Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/122/2025.19604

The Relationship Between Urban Morphology and the Urban Heat Island Effect: A Study of Cooling Strategies in Urbanized Areas

Yixi Kong[1,a,*]

[1]*Politecnico di Milano, Milan, Italy*
a. yixi.kong@outlook.com
**corresponding author*

Abstract: With more and more cities experiencing urbanisation, the issue of Urban Heat Island (UHI) effects has become a concern in urban areas worldwide. This paper evaluates the impact of urban morphology, particularly urban expansion and densification, on the UHI effect, and examines the trajectory of UHI in Chinese cities. The 2D Layout BCR (Building Coverage Ratio) model shows that horizontal expansion tending to increase impervious surfaces, and the increased proportion of impervious surfaces will lead to more heat retention, while the physical air barrier in densely built environments can worsen the UHI effect by obstructing the natural ventilation of air. The longitudinal data of urban planning variables of Beijing, Shanghai, Guangzhou and Shenzhen showed that expansion and densification had a long-term trend in recent decades, and the increase of night-time temperature had a positive correlation with expansion rate and building intensity. Through the analysis of urban characteristics and the discussion of heat mitigation measures, this paper emphasises the role of proactive urban planning in balancing urban expansion and cooling needs, and the importance of the cooling strategy embedded in the urban form. Heat mitigation measures, especially greening, reflective roofs and district cooling systems, can offset the UHI effect to some extent.

Keywords: Urban Heat Island, Urban Morphology, Densification, Expansion, Cooling Strategies.

1. Introduction

Through the turn of the 21st century, the world has witnessed the most dramatic urbanization process than ever in history, with the newly formed cities and the rejuvenation of old ones. The most astonishing growth of the cities happened in the developing world, especially in Asia, posing significant challenges and opportunities for the global urban environment. The outspread of urban sprawl and city's built-up areas growing vertically are the two main urban forms for the unprecedented pace of urbanization. These two urban forms have led to the Urban Heat Island (UHI) effect, the famous residential temperature anomaly in the city, which is higher than its surrounding rural area by many degrees. The primary reason is that, with the expansion and densification trend of cities, more natural landscapes have been replaced with impervious surfaces such as concrete, asphalt and steel, which tend to absorb the solar energy and retain heat in the urban atmosphere, resulting in

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/122/2025.19604

a higher daytime and nighttime ambient temperature in an urban area. In recent years, the UHI effect has gradually drawn the attention of urban researchers, as the temperature rise in the city implicates higher energy consumption and carbon emissions, entailing more health risks and spoiled living environments. The fast growth of cities, be it in urban expansion or urban densification, also means that the ratio of built-up area to total land area, the 2D Layout BCR model, has become more imbalanced towards built-up area, signaling a weaker ability for a city to disperse the heat accumulation [1]. This paper will specifically investigate how the two urban morphological forms, urban expansion and urban densification, will influence the intensity of urban heat island effect when a given city is growing. The case studies will be placed in China, especially four big cities, Beijing, Shanghai, Guangzhou and Shenzhen.

2. Urban Expansion and the UHI Effect

Horizontal expansion of cities is the more common form of urbanisation, in which a city covers more and more peripheral rural areas with reduced areas of natural land cover and increased impervious surfaces (roads, buildings and parking lots). The expansion index, which represents the volume of outward city growth in China, correlates positively with the UHI effect – sprawling cities have more areas exposed to solar radiation and less vegetation to absorb it and become natural coolers.

2.1. Impact of 2D Layout on Urban Expansion

The 2D layout BCR (Building Coverage Ratio) model is an effective tool for analyzing the spatial configuration of urban expansion. By mapping the ratio of buillt-up areas to the total land area, this model highlights how urban layouts contribute to heat accumulation. The formula for BCR is

$$BCR = \frac{A_{built\text{-}up}}{A_{total}} \quad (1)$$

where $A_{built-up}$ represents the total built-up area, such as buildings and impervious surfaces, and A_{total} is the total land area under consideration. A larger BCR means that more of that land area is covered by built-up surfaces, which absorb more solar radiation and provide less natural cooling. Low-density sprawling cities, with a large amount of land covered, but low-rise buildings, reduce the landscape's capacity for shading and natural cooling through green space. Wider dispersion of buildings increases the amount of land area exposed to solar radiation, which leads to more heat being absorbed by these surfaces during the day. The lack of green spaces and shading means that surfaces such as concrete and asphalt in these expanded areas will retain the heat and then re-emit it at night, which keeps high temperatures during the night [2].

This further exacerbates the UHI effect, especially in sprawling cities with a high index of expansion and high BCR values, where rapid horizontal growth leads to a lack of integrated planning and spatial control over the cooling of the city. In these contexts, large-scale cooling systems and green cover are particularly difficult to implement, especially once the urban fabric is consolidated. As a consequence, urban morphologies with a high BCR tend to experience permanent increases in temperature and reduced liveability due to the additive effect of the retention capacity of impervious areas.

2.2. Cooling Strategies for Expanding Cities

While urban expansion does contribute to the UHI effect, mitigation strategies can be employed through careful planning. Increasing green infrastructure – such as parks, tree-lined streets and urban forests – can significantly reduce surface temperatures due to evapotranspiration-induced cooling of the surrounding air. Due to the critical importance of green infrastructure in the built environment, it must be planned for early in the development process. For example, large parks in the centre of

DOI: 10.54254/2755-2721/122/2025.19604

expanding districts could create a cooling core with positive impacts extending into the surrounding areas. Water features, such as artificial lakes and ponds, too, can improve evaporative cooling and benefit temperature reductions. These cooling strategies, which focus on maximising green areas and water bodies, can significantly improve the aesthetics and livability of expanding urban areas. In addition to green areas, reducing the absorption of solar radiation is also a potential mitigation strategy. By using materials with high solar reflectivity in roadways and building exteriors, solar radiation absorbed on the ground or by building walls and roofs can be minimised, limiting the amount of heat that is 'trapped' by the urban fabric [3].

2.3. Longitudinal Analysis of Urban Expansion in China

A longitudinal study of urban expansion in Chinese cities in recent decades can shed light on the evolving relationship between city growth and the UHI effect. For instance, looking at the past 40 years of development for some of the largest Chinese cities such as Beijing, Shanghai and Guangzhou, we can see that their horizontal growth has been very intensive and this has led to a high increase in the proportion of impervious surfaces and, as a result, in the UHI effect. Table 1 depicts the time changes in the urban form for a selection of Chinese cities and we can see that cities which have a high expansion index show a lot more bumping up in night-time temperatures in the urban cores compared with the rural areas around the cities.Lately, some urban expansion policies have been developed to slow down the uncontrolled expansion, for example the compact city development and the green belt planning [4]. Cities that have been successful in this regard, for example Shenzhen, show lower investigation outcomes in temperature comparison with the 2D layout BCR model. This type of analysis can be helpful to demonstrate that a proactive approach to urban planning is key in mitigating the thermal impact of city expansion.

Table 1: Longitudinal Analysis of Urban Expansion in Major Chinese Cities

City	Year 2000 BCR	Year 2010 BCR	Year 2020 BCR	Expansion Index (%)	Average Night-time Temp Increase (°C)	Green Space Integration Score (out of 10)
Beijing	0.35	0.42	0.47	34	2.3	6
Shanghai	0.38	0.45	0.5	31	2.1	5
Guangzhou	0.33	0.4	0.45	36	2.4	4
Shenzhen	0.28	0.35	0.39	25	1.7	8

3. Urban Densification and the UHI Effect

Urban densification implies increasing building coverage within the existing urban footprint by building upwards and compactly. Densification can reduce the spread of impervious surfaces over a large area, but can also contribute to worsening of the UHI effect by concentrating buildings in high-density built-up areas, reducing ventilation. In China, the density index (a measure of increase in building density) has been associated with rising temperature, especially in densely built-up areas with concrete and steel dominating the built environment.

3.1. Impact of Densification on Thermal Regulation

2D layout BCR model showing increased building coverage and the reduced space between buildings in dense urban environments.The higher building coverage and reduced inter-building distances in dense urban environments reduce the airflow, thereby increasing the thermal retention in the urban canopy layer. It also increases the energy imbalance through the reduction of wind speeds that would

DOI: 10.54254/2755-2721/122/2025.19604

evaporate or dissipate the accumulated urban heat. The densification index of cities highlights the potential of densification to create urban canyons. In urban areas with high densification index, the presence of tall buildings flanking narrow streets can create urban canyons, which enhance the thermal trapping and increase surface and air temperatures.Densification, however, does not always increase thermal trapping but, rather, creates the need for more carefully managed thermal regulation. For example, high-density cities can take advantage of district cooling systems and distribute cool air for multiple buildings [5]. This system allows the sharing of resources and reduces the overall energy-related consumption.

3.2. Passive Cooling in Densified Areas

Even so, built environments can employ passive cooling strategies to mitigate the UHI effect through highly reflective building materials, well-planned building orientation to maximise cross and stack ventilation, and features of green infrastructure such as green roofs and walls. Reflective building materials on rooftops and building exteriors can reduce total heat absorption by increasing solar reflectance. Green roofs and walls with dense plantings provide internal insulation that lowers surface temperatures, and improve air flow with evapotranspiration while decreasing temperature. Particularly in high-density areas where existing buildings take up most of the land, green infrastructure to provide shade, cool the environment and reduce the thermal load on residents and workers can be especially valuable [6]. At the street level, designers can provide shade, reduce paved surfaces and incorporate features such as water for evaporative cooling, and porous pavements through which water can infiltrate.

3.3. Densification and Public Health

Urban densification has direct implications for public health, not least through the increased risk of heat-related illnesses during extreme heat events. High-density urban areas with insufficient ventilation and green spaces are often heat islands, and hot spots for vulnerable groups such as elderly, children and those suffering from conditions such as heart and lung diseases. In these settings, the UHI effect can exacerbate existing health injustices as low-income communities tend to be settled in areas with least access to cooling infrastructure. During heatwaves, mortality rates in densely populated areas are typically about 10 times higher than in more rural areas This, in turn, highlights the importance of incorporating public health concerns from the outset of urban planning, as shown in Table 2 below. Rising urban temperatures can pose serious health risks and, to reduce these dangers, densifying cities will have to systematically develop shaded public spaces, improve access to cooling centres, and promote the building design with a low heat-receiving capacity to keep indoor temperatures down without environments and without relying on energy-intensive air conditioning [7].

Table 2: Study on Urban Densification and Public Health

City	Population Density (people/km^2)	Average Green Space per Capita (m^2)	Mortality Rate during Heatwaves (per 100,000)	Access to Cooling Centers (%)	Energy-efficient Building Adoption (%)
New York	10833	23.1	8.2	45	40
Tokyo	6369	5.8	5.4	30	35
London	5700	27	4.1	55	50
Shanghai	16000	3.8	11.5	20	25

DOI: 10.54254/2755-2721/122/2025.19604

4. The Role of Urban Green Spaces in Mitigating UHI

Plenty of green space provides that, by cooling buildings and the city generally. The presence of trees, vegetation and water features increases evapotranspiration, thereby lowering the temperature of the air and the surfaces. With both horizontal and vertical expansion, green spaces are an important component of mitigating the UHI effect.

4.1. Cooling Effects of Urban Parks

An effective way in which parks can mitigate rising temperatures is through creating a large area exposed to cooler microclimates. The shading of a tree-covered park lowers temperatures at the ground level and facilitates the process of evapotranspiration into the air above. As cities expand into open areas, parks can be placed along the urban fringe to create a thermal buffer zone that incorporates cooler areas and wider pockets of open space [8]. Parks can also cool the surroundings. Research has shown that when compared with the urban areas around them, the cooling effects of parks can reach up to 1-2 degrees Celsius just a few metres away. For larger parks, the cooling effect can be as much as 6 degrees Celsius. This is partly because the tree cover, water bodies and grassy areas of a park help to reduce surface temperatures, thus improving the microclimate for residents living nearby. Well-located parks in expanding urban areas can, cumulatively, help alleviate the UHI in an entire city by forming bands of cool zones across the urban landscape.

4.2. Green Roofs and Vertical Gardens

Green roofs and vertical gardens allow for a valuable green infrastructure alternative, especially in high-density urban environments where access to traditional parks is limited by a lack of space. Green roofs – that is, the vegetation layer covering a building roof – offer insulation for the building below and decrease surface temperatures. They also improve air quality. Vertical gardens, by contrast, consist of plants growing on the exterior walls of buildings [8]. They can create microclimates that are cooler than the surrounding air temperatures by shading the surface of the building and creating airflow. With densely populated urban cores characterised by high-rise buildings and little green space available, integrating green infrastructure into building design is crucial for reducing the UHI effect while also making the urban setting more pleasant and livable.

4.3. Water Bodies as Cooling Elements

Lakes, rivers and fountains have a significant cooling impact on large areas of cities through evaporation This evaporative cooling of water bodies is a vital natural resource for the cooling of expanding and densifying cities. Both are significant contributors to the heat island effect through the absorption by the built environment of solar radiation striking impervious surfaces. Large water bodies or artificial lakes have a significant cooling impact on large areas of cities, creating cooler microclimates that improve residents' quality of life. Smaller water features such as fountains or ponds in high-density areas can provide localised cooling, as can water features incorporated into green spaces [9].

5. Technological Solutions for Reducing the UHI Effect

5.1. Reflective and Cool Roof Technologies

Reducing absorption could be accomplished by using reflective roof technologies. Among other applications, such roofs are made of materials that reflect more sunlight than they absorb, thus

DOI: 10.54254/2755-2721/122/2025.19604

keeping the surface of buildings cooler. Cool roofs can reduce building temperatures and indoor AC use in both expanding and densifying cities. Decreasing the cooling load relieves the grid and reduces greenhouse gas emissions. This cooling effect also reduces the UHI effect. Cool roof retrofits for existing, aging buildings are a cost-effective way to improve the thermal performance of urban areas. Cool roof technologies can especially benefit densely populated areas, which cause a larger proportion of buildings to heat up and retain that heat.

5.2. District Cooling Systems

Reducing absorption could be accomplished by using reflective roof technologies. Among other applications, such roofs are made of materials that reflect more sunlight than they absorb, thus keeping the surface of buildings cooler. Cool roofs can reduce building temperatures and indoor AC use in both expanding and densifying cities. Decreasing the cooling load relieves the grid and reduces greenhouse gas emissions. This cooling effect also reduces the UHI effect. Cool roof retrofits for existing, aging buildings are a cost-effective way to improve the thermal performance of urban areas. Cool roof technologies can especially benefit densely populated areas, which cause a larger proportion of buildings to heat up and retain that heat.

6. Conclusion

The findings of this study underscore the complex relationship between urban morphology and the Urban Heat Island effect. Urban expansion and densification both contribute to increased heat retention, albeit in different ways. Expansion leads to the spread of impervious surfaces over large areas, exacerbating the UHI effect by limiting green space integration and creating vast heat-absorbing zones. On the other hand, densification concentrates heat in compact urban cores, where tall buildings and narrow streets trap heat, reducing natural ventilation and intensifying the UHI effect. However, both forms of urban growth offer opportunities for effective mitigation strategies. The use of green infrastructure, such as parks, green roofs, and vertical gardens, can help offset the heat accumulation, while technological solutions like reflective materials and district cooling systems further enhance urban cooling capabilities.

References

[1] *Yadav, Namita, et al. "Systematic exploration of heat wave impact on mortality and urban heat island: A review from 2000 to 2022." Urban Climate 51 (2023): 101622.*

[2] *Diem, Phan Kieu, et al. "Remote sensing for urban heat island research: progress, current issues, and perspectives." Remote Sensing Applications: Society and Environment (2023): 101081.*

[3] *Irfeey, Abdul Munaf Mohamed, et al. "Sustainable mitigation strategies for urban heat island effects in urban areas." Sustainability 15.14 (2023): 10767.*

[4] *Elhabodi, Tarek S., et al. "A review on BIPV-induced temperature effects on urban heat islands." Urban Climate 50 (2023): 101592.*

[5] *Arunab, K. S., and Aneesh Mathew. "Quantifying urban heat island and pollutant nexus: A novel geospatial approach." Sustainable Cities and Society 101 (2024): 105117.*

[6] *Javanroodi, Kavan, et al. "Designing climate resilient energy systems in complex urban areas considering urban morphology: A technical review." Advances in Applied Energy (2023): 100155.*

[7] *Patel, Pratiman, et al. "Deep learning-based urban morphology for city-scale environmental modeling." PNAS nexus 2.3 (2023): pgad027.*

[8] *Kolkwitz, Mario, Elina Luotonen, and Satu Huuhka. "How changes in urban morphology translate into urban metabolisms of building stocks: A framework for spatiotemporal material flow analysis and a case study." Environment and Planning B: Urban Analytics and City Science 50.6 (2023): 1559-1576.*

[9] *Labetski, Anna, et al. "3D building metrics for urban morphology." International Journal of Geographical Information Science 37.1 (2023): 36-67.*