How Urban Morphology Affects Wind-Heat Environment: An Example in Beijing from Ancient Cities to Modern Cities

Jiankun Lou[1], Lan Wang[1], Jiayu Li[1], Yinghui Jia[1]
1 Tongji University, College of Architecture and Urban Planning
loujiankun@tongji.edu.cn

Abstract
The urban wind-heat environment is a critical component affecting residents' health. This research investigates the impact of urban morphology on the heat and wind environment, focusing on three distinct residential blocks in Beijing's Nanluoguxiang Historic District. The three neighborhoods represent ancient, modern, and a mix of historical and modern urban forms. The ENVI-met was utilized to simulate wind speeds and temperatures for ancient times (1880) and modern times (2023). The results reveal that traditional urban forms with compact buildings and courtyards create more moderate wind and heat conditions. Modern urban forms with high-rise buildings and open spaces result in higher wind speeds and temperatures. The findings highlight the importance of preserving traditional urban layouts for comfortable microclimates.

Keywords: Urban microclimate, Urban design, Historic district, Numerical simulation, China

1 Introduction

Climate change has stood as one of the most formidable global challenges, with far-reaching implications for the environment and human societies. This challenge pertains to urban areas, where most of the world's population resides. The urban wind-heat environment, an integral component of the urban climate system, profoundly influences city residents' health and well-being. The morphology of modern cities often plays a crucial role in the urban wind-heat environment. Research has shown that urban morphology, including building layout and street design, can either facilitate or obstruct natural ventilation, with implications for heat dissipation and air quality management (Yuan *et al.*, 2014; Tsichritzis and Nikolopoulou, 2019; Palusci *et al.*, 2022). The concept of urban morphology has also been extensively studied in the context of the heat environment. The increase in global average temperatures has intensified the urban heat island effect, resulting in significantly higher temperatures in city centers than in suburban areas (Zhao *et al.*, 2011; Zhang *et al.*, 2022; Wu *et al.*, 2022). Numerous studies have delved into the role of building height, street orientation, and density in modifying urban temperatures (Johansson, 2006; Apreda *et al.*, 2020). This elevates the risk of residents experiencing heat stress and heat-related illnesses such as heatstroke, dehydration, and cardiac arrest. Therefore, improving the urban wind-heat environment is increasingly receiving attention from scholars and city administrators. However, most of these studies have been conducted within the context of modern cities. The research of microclimates in ancient cities or historical urban areas can assist in urban construction in two key respects. Firstly, it aids in enhancing the understanding of the microclimate within traditional urban form districts in modern cities, thereby safeguarding the health of residents. Secondly, it offers references and support for the climate adaptability design of future cities.

The harmonious coexistence of ancient cities with the natural environment contrasts sharply with the modern approach of reshaping the natural environment through planning, reflecting different philosophies and methods of human adaptation to and transformation of the environment (Shi and Zhao, 2022). The study of ancient urban forms provides traditional architecture, and planning often includes elements that enhance natural cooling and ventilation (Yang *et al.*, 2022). Indraganti's (2010) research on Indian settlements also emphasized the strategic use of layout, street design, and materials for climate adaptation, noting the effectiveness of centralized, narrow streets in xerothermic conditions. Dili *et al*. (2010) analyze the passive environment control systems inherent in Kerala's vernacular architecture, demonstrating how traditional design principles effectively address the region's warm-humid climate. Arrar *et al*. (2022) investigated the outdoor thermal comfort levels in the historical urban fabric of Algiers Casbah, which informs urban design strategies to mitigate heat stress in traditional city settings. These findings suggest critical insights into sustainable design principles, particularly in their adaptive response to climate. The research of these ancient urban forms can inform modern urban planning and design practices, particularly in the context of climate change adaptation. The design of traditional Chinese cities often reflects a profound understanding of the local climate. Research on the renovation of traditional blocks guided by wind-heat environment simulations is also gradually emerging in China (Liu et al., 2022; Xiong et al., 2023; Zheng and Wang, 2019). However, given the vast territory of China and the complexity of various traditional blocks, fundamental research on the microclimate of different urban blocks is still relatively weak.

Historical blocks, characterized by a concentration of cultural relics and landmarks, or those broadly reflecting the traditional style and ethnic local features of a particular historical period, are integral to the urban fabric. In northern China, the morphology of historical blocks often evolves from the traditional Chinese courtyard, with building heights typically ranging from one to three stories. These structures generally incorporate construction techniques tailored to address the local climate conditions (Jin *et al.*, 2018). These areas, designed in response to the social context and climate of their time, offer urban residents natural, safe, comfortable, and pleasant spatial environments, thereby contributing significantly to urban construction, the preservation and enhancement of urban history and culture, and the quality of life for city dwellers. Therefore, this study selects the Nanluoguxiang Historic District in Beijing, China, which includes an area representative of ancient cities, a modern urban area, and an area that integrates ancient and modern elements, each representing different periods of urban development, and aims to address these gaps by examining the relationship between urban morphology and the wind-heat environment across different temporal scales, from ancient to modern cities. Through a series of simulations by ENVI-met under various climatic conditions, the research aims to analyze the differences and advantages and disadvantages of the three urban form types in terms of the wind-heat environment, providing insights and inspiration for the construction of climate-adaptive cities and the preservation and development of historic districts.

2 Methodology

2.1 Study Sites

China's urban construction boasts a long history, extensive distribution, and a multitude of cities, making it an excellent subject for studying ancient human settlements. The forms of ancient Chinese cities evolved under various historical, geographical, cultural, and economic conditions, reflecting the ways and characteristics of how ancient Chinese people organized and utilized urban space, as well as the extent and manner in which they met the needs of social life. With its long history, Beijing is among the first batch of China's national historical and cultural cities and holds immense research value. Beijing Old City (39°28′ ~41°50′ N, 96,115°25′ ~117°30′ E), located in the center of Beijing. It has been developed for 3000 years and has been the capital city for 800 years. The Old City represents the unique scenery of traditional Beijing, featuring Siheyuans (courtyards with buildings on four sides) and Hutongs (lanes between Siheyuans). Beijing is rich in research materials, with a wealth of historical maps, documentary records, and numerous cultural heritages and historical blocks, making it feasible for research.

The Nanluoguxiang Historic District, the focus of this study, is situated in the northeastern part of the Beijing Old City, covering an area of 0.84 km^2. It was established during the same period as the Yuan Dadu(the name of Beijing in the Yuan Dynasty) and has a history of over 740 years. During the Ming and Qing dynasties, it was an upscale residential area for officials and gentry, and in modern times, it became a cluster of former residences of notable figures. In 1990, it was designated as one of Beijing's first historical and cultural protection areas. It is the only area that has preserved the Yuan Dynasty's "Li Fang System" of alleys and is the largest, most prestigious, and most resource-rich traditional residential area within the Yuan Dadu site (Fig.1). In 2016, the Design Guide for the Preservation and Renewal of Nanluoguxiang Historic and Cultural District was implemented, and the residential function began to be restored.

For this study, three sites within the Nanluoguxiang Historic District were selected as experimental sites. All three sites are located in the core area of the Historic District, on Mao'er Hutong, and are predominantly residential in function (Fig.1, 2). Site A is the courtyard at No. 5 Mao'er Hutong and the surrounding area of Ke Garden, representative of ancient cities. They are critical national and Beijing's cultural relics, preserving many historical features. Site B is the "Old Residence" and its surrounding area, which includes cultural relics, general traditional buildings, and many modern buildings constructed later that are in harmony with the traditional style. It represents the basic situation of a larger area of the Nanluoguxiang Historic District and is also the essential condition of many historical blocks in China. Site C is the courtyard at No. 45 Mao'er Hutong, located on the westernmost side of the Historic District. This group of residential buildings, constructed after the 1980s and approximately six stories high, is consistent with the large-scale commodity housing communities built in China in the last century, representing a modern urban area.

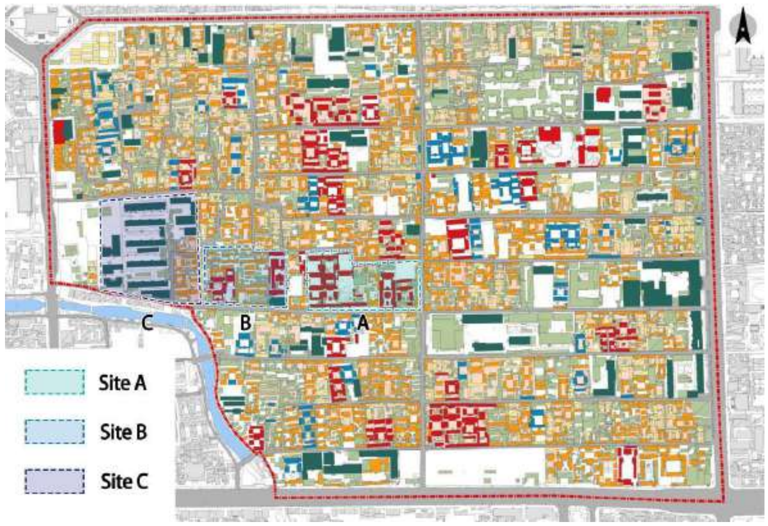


Fig.1 Experimental sites selection

a. Site A b. Site B c. Site C

Fig.2 Computational models

2.2 Numerical Simulation

Beijing experiences a monsoon-influenced humid continental climate, marked by hot and humid summers and generally cold, windy, and dry winters. As the capital city for both the Ming and Qing dynasties, Beijing has an extensive record of climate observations. From the first year (1875) to the fifth year (1880) of the Guangxu period, the Russian Church, located at the northeast corner of Beijing city, used meteorological instruments calibrated by the Central Observatory of St. Petersburg to measure meteorological data, resulting in the average monthly meteorological data for Beijing during the first to fifth years of the Guangxu era (Zhu, 1936). This data is consistent with the recent collection and organization of historical documentary records of warm and cold temperatures, which indicate that since the Yuan Dynasty, the eastern region of China has essentially been in a cold period, with a temperature difference of approximately 1-2°C compared to the present (Fig.3) (Ge *et al*., 2002). Intensive urbanization during recent decades has dramatically modified the urban heat environment (Yan *et al*., 2010).

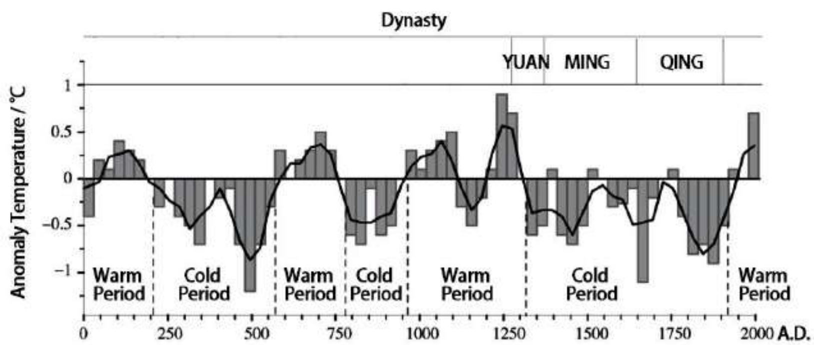


Fig.3 The sequence of average temperature changes in the winter half-year over the past 2000 years in the eastern region of China (Ge *et al*., 2002)

The simulation analysis software adopts the ENVI-met. It can simulate the energy, momentum, and material exchange processes between buildings, the ground, vegetation, and the atmosphere in small-scale urban spaces with the function of calculating the wind field, turbulence, radiation, air temperature, and humidity, which is based on the related theories of fluid mechanics, thermodynamics, and urban meteorology. ENVI-met has been widely used in urban microclimate research in different regions of the world (Andreou and Axarli, 2012; Ng *et al.*, 2012).

The ENVI-met numerical simulation encompasses two fundamental steps: constructing the computational model and setting parameters. The computational domain for Sites A and B is 100m×200m, while for Site C is 200m×200m, with a grid resolution of 4m. The computational model for the study area is constructed based on the building outlines within the modeling range (data sourced from Baidu Maps Open Platform at https://lbsyun.baidu.com), delineating elements such as buildings, underlying surfaces, and vegetation (Fig.4). The parameter settings for the data are primarily derived from the measurement data during the Guangxu period (1880). The observational data from the meteorological station (2023) (Tab.1). Site A, representative of ancient cities, underwent simulation for the year 1880. Site C, representative of modern cities, was simulated for 2023. Meanwhile, Site B was subjected to simulations under both meteorological conditions.

Tab.1 Wind-heat environment parameter settings

	Parameter setting 1880	Parameter setting 2023
Wind speed (m/s)	1.20	1.94
Average Air Temperature (°C)	26.9	28.5
Air Temperature at 14:00 (°C)	33.2	35

Humidity (%)	72	60

3.3 Data Analysis

The study simulated the variations in the wind-heat environment throughout the hottest day of the year in Beijing, July 30th, focusing on the pedestrian-level (1.4m above ground) wind speed, temperature, and relative humidity at different time points of a typical meteorological day. For this paper, the numerical simulation maps of the wind-heat environment at the peak heat of the day, 14:00, were selected for detailed analysis. The simulation results were analyzed to compare the wind and heat conditions across the three study sites.

4 Results

4.1 Wind Environment

Representing the ancient cityscape, Site A's simulation for the year 1880 reveals an average wind speed of 0.57 m/s, which is a significant deviation from the parameter wind speed of 1.20 m/s, indicating a -52.83% difference (Tab.2). The maximum wind speed recorded was 1.12 m/s, which also saw a decrease, dropping by 0.08 m/s. That is to say, the wind speed in all areas of Site A was less than the ambient wind speed.

Site B, which includes both cultural relics and modern buildings, was simulated under two different sets of meteorological conditions, allowing for a temporal comparison. In 1880, the average wind speed was 0.56 m/s, with a deviation of -53.75% from the parameter. By 2023, the average wind speed slightly increased to 0.82 m/s, a deviation of -58.00%. The comparison between the two time periods suggests that the overall impact on pedestrian-level wind conditions remains moderate. Among them, the simulation for the year 1880 showed no particularly significant difference compared to Site A. However, the simulation for the year 2023 exhibited the greatest proportionate decrease in wind speed among the four simulations.

As a representative of a modern urban area, Site C's simulation for the year 2023 shows the highest average wind speed among the three sites at 1.01 m/s, which is the greatest of all simulations. Among the four simulations, Site C's wind speed deviation from the parameter is the smallest, at only -15.83%. At the same time, the maximum wind speed was recorded at 3.37 m/s, which is significantly higher than the ambient wind speed and also the highest among all simulations. Compared to Site B's simulation for the year 2023, Site C's average, maximum, and median wind speeds are all considerably higher.

Tab.2 Simulation results of the wind environment

	Site A (1880)	Site B (1880)	Site B (2023)	Site C (2023)
Wind Speed Parameter(m/s)	1.20	1.20	1.94	1.94
Average	0.57	0.56	0.82	1.01

Wind speed (m/s)				
Deviation from the Parameter (m/s)	-0.63	-0.65	-1.13	-0.19
Deviation from the Parameter (%)	-52.83	-53.75	-58.00	-15.83
Maximum (m/s)	1.12	1.40	2.15	3.37
Minimum (m/s)	0.00	0.00	0.00	0.00
Median (m/s)	0.64	0.59	0.84	1.11

4.2 Heat Environment

The simulation results for Site A in the year 1880 indicate an average air temperature of 32.22°C, which is slightly below the parameter setting of 33.2°C, showing a deviation of -0.99°C or -2.97% (Tab.3). This change represents the only instance of a temperature decrease among all simulations. The maximum temperature recorded was 35.58°C, the minimum was 30.74°C, and the median temperature was 32.18°C.

For Site B, the comparison between the simulations of 1880 and 2023 reveals a gradual increase in the average air temperature. In 1880, the average temperature was 33.26°C, with a deviation of 0.06°C or 0.19% from the parameter. By 2023, the average temperature rose to 35.10°C, a deviation of 0.10°C or 0.28%. The difference between the simulations of the two meteorological conditions is not significant. Among them, the simulation for the year 1880 showed a distinct difference compared to Site A. The average value increased by 1.04°C, and the difference from the ambient temperature changed from negative to positive. Site B's highest temperature was 35.71°C, 0.13°C higher than Site C. Meanwhile, Site B's lowest temperature was 32.10°C, 1.36°C higher than Site C's. Regarding the median, Site B was 1.07°C higher than Site C.

Representing the modern urban context, Site C's simulation for 2023 shows the highest average air temperature among the sites at 35.33°C, with a deviation of 0.33°C or 0.94% from the parameter. This site represents the most significant increment among the three simulations with increasing temperatures. The maximum temperature reached 38.79°C, a 3.79°C increase from the ambient temperature. The median was 35.21°C, a 0.21°C increase from the ambient temperature, indicating that most of the area's temperatures are above the ambient temperature. Compared to Site B's simulation for the year 2023, Site C's average, maximum, and median temperatures are all significantly higher. However, Site C's minimum temperature, which was 33.41°C, is lower than the minimum value of Site B's 2023 simulation, which was 33.91°C.

Tab.3 Simulation results of the heat environment

	Site A (1880)	Site B (1880)	Site B (2023)	Site C (2023)
Air Temperature Parameter at 14:00(m/s)	33.20	33.20	35.00	35.00
Average	32.22	33.26	35.10	35.33

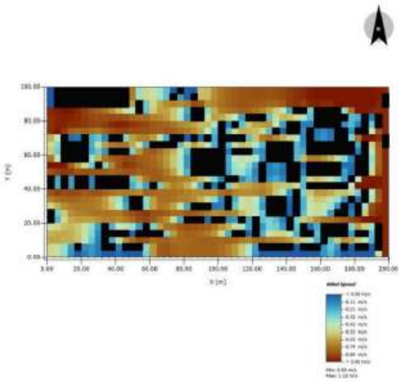
Air Temperature (℃)				
Deviation from the Parameter (℃)	-0.99	0.06	0.10	0.33
Deviation from the Parameter (%)	-2.97	0.19	0.28	0.94
Maximum (℃)	35.58	35.71	37.43	38.79
Minimum(℃)	30.74	32.10	33.91	33.41
Median(℃)	32.18	33.25	35.08	35.21

4.3 Comparison of Urban Morphologies

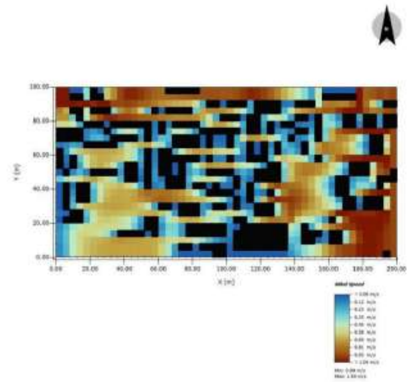
Site A represents the ancient city form, characterized by traditional courtyards (Siheyuans) and narrow lanes (Hutongs). This area is rich in cultural relics and historical features, providing a unique landscape preserved over time. The simulation results for Site A in 1880 indicate that the wind environment is influenced by the compact arrangement of buildings and the narrow streets (Fig.4a). The maximum wind speed is observed in the open courtyard areas, where the flow is less obstructed. Conversely, the minimum wind speed occurs in the confined spaces between buildings, where the flow is restricted and turbulence increases. The heat environment of Site A is moderated by a dense network of courtyards and Hutongs (Fig.5a). The extensive greenery within the courtyards played a significant role, providing shade and promoting natural ventilation. The lowest temperatures are observed in the shaded areas under the plants within the courtyards. The highest temperatures occur in the courtyards without plants that are directly exposed to sunlight. There is no significant difference between the south and north of the buildings.

Site B encompasses a mix of cultural relics, traditional structures, and modern constructions harmoniously integrated with the traditional style. This site represents the evolution of urban form over time, reflecting both historical preservation and modern development (Fig.4b, c). Similar to Site A, Site B shows a wind environment influenced by the traditional urban layout. The maximum wind speed is recorded in the open areas, while the minimum is found in the narrow passages between buildings. Similarly, Site B's air temperature is akin to Site A. Courtyards filled with vegetation offer better cooling effects. In contrast, enclosed courtyards without plants experience the highest temperatures (Fig.5b, c).

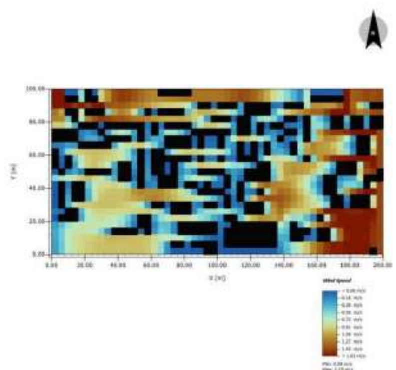
Site C represents the modern urban form, characterized by high-rise residential buildings and large-scale housing communities. This area resembles the urban development patterns seen in many contemporary Chinese cities. The simulation for Site C in 2023 shows that the wind environment is significantly different from the traditional forms (Fig.4d). The taller and more widely spaced buildings result in larger open areas with higher wind speeds. The wind speed at the edges of high-rise buildings is higher than the lowest at the edges of buildings, as in Sites A and B. The minimum wind speed for Site C is found within the central open spaces where the flow is more turbulent than elsewhere. The highest temperature at Site C occurs on the south side of the high-rise buildings, even though some plants are present (Fig.5d). The temperature on the north side of the buildings is comparatively lower. The lowest temperature is found in the courtyard enclosed by several buildings at the northeast corner. This courtyard is surrounded by three buildings, with some plants in the middle.



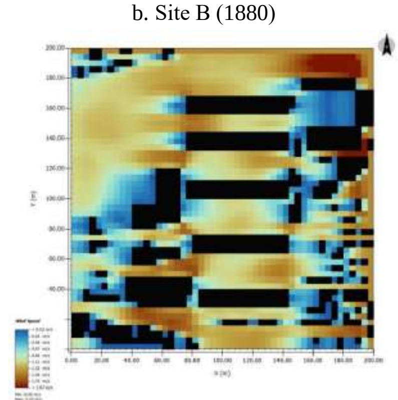
a. Site A (1880)



b. Site B (1880)

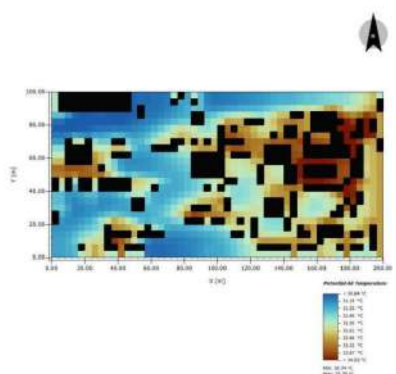


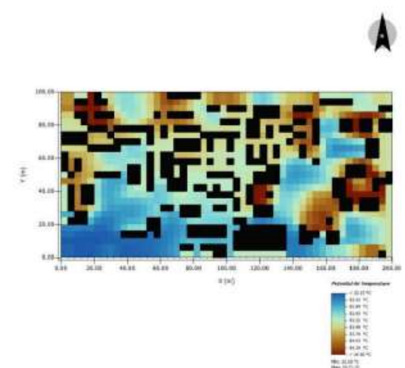
c. Site B (2023)



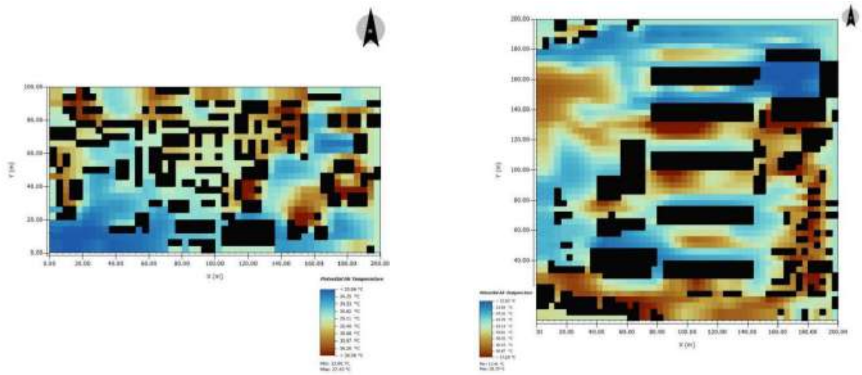
d. Site C (2023)

Fig.4 Diagrams of simulation results of the wind environment





a. Site A (1880) b. Site B (1880)



c. Site B (2023) d. Site C (2023)

Fig.5 Diagram of simulation results of the heat environment

5 Discussion

5.1 Urban Morphology and Wind Environment

Urban morphology profoundly influences the wind environment at the pedestrian level. The study's findings from the three sites in Beijing reveal that traditional urban forms, characterized by low-rise buildings and narrow streets, tend to create a more sheltered microclimate with reduced wind speeds. This is particularly evident in Site A, which represents the ancient city form, where the compact arrangement of buildings and the presence of courtyards and narrow lanes act as a buffer against the wind, resulting in a more moderate wind environment.

However, the modern urban form, exemplified by Site C, presents a different scenario. The taller and more widely spaced buildings in the modern urban area create larger open areas prone to higher wind speeds. While increased wind speeds can enhance natural ventilation and dissipate heat, they can also lead to discomfort and potential safety hazards, such as the risk of blown debris or difficulties walking against strong winds.

The transition from the traditional to the modern urban form, as seen in the evolution of Site B from 1880 to 2023, highlights the impact of urban development on the wind environment. The modernization process, marked by the construction of taller buildings and wider streets, has increased wind speeds at the pedestrian level (Kubota *et al*., 2008). This shift underscores the need for urban planners to consider the wind environment implications when designing modern cityscapes, ensuring that the benefits of increased ventilation are balanced against the potential discomfort and safety concerns associated with higher wind speeds (Yang *et al.*, 2013).

5.2 Urban Morphology and Heat Environment

The heat environment analysis in this study offers a perspective on how urban morphology can shape the thermal conditions experienced by city residents. In the traditional urban form, such as that represented by Site A, the compact building arrangement and the presence of courtyards and narrow streets contribute to a cooler microclimate (Nasrollahi *et al.*, 2017). The courtyards, often filled with vegetation, provide shade and promote natural ventilation, which can help to reduce the urban heat island effect (Su *et al.*, 2022). The dense network of courtyards and Hutongs in Site A creates shaded areas cooler than the surrounding environment, providing thermal comfort during the hot summer months. From 1880 to 2023, the rise in temperature at Site B was mainly due to the increase in ambient temperature. This change reminds us to pay attention to the new requirements for urban form design posed by global warming (Tringa and Tolika, 2023).

As seen in Site C, the modern urban form presents a different set of challenges. Taller buildings require greater distances between them, leading to larger open spaces and a more distant relationship between the buildings and the vegetation. These morphological characteristics can exacerbate the urban heat island effect. The simulation results for Site C indicate the highest average air temperature among the sites, highlighting the potential for increased heat stress on residents and the need for effective strategies to mitigate this impact.

5.3 Limitations and Future Research

While the study offers valuable contributions to the field, it has limitations. The simulations, though based on detailed urban models and climate data, represent a controlled environment and may only partially capture the dynamic nature of real-world urban spaces. Future research could enhance the accuracy of these findings by incorporating real-time meteorological data and conducting field measurements to validate the simulation results. Additionally, the vegetation modeling in this simulation is not sufficiently detailed, and there may be considerable variations in the plants over time, which is also a limitation.

Additionally, the study focused on a limited number of urban districts in Beijing, which may only represent some urban environments. Expanding the scope to include a diverse range of cities worldwide and climates would provide a more comprehensive understanding of the relationship between urban morphology and the wind-heat environment. In particular, there should be more exploration of the relationship between ancient urban forms and meteorological conditions. Urban form can not only be based on existing historical districts with characteristic features but also modeled according to records from historical maps to further investigate the interplay between urban form and other environmental factors of the microclimate, such as air quality and noise pollution.

6 Conclusion

Understanding the relationship between urban morphology and the wind-heat environment is crucial for creating urban spaces that are comfortable and sustainable. This study's comparative analysis of urban morphologies within Beijing's Nanluoguxiang Historic District reveals that traditional forms, characterized by compact buildings and courtyards, foster more moderate wind and heat environments. In contrast, the modern urban form exhibits higher wind speeds and temperatures, potentially intensifying the urban heat island effect. The comparison of urban morphologies across the three sites reveals the complex interplay between architectural form, urban layout, and microclimatic conditions. It emphasizes the need for a balanced approach to urban planning that respects historical contexts while addressing contemporary environmental challenges. The findings underscore the importance of preserving traditional urban layouts for comfortable microclimates and suggest that urban planning must adapt to mitigate the impacts of modernization and global warming on urban thermal comfort.

A balanced approach to urban form design is essential, one that respects historical contexts while addressing contemporary environmental challenges. On one hand, attention should be paid to the adaptability of historical blocks to the contemporary climate. The current protection of historical blocks often needs more consideration of the microclimate environment, with related regulations and standards having broad indicators. It is necessary to refine these standards to protect historical blocks from extreme climate damage and provide residents with a climate-appropriate place. On the other hand, the climate adaptability design of new buildings should be emphasized. The experiences and lessons from ancient cities' architectural styles and planning principles can be utilized to adapt the urban form to climatic conditions effectively. For instance, controlling the building heights in residential areas and enhancing the integration of architecture with vegetation can be adopted.

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