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Urban Renovation and the Simulation Evaluation of Urban Climate Change in Residential and Commercial Districts: A Case of Xi'an, China

Wang Yupeng, Ma Dixuan, Li Man and Zhou Dian

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Abstract

The urban heat island (UHI) effect has drawn attention to monitor and evaluate outdoor thermal comfort in cities worldwide. The rapid, large-scale urban development in China is producing urban climate change in large cities, creating other urban environmental problems such as haze weather, which is one of the most important environmental issues in China. High-density building development will change the urban typology, leading to changes in the urban sky view factor (SVF) and microclimate. Since the energy consumed by indoor heating and air conditioning is highly related to the outdoor mean air temperature, a high SVF should be considered in the planning period. In this chapter, the typical urban planning styles in China are evaluated. Four microscaled residential and three commercial districts in Xi'an city are selected, to represent the typical urban typology of residential and commercial districts that developed during different historical periods and used the urban simulation system scSTREAM to evaluate the impact of urban renovation types on urban climate change.

Keywords: urban renovation, urban typology, climate change, outdoor comfort, environmental simulation

1. Introduction

1.1. Urban climate change in cities

In recent years, urban climate change has been observed in most of the world's developed cities. In central Beijing, the annual air temperature rose 0.36°C during 1961–1980. However,

during the building boom between 1981 and 2000, it rose 0.94°C [1]. The correlation coefficient between the impervious surface rate and land surface temperature in Beijing reached 0.93, which means the impervious of urban surface is providing a large contribution to urban climate change [2]. Climate models indicate that due to the expected warming of up to 9°C by the 2080s in the Arctic and the southern and central Prairies [3], the number of days with average temperatures above 30°C 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 O^3 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 [7–9]. 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. The urban typology changes of cities

With the accelerated speed of urban development and the constant expansion in Chinese cities, the urban typology has undergone drastic changes in the past 10 years. Xi'an is a historical city as well as one of the most developed cities in China's central plains, which is experiencing rapid urbanization development, urban renewal and expansion. Most of the current urban buildings were constructed after 1979 [10]. Different development styles and residential building types can be observed for the different periods of rapid urban development. The urban typology changes of Xi'an is the epitome and representative that of China.

In China, the government started to pay attention on economic development and infrastructure redevelopment after 1979. In the process of redeveloping existing urban areas, new construction was continuously built on the edges of central urban areas. In order to meet the residential demand for citizens, large factories led to developed residential communities around the factories for their staff and workers. During this period, most of the buildings are built in 5–6 stories, and some of these have seven floors.
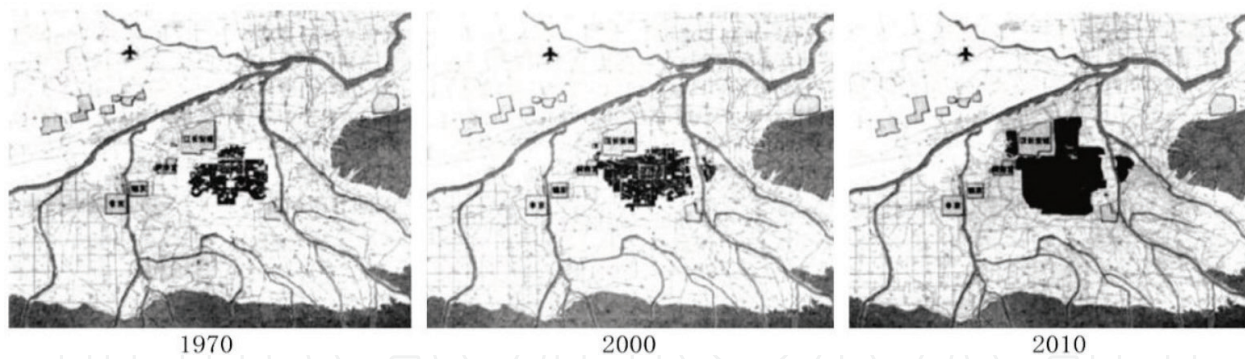
Figure 1. Urban expansion in Xi'an [11].

After the high-speed urban expansion, real estate developers started to have a major impact on urban reform after 1990s. New large-scale developments started occurring outside the city core. During this period, the sense of building design and construction quality became more important than that in the past. High-rise and detached houses were also developed in some of the projects, and most buildings were still 5–7 stories.

After 2000, because of the increased population density, the high-rise building has become the most common construction style in residential development projects. The first demand of residential construction has shifted from meeting the citizens' living to promoting real estate and the urban economy status. The process of urban expansion in Xi'an is showed in **Figure 1**. It is clearly showing that urban occupation has grown rapidly during 2000–2010. Meanwhile, urban building density has also increased because of the high building density of recent development projects.

2. Methods

Residential building is the most typical form of architecture in the city as some related research points out. From 2000 to 2010, area of residential land accounts for the largest proportion in urban land use type [12]. In this study, typical urban planning styles in China were selected and analyzed. Microscale residential districts in Xi'an were selected for representing the typical urban typology of residential districts that developed during different periods and used the urban simulation system scSTREAM (Software Cradle Co., 2011) to evaluate the impact of urban typology change on urban climate change.

2.1. Urban typology in Xi'an city

To estimate the impact of urban typology to urban ventilation and urban air quality, four typical residential areas were selected. The first area, Sanxuejie, is a low-rise area, a traditional residential zone rebuilt after the 1950s. It retains the urban form used in China Science the Ming and Qing Dynasties (about 600 years ago), with narrow streets between residential buildings, most of which have two floors. The second area, Xitiedaminggong, is a middle-rise neighborhood developed in the early 1990s. All of the residential buildings are five floors in

height and perfectly represent the character of the building type constructed in the period between 1979 and the beginning of the 1990s. The third neighborhood, Jiaodayicun, is a mix-rise area of low-rise and high-rise buildings, home to a variety of building styles developed around the 1980s and 2000s. The last selected neighborhood, Gongyuantianxia, is a high-rise residential neighborhood developed in 2009. The average building floor in this area was 17 floors in height, representing the common development style after 2000 (**Figure 2**).

Besides, three typical shopping areas in different layout which present the typical urban typology of shopping district are selected. A domain of 500 × 500 m was chosen for the simulation models, and the detailed input domain data and weather data are presented in **Tables 3** and **4**.

The first is Xiao Zhai shopping district, which is located in Xi 'an Yan Ta district. Since 2001, it has become the second largest business circle in Xi 'an, and the area is mainly composed of small retail shops and large shopping centers, and these commercial buildings have no unified planning, and they are not built in the same period. In this district, they also have some residential architectures. Therefore, it can be said to be a traditional kind of mixed layout shopping district, and it is common in Xi'an. The second is Shu Yuan men shopping district, and it is located in the east side of the south gate in Xi'an. It has been developed since the Ming dynasty, and it has become a kind of antique commercial street with Ming dynasty and Qing dynasty architecture style. In this area, building density is relatively high, but building height is low, generally only 2–3 levels of height. Meanwhile, there are some old residential one-storied houses in the area. Therefore, it is a traditional historical and cultural district for shopping. The third is Tang West Market Group shopping district. It is the only project that was rebuilt on its original site in China. Through overall planning and design, this area was
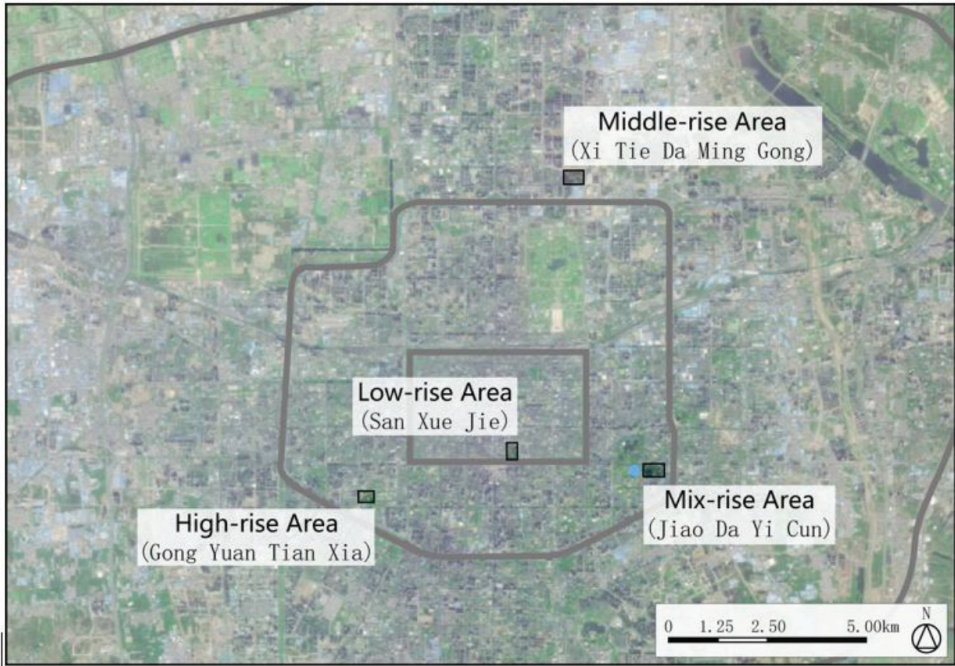
Figure 2. Xi'an satellite photo with the four areas selected for this study and defined as low-rise area (Sanxuejie), middle-rise area (Xitiedaminggong), mix-rise area (Jiaodayicun) and high-rise area (Gongyuantianxia). The area represented in this figure is indicated in **Figure 3** and **Tables 1** and **2**.

open in 2012. In this area, there are one big shopping center, one supermarket, one hotel, one museum and an antique market. They are basically multistoried buildings. Therefore, it is a new mixed-use shopping district.

	Low-rise	Middle-rise	Mix-rise	High-rise
Site size (m)	280 × 440	520 × 364	450 × 340	410 × 300
Simulation size (m)	1080 × 1240	1520 × 1364	1450 × 1340	1410 × 1300
Grid size (m)	0.6–6.0			

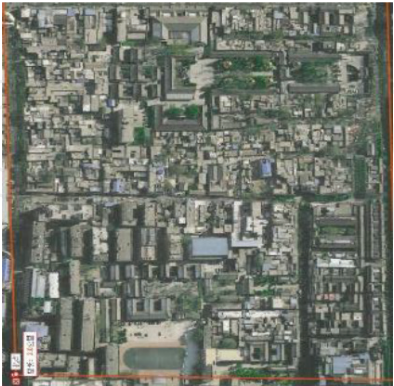**Table 1.** Details of simulation domain size in the four selected areas.
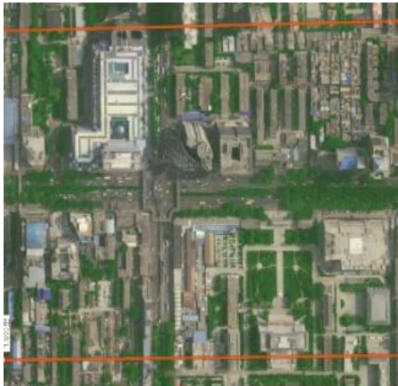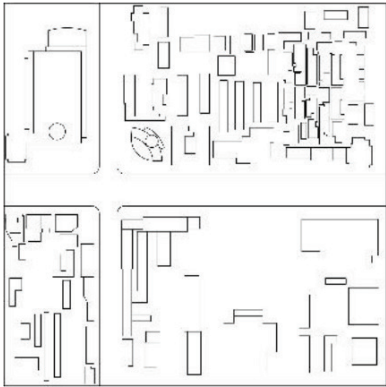
	Low-rise	Middle-rise	Mix-rise	High-rise
Site area (m²)	123,200	189,280	153,000	95,850
Built area (%)	51	19	14	6
Green area (%)	22	28	41	49
Floor area (%)	106	153	242	254
Average floor	2	5	7	17

Table 2. Land use and building height properties in the four selected areas.

Figure 3. Image selected areas and simulation domain data.
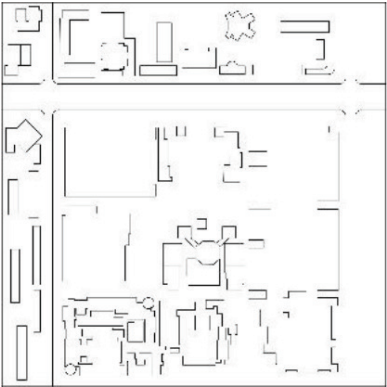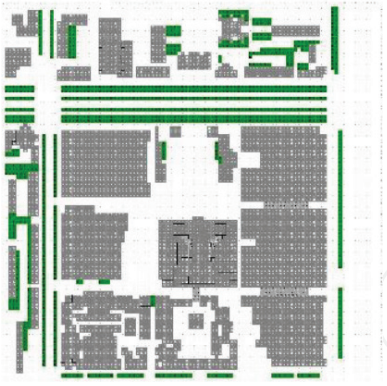
	Satellite image	CAD map	ENVI-met input data
Xiao Zhai			
Shopping district			

Satellite image	CAD map	ENVI-met input data
Shu Yuan men		

Table 3. Image selected areas and simulation domain data

2.2. Simulation

A commercial CFD code, scSTREAM (Software Cradle Co., 2011), was used to simulate the urban ventilation properties. Detailed distributions of air current and pressure per direction can be visualized. The simulation models were built according to the realities shown in **Figure 3**, and the detailed input data are presented in **Tables 1**, **2** and **5**.

The wind environment (Xi'an Weather Station, 2016) on a typical summer day (21st July, 2016) and a typical winter day (21st December, 2015) is selected for analysis. The wind direction and wind speed between 6:00 a.m. and 8:00 p.m. are shown in **Figure 4**. The average wind speed

	Xiao Zhai	Shu Yuan men	Tang West Market Group
Layout type	Layout along the street shopping district	Traditional historic and culture block shopping district	New
Construction time	2002	1991(1906)	2012
Building coverage (%)	32	46	33
Average building height (m)	40.6	5.6	28.3
Green coverage (%)	32.4	24.3	26.6

Table 4. Related parameters of three areas

	Materials	Density [kg/m³]	Specific heat [J/(kg K)]	Thermal conductivity [W/(m K)]
Building	Concrete	1600	1000	0.65
Road	Asphalt	2120	920	0.74
Side walk	Redbrick	1650	840	0.62
Inside surface	Mortar	2000	800	1.3
Green	Soil	1340	1700	0.7

Table 5. Details of ground surface material characteristics for simulation
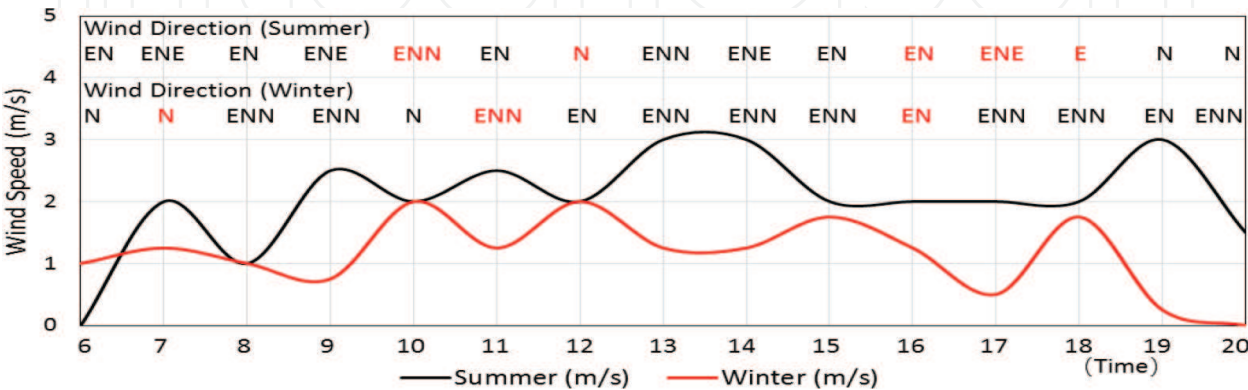
Figure 4. The wind condition in a typical summer day (21st July, 2016) and a typical winter day (21st December, 2015). The main wind directions are shown in red.

on the summer day was 2 m/s, and the wind directions were N, ENN, EN, ENE, and E, the main being EN; the average wind speed on the winter day was 1.25 m/s, and the wind directions were N, ENN, and EN, the main direction being ENN. The average wind speed and all of the wind directions in different seasons served as the initial condition for the simulations in scSTREAM. The main wind directions were here used for detailed results analysis and discussion.

3. Results

3.1. Results of urban air quality and urban ventilation

3.1.1. Air pollution distribution in Xi'an city

The field measurement results of the PM10 concentration distribution in the summer of 2016 are shown in **Figure 5**. The air pollution concentration distribution was not averagely distributed in the city. Comparison of **Figure 4** and the satellite photo in **Figure 2** showed the distribution of air pollution to be partially but directly related to urban density. This is because the urban typology affects urban ventilation and accelerates aggregation, and the air pollution in high-density urban districts is subsequently high.

In order to clarify the mechanism of the air pollution concentration in high-density areas, the low-rise and middle-rise areas that located in highly polluted areas are selected for simulation. This phenomenon will be discussed with the simulation results.

3.1.2. Wind environment simulation

On a summer day, five wind directions (N, ENN, EN, ENE, E) were simulated at a wind speed of 2 m/s. On a winter day, three wind directions (N, ENN, EN) were simulated at a wind speed of 1.25 m/s. **Figures 6** and **7** present the simulation results in the selected four urban areas.

In summer (**Figure 6**), with the effects from trees, the median wind speed in the low-rise area was slower than in the other areas, and the wind speed in the mix-rise area was fastest. With a wind direction of EN, the median wind speed in mix-rise area was 0.35 m/s, which was 0.15 m/s higher than in the low-rise and middle-rise areas, respectively. The median wind speed in high-rise area was slightly slower (0.03–0.06 m/s) than in the low-rise and middle-rise areas, but there were small areas of higher wind speed in the high-rise area, and these reached 2.13 m/s (2–3 times of the max wind speed in the low-rise and middle-rise areas). This could explain the results of high PM10 concentration measured in low-rise and middle-rise areas shown in **Figure 7**.

In winter (**Figure 7**), without the effects from trees, the median wind speed in the mixed-rise area was higher than in the other areas. With a wind direction of ENN, the median wind speed in mixed-rise area was 0.24 m/s higher than in the low-rise area and 0.19 m/s higher than in the middle-rise area. The median wind speed in the high-rise area is 0.09 and 0.28 m/s lower than in the middle-rise and mixed-rise areas. This is to say, the low-rise area (high-built density) and the high-rise area (high urban roughness) are reducing the urban wind speed.
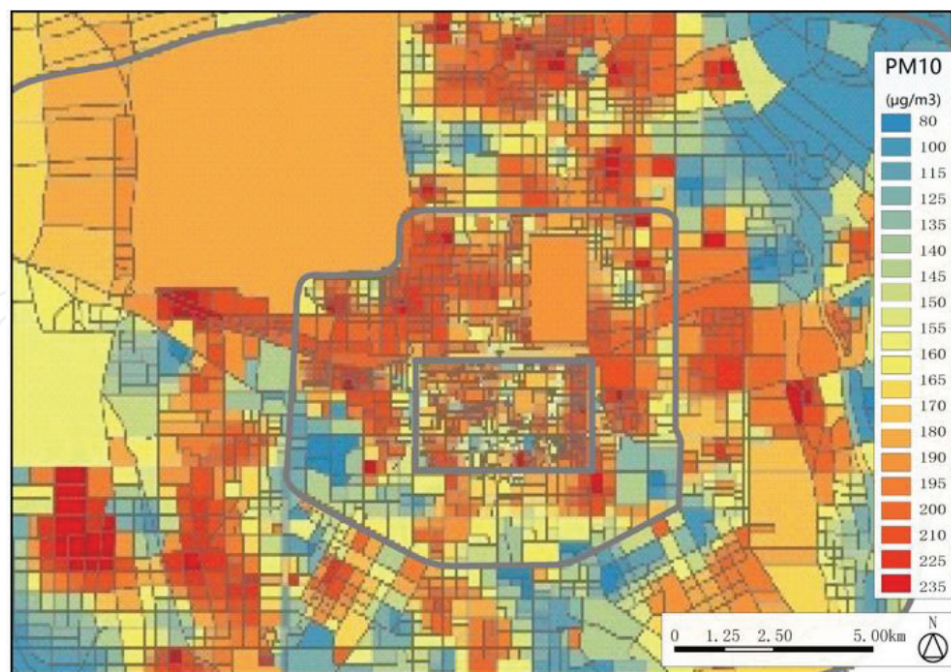
Figure 5. Distribution of PM10 concentration in the central of Xi'an.

In most of the cases, wind direction of EN provides the highest wind speed in allover the area. But, the results of high-rise area in summer are lower than the other directions. This is because of the effects from trees.

3.1.3. Wind speed distribution

Figures 8 and **9** show the details of wind speed distribution inside these four areas in the summer and winter. In the low-rise area, because of the high building density and narrow corridors between buildings, the overall wind speed was low, and it also had a pronounced effect on downwind areas. In the high-rise area, some areas of high wind speed were observed in between the high-rise buildings, but the wind speed in the leeside of the big volume buildings was extremely low. The mix-rise area showed the best ventilation properties of the four areas. Therefore, the traditional urban typology with low density and high built coverage creates the low urban ventilation at the human level. High-rise districts with large open space inside the district also reduce the overall wind speed.

In winter, without the effects from the trees, higher ventilation could be observed inside the four districts. Especially in the high-rise district, the wind property inside the community is promoted in the winter.

3.2. Results of urban typology and urban environment in typical shopping areas

ENVI-met was used to calculate the wind speed, the air temperature and the sky view factor (SVF) in all over the area at human height level (1.5 m height from the ground). The results are shown in **Figure 10**. They are all stimulated data at 1400 h.
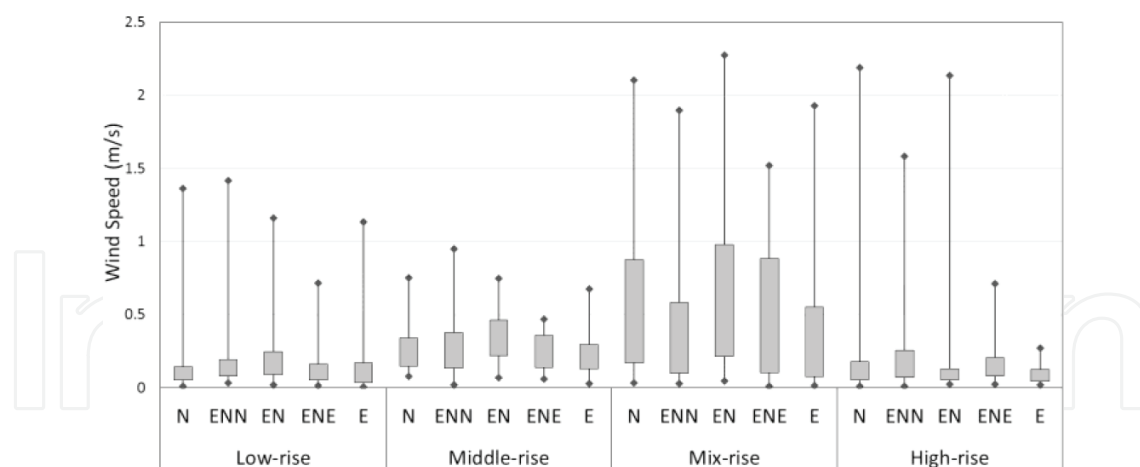
Figure 6. Wind speed in four selected areas in a typical summer day (21st July, 2016).
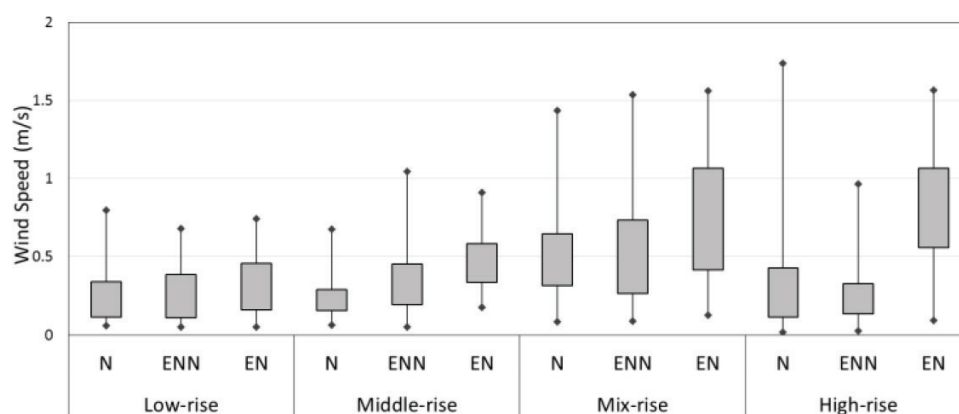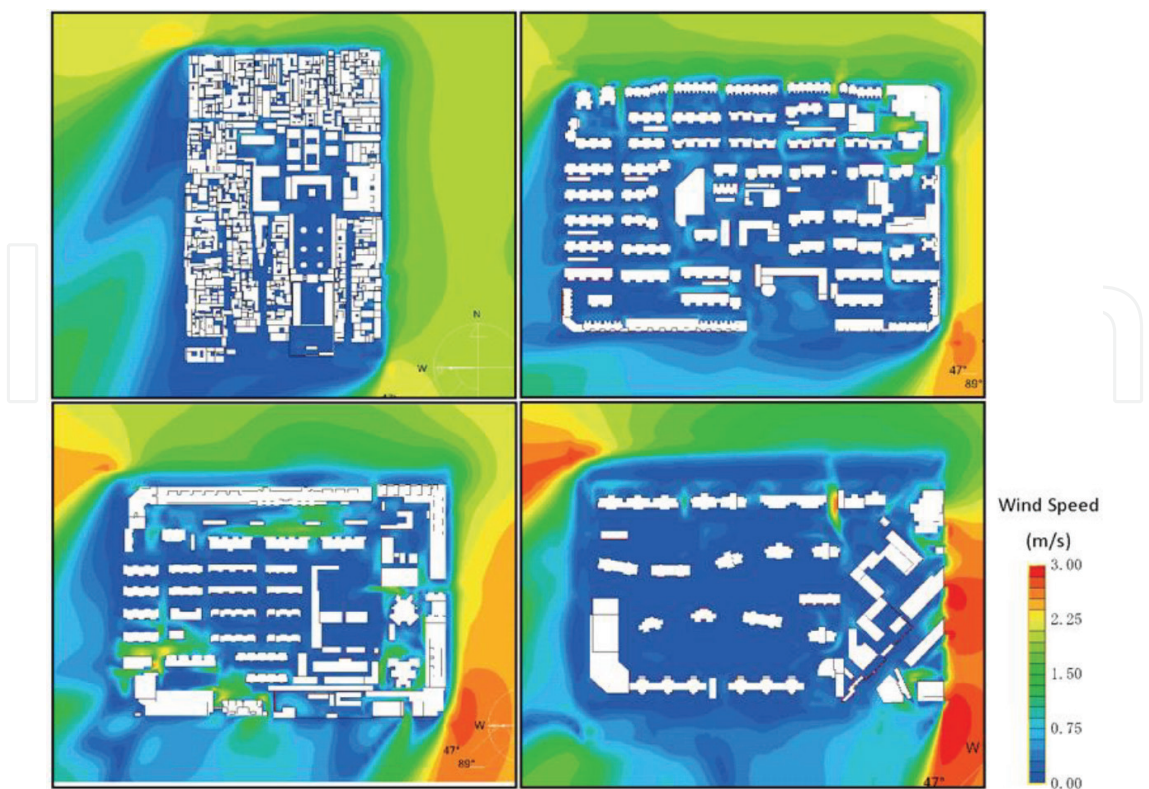

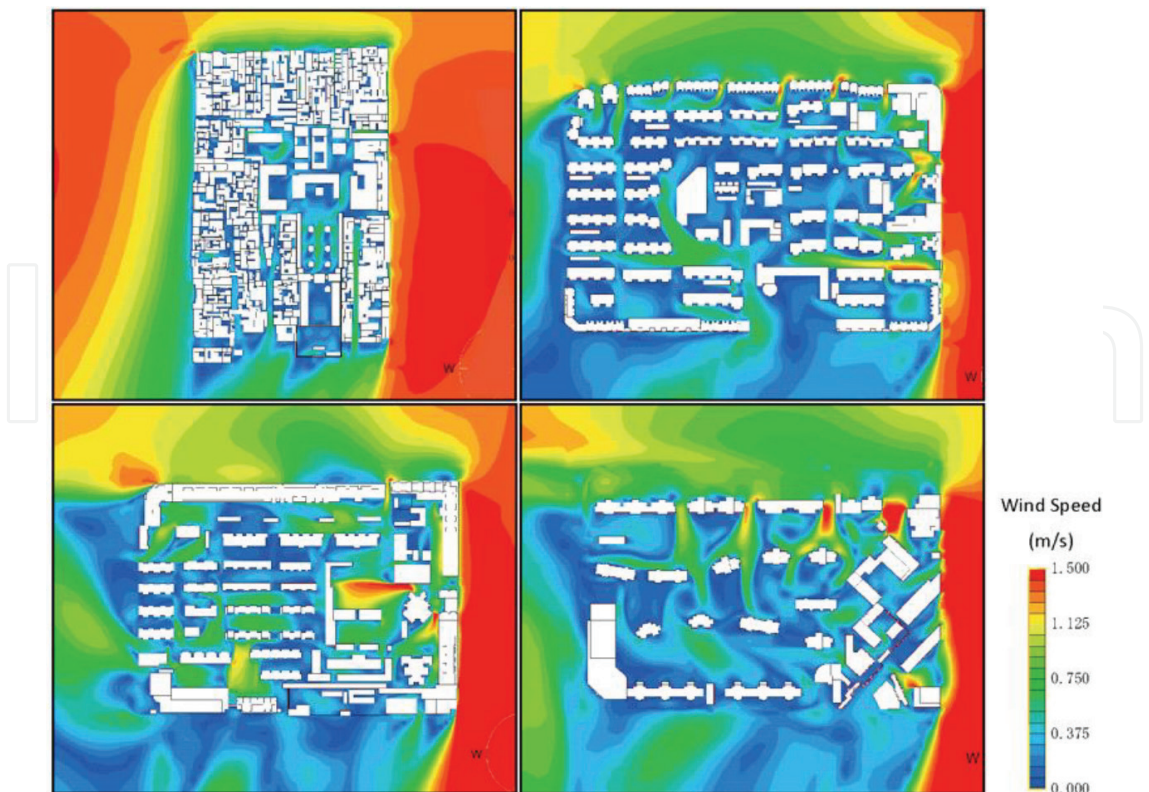**Figure 7.** Wind speed in four selected areas in a typical winter day (21st December, 2015).

In **Figure 11**, it is shown the result of the wind speed stimulation of three shopping districts. In a previous paper, Steemers selected six different layouts of building combinations to simulate the wind speed of the regional environment and found when the building parallel to the direction of the wind, ventilation rate is the highest in the street space, but the ventilation rate of building space is poor in the combination of combination and courtyard [13]. As can be seen from the simulation diagram, the average wind speed in Tang West Market Group shopping district (0.77 m/s) is stronger than others (Xiao Zhai is 0.75 m/s and Shu Yuan men is 0.76 m/s). This is because of the lower land cover in Tang West Market Group shopping district which creates more open spaces and wider streets. Meanwhile, the street space in this area is more orderly and vertical. However, Shu Yuan men shopping district's wind speed is stronger than Xiao Zhai, although its site coverage is higher. Because it has less trees in the area and its average building height is lower than Xiao Zhai.

In **Figure 12**, it shows the air temperature of three areas. We can see Xiao Zhai's temperature value is lower than other two. Shu Yuan men's average air temperature is 29°C, and it is 1°C higher than Xiao Zhai's and Tang West Market Group. The proposed reason for this is that more plants are built in Xiao Zhai shopping district, and these trees can effectively reduce
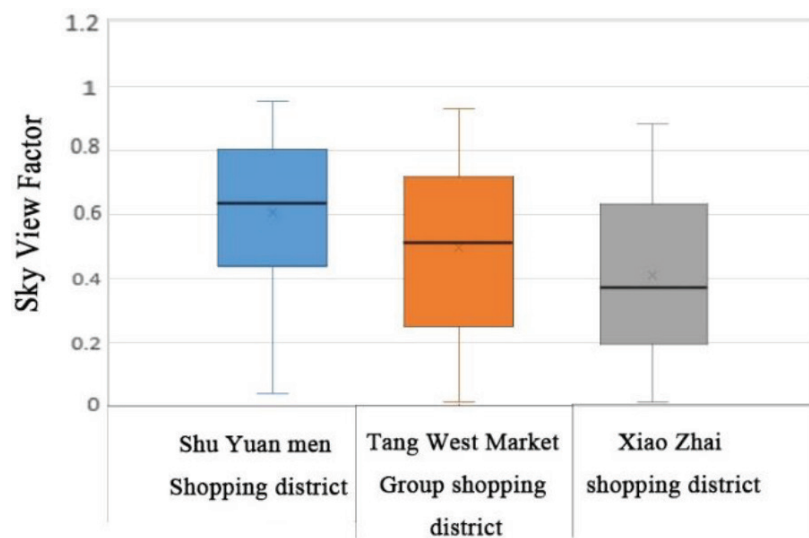
Figure 8. Wind speed distribution in four selected areas at 1.5 m height from the ground in summer (wind speed: 2 m/s; wind direction: EN).
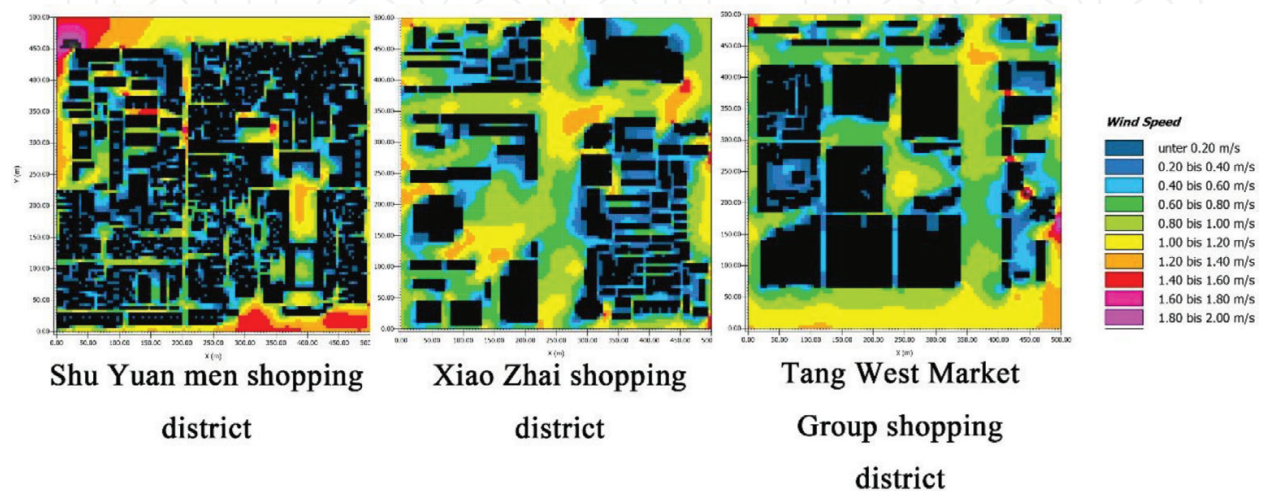

Figure 9. Wind speed distribution in four selected areas at 1.5 m height from the ground in winter (wind speed: 1.25 m/s; wind direction: ENN).

the air temperature in the area. Because the green plants mainly reduce the environment temperature by shadow and evapotranspiration. Through the role of the cover plants, two buildings 'walls and roof surface' temperature can be reduced by 11–25°C [14]. Moreover, the high-temperature area in Shu Yuan men is larger than others because it has less vegetation in the area. This is to say, tree planting in the urban area is providing contribution on wind speed and air temperature reducing, and it can enhance thermal comfort.

In **Figures 10** and **13**, we can see the SVF images of three study areas. View factor is a geometric ratio, which is a part of radiation from the surface A blocked by object B [15]. Unger studied on the 35 city areas for 0.25 km² in Hungary Szeged and proved the SVF closely related to the intensity of thermal environment in the microenvironment, which existed a good linear relationship [16]. As the SVF increases, heat intensity decreases [17]. The average of Xiao Zhai shopping district's SVF value is 0.36, but in Shu Yuan men is 0.52 and in Tang West Market Group is 0.45. Therefore, the SVF of Shu Yuan men is the highest of the three.

Figure 10. Sky view factor in the three shopping districts.

Figure 11. Wind speed distribution in the middle of a summer day (22nd July, 2016) at 1.5 m height.
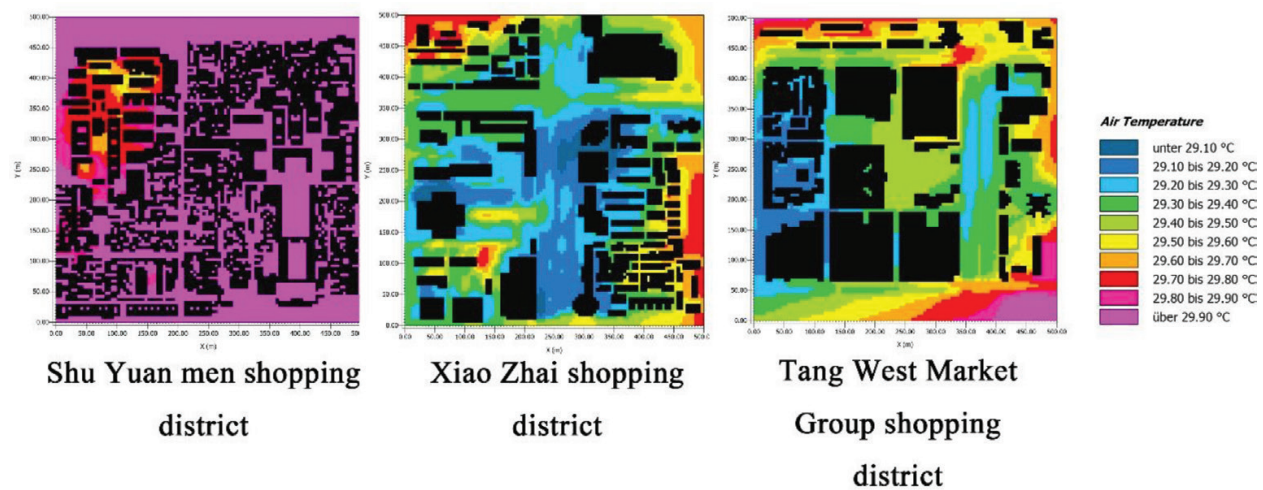
Figure 12. Air temperature distribution in the middle of a summer day (22nd July, 2016) at 1.5 m height.
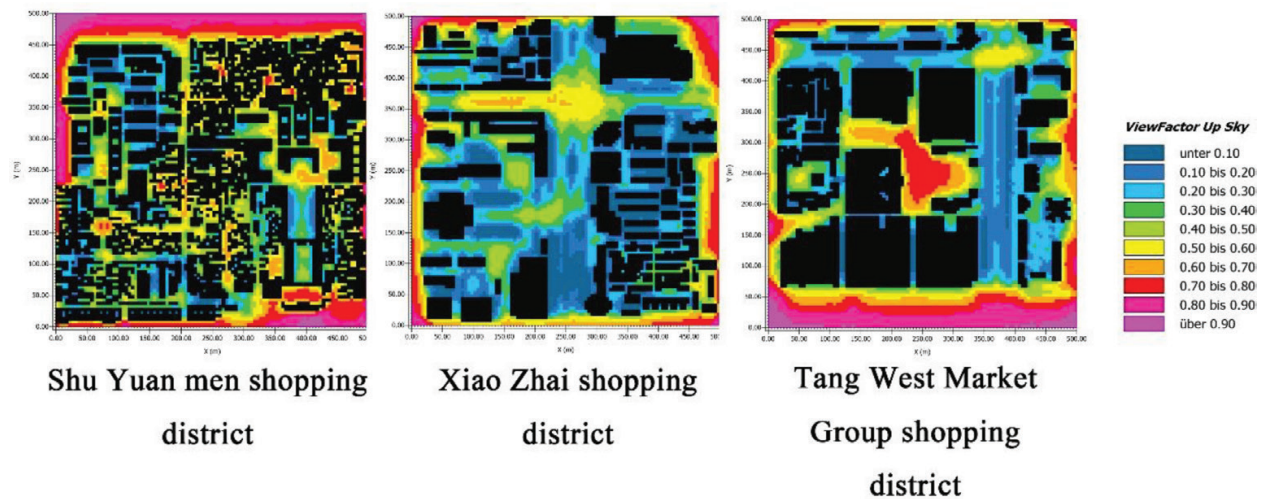

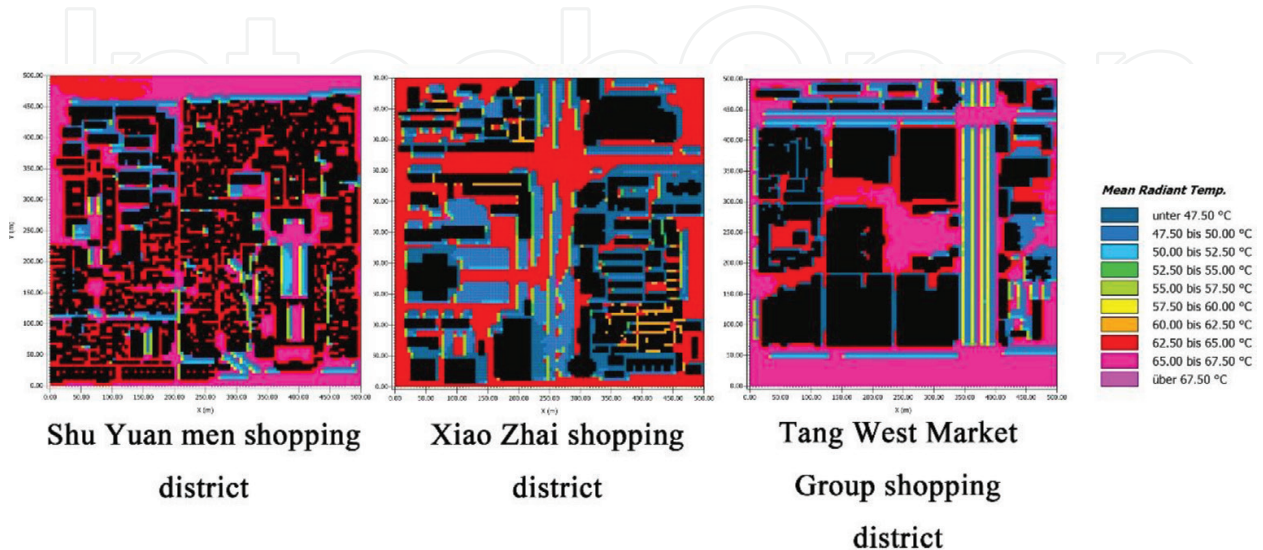**Figure 13.** Sky view factors in the middle of a summer day (22nd July, 2016) at 1.5 m height.

Figure 14. Mean radiant temperature in the middle of a summer day (22nd July, 2016) at 1.5 m height.

This is because the high building density creates deeper urban canopy, and less vegetation in this area model makes more open space. Therefore in Tang West Market Group, we also can see a high numerical concentration in the central area, which is an open square. However, in Xiao Zhai, although there are many open spaces in the area, there are a lot of plants that cover them. Therfore, its SVF value is the lowest of three districts.

In **Figure 14**, these are results of mean radiant temperature in three areas. In these images, we can see that lower values mainly concentrate in the green plants area in the shopping district, and higher values is in the other spaces without vegetation.

4. Discussion

Urban ventilation plays an important role in the urban environment. In summer, urban ventilation contributes to urban heat dissipation and urban heat island mitigation. In winter, high wind speed accelerates the aggregation of air pollution. Results demonstrated that the urban typology affects urban ventilation and urban air quality. However, it is usually difficult to change the urban form over a short period in areas that have already been developed.

Most of China's cities have undergone fast economic growth, urban expansion, and urban redevelopment. This unique situation is the reason of the rapid environmental degradation in Chinese cities, which could also be useful to the other countries. The fast change in form in China's urban areas has provided an opportunity to optimize urban environments in short periods. This requires an urgent establishment of related policies to regularize environmental urban development and redevelopment.

5. Conclusion

This work demonstrated that the wind environment in the low-rise area and the high-rise area are characterized by high building density and the pronounced urban roughness. Wind speed was 0.04–0.09 m/s lower in the high-rise area than in the middle-rise area and 0.04–0.14 m/s lower in the low-rise area than in the middle-rise area. Wind speed is 0.19–0.27 m/s lower in the high-rise area than in the mixed-rise area and 0.21–0.28 m/s lower in the low-rise area than in the mixed-rise area. Overall, the balance between building height and building ratio should be considered in future urban development projects. The information from this work provides information useful to the cultivation of environmental urban policy.

Overall, high-density urban residential and commercial development is providing a big impact on the urban wind environment and urban thermal environment. While this gives hints for UHI mitigation during the day, and it creates physical obstacles for heat release during the nights. A lower SVF reduces the urban radiation absorption from the Sun, but also reduces the outgoing longwave radiation from the urban surfaces. The spread of air pollution is affected by the wind turbulence around high buildings. Future studies should consider more details of the layout and volume of high-rise buildings in urban development projects

to reduce urban climate change. The results of this study provide clues for related environmental urban development mechanisim in Chinese cities as well as in the other cities in all over the world.

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