitigating the Heat Vulnerability from the Perspective of Morphological Regions: A Case Study in Beijing

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Abstract Against the backdrop of climate change, heat waves have become increasingly detrimental to cities. Urban morphology, a comprehensive reflection of material and non-material elements in the physical world, is closely related to environmental quality, thermal environment, population health, and other elements. From the perspective of urban morphological regions, this paper examines the characteristics of heat exposure, sensitivity, adaptability, and vulnerability of the main urban areas and its surrounding areas in Beijing, in combination with land surface temperature, air temperature, population characteristics, vegetation distribution, and other indicators. The results indicate that the built-up areas of Beijing are dominated by compact classes, making them most vulnerable to heat waves due to the unfavorable thermal environment, high population density, a large proportion of young and old people, and sparse vegetation cover. In contrast, the open low-rise class shows the highest adaptive capacity due to better economic condition of the population and high vegetation cover. This paper provides mitigation strategies from angles of morphology optimization and policy guidance, and suggests that the assessment and analysis of heat vulnerability based on urban morphology can provide a reference for climate change-oriented planning and design, and promote urban high-quality development and sustainable construction.

Keywords morphological regions; urban morphology; thermal environment; heat vulnerability; Beijing

1. Introduction

In recent years, the effects of global warming have become increasingly evident, with a rise in the frequency and intensity of disasters, such as extreme heat waves in summer, heavy rainstorms, and typhoons (Corburn, 2009; Vardoulakis et al., 2015). Among them, heat waves are becoming particularly concerning due to their long duration and wide range of influences on urban development and health of the population (Robine et al., 2008; Gasparrini et al., 2012; Elizabeth, 2020). For example, in order to withstand hot weather, people tend to increase their energy consumption, especially electricity (Shen et al., 2016), which in turn leads to higher levels of carbon emissions in cities. Furthermore, heat waves significantly reduce people's willingness to go outdoors (Huang et al., 2016), thus decreasing their outdoor activities, such as exercise, walking, and recreation, which increases the risks of cardiovascular, obesity, and other diseases (Dye, 2008). More seriously, prolonged exposure to extreme heat waves significantly increases the risk of death in the population (Gasparrini et al., 2012; Fouillet et al., 2006). A study by Zhao et al. (2021) revealed that more than 480,000 deaths per year during 2000 – 2019 globally were attributed to heat waves. Therefore, how to reduce the risk of heat waves and increase the resistance capacity of cities, which has become one of the urgent issues that cities need to cope with climate change.

By now, many scholars have conducted researches on the causes, impacts, and mitigation strategies of heat waves in cities. Among them, heat vulnerability has gradually gained more attention because it involves multiple dimensions such as environmental quality, population characteristics, and socio-economic status, and can reflect the capacity of a city to withstand and cope with the risk of heat waves in a more comprehensive way (Mallen et al., 2019; Cai et al., 2019). Referring to the definition of vulnerability by Intergovernmental Panel on Climate Change (IPCC), heat vulnerability refers to the degree to which urban residents are susceptible to, or incapable of coping with the negative impacts of heat wave hazards, including sensitivity and adaptability to heat hazards (Pörtner et al., 2022). In general, heat vulnerability includes three dimensions, i.e., exposure, sensitivity, and adaptability, involving different aspects of indicators (see Table 1). Among them, exposure is mainly used to measure the degree to which cities or populations are exposed to heat waves, the higher the temperature, the greater the exposure (De Carolis, 2012); sensitivity is used to measure the ability of populations to withstand high-temperature heat waves, e.g., the elderly exhibit high sensitivity to heat waves due to their poorer physiological conditions (Wolf and McGregor, 2013); and adaptability is used to assess the population's response to heat waves and their ability to recover from them, e.g., the better the economic condition, the higher the adaptability to heat waves (Manik and Syaukat, 2015).

Table 1 Particular indicators concerning exposure, sensitivity, and adaptability in different studies

References	Exposure	Sensitivity	Adaptive capacity
Wolf and McGregor, 2013	Urban heat island, population, air conditioning, etc.	Elderly, economic status, education, etc.	Access to resources, mobility, demographics, health status, etc.
Inostroza, 2016	Land surface temperature	Education, unemployment, elderly population, etc.	Medical services, NDVI, etc.
Van der Hoeven and Wandl, 2014	Land surface temperature, imperviousness, Albedo, vegetation index (NDVI), sky view factor, etc.	Population, age, electricity consumption, etc.	N/A
Manik and Syaukat, 2015	Community knowledge of climate change, climate variability	Health related to air temperature, energy consumption	Education, income, etc.
De Carolis, 2012	Temperature, public equipment (e.g., shelters, medical clinics)	Age, education, income, etc.	N/A

Despite the multiple dimensions of heat vulnerability assessment and the complexity of the indicator system, related research has faced issues concerning indicator selection, weighting, and synthesis. Regarding indicator system, Table 1 illustrates disparities in the indicators chosen due to different interpretations of heat vulnerability. As for indicator weighting, there are various methods, such as layer stacking, principal component analysis, and multi-criteria decision-making (Xie et al., 2015). Lastly, there is also a wide range of methods for indicator synthesis. At present, the mainstream indicator synthesis methods are mainly the multiplication and division methods and the addition and subtraction methods. For example, Chen et al. (2019) believe that vulnerability can be expressed by "exposure × sensitivity ÷ adaptation," while Cai (2019) expresses vulnerability as "exposure + sensitivity - adaptation." All of these discrepancies greatly affect the assessment results of heat vulnerability and may lead to its disconnection from the practical application in reality.

In recent years, the study of urban morphological regions has seen great advances in urban morphology and urban climate. It has been established that urban morphological characteristics are closely related to demographic, economic, and environmental elements (Cai et al., 2021; Cai et al., 2022). A standardized and systematic morphological regions scheme provides a reference for global comparison of heat vulnerability studies, which can also bridges the gap between heat vulnerability assessment and urban planning, allowing for the implementation of refined response strategies. This paper aims to analyze the spatial distribution of heat vulnerability and its characteristics in summer based on the morphological regions scheme, taking the main urban area of Beijing and its surrounding areas as an example, which aims to provide a reference for improving the resilience of the city and its capacity to cope with climate change.

2. Data and methodology

2.1 Study area

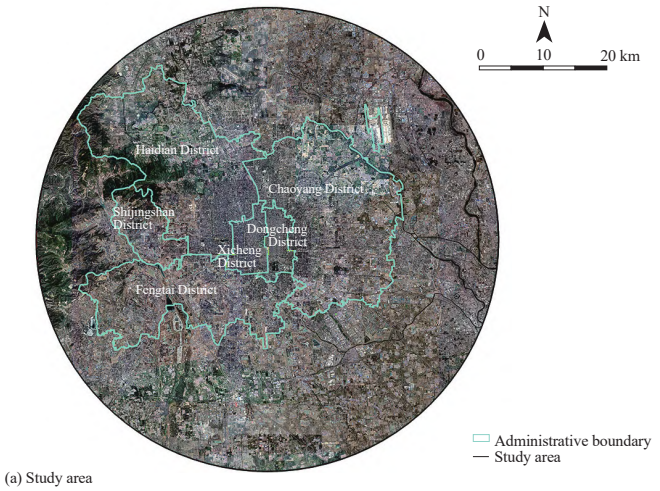
This study covers an area with a diameter of 36 km radiating outward from Tiananmen Square (see Figure 1a), including not only Beijing's six main districts, i.e., Dongcheng, Xicheng, Chaoyang, Haidian, Fengtai, and Shijingshan, but also parts of the surrounding districts, such as Changping, Mentougou, Tongzhou, Shunyi, Tongzhou, Daxing, and Fangshan.

2.2 Data source and preprocessing

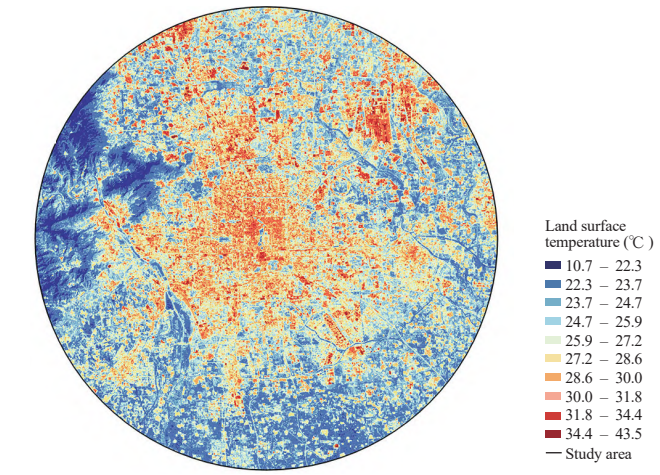
The data used in this paper include land surface temperature, air temperature, population distribution, vegetation cover, and economic status. Among them, the land surface temperature data were retrieved using the thermal infrared band (with a spatial resolution of 100 m) from Landsat 8 satellite imagery, the data source was USGS (https://earthexplorer.usgs.gov), and the image was acquired at 10:53 pm on Aug. 3, 2020 (local time). The air temperature data were obtained from Beijing meteorological weather stations, including the hour-by-hour minimum, maximum, and average temperatures of 223 meteorological weather stations in the study area. In the study, the average temperatures from 22:00 on Aug. 3 to 2:00 on Aug. 4, 2020, were used as the basis for obtaining the nighttime air temperature distribution in the study area at a 100 m spatial resolution using the spatial interpolation methods. Population distribution data were downloaded from the world population website (https://www.worldpop.org), including information on population distribution by age, population density, etc., with an original spatial resolution of 1 km. The vegetation cover data uses the Normalized Difference Vegetation Index (NDVI), which is mainly based on the near-infrared (NIR) and red bands in the Landsat 8 image dataset, with a spatial resolution of 30 m. And the economic data were mainly the Gross Domestic Product (GDP), obtained from the World Bank (https://data.worldbank.org), with an original spatial resolution of 1 km. To ensure the consistency of the spatial scale, all of the data were resampled with a spatial resolution of 100 m.

2.3 Urban morphology regions

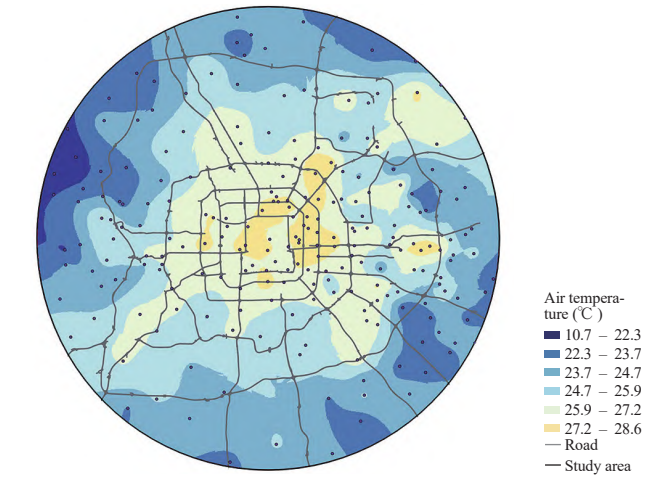
By referring to related research results (Stewart & Oke, 2012; Cai et al., 2022), this paper classifies the urban morphology into two categories – built-up area and area with natural land cover – and 10



(a) Study area



(b) Daytime land surface temperature retrieved from Landsat 8 satellite



(c) Nighttime air temperature distribution interpolated from weather station

Figure 1 Study area, daytime land surface temperature, and nighttime air temperature distribution

subcategories, including compact high-rise, open mid-rise, large low-rise, water body, etc. (see Figure 2). To identify and classify urban morphology in a large-scale area with high accuracy, this research employs a machine learning method based on remote-sensing images. This method consists of four processes: sample training, machine learning, accuracy assessment, and adjustment and feedback. Further details can be found in Cai et al. (2022). The final results achieved an overall accuracy (OA) of more than 65%, which fulfills the research needs.

2.4 Procedure and methodology of heat vulnerability assessment

Previous studies (Xie et al., 2014; Chen et al., 2019) indicates that the urban heat vulnerability assessment procedure consists of three processes: indicator selection, indicator weighting, and indicator synthesis. To assess the actual conditions in the study area, seven indicators were chosen: air temperature (AT), land surface temperature (LST), population density (PD), age of the population (Age), GDP, and NDVI index. Three of these indicators – AT, LST, and PD – were used to assess heat exposure, age of the population was used to assess heat sensitivity, and GDP and NDVI index were used to assess heat adaptability (see Table 2). According to the results of previous studies (Gasparrini et al., 2012), the higher the values of temperature and population density, the higher the risk of exposure of the population to heat waves, which in turn produces positive influences on heat vulnerability. Elderly people and infants are more sensitive to high-temperature heat waves due to their poorer physiological condition (Wolf et al., 2012). The physiological condition of the human body increases and then decreases with age, so it can be considered that the population's sensitivity to heat waves also shows a trend of decreasing and then increasing with age. In general, the GDP reflects the economic status of the population, and the better the economic status of the population, the more they can afford to spend on air-conditioning, cooling, medical care, etc., thus showing a high degree of adaptability to heat waves (Sun et al., 2022). While the NDVI index can reflect the vegetation cover, a large number of studies have pointed out that there is a significant negative correlation between vegetation cover and temperature (Hang and Cai, 2016; Jiang et al., 2021), and that higher vegetation cover can bring more space for residents to cool down and relax. Therefore, higher GDP and NDVI can reduce the heat vulnerability of the city.

In terms of indicator weighting and indicator synthesis, this study uses the method of equal weight addition and subtraction. Specifically, the indicators are first normalized (Equation 3) to eliminate the difference in magnitude between them. They are given the same

weights according to the number of indicators, and finally, they are added according to the positive and negative impacts of each indicator on heat vulnerability (Equation 1). The specific equations are as follows:

$$HV = \sum D_n \quad (n = E, S, A) \tag{1}$$

$$D_n = (\sum_{i \in j} \overline{I}_{ni})/j \tag{2}$$

$$\overline{I}_{ni} = (x - x_{min})/(x_{max} - x_{min}) \tag{3}$$

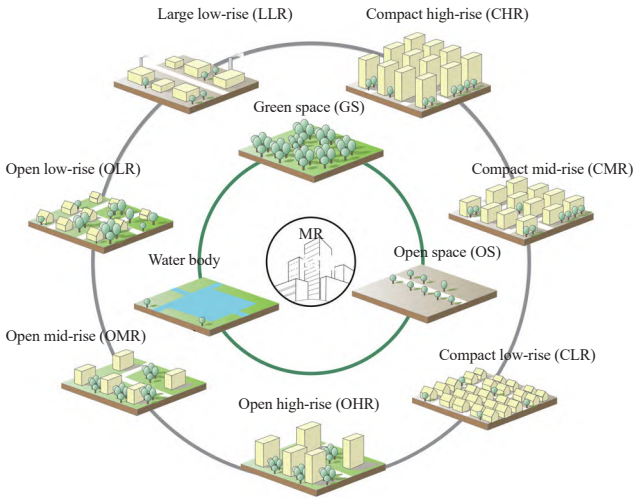
where, HV is the heat vulnerability index, D_n is the three dimensions of heat vulnerability. DE, DS, and DA represent exposure, sensitivity, and adaptability, respectively. $\overline{I}$ is the normalized indicator value, j is the number of indicators selected on a dimension, i is the serial number of the indicator on a dimension, e.g., $\overline{I}_{E2}$ represents the normalized value of the second indicator on the exposure degree. x is the actual value of an indicator, x_{max} is the maximum value of an indicator, and x_{min} is the minimum value of an indicator.

3. Urban morphology and its characteristics of heat vulnerability

3.1 The composition and spatial distribution of Beijing's morphological regions

In terms of urban morphology regions (see Figure 3b), Beijing's built-up areas are dominated by compact classes, which account for 22% of the total land area in the study area, and show a decreasing trend in the order of compact low-rise (CLR), compact mid-rise (CMR), and compact high-rise (CHR). The open classes have a relatively low proportion of about 13.5% in the total land area in the study area, and also shows a decreasing trend in the order of open high-rise (OHR), open mid-rise (OMR), and open low-rise (OLR). The class of large low-rise (LLR) also has a notable presence, comprising 5.8% of the study area. The non-built-up area, such as green space, occupies more than 50% of the study area. In terms of spatial distribution, Beijing's built-up area follows a "finger-shape + multi-center" pattern, with the main city at the core and peripheral urban built-up areas developing along the roads radiating outward, connecting with the sub-centers of the city (see Figure 3a). In terms of specific forms, CLR is dominant within the 2nd Ring Road, CMR and CHR are dominant between the 2nd Ring Road and the 4th Ring Road, and OHR and OMR are dominant in the built-up area outside the 4th Ring Road. In addition, due to the differences in urban functions and industrial layout, the types of urban morphology in the peripheral districts also differ greatly. For example, the urban morphology of the Tongzhou sub-center with a large population is dominated by OHR, while the Yizhuang area, an important logistics distribution and production base in Beijing, is dominated by LLR. Rural settlements show a point-based layout, mainly in CLR class.

Despite the differences in the three dimensions and the composition of the indicators for heat vulnerability evaluation, we can see that the values of the indicators for heat vulnerability evaluation show a high degree of consistency when considering urban morphology regions (see Figure 5). Compact classes have higher exposure, sensitivity, and

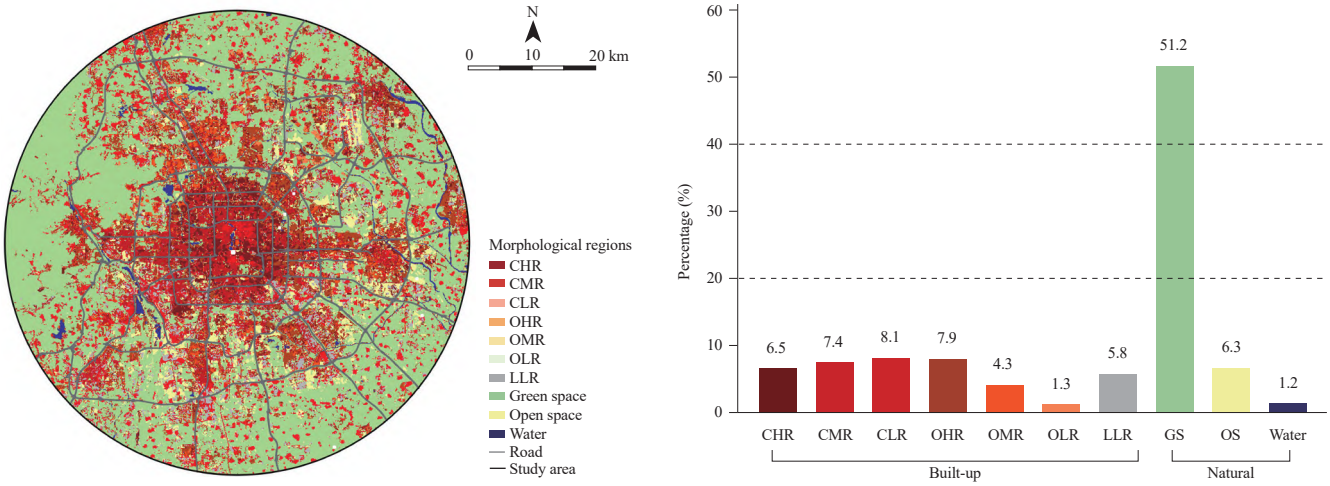


Urban morphology regions		Common urban land use and functions
Built-up (B)	B1. Compact high-rise	CBD, high-intensity residential and office areas
	B2. Compact mid-rise	Old city centers, commercial streets
	B3. Compact low-rise	Urban villages and old neighborhoods
	B4. Open high-rise	Typical high-rise housing development
	B5. Open mid-rise	High-quality neighborhoods, schools
	B6. Open low-rise	Villa area, part of rural settlements
	B7. Large low-rise	Industrial areas, logistics centers, wholesale centers
Natural land cover (N)	N1. Green space	Park and forest
	N2. Open space	Roads, squares, demolition areas, parking lots
	N3. Water	Rivers and lakes

Figure 2 Urban morphological regions and explanation of common urban land use

Table 2 Three dimensions of heat sensitivity and selection of assessment indicators

	Dimensions	Indicators	The contributions to heat vulnerability
Heat vulnerability	DE – Exposure	LST	Positive (+)
		Air temperature	Positive (+)
		Population density	Positive (+)
	DS – Sensitivity	Age < 35	Negative (-)
		Age ≥ 35	Positive (+)
	DA – Adaptability	GDP	Negative (-)
		NDVI	Negative (-)



(a) Distribution of urban morphological regions in Beijing

(b) Proportion of urban morphological regions' classes in the study area

Figure 3 Distribution of urban morphological regions in Beijing and proportion of urban morphological regions' classes in the study area

vulnerability degrees than open classes, and mid-rise classes have significantly higher exposure, sensitivity, and vulnerability degrees than high-rise and low-rise types. However, the adaptability capacity is the opposite, i.e., the compact classes were less adaptive to heat waves than the open classes. This is evidenced by the highest degree of exposure, sensitivity, and vulnerability in CMR, while OLR has the lowest degree. Similarly, OLR has the highest adaptability and CLR has the lowest.

4. Planning countermeasures for heat vulnerability in Beijing

In order to reduce the vulnerability of urban populations to heat waves, three measures can be applied - reducing environmental exposure, weakening population sensitivity, and improving population adaptability. However, as urban heat vulnerability involves multiple dimensions and indicators of different fields, corresponding mitigation strategies must be proposed for specific indicators and dimensions. These strategies should include optimization of urban morphology at the material level, as well as policy guidance and institutional design at the non-material level.

4.1 Optimization of urban morphology

Urban morphology is the comprehensive expression of various material and non-material elements, influencing the social economy and environment. Studies have shown that optimizing urban morphology effectively reduces the urban heat island effect and improves the thermal environment (Yang et al., 2020; Lai et al., 2019). Additionally, our research has demonstrated that heat vulnerability varies across different urban morphological regions, with highly vulnerable areas concentrated in spaces with high construction intensity (see Figure 5d). Consequently, changing urban morphology through demolition and redevelopment can be a viable strategy for cities to mitigate heat waves. For example, many cities opt for the push-button urban renewal method, which includes redeveloping CLR settlements into OHR or OMR. However, as the city develops and an emphasis is placed on stock-based development and micro-renewal, implementing such a radical change of physical space becomes increasingly difficult due to economic and cultural constraints. Furthermore, it is also unlikely to reduce heat vulnerability by changing the urban morphology from high-intensity (e.g., CHR, OHR) to low-intensity (e.g., OMR and OLR) forms, which is rare in planning and construction.

To reduce heat vulnerability, it is necessary to implement optimized regeneration strategies that are tailored to different urban morphologies and causes of heat vulnerability. For example, in CHR space with high land surface temperature and air temperature, population concentration, and sparse vegetation cover, increasing permeable paving, opening up key ventilation nodes, and increasing vertical greening can improve the thermal environment (Hsieh and Huang, 2016; Morakinyo et al., 2019). Additionally, population density should be reduced if possible (Cai et al., 2020). Green roofs and building shadows can improve the thermal environment in CLR space with high land surface temperature, low vegetation cover, and poor economic status of the crowd (Zuo et al., 2022). Moreover, industrial implantation, space revitalization, and other strategies can help to improve the income of the crowd, thus increasing their adaptive capacity to heat waves.

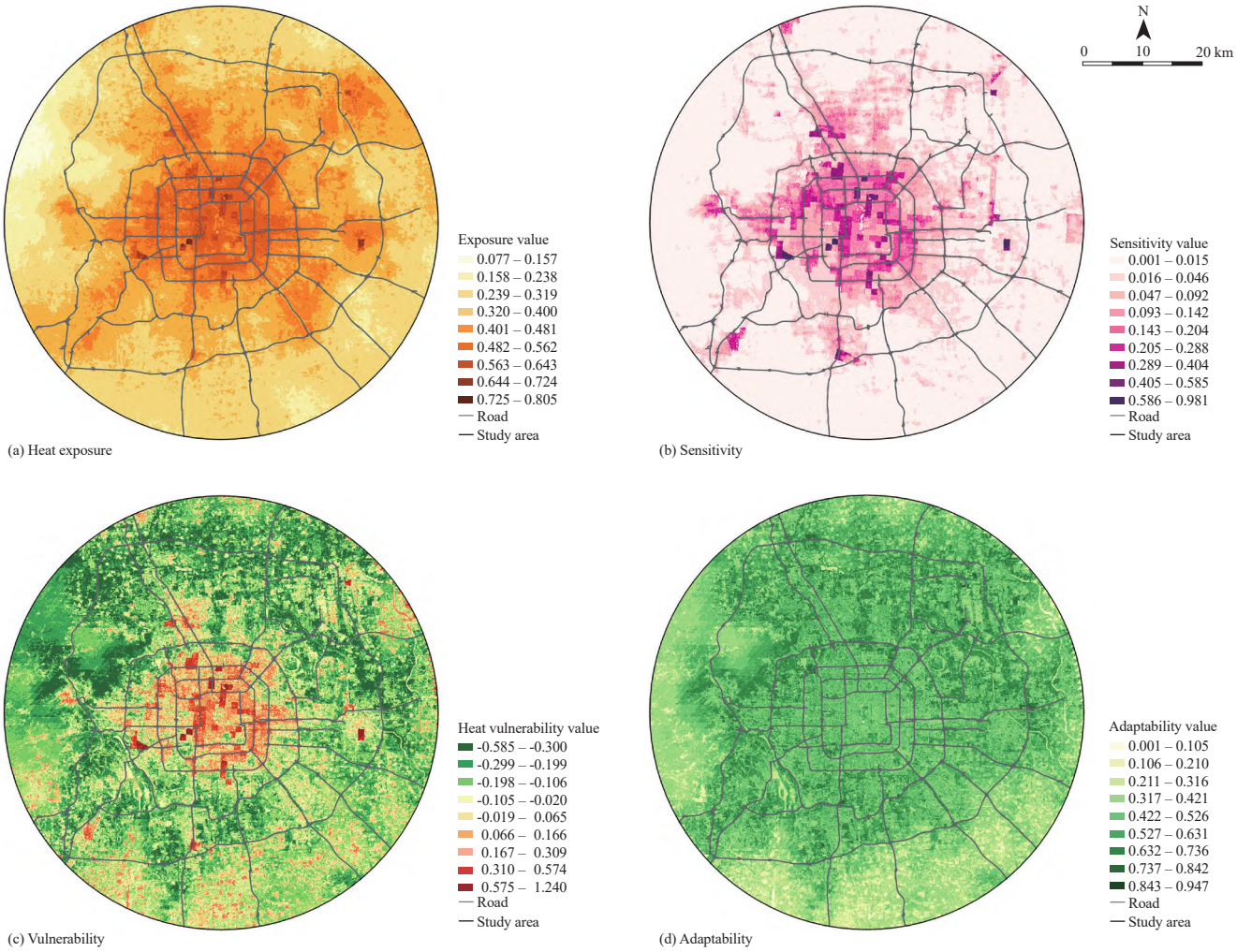


Figure 4 Spatial distribution of heat exposure, sensitivity, vulnerability, and adaptability in summer Beijing

4.2 Enhancement of policy guidance and institutional design

In addition to optimizing physical forms, relevant policy guidance and institutional design can reduce the heat vulnerability of cities. Despite the attention given to the negative impacts of summer heat waves, the relevant policies and institutional frameworks for them are still absent in most cities in China. Recently, some cities have begun developing high-temperature early warning mechanisms and providing heat-relieving products in certain areas. To enhance a city's capacity to cope with high-temperature climate disasters, measures such as formulating special planning, establishing disaster relieving organizations and institutions, forming high-temperature action plans and guidelines, and promoting science knowledge popularization to the public should be taken. For example, New York City in the United States formulated the New York City Hazard Mitigation Plan (Blasio and Bruno, 2014) and constructed a systematic organizational structure involving the plan preparation team, the Hazard Mitigation Planning Council, citizens, and other organizations. Similarly, England has prepared the Heatwave Plan for England, constructed a cascading heatwave warning system and action plans, and also provided specific health guidance and advice to the public, local communities, and others (Williams et al., 2019). Since the Chinese government has considerable power in allocating resources, strengthening relevant policy guidance and institutional design will effectively address climate hazards and heat waves.

5. Conclusions

This paper assesses the spatial distribution and causes of heat

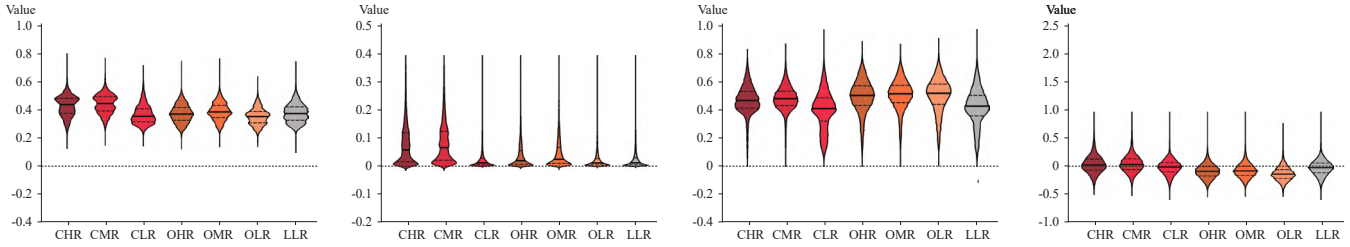


Figure 5 Violin plots of heat exposure, sensitivity, adaptability, and vulnerability for urban morphological regions in built-up classes
Note: Lower dashed, middle bold, and upper dashed lines inside the violin represent 25%, medium, and 75%, respectively.

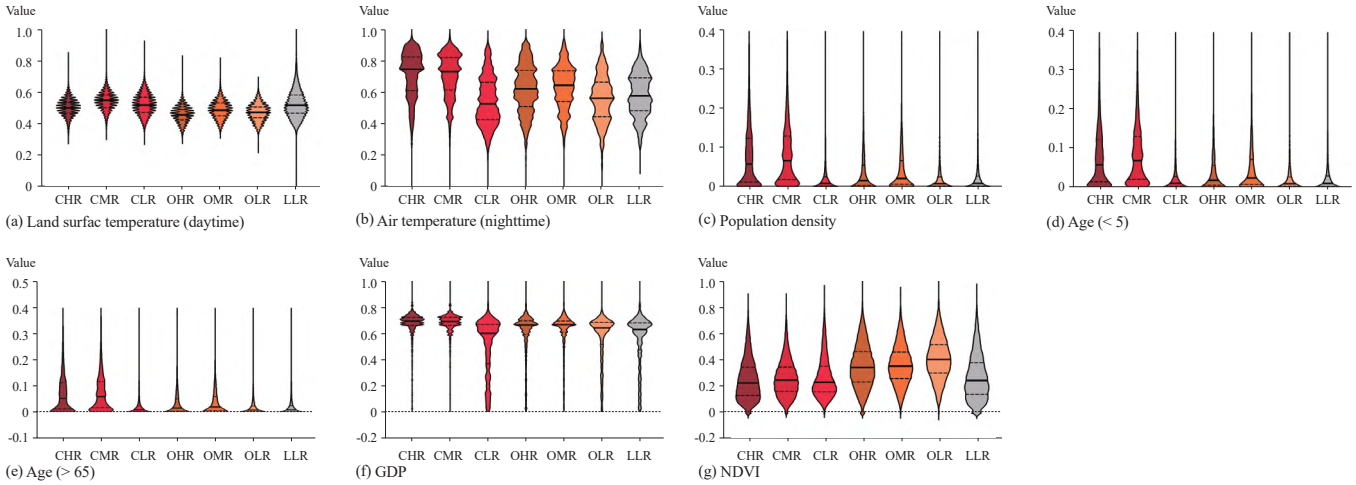


Figure 6 Violin plots distribution with normalized values for each indicator of urban morphological regions in built-up classes

vulnerability in Beijing from the perspective of morphological regions. Results reveal that compact urban morphology classes have higher exposure and sensitivity degrees, while open classes have higher heat adaptability. Temperature, population density, population characteristics, and vegetation cover in different urban morphological regions are the main causes of variation in heat vulnerability. This paper proposes corresponding mitigation strategies in terms of urban morphology optimization and policy guidance. In general, the heat vulnerability assessment and analysis based on urban morphology directly points out the connection between spatial forms and vulnerability, providing a direct reference for relevant planning decision-makers, and avoids the drawbacks of multi-dimensionality and complex indicator system in the vulnerability assessment process. Though limited indicators and a single assessment method were used, this study emphasizes the need for a systematic and comprehensive assessment with multiple indicators and methods in the future.

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References:

Cai Z, Demuzere M, Tang Y, and Wan Y (2022). The Characteristic and Transformation of 3D Urban Morphology in Three Chinese Mega-Cities. *Cities*, 103988.

Cai Z, Tang Y, Chen K, and Han G (2019). Assessing the Heat Vulnerability of Different Local Climate Zones in the Old Areas of a Chinese Megacity. *Sustainability*,11 (7), 2032.

Cai Z, Tang Y, and Zhan Q (2020). Changes of the Thermal Environment Caused by a City-Wide Lockdown: The Case of Wuhan City. *China City Planning Review*, 29 (3), pp. 55-62.

Cai Z, Tang Y, and Zhan Q (2021). A Cooled City? Comparing Human Activity Changes on the Impact of Urban Heat Environment Before and After City-Wide Lockdown. *Building and Environment*, 195, 107729.

Chen K and Tang Y (2019). Identification of Urban Areas Vulnerable to Heat Waves and Coping Strategies: A Case Study of Beijing Central City. *City Planning Review*, 43 (12), pp. 37-44, 77.

Chen X, Zhao H, Li P, and Yin Z (2006). Remote Sensing Image-Based

Analysis of the Relationship Between Urban Heat Island and Land Use / Cover Changes. *Remote Sensing of Environment*, 104 (2), pp. 133-146.

Corburn J (2009). Cities, Climate Change and Urban Heat Island Mitigation: Localising Global Environmental Science. *Urban Studies*, 46 (2), pp. 413-427.

De Blasio B and Bruno J F (2014). *New York City Hazard Mitigation Plan (2014)*. Hazard Mitigation Unit, New York City Office of Emergency Management. 2014.

De Carolis L (2012). The Urban Heat Island Effect in Windsor, ON: An Assessment of Vulnerability and Mitigation Strategies (Report Prepared for the City of Windsor).

Dye C (2008). Health and Urban Living. *Science*, 319 (5864), pp. 766-769.

Elizabeth P (2020). Living with Heat. *Science*, 370 (6518), pp. 778-781.

Fouillet A, Rey G, Laurent F, Pavillon G, Bellec S, Guihenneuc-Jouyaux C, Clavel J, Jougla E, and Hemon D (2006). Excess Mortality Related to the August 2003 Heat Wave in France. *International Archives of Occupational and Environmental Health,* 80 (1), pp.16-24.

Gasparrini A, Armstrong B, Kovats S, and Wilkinson P (2012). The Effect of High Temperatures on Cause-Specific Mortality in England and Wales. *Occup Environ Med*, 69 (1), pp. 56-61.

Hsieh C M and Huang H C (2016). Mitigating Urban Heat Islands: A Method to Identify Potential Wind Corridor for Cooling and Ventilation. *Computers, Environment and Urban Systems,* 57, pp. 130-143.

Huang J, Zhou C, Zhuo Y, Xu L, and Yi J (2016). Outdoor Thermal Environments and Activities in Open Space: An Experiment Study in Humid Subtropical Climates. *Building and Environment*, 103, pp. 238-249.

Inostroza L, Palme M, and De La Barrera F (2016). A Heat Vulnerability Index: Spatial Patterns of Exposure, Sensitivity and Adaptive Capacity for Santiago de Chile. *PLOS One*,11 (9), 0162464.

Jiang Y, Huang J, Shi T, and Wang H (2021). Interaction of Urban Rivers and Green Space Morphology to Mitigate the Urban Heat Island Effect: Case-Based Comparative Analysis. *International Journal of Environmental Research and Public Health*, 18 (21), 11404.

Lai D, Liu W, Gan T, Liu K, and Chen Q (2019). A Review of Mitigating Strategies to Improve the Thermal Environment and Thermal Comfort in Urban Outdoor Spaces. *Science of the Total Environment*, 661, pp. 337-353.

Mallen E, Stone B, and Lanza K (2019). A Methodological Assessment of Extreme Heat Mortality Modeling and Heat Vulnerability Mapping in Dallas, Texas. *Urban Climate*, 30,100528.

Manik T K and Syaukat S (2015). The Impact of Urban Heat Islands: Assessing Vulnerability in Indonesia. *Asian Cities Climate Resilience Working Paper Series*, 13.

Morakinyo T E, Lai A, Lau K K, and Ng E (2019). Thermal Benefits of Vertical Greening in a High-Density City: Case Study of Hong Kong. *Urban Forestry & Urban Greening*, 37, pp. 42-55.

Pörtner H O, Roberts D C, Adams H, Adler C, Aldunce P, Ali E, Begum RA, Betts R, Kerr RB, Biesbroek R, and Birkmann J (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. IPCC Sixth Assessment Report.

Robine J M, Cheung S L K, Le Roy S, Van Oyen B H, Griffiths C C, Michel D J, and Herrmann F R (2008). Death Toll Exceeded 70,000 in Europe During the Summer of 2003. *Comptes Rendus Biologies*, 331 (2), pp. 171-178.

Shen T, Chow D H C, and Darkwa J (2016). Simulating the Influence of Micro-Climatic Design on Mitigating the Urban Heat Island Effect in the Hangzhou Metropolitan Area of China. *International Journal of Low-Carbon Technologies*, 11 (1), pp. 130-139. Available at <http://dx.doi.org/10.1093/ijlct/ctt050>.

Stewart I D and Oke T R (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society*, 93 (12), pp. 1879-1900.

Sun Y, Li Y, Ma R, Gao C, and Wu Y (2022). Mapping Urban Socio-Economic Vulnerability Related to Heat Risk: A Grid-Based Assessment Framework by Combing the Geospatial Big Data. *Urban Climate*, 43, 101169.

Van der Hoeven F and Wandl A (2015). Amsterwarm: Mapping the Landuse, Health and Energy-Efficiency Implications of the Amsterdam Urban Heat Island. *Building Services Engineering Research and Technology*, 36 (1), pp. 67-88.

Vardoulakis S, Dimitroulopoulou C, Thornes J, Lai K, Tylor J, Myers I, Heaviside C, Mavrogianni A, Shrubsole C, Chalabi Z, and Davies M (2015). Impact of Climate Change on the Domestic Indoor Environment and Associated Health Risks in the UK. *Environment International*, 85, pp. 299-313.

Williams L, Erens B, Ettelt S, Hajat S, Manacorda T, and Mays N (2019). Evaluation of the Heatwave Plan for England. Policy Innovation and Evaluation Research Unit: London, UK.

Wolf T and McGregor G (2013). The Development of a Heat Wave Vulnerability Index for London, United Kingdom. *Weather and Climate Extremes*, 1, pp. 59-68.

Xie P, Wang Y L, Peng J, and Liu Y (2015). Health Related Urban Heat Wave Vulnerability Assessment: Research Progress and Framework. *Progress in Geography*, 34 (2) , pp. 165-174.

Yang J, Wang Y, Xiu C, Xiao X, Xia J, and Jin C (2020). Optimizing Local Climate Zones to Mitigate Urban Heat Island Effect in Human Settlements. *Journal of Cleaner Production*, 275, 123767.

Yuan Y, Li C, Geng X, Yu Z, Fan Z, and Wang X (2022). Natural-Anthropogenic Environment Interactively Causes the Surface Urban Heat Island Intensity Variations in Global Climate Zones. *Environment International*, 107574.

Zhao Q, Guo Y, Ye T, Gasparrini A, Tong S, Overcenco A, Urban A, Schneider A, Entezari A, Vicedo-Cabrera A M, and Zanobetti A (2021). Global, Regional, and National Burden of Mortality Associated with Non-Optimal Ambient Temperatures from 2000 to 2019: A Three-Stage Modelling Study. *The Lancet Planetary Health*, 5 (7), pp. 415-425.

Zuo J, Ma J, Lin T, Dong J, Lin M, and Luo J (2022). Quantitative Valuation of Green Roofs' Cooling Effects Under Different Urban Spatial Forms in High-Density Urban Areas. *Building and Environment*, 222, 109367.

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