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Simulation Study of Urban Residential Development and Urban Climate Change in Xi'an, China

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Abstract

Increased awareness of the urban heat island (UHI) effect has drawn attention to monitoring and evaluating outdoor thermal comfort in cities worldwide. Especially in China, rapid, large-scale urban development is producing urban climate change in large cities, creating other urban environmental problems such as haze weather. Currently, studies are being conducted in China to reveal the impact of urban development on urban climate change. Few studies, however, have focused on microscale urban planning styles and urban typology.

High-density building development will change the urban typology, leading to changes in the urban sky view factor (SVF) and microclimate. Our previous study explored the relationship between SVF and the UHI effect by assessing the effect of SVF on the urban thermal environment. Since the energy consumed by indoor heating and air conditioning is affected by mean air temperature (Ta), a high SVF should be considered in the urban planning stage. In this study, we analyzed typical urban planning styles in China. We selected microscale residential districts in Xi'an to represent the typical urban typology of residential districts that developed during different periods and used the numerical urban simulation system ENVI-met to evaluate the impact of urban typology change on urban climate change. Using this approach, we determined the effects of building density, building styles, and vegetation system design, thus demonstrating the mechanism of urban climate change in China's larger cities. This analysis of planning styles can provide guidance for future environmental urban development.

Keywords: urban planning; urban climate change; environmental simulation; urban typology

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1. Introduction

High-speed, high-density urban development has contributed to urban environmental problems, including climate change, increased energy consumption, and haze weather. Such effects are observed in large Chinese cities such as Xi'an. Given these urban environmental problems, sustainable urban development is becoming an important task in China. However, there remains a lack of mechanism studies investigating urban geometry and urban climate change.

1.1. Urban climate change in cities

In recent years, urban climate change has been observed in most of the world's developed cities. Between 1961 and 1980, the annual air temperature rose 0.36oC in central Beijing. However, during the building boom between 1981 and 2000, it rose 0.94oC [1]. The correlation coefficient between the impervious surface rate and land surface temperature in Beijing reached 0.93 [2]. Climate models indicate that, due to the expected warming of up to 9oC by the 2080s in the Arctic and the southern and central Prairies [3], the number of days with average temperatures above 30oC is likely to increase in cities across Canada, especially those in the Windsor–Quebec corridor (such as Toronto) and portions of British Columbia. Thus, urbanization patterns, especially in the central parts of cities, have a large impact on urban climate change. The spatial variability of urban heat islands (UHIs) in cities has been found to be a function of urban surface properties, which in turn are influenced by land cover, especially vegetation cover and building density [4].

The deep urban canopy created by high-rises can increase the wind speed in urban areas and affect the urban thermal environment. A simulation comparison of high-rise and low-rise buildings in the Lujiazui district of Shanghai found that with low-rise buildings, wind speed declined 22%, air temperature decreased 7%, and O3 decreased 9% [5]. Another study used wind tunnel measurements to examine wind velocities in Toronto, confirming that among several high-rise towers, wind often accelerated above 10 m/s; this created wind-chill effects and exerted mechanical forces on pedestrians, making it unsafe for them to walk [6]. The openness of urban geometry can be defined using the sky view factor (SVF). The correlation between SVF and the urban thermal environment has been demonstrated in Montreal, Canada [7, 12, 13]. A high SVF, which means more open urban space, could be related to a lower UHI index.

Urban development largely serves the purposes of economic development. Especially in China, large-scale, rapid urban development mostly focuses on the operational efficiency of cities, with little attention to the long-term environmental effects. This is a major cause of China's current environmental crisis, and the problem is rapidly spreading to India as well as other countries of Southeast Asia and the Middle East.

1.2. Different periods of building development in Xi'an

Xi'an is a historical city as well as one of the most developed cities in China's central plains. Most of the current urban buildings were constructed after 1979 [8]. Different development styles and residential building types can be observed for the different periods of rapid urban development.

Between 1979 and 1989, the Chinese government started to focus on economic development and infrastructure. Along with the redevelopment of existing urban areas, new construction was carried out on the edges of central urban areas. To meet the residential demand in the city, large factories developed residential areas nearby for staff and workers. Most buildings built during this period are five to six stories, though some have seven floors.

After 1990, real estate developers started to have a major impact on urban reform and urban expansion. New, large-scale developments started occurring outside the city core. During this period, building design and quality became more important than in the past. Most buildings were still five to seven stories, but high-rises and detached houses were also developed in some of the projects.

Since 2000, the high-rise has become the most common construction style in residential development projects. The purpose of residential development has shifted from meeting the basic needs of citizens to promoting real estate and the urban economy. Fig. 1 shows the process of urban expansion in Xi'an. It is clear that urban occupation has grown rapidly. Meanwhile, urban building density has also increased because of the high building density of recent development projects.

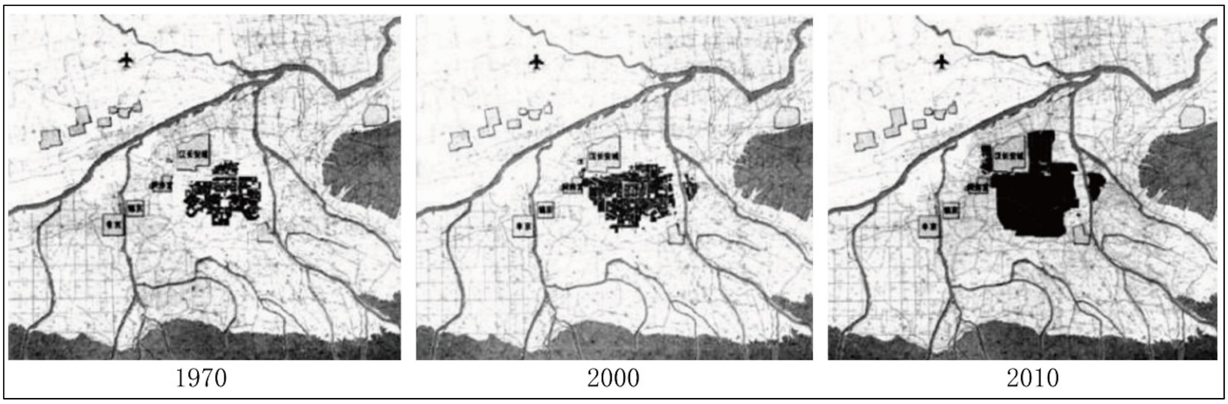


Fig. 1. Urban expansion in Xi'an **[9]**.

This study selected two microscale residential districts in Xi'an to present the typical urban typology of residential districts in different historical periods. Using the numerical urban simulation system ENVI-met, we evaluated the impact of urban typology changes on urban climate change. We determined the effects of building density, building styles, and vegetation system design in the districts, thus demonstrating the mechanism of urban climate change in Xi'an. This analysis of planning styles can provide guidance for future environmental urban development

2. Methodology

2.1. Study areas

Fig. 2. Street image: (a) mid-rise area; (b) high-rise area.

Two typical residential areas were selected for simulation and discussion. The first (Xitiedaminggong) is a mid-rise building neighborhood developed in the early 1990s. All of the residential buildings are seven stories, perfectly representing the building types constructed between 1979 and the early 1990s. The second (Jinyuanjunyi) is a high-rise residential building neighborhood developed in 2013. The tallest building in this area is 28 floors, and the average building height is about 40 m, representing the development style common since 2000. Street images of the two neighborhoods are shown in Fig. 2. A domain of 240 m × 240 m was chosen for the simulation models, and the detailed input domain data and weather data are presented in Tables 1 and 2. In the high-rise area, the building land cover is 29.1%, which is 6.4% lower than in the mid-rise area. This could be a result of the space requirement between high-rise buildings. In other words, there is more open space in the high-rise area that could be used for planting vegetation or for the local community. The global floor area provided in the high-rise area is about 1.6 times that of the mid-rise area. A high floor density increases urban population density, making it advantageous for urban economic development and real estate.

Table 1. Image selected areas and simulation domain data.

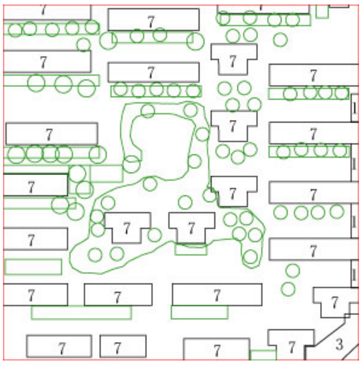
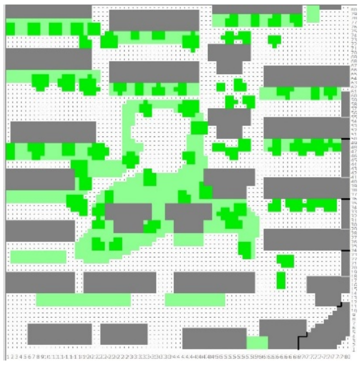
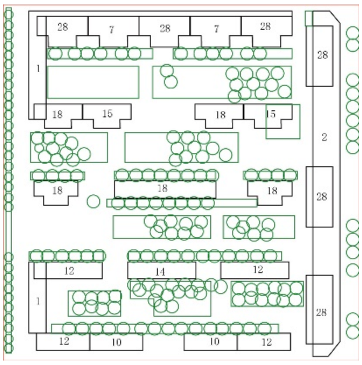
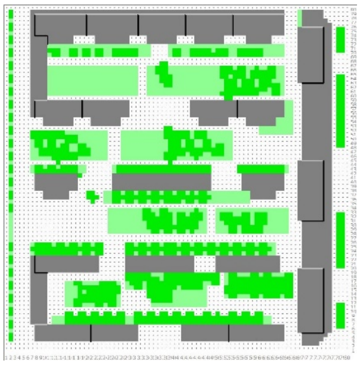
	Satellite Image	CAD Map	ENVI-met Input Data
Mid-rise Area			
High-rise Area			

Table 2. Land use and building height properties in Concordia model areas.

	Mid-rise Area	**High-rise Area**
Construction Time (Y)	1990s	2013
Land Coverage (%)	35.5	29.1
Green Coverage (%)	22.0	21.6
Asphalt Coverage (%)	42.5	49.3
Global Floor Area (m^2)	217782	346950
Average Building height (m)	21	40
Median Building height (m)	21	36

2.2. Simulation

We used ENVI-met (3-D software that analyzes microscale thermal interactions in urban environments) [10] to simulate environmental conditions in the two selected areas in Xi'an. ENVI-met is designed to simulate surface-plant-air interactions in urban environments. It has a typical spatial resolution of 0.5–10.0 m and a temporal resolution of 10 seconds. Simulations can be conducted for as little as six hours but usually last 24–48 hours. The optimal start time for a simulation is at night or sunrise so the simulation can follow atmospheric processes. ENVI-met requires an area input file that defines the 3-D geometry of the target area. This includes buildings, vegetation, soils, and receptors. A configuration file that defines the initialization input is also required [11]. Two microurban canopy models were built and simulated for the discussion about the environmental effects (air temperature, mean radiant temperature, and wind speed) of various building development styles. The input domain area images are shown in Table 1, and the properties of the ENVI-met inputs for the models are given in Table 3.

For these simulations, the geometry of an urban street canyon in Xi'an was identified using satellite images and street maps from Baidu Maps (map.baidu.com). The area input files were built by ENVI-met; we input satellite images into the editing files and defined the ground, vegetation, building façade, and building layout in cubic grids of 27 m3 (3 m × 3 m × 3 m). However, the simulation model's spatial limitation caused a deviation around the edge of the model, which affected the UHI simulation results in ENVI-met. This led to an omission of the effects from surrounding buildings outside the selected area and an overestimation of the effects from the environment (air temperature, wind speed, humidity) outside the city.

Table 3. Details of the initialization input parameters for the simulation.

Category	**July 24, 2015**
Starting Time	20:00
Wind Speed	2.0 m/s
Wind Direction	South West
Air Temperature	305.05K (31.9℃)
Specific Humidity in 2500m	7 g/kg
Relative Humidity in 2m	36%
Building Interior Temperature	299.15 K (26℃)

2.3. 2.3. Simulation validation with actual measurements

Fig. 3 shows the correlations between the simulation results in the two selected districts and the measurements obtained from the Chinese government's website. ENVI-met was found to represent the trends of the mean air temperature of the whole area (Ta), with a high correlation coefficient (R2) of 0.97 between the results for the mid-rise district simulation and the measurements, and 0.98 between the high-rise district simulation and the measurements. The maximum temperature difference between the measurements and the simulations was about 2°C, observed around sunset at 5:00 p.m. The unified and assumed numerical values of material properties for the simulations could have been the main cause of the deviation between the simulations and the measurements.

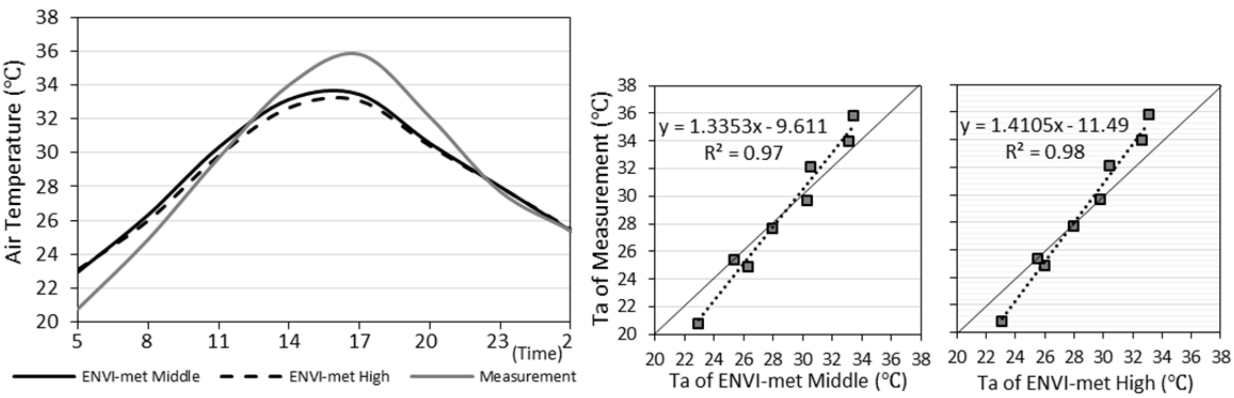


Fig. 3. Correlations between simulation results and measurement data.

3. Results

3.1. Urban Typology

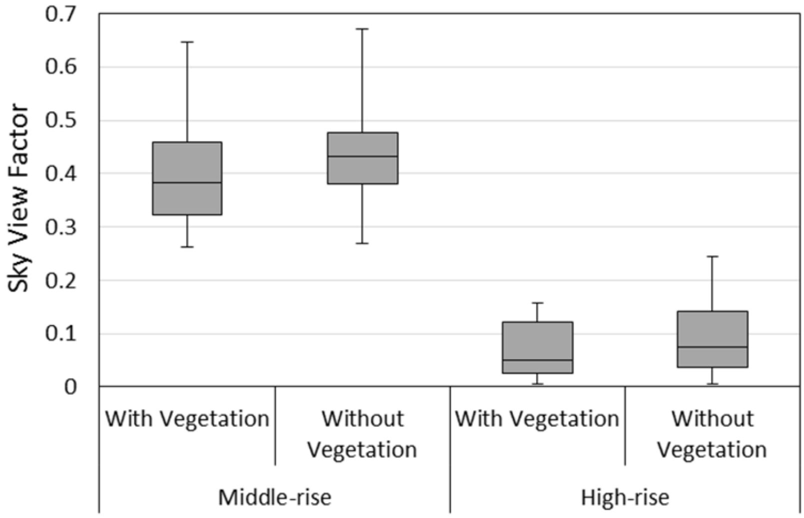


Fig. 4. Sky view factor in the mid-rise and high-rise models.

ENVI-met was used to calculate the SVF all over the areas at human height level (1.5 m from the ground). The results are shown in Fig. 4. The results for “with vegetation” include the calculation of the effects from buildings and trees; the results for “without vegetation” only represent the urban geometry of buildings. The median SVF value in the mid-rise area was about 0.36 higher (without vegetation) than in the high-rise area. This was because the high building density in the high-rise model created a deeper urban canopy. Including the effects from vegetation, the median SVF value decreased by 0.048 in the mid-rise area and 0.025 in the high-rise area, compared to the results without vegetation. In other words, in the developed urban areas, trees reduced the urban SVF and changed the urban geometry, but the effect from trees was insignificant compared to buildings.

3.2. Urban Environment

Fig. 5 shows the wind speed, mean radiant temperature, and air temperature for the whole area of mid-rise and high-rise models. The data present the measurements for each grid in the models, which are 3 m × 3 m × 3 m. Thus, 4,128 data sets for the mid-rise model and 4,538 for the high-rise model at human height level were exported and compared, excluding the built-up areas. Regarding the results for wind speed, compared to the median value in the mid-rise model, the value for the high-rise model was 0.06 m/s (7.5%) lower at noon and 0.03 m/s (4.9%) lower at mid-night. This was because the large building volume and high development density in the high-rise area reduced the overall wind speed. However, relative to the mid-rise model, the maximum wind speed value in the high-rise model was 0.93 m/s (29.1%) higher at noon and 0.99 m/s (31.5%) higher at mid-night. This can be explained by the wind turbulence around high-rise buildings. Regarding mean radiant temperature, the median value for the mid-rise model was 8.3°C (14.3%) higher than in the high-rise model at mid-day. At mid-night, the median value for mean radiant temperature in the high-rise model was slightly higher than in the mid-rise model (2.4%). This was because mean radiant temperature mostly depends on solar radiation during the day, and the low SVF of the high-rise area (see Fig. 3) could have reduced solar radiation absorption at the human height level. The median air temperature value in the high-rise model was about 0.6°C lower than in the mid-rise model at mid-day, and there was no difference at mid-night. However, the minimum and maximum values for the high-rise model were 0.1°C higher than for the mid-rise model.

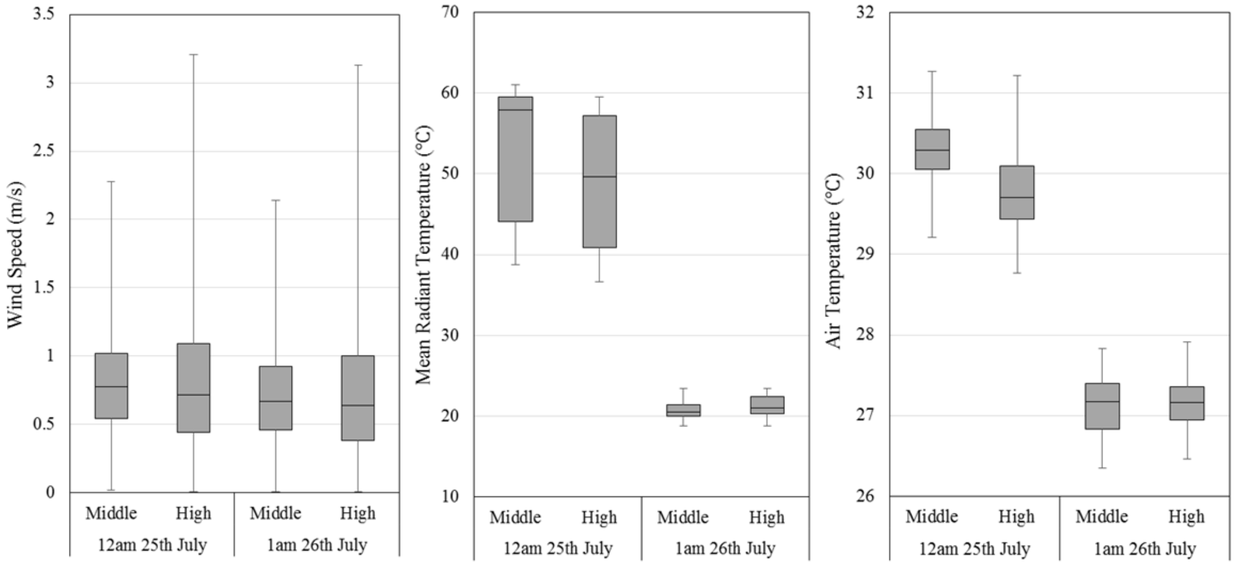
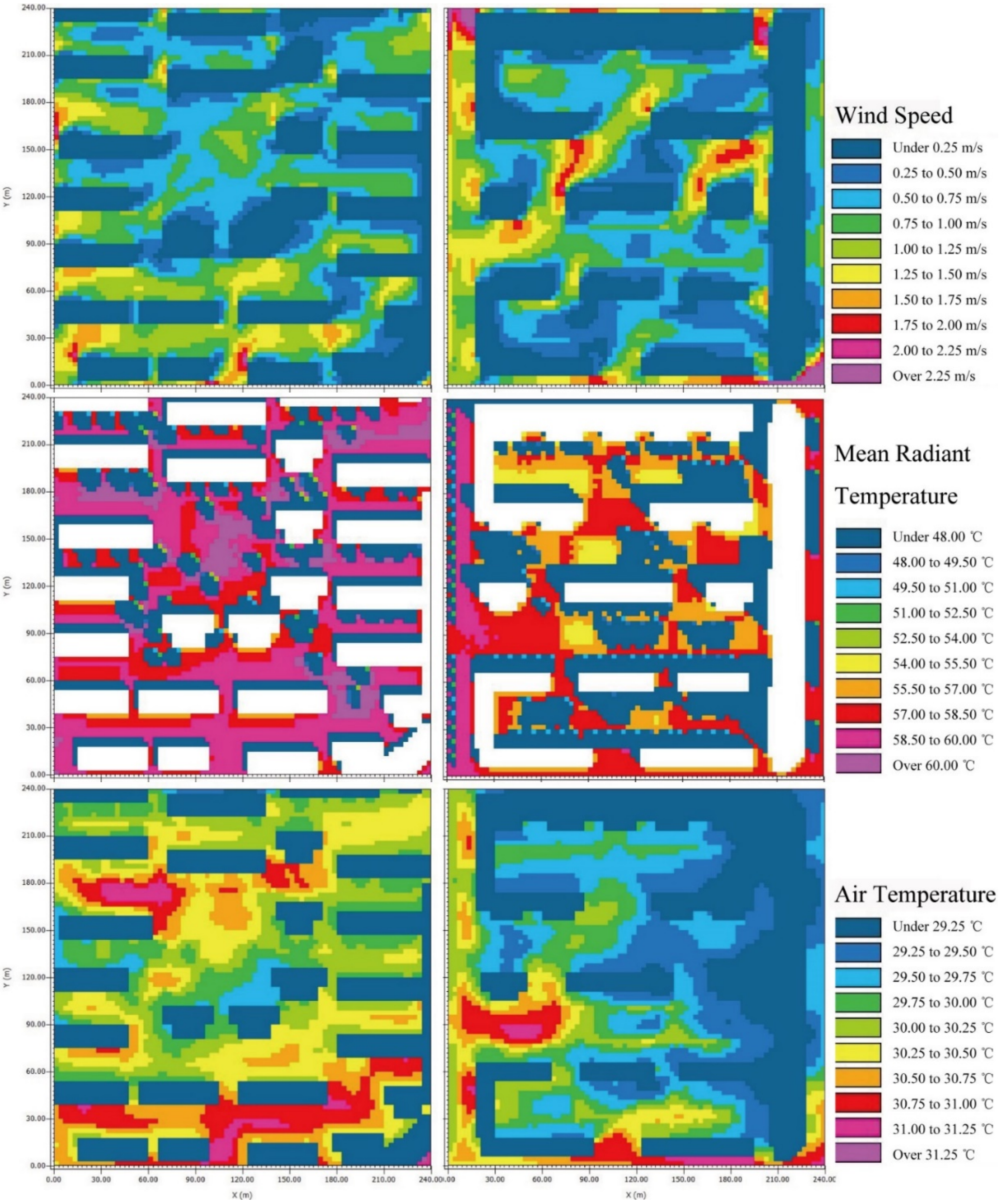


Fig. 5. Wind speed, mean radiant temperature, and air temperature distribution at noon (12:00 a.m., July 25, 2015) and mid-night (1:00 a.m., July 26, 2015) on a summer day at human height level (1.5 m from the ground).

Fig. 6 shows the environmental images of the two neighborhoods during mid-day. High wind speed spots were found in the high-rise model, and the overall wind flow distributed averagely in the mid-rise area. This was because of the large building volume in the high-rise area, and high-rise buildings also induce air turbulence. Referring to the tree planting locations in Table 1, the low mean radiant temperature spots in the two models were highly related to the trees as well as the shadows of the buildings. The air temperature distribution was also somewhat related to the shadows. In other words, tree planting in the urban area contributed to UHI mitigation at mid-day.

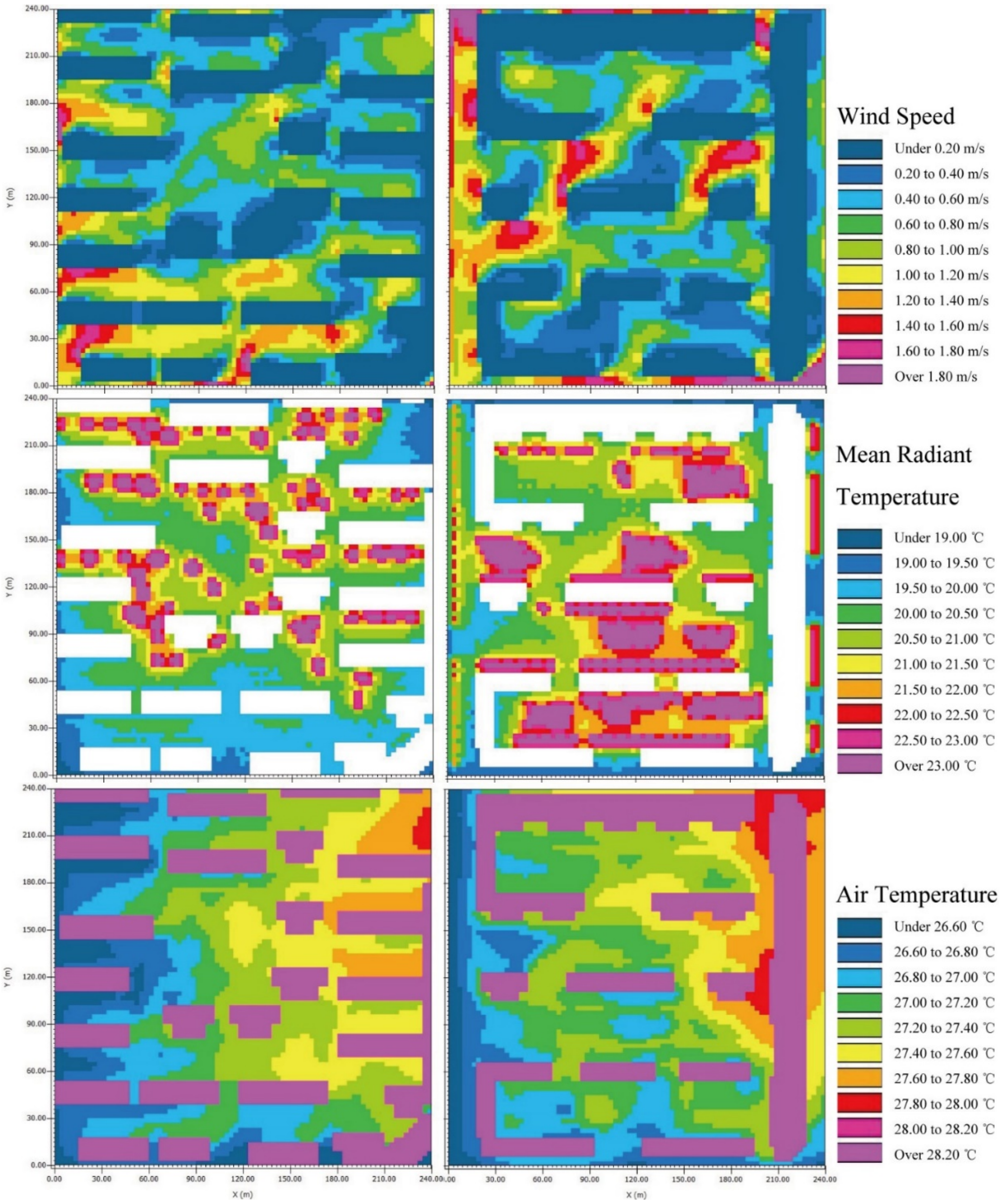
Fig. 7 shows the environmental images of the two neighborhoods at mid-night. The high wind speed spots in the images were almost the same as the spots at mid-day (see Fig. 5). In other words, urban wind conditions were not strongly related to temperature changes in the microclimate. The high mean radiant temperature spots were related to tree locations—the opposite of mid-day. This was because the tree canopy reduced solar radiation absorption during the day and reduced outgoing radiation at night. The high and low air temperature distribution at mid-night was mostly the opposite of that at mid-day. This was because building surface heat storage increases the air temperature around the surface at night, and building shade provides lower temperatures around buildings during the day. This was more obvious in the high-rise model because the taller buildings produced more shade while the larger building volumes created more heat capacity for heat release at night.

In the mid-rise area, both wind speed and air temperature were uniformly distributed all over the area. In the high-rise area, there were obvious high wind speed spots and cool spots in the area. This was because wind could easily pass between the mid-rise buildings, and there was little air turbulence. At mid-day during the summer, high-rise buildings with a large building volume create a lower SVF (deeper urban canopy), provide more shadows, reduce solar radiation absorption at the human level, and reduce air temperature around the buildings. On the other hand, a high-rise area with a low SVF reduces outgoing longwave radiation after sunset. This could disturb the urban area’s ability to cool down at night during the summer [7].



Mid-rise area **High-rise area**

Fig. 6. Wind speed, mean radiant temperature, and air temperature distribution images in the mid-day (12:00am) of a summer day (25th July, 2015) at human height level (1.5m height from the ground).



Mid-rise area **High-rise area**

Fig. 7. Air temperature, mean radiant temperature, and air temperature distribution images in the mid-night (1:00am) of a summer day (26th July, 2015) at human height level (1.5m height from the ground).

4. Conclusions

In this study, historical urban development styles were analyzed. Two typical residential neighborhoods (mid-rise and high-rise areas) in Xi’an were selected to present the urban development styles of different periods and compare their effects on the urban climate. High-rise buildings produced a lower urban SVF and less open spaces. It was shown that the median wind speed value in the high-rise area was about 0.06 m/s lower than in the mid-rise area.

Because of the low SVF (deep urban canopy) in the high-rise area, the median value for urban air temperature was about 0.6°C lower than in the mid-rise area at mid-day during the summer. The lower air temperature in the high-rise area was mostly caused by the high wind speed. This can also be explained by the shadows created by the urban trees and high-rise buildings, which reduce radiation absorption from sunshine at the human height level.

Overall, high-density urban residential development changes the urban thermal environment. While this could be advantageous for UHI mitigation during the day, it creates obstacles for heat release at night. A lower SVF reduces radiation absorption but also reduces outgoing longwave radiation. Meanwhile, wind turbulence around high buildings partly contributes to the spread of air pollution. Future studies should consider the layout and volume of high-rise buildings in urban development projects in more detail to help reduce urban climate change. The results of the present study provide clues for related environmental urban development in China as well as other countries.

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