Urban Morphological Parameters of the Main Cities in China and Their Application in the WRF Model

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Abstract As one of the effective ways to study urban climate and environmental problems, the performance of numerical model could be improved in urban areas by enhancing the description of urban morphology. One of the largest challenges faced by researchers is the lack of real urban canopy parameters (UCPs) to represent urban morphological characteristics. In this study, the urban morphological parameters were estimated and a high-resolution urban morphological parameter data set for the main cities in China was developed. The results show that the distribution of urban morphological parameters is of regional characteristics and cities in China are mainly dominated by low-rise buildings. Chinese cities can be broadly divided into two types based on the probability distribution of building height: single-peak and double-peak. The number of low-rise buildings in single-peak cities is much larger than that of double-peak cities, which contributes to the difference between the two types of cities. The equivalent street width of northern cities in China is higher than that of southern cities, and the equivalent building width is almost the same. However, the default UCPs of the Weather Research and Forecasting (WRF) model distort the morphology of Chinese cities. The sensitivity of the WRF model to urban morphological parameters was also investigated in Nanjing. Overall, our results indicate that urban morphological parameters have a significant influence on the energy balance process in cities and improve the performance of the WRF model in simulating the air temperature and canopy wind speed.

Plain Language Summary The urban morphological parameters are important for simulation in urban areas using numerical models. In this study, we develop a data set of the urban morphological parameters for the main cities in China. The regional characteristics of urban morphological parameters in China are summarized, and we find that Chinese cities can be divided into two types: single-peak cities and double-peak cities. The sensitivity of the urban canopy parameterization schemes of Weather Research and Forecasting (WRF) to the new data set is also investigated. The urban morphological parameters can significantly improve the performance of WRF in simulations of wind speed and temperature in urban areas compared with the default values in WRF.

1. Introduction

With the rapid development of the economy, the world population has been rapidly gathering in cities during the last half century. The number and size of cities have ushered in a period of explosive growth. Currently, more than half of the planet’s population lives in urban areas, and the urban population is projected to reach 6.7 billion by 2050 (Nations et al., 2019). As a product of the human transformation of nature, the complex spatial and physical properties of the underlying surface of a city are obviously different from those of the natural underlying surface (extensive impervious surface, shadowing of the buildings, and trapping of radiation caused by buildings). Coupled with the heat and pollution generated by human activities, cities have a significant impact on the local climate. With ever-increasing urban populations, a series of climatic and environmental issues have become apparent, such as urban heat islands (UHIs), air pollution and extreme weather (Miao et al., 2009; Wang et al., 2016; C. L. Zhang et al., 2009). As one of the important methods of solving the above issues, regional climate models play a very important role in understanding the complex interactions of urban surfaces and the atmosphere so that scientific and reasonable suggestions could be provided for urban planners (Y. Li et al., 2017; H. Zhang et al., 2016).
The urban canopy model is an important tool used to parameterize the process of exchange between the urban underlying surface and atmosphere above. The Weather Research and Forecasting (WRF) model developed by NCEP and NCAR is the most commonly used mesoscale numerical model that has been widely employed in simulations of urban meteorological environments (Grimmond et al., 2010; Millstein & Menon, 2011; Skamarock et al., 2005; Susca et al., 2011). There are currently three urban canopy schemes in WRF, including the single-layer urban canopy model (SLUCM), BEP (the building effect parameterization) and BEP + BEM (a simple building energy model coupled with BEP). The SLUCM hypothesizes that urban areas are composed of infinitely long street canyons assuming buildings have the same architectural form and recognizes the three-dimensional nature of urban surfaces (Kusaka et al., 2001, 2004). SLUCM calculates the surface temperature of roofs, walls, and roads based on the surface energy budget and considers the drag effect of the canyon. In BEP and BEP + BEM, urban grid cells are assumed to be composed of an array of buildings that are located at the same distance and have the same building width but different building heights (Martilli et al., 2002). The BEP divides the building into several levels and calculates momentum and heat fluxes at each level. The BEP accounts for the impacts of horizontal (roofs and streets) and vertical (walls) urban surfaces on the prognostic momentum, heat, and turbulent kinetic energy (TKE) flux and considers the impact of radiative shadowing and trapping effects on the surface energy balance but does not take the AH into account (Gutiérrez et al., 2015). The BEP + BEM scheme adds a simple BEM based on the BEP scheme to improve the estimation of energy exchanges between the building interior and the outdoor environment (Salamanca et al., 2010). The impact of human activities and air conditioning (AC) on the outdoor atmosphere could be dealt with reasonably by the BEP + BEM scheme.

Research has found that urban canopy parameterization schemes have important impacts on the simulation of UHIs, boundary layer structure and summer precipitation in urban areas, which are heavily affected by the urban morphology determined by urban canopy parameters (UCPs) (Kusaka et al., 2004; D. Li et al., 2013; Miao et al., 2009; Monaghan et al., 2014; Otte et al., 2004; Salamanca et al., 2011). Although three urban canopy schemes have simplified urban morphology to varying degrees and WRF has provided default UCPs, urban morphological characteristics vary among cities. The unified parameters obviously cannot represent the morphological characteristics of all cities. Therefore, the establishment of the data set that contains urban morphological parameters of different cities is of great significance for improving the simulation performances of the WRF model in urban areas. For that purpose, the National Urban Database and Assess Portal Tool (NUDAPT) and World Urban Database and Access Portal Tool (WUDAPT) were proposed (Ching, 2007; Mills et al., 2015). NUDAPT provides UCPs that were gridded at 1 km, as needed by climate models for 44 cities in North America. These parameters well represent the morphological characteristics of buildings on the grid scale and enhance the performance of numerical models in urban areas compared with the default UCPs of WRF (Fei Chen, 2007; He et al., 2019; Wong et al., 2019). However, such high-resolution datasets of 3-D UCPs are rarely available for cities outside the United States, especially in China. As the region with the fastest urbanization progress in recent decades, the establishment of the high-resolution urban morphological parameter data set of Chinese cities has an important role in promoting urban climate research in China. Research on the urban morphological parameters of Chinese cities has been carried out, and high-resolution urban morphological parameters have been found to improve simulations of air temperature and wind speed in urban areas, especially for multilayer urban canopy schemes (He et al., 2019; Wong et al., 2019). However, the existing research in Chinese cities is only focused on an individual city or a limited area, no research about the characteristics of urban morphologic parameters of main Chinese cities was carried out. And the discussion of influence mechanism of UCPs on urban climate is also very lacking.

In this study, the first high-resolution data set which contains the urban morphological parameters for 60 main Chinese cities was developed. We also investigated the statistical characteristics of main Chinese cities and found that the urban morphology of Chinese cities has obvious regional distribution characteristics. And the suggested values of UCPs for Chinese cities are given based on the regional distribution characteristics. Nanjing was taken as an example to examine the sensitivity of the WRF model to high-resolution urban morphological parameters. And we also preliminarily investigated the influence mechanism of UCPs on the related physical processes in urban area.
2. Data and Methods

2.1. Estimation of Building Height

Building height data in Chinese cities are difficult to obtain, especially on a nationwide scale. In this study, the detailed vector-format building floor number data of 60 main cities in China (http://www.resdc.cn/data.aspx?DATAID=270) were used to estimate the urban morphological parameters. These data include polygons with a series of attributes (e.g., the floors and footprint outline of the building, the area and perimeter of the building base, etc.) for each building. Considering that numerical models generally use building height as data input instead of floors, it is necessary to convert floor number to building height. Based on Chinese building standards, the floor height of residential buildings is generally 3 m but low-rise buildings in China usually have an insulation layer on top of the building, which would increase the average floor height of low-rise buildings. In addition to the impact of the insulation layer of low-rise buildings, nonresidential low-rise buildings (large shopping malls, office buildings, etc.) also have high floor heights. Such buildings generally have fewer floors, but the height of each floor is significantly larger than that of residential buildings, so the average floor height of low-rise buildings is increased. Table 1 shows the average floor height varying with the building floors in the Xinjiekou area (the building height was measured by drone-mounted lidar). The average floor height of buildings above six floors is concentrated at 3 m, and the deviation is mainly located in buildings below six floors whose floor height distribution span is relatively large and the median floor height is ∼3.5 m. Buildings with more floors are commonly residential buildings that are built in recent decades according to current national standards, and their floor heights are almost the same (∼3 m). There are also some nonresidential high-rise buildings with larger floor height, but the proportion is very small. Therefore, we take the average floor height of buildings below six floors as 3.5 m and the rest as 3 m to convert the building height.

To evaluate the accuracy of the estimated building height, we use drone-mounted lidar observation data with a spatial distribution of building height with a 1 m resolution for a typical central business district (CBD) and a residential area to verify the estimations. Figure 1 shows the horizontal distribution of building floor and building height of CBD and residential area in Nanjing. Overall, the spatial distribution of building height and building floor are in good agreement. We compared the average building heights with the estimated building heights in CBD and residential area (Figure 2). The estimated building heights agree well with the real building heights for buildings below 25 floors. But for the high-rise buildings in CBD (buildings over 25 floors), we slightly underestimated the building height (about 10 m). Due to the small proportion of the high-rise building (less than 5%), this estimation error is acceptable for the mesoscale and regional climate simulations.

### Table 1

| Floor height (Unit: m) | 1–5 | 6–10 | >10 |
|------------------------|-----|------|-----|
| Mean                   | 3.1 | 3.8  | 3.0 |
| Median                 | 3.0 | 3.6  | 3.0 |
| SD                     | 1.6 | 1.8  | 0.7 |

### Table 2

| Urban morphological parameters | FRC_URB |
|--------------------------------|---------|
| Glandahl urban canopy parameterization scheme | Glotfelty et al., 2013 |

2.2. Calculation Methods of Urban Morphological Parameters

In this study, cities were divided into grids of 1 km resolution (which can also be divided into other resolutions as needed) to calculate the urban morphological parameters. Referring to the definition in WRF, we took the grids whose impervious surface coverage (FRC_URB) was no less than 0.5 as urban land use, and the impervious surface data were from FROM-GLC10 (Gong et al., 2019). Table 2 lists the urban morphological parameters used in the WRF model and the urban canopy parameterization schemes to which they apply (Glotfelty et al., 2013).

The mean and standard deviation of building height are calculated as follows:

\[ \bar{h} = \frac{\sum_{i=1}^{N} h_i}{N} \]  

\[ s_h = \sqrt{\frac{\sum_{i=1}^{N} (h_i - \bar{h})^2}{N - 1}} \]
where $\bar{h}$ is the mean building height, $s_h$ is the standard deviation of building height, $h_i$ is the height of building $i$, and $N$ is the total number of buildings in a grid.

The average building height weighted by building plan area ($h_{AW}$) is calculated using the following equation:

$$h_{AW} = \frac{\sum_{i=1}^{N} A_i h_i}{\sum_{i=1}^{N} A_i}$$  
\hspace{1cm} (3)

where $A_i$ is the plan area on the ground level of building $i$, and $h_i$ is the height of building $i$.

The building plan area fraction ($\lambda_p$) is defined as the ratio of the plan area of buildings to the total surface area of the study region:

$$\lambda_p = \frac{A_p}{A_T}$$  
\hspace{1cm} (4)

where $A_p$ is the plan area of buildings at the ground level, and $A_T$ is the total plan area for the region of interest.

Figure 1. Spatial distribution of (a) building floor, (b) building height of the central business district (CBD) area, (c) building floor and (d) building height of the residential area in Nanjing (unit: m).

Figure 2. Comparison of the average real building heights with the estimated building height in the central business district (CBD) and residential area in Nanjing (the black solid line is the estimated building height and the column is the difference between the estimated building height and the real building height).
### Table 2
Urban Morphological Parameters Used in the WRF Model and the Applied Urban Canopy Parameterization Schemes

| Urban morphological parameters | Applied urban canopy schemes |
|-------------------------------|-----------------------------|
| Mean building height          | SLUCM                       |
| Standard deviation of building height | SLUCM                       |
| Area weighted mean building height | SLUCM, BEP, BEP + BEM      |
| Plan area fraction            | SLUCM, BEP, BEP + BEM      |
| Building surface to plan area ratio | SLUCM, BEP, BEP + BEM  |
| Frontal area index            | SLUCM                       |
| Distribution of building heights | BEP, BEP + BEM            |

Abbreviations: BEM, building energy model; BEP, building effect parameterization; SLUCM, single-layer urban canopy model; WRF, Weather Research and Forecasting.

The building surface area to plan area ratio ($\lambda_b$) is defined as the sum of building surface area divided by the total plan area:

$$\lambda_b = \frac{A_p + A_w}{A_T}$$  \hspace{1cm} (5)

where $A_p$ is the plan area of rooftops, $A_w$ is the total area of nonhorizontal roughness element surfaces (e.g., walls), and $A_T$ is the total plan area for the region of interest.

The frontal area index ($\lambda_f$) is defined as the total area of buildings projected onto the plane normal to the approaching wind direction ($A_{proj}$) divided by the plan area of the study site($A_T$):

$$\lambda_f(\theta) = \frac{A_{proj}}{A_T}$$  \hspace{1cm} (6)

where $\theta$ is the wind direction. The $\lambda_f(\theta)$ value for each grid cell in this study is determined for northerly, northeasterly, easterly and southeasterly winds, and it is expected that opposite wind directions (e.g., north and south) have nearly identical frontal area indices.

### 3. Analysis of the Characteristics of Urban Morphological Parameters in China

The territory of China is very vast, and the distribution of city numbers and urban population shows certain regional characteristics due to the terrain conditions and climate background. There are two important geographical dividing lines in China (“Heihe-Tengchong Line” and “Qinling-Huaihe Line”). The Heihe-Tengchong (from Heihe, Heilongjiang Province to Tengchong, Yunnan Province) Line is used to represent the population distribution of China (Yue et al., 2003). The high-density populated area (region II: southeast to the line, Figure 3) covers ~40% of the territory of China but is inhabited by more than 90% of the population where the urban population is much larger than the low-density populated area (region I: northwest to the line). The Qinling-Huaihe Line is recognized as an extremely important north-south geographical demarcation line in China and is often used to divide the northern and southern regions. A preliminary analysis of the urban morphological parameters of Chinese cities shows that there are also large differences in urban morphology in addition to the differences in the urban population. As seen in Figure 3, Chinese cities are mainly located on the southeast side of the Heihe-Tengchong Line (region II), and the average height, median height and mean standard deviation of urban buildings all show the pattern that the south (region S) is larger than the north (region N). This conclusion is consistent with the result obtained through remote sensing (M. M. Li et al., 2020). The average height and median height of urban buildings can characterize the overall height of the city, while the average standard deviation of building height can represent the discretization of building height, i.e., the height span size of buildings. In 60 main cities, the average height, median height and mean standard deviation of buildings of Lhasa are the smallest (6.4, 6 and 2.5 m, respectively), indicating that Lhasa's building height is relatively uniform, and mostly comprises low-rise buildings. In contrast, the values that characterize Hong Kong’s building height are the largest except for the median height (the second largest), which are 23.3, 15 and 24.1 m, respectively, indicating that there are more tall buildings in Hong Kong.

In addition to the difference in the spatial distribution of building height, the urban morphological parameters of different cities also show different characteristics. The spatial distribution of the building plan area fraction ($\lambda_p$), building surface area to plan area ratio ($\lambda_b$), and frontal area index ($\lambda_f$) is shown in Figure 4. The building plan area fraction of cities in region I and the southeast coastal area is larger than that of other regions. Cities in these regions are commonly surrounded by mountains or coastline, so the urban expansion was limited. The buildings in these cities usually densely distributed, which results to the large building plan area fraction. The average value of the Pearl River Delta is the largest among the three major urban clusters, the second largest is the Beijing-Tianjin-Hebei Region, and the smallest
is the Yangtze River Delta. The distribution characteristics of building surface area to plan area ratio are similar to those of building plan area fraction. The top three cities with the largest $\lambda_b$ are Macao, Hong Kong and Shantou (1.2, 0.8 and 0.7, respectively). Overall, $\lambda_b$ of cities in southeast coastal area and western China are larger than those of other regions. The analysis of the frontal area index of 60 main cities in China shows that there is little difference among the frontal area indices for different directions in Chinese cities, which indicates that the shapes of buildings in China are relatively uniform and the morphologies of all directions are almost the same, so the average frontal area index is used to represent the characteristics of building frontal area in China (Figure 4c). The frontal area index is related to the building height and building density. Considering daylighting and ventilation in urban area, the building height and building density are usually negatively correlated. Therefore, the difference of the average frontal area index between cities is small. There is little difference in the frontal area index of Chinese cities except for the cities of Shantou, Hong Kong, and Macao. They are the top 3 in terms of frontal area index. Because the buildings in these cities are not only tall but also densely distributed. Both of them would induce the high frontal area index.

The spatial distribution of building height weighted by building plan area ($h_{AW}$) of 60 main cities in China is shown in Figure 5, which represents the ratio of the volume to the plan area of buildings in urban grids. The spatial distribution of building height weighted by building plan area and average height of buildings have a strong consistency, which indicates that there is no big difference in the plan area between short and tall
To further illustrate this phenomenon, the difference between $\bar{h}_{AW}$ and $h_{mean}$ is used to reveal the difference between short and tall buildings. The result shows that there are 51 cities with a difference of less than 1 m, and only Hong Kong has a difference of more than 3 m, indicating that there is no big difference in the building plan area in most Chinese cities.

To obtain the building height distribution of Chinese cities, we have conducted statistics on the building floor distribution for 60 main cities in China. In the 60 main cities, the probability distribution of the building floor can be divided into two types: single-peak and double-peak. The probability distributions of the building floor of two typical cities are shown in Figure 6. The buildings of a single-peak city are concentrated at two floors, the probability decreases with the floor, and the proportion of high-rise buildings is small. The double-peak city has another peak at six floors apart from the peak at two floors. Combined with the floor distribution of the two types of cities, the buildings in Chinese cities are mainly low-rise buildings, the proportion of high-rise buildings is relatively small, and most of the buildings are located at less than 12 floors (~40 m). According to the definition of two types of cities based on the distribution of building floors, these 60 main cities can be divided into two groups (29 single-peak cities and 31 double-peak cities). Figure 7 shows how the number of buildings in two types of cities varies with the building floor. It is obvious that there are significant differences between single-peak cities and double-peak cities. The average number of buildings of single-peak cities is much larger than that of double-peak cities (single-peak: 105,000; double-peak: 68,000). The differences between the two types of cities are mainly reflected in buildings below
10 floors, especially low-rise buildings, and there is little difference in the buildings above 10 floors, indicating that low-rise buildings are the main reason for the different types of cities.

The spatial distribution of the urban type of 60 main Chinese cities is shown in Figure 8. Overall, cities in northern China are mainly double-peak cities, but southern China and the southeastern coastal area are dominated by single-peak cities. The cities in the Beijing-Tianjin-Hebei and Pearl River Delta region are mainly single-peak, and the cities in the Yangtze River Delta region and southwestern China are mainly double-peak. The differences between single-peak cities and double-peak cities are also obviously reflected in the urban morphological parameters. Table 3 gives the comparison of the main urban morphological parameters of the two types of cities. As seen from Table 3, the average height of buildings (h$_{mean}$), median height of buildings (h$_{median}$) and building height weighted by building plan area ($h_{AWh}$) of single-peak cities are less than those of double-peak cities, while the mean standard deviation (h$_{sd}$) of single-peak cities is greater than that of double-peak cities. Meanwhile, the building plan area fraction ($\lambda_p$), the building surface area to plan area ratio ($\lambda_b$) and the frontal area index ($\lambda_f$) of single-peak cities are greater than those of double-peak cities.

Combined with the above analysis, the morphology of Chinese cities can be divided into two types based on the distribution of building floors: single-peak and double-peak. There is little difference in high-rise buildings between the two types of cities, and the difference is mainly reflected in the low-rise buildings. The number of low-rise buildings in single-peak cities is much larger than that of double-peak cities, causing the differences in urban morphological parameters between the two types of cities. The reasons for the different distributions of building floor numbers are complicated, but the proportion of low-rise buildings is closely related to the development history of cities. Generally, low-rise buildings account for a lower percentage in cities with a short urbanization period but with fast urbanization speed. These cities are mostly double-peak (e.g., Shenzhen). Nevertheless, cities with long history, expanded at a lower rate, their main bodies were low-rise buildings. Therefore, those cities are usually single-peak (e.g., Guangzhou).
4. Representative Analysis of the Default Urban Canopy Parameters in WRF for China

There are currently three urban canopy schemes in WRF: SLUCM, BEP and BEP + BEM. Compared with SLUCM, BEP and BEP + BEM are closer to the real situation in a city in the assumption of urban morphology. Some studies have found that the simulation of temperature and wind speed in urban areas employing multilayer urban canopy schemes is more accurate than the single-layer urban canopy scheme, but there is still some error compared with the observations (He et al., 2019; Liao et al., 2014; Salamanca et al., 2011). Due to a lack of real UCPs, WRF provides the default value of UCPs by look-up tables. After adopting the actual local UCPs instead of the default parameters in WRF, the simulation of the temperature and wind speed in urban areas was improved, which indicates that the current default UCPs in WRF cannot represent the real urban morphology well in China (He et al., 2019; Shen et al., 2019; Wong et al., 2019). For the urban canopy schemes in WRF, the most important parameters representing the urban morphology are street width, building width, and building height, which directly affect the calculation of radiation processes in urban canopy and then affect the energy balance in urban areas. The average building height in China shows a pattern where the southern area is greater than the northern area, so the fixed value of building height given by WRF obviously cannot represent the actual building height in the cities in China. In addition to building height, street width and building width also have important impacts on energy balance calculations in urban canopy. However, related research evaluating the representativeness of default street width and building width in WRF has not been carried out.

The default values of street width (sw) and building width (bw) in multilayer urban canopy schemes in WRF are set as follows: the street width and building width of low-density residential areas are 30 and 13 m, respectively; the street width and building width of high-density residential areas are 25 and 17 m, respectively, which are both 20 m for commercial areas. The building height required for urban canopy schemes in WRF are set as follows: the street width and building width of low-density residential areas are 30 and 13 m, respectively; the street width and building width of high-density residential areas are 25 and 17 m, respectively, which are both 20 m for commercial areas. The building height required for urban canopy schemes is easy to obtain through the high-resolution urban morphological parameter database established in this study, and the street width and building width can also be replaced by the equivalent street width and building width of each grid calculated by the urban morphological parameters (Shen et al., 2019).
width and building width is shown in Figures 9a and 9b. The equivalent street width of the northern cities in China is greater than that of southern cities; the eastern area is greater than that of western cities and the southeastern coastal area is smaller than that of inland cities. The span of the equivalent street width of Chinese cities is very large. The equivalent street width of Macao is the smallest (14 m), while Dalian is the largest (60 m). Compared with the average equivalent street width, there is only a small difference among the average equivalent building widths of Chinese cities. The equivalent building width is concentrated at 10–13 m and has no obvious spatial distribution characteristics.

Combined with the analysis of equivalent street width and building width above, we can see that the default values in WRF obviously underestimate the street width but slightly overestimate the building width in Chinese cities. Notably, the street width and building width in this study are estimated as equivalent values

### Table 3

|                | \(h_{\text{mean}}\) | \(h_{\text{median}}\) | \(h_{sd}\) | \(\bar{h}_{AW}\) | \(\lambda_{p}\) | \(\lambda_{b}\) | \(\lambda_{f}\) |
|----------------|----------------------|------------------------|------------|-------------------|-----------------|-----------------|-----------------|
| Single_peak    | 13.1                 | 9.0                    | 18.2       | 14.5              | 0.17            | 0.66            | 0.08            |
| Double_peak    | 14.2                 | 10.3                   | 13.4       | 15.1              | 0.11            | 0.41            | 0.06            |

**Figure 9.** The spatial distribution of (a) the average equivalent street width, (b) the average equivalent building width and (c) the average sky-view factor in the main Chinese cities (the blue line is the Heihe-Tengchong Line and the green line is the Qinling-Huaihe Line, unit: m).
that depend on the assumption of urban morphology. There are two commonly used urban morphology assumptions: the two-dimensional street canyon assumption and the three-dimensional matrix assumption. The two-dimensional street canyon assumes that buildings and streets are parallel and independent of each other, while the three-dimensional model assumes buildings in a grid-like distribution with orthogonal streets between the buildings. Martilli (2009) compared the sky-view factors (street-to-sky) computed for the 2D and 3D simplified morphologies with the sky-view factors derived from real data, and found that the 2D simplified morphology seems to be a better representation of the real morphology. Figure 9c gives the spatial distribution of average sky-view factor of main cities in China. The sky-view factors of western cities and southeastern coastal area are smaller than that of northern cities and cities of Yangtze River Delta.

To further evaluate the applicability of default street width and building width in WRF in China, three major cities (Beijing, Shanghai, and Guangzhou) were taken as examples to reveal the features of street width and building width in different urban categories. Table 4 shows the estimated equivalent building width and street width of different urban categories in Beijing, Shanghai, and Guangzhou based on different urban morphology assumptions. There is little difference in the equivalent building widths in different urban categories, and the equivalent building widths in different cities are almost the same. However, the estimated equivalent street width shows greater differences in three aspects: between cities, between urban categories, and between different urban morphology assumptions. The locations of Beijing, Shanghai, and Guangzhou are from north to south geographically, and the corresponding equivalent street width is also descending, which is consistent with the feature of equivalent street width for Chinese cities mentioned above. The three urban categories are divided based on the coverage of impervious surfaces. $\lambda_p$ and $\lambda_b$ show an increasing trend with increasing impervious surface coverage, but the equivalent street width is opposite which agrees with the default values in WRF. The equivalent street widths estimated according to different urban morphology assumptions vary greatly among the three cities, especially in Beijing where the difference is nearly 30 m. Because there is much urban open space in Beijing contributing to a large equivalent street width estimated on the two-dimensional street canyon assumption. Notably, the $h_{AW}$ of business districts is smaller than residential districts in Beijing and Guangzhou, which may be caused by the inappropriate threshold of FRC_URB during the definition of urban categories. This finding also reflects that the classification of urban categories in WRF is not applicable in some cities and that the representation of the urban morphology in WRF still needs to be improved.

On the urban scale, the equivalent building width and street width of Chinese cities show certain regional characteristics. The default fixed building width and street width in WRF cannot accurately represent the spatial distribution of urban street width and building width in China. Overall, WRF significantly
underestimates the urban street width but overestimates the building width. WRF is poorly representative of urban morphology in China.

Based on the regional distribution characteristics of urban morphological parameters of 60 main cities in China, we simply divided China into three regions (Region 1: western of the Heihe-Tengchong Line, Region 2: southern coastal area and Region 3: eastern of the Heihe-Tengchong Line and northern of the Yangtze River Delta). And the suggested urban morphological parameters for each region are given in Table 5.

### 5. Analysis of the Sensitivity of Urban Canopy Schemes in WRF to High-Resolution Urban Morphological Parameters

In the WRF model, the required urban morphological parameters vary with urban canopy schemes. To explore the sensitivity of the urban canopy schemes to the high-resolution urban morphological parameters, WRF simulations were performed for 8 clear-sky days (from 0800 LST July 25, 2017 to 0800 LST August 2, 2017) in Nanjing. As shown in Table 6, six WRF numerical experiments were conducted with three different urban canopy parameterizations. The only difference between the default cases and UCP cases is that urban morphology parameters were assigned based on the look-up table or were determined by the gridded data set of urban morphological parameters, as documented in Table 2 (the default urban canopy parameters used in WRF and UCP cases were shown in the Supporting Information, Table S1). All the simulations have three two-way nested domains (Figure 10a) centered at 32.06°N, 118.8°E with horizontal grid spacing of 9, 3, and 1 km. The grid point dimensions were 100 × 100, 88 × 88, and 100 × 100. The vertical coordinate contains 43 sigma levels form the surface to 50 hPa. Simulations were conducted with the initial and boundary conditions provided by data from the National Center for Environmental Prediction operational Global Final Analyses at a horizontal resolution of 0.25° × 0.25°. We also updated the urban fraction of the underlying surface of Nanjing based on the impervious surface coverage data from FROM-GLC10. To remove the influence of nonurban area impervious surfaces on WRF simulations, we only updated the data for urban grid cells in the default MODIS data set of WRF. The physical parameterization schemes used in these simulations are listed in Table 7.

The spatial distributions of $\lambda_p$, $\lambda_b$, and impervious surface coverage (FRC_URB) are shown in Figure 10. Figure 11 gives the building height probability distribution of Nanjing. The maximum values of $\lambda_p$ and $\lambda_b$ are located in the city center, indicating that the building surface of the city center is the largest. The main contribution of the building surface of the city center comes from low-rise buildings because the proportion of low-rise buildings in the city center was significantly larger than that in other areas (buildings below 10 m accounted for more than 50%). The number of buildings in the city center of Nanjing is far greater than that in other areas, contributing to a larger building density in the city center. The buildings above 20 m are mainly located in the outer areas of Nanjing (Figures 11d–11f), which explains why $h_{AW}$ has a large value in the outer areas of Nanjing (Figures 11h).

The complete building surface plays an important role in the urban energy balance process. When the urban impervious surface coverage is fixed, the complete building surface derived from SLUCM is mainly affected by the average building height, while BEP and BEP + BEM are determined by the probability distribution

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### Table 5

| Region | Urban_category | BW   | SW   | H_mean |
|--------|---------------|------|------|--------|
| 1      | Low density residential | 10.7 | 43.0 | 7.9    |
|        | High density residential | 9.8  | 34.0 | 11.1   |
|        | Commercial     | 10.5 | 32.0 | 14.2   |
| 2      | Low density residential | 10.6 | 41.5 | 12.4   |
|        | High density residential | 10.8 | 34.0 | 13.1   |
|        | Commercial     | 11.7 | 33.2 | 12.2   |
| 3      | Low density residential | 10.9 | 57.9 | 11.4   |
|        | High density residential | 10.9 | 48.4 | 14.3   |
|        | Commercial     | 11.1 | 43.8 | 13.4   |

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### Table 6

| Urban canopy model | Default cases | UCP cases |
|--------------------|---------------|-----------|
|                    | SLUCM_DEF     | BEP_DEF   | BEM_DEF   |
|                    | SLUCM_UCPs    | BEP_UCPs  | BEM_UCPs  |
| UCPs               | Look-up table | Look-up table | Look-up table |
|                    | GriddedUCPs data set | Gridded UCPS data set | Gridded UCPS data set |

Abbreviations: BEM, building energy model; BEP, building effect parameterization; SLUCM, single-layer urban canopy model; UCPs, urban canopy parameters.
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of building height. SLUCM normalizes the street canyon width (the sum of street width and building width) equal to 1 and the street width, building width and building height are treated as their proportions of the street canyon width. Figure 12 shows the horizontal distribution of the difference in the complete building surface between the UCP case and the default case (SLUCM is expressed by the difference in the normalized building height). To further investigate the sensitivity of WRF urban canopy parameterization schemes to UCPs, two regions with a large difference in complete building surface between the UCP case and the default case were selected as examples. Region 1 is the city center whose average building height and complete building surface of UCP cases are both larger than those of the default cases, and region 2 is the opposite.

Figure 10. (a) Configuration of two-way nested domains for Weather Research and Forecasting (WRF) simulations; the spatial distribution of (b) building plan area fraction (dimensionless); (c) building surface area to plan area ratio (dimensionless); and (d) impervious surface coverages (dimensionless) in Nanjing.

Table 7
A List of Physical Parameterization Schemes Used in Simulations

| Domains          | d01                                      | d02                                      | d03                                      |
|------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| Longwave radiation| Rapid radiative transfer model scheme (Mlawer et al., 1997) | Duffia scheme (Dudhia, 1988)             |                                           |
| Shortwave radiation|                                          |                                          |                                           |
| Land surface     | Noah land-surface model (Chen & Dudhia, 2001) |                                          |                                           |
| Boundary layer   | BL scheme (Bougeault & Lacarrere, 1989)   |                                          |                                           |
Figure 11. The percentage of building heights (%) with 5 m bins spanning 0–75 m in Nanjing: (a) 5 m; (b) 10 m; (c) 15 m; (d) 20 m; (e) 25 m; and (f) larger than 30 m. The spatial distributions of (g) building number; and (h) area weighted mean building height (m) in Nanjing.
Figure 13 depicts the diurnal cycles of averaged 2-m surface air temperature and canopy wind speed in region 1 and region 2 from 0800 LST July 31, 2017 to 0800 LST August 1, 2017. Since the wind speed observation data comes from the city's automatic weather station which represents the wind speed within the urban canopy and the SLUCM output is the wind speed above the canopy, we have corrected the SLUCM wind speed (Kusaka et al., 2001). As shown in Figure 13, WRF significantly improved the simulation of 2-m surface air temperature and canopy wind speed after employing urban morphological parameters, indicating that WRF is sensitive to urban morphological parameters. The impact of urban morphological parameters on 2-m surface air temperature is mainly reflected in the daytime, but the impact on wind speed within the canopy is throughout the day. In the city center (region 1), all the default cases tend to underestimate the 2-m surface air temperature during the daytime, especially the BEP_DEF and BEM_DEF cases. Table 3 shows the evaluation results of simulations against observations. Before applying the urban morphological parameters, SLUCM_DEF simulated the 2-m surface air temperature best among the three schemes in the
city center. After the urban morphological parameters were applied, the mean absolute error (MAE) and root mean square error (RMSE) of 2-m surface air temperature of BEP and BEP + BEM decrease significantly and BEM_UCPs agrees best with observations.

The buildings in the city center (region 1) have complex vertical distribution, but the default parameters in WRF can’t represent this complexity. After applying the real UCPs, BEP and BEP + BEM can better describe the influence of buildings on radiation progress (trapping of radiation, shadowing of the buildings). So, the capabilities of simulation for 2-m surface air temperature of BEP and BEP + BEM are greatly improved in region 1. In region 2, due to the relatively uniform building height distribution, there is no big difference in the simulation of 2-m surface air temperature between UCP cases and default cases.

Overall, the complete building surface of the city center (region 1) is larger than that of the default cases, so the building surface absorbs more solar radiation, which increases the air temperature (region 2 is the opposite). Judging from the simulation of the 2-m surface air temperature of three urban canopy schemes, the improvement in urban morphological parameters on the 2-m surface air temperature of BEP and BEP + BEM is better than that of SLUCM. BEP and BEP + BEM consider the probability density distribution of building height, so they can better describe the influence of buildings on the radiation progress in the urban canopy. SLUCM only considers the influence of the mean building height on the radiation progress but ignores the influence of building height fluctuation. Therefore, the simulation of the 2-m surface air temperature of SLUCM is relatively insensitive to urban morphological parameters.

For the canopy wind speed, urban morphological parameters have the largest increase in the simulation of SLUCM. The MAE and RMSE of canopy wind speed of SLUCM significantly decrease in both region 1 and region 2 (Table 8). This result is because SLUCM_UCPs directly calls the frontal area index ($\lambda_f$), which is related to the surface roughness accounting for the drag effects of buildings, thus overcoming the shortcoming of the WRF model regarding overestimating wind speed in urban areas. Although the MAE and RMSE of SLUCM_UCPs are smaller than SLUCM_DEF, there is no significant improvement in the correlation of wind speed (the correlations are all less than 0.3). This is because of the small standard deviation of building height given by SLUCM. The standard deviation of building height in region 1 and region 2 are 15 and 5 m separately, which are greater than the default value in WRF (3 m). The standard deviation of building height represents the undulation of buildings. The greater the standard deviation of building height, the more conversion of the average wind to the turbulence and result in the attenuation of the wind speed. And

| Simulation cases | T2(°C) | WS(m s$^{-1}$) |
|-----------------|--------|----------------|
|                 | MAE    | RMSE           | MAE    | RMSE           |
| Region 1        |        |                |        |                |
| SLUCM_DEF       | 0.73   | 0.86           | 5.07   | 5.13           |
| SLUCM_UCPs      | 0.73   | 0.85           | 1.22   | 1.39           |
| BEP_DEF         | 1.20   | 1.29           | 3.75   | 3.84           |
| BEP_UCPs        | 0.91   | 1.08           | 2.02   | 2.17           |
| BEM_DEF         | 0.93   | 1.01           | 3.90   | 3.99           |
| BEM_UCPs        | 0.69   | 0.83           | 2.13   | 2.27           |
| Region 2        |        |                |        |                |
| SLUCM_DEF       | 0.85   | 1.19           | 4.48   | 4.54           |
| SLUCM_UCPs      | 0.74   | 1.12           | 1.93   | 2.08           |
| BEP_DEF         | 0.68   | 1.02           | 3.29   | 3.39           |
| BEP_UCPs        | 0.66   | 1.01           | 4.10   | 4.20           |
| BEM_DEF         | 0.72   | 1.13           | 3.45   | 3.55           |
| BEM_UCPs        | 0.65   | 1.06           | 4.10   | 4.30           |

Note. Statistic metrics were averaged for the period from 0800 LST July 31, 2017 to 0800 LST August 1, 2017. Abbreviations: BEM, building energy model; BEP, building effect parameterization; MAE, mean absolute error; RMSE, root mean square error; SLUCM, single-layer urban canopy model; UCPs, urban canopy parameters.
the attenuation increases with increasing wind speed. Therefore, after applying UCPs, the model loses part of its ability to describe the diurnal variation of wind speed.

From the above analysis, we can see that the responses to urban morphological parameters vary from the urban canopy parameterization schemes of WRF. To further investigate the sensitivity of urban canopy schemes to urban morphological parameters, we will separately discuss the impacts of UCPs on the physical processes related to urban areas in different urban canopy schemes.

5.1. Single-Layer Urban Canopy Scheme (SLUCM)

The single-layer urban canopy is composed of roofs, walls, and roads where energy balance equations were established. The urban morphological parameters mainly describe the urban morphology, and the most important impact of urban morphology on the urban energy budget is the radiation process.

From Section 4, we know that WRF underestimates the street width in China, which leads to a reduction in the aspect ratio of urban grids. As the aspect ratio decreases, the trap effect of urban radiation is weakened. More radiation is reflected in the atmosphere above, so the air temperature of urban areas is decreasing. However, in the city center (region 1), the solar radiation received by the walls increases due to the increase in building height which contributes to the increase in air temperature. These two effects cancel each other out, so the difference in surface air temperature between SLUCM_UCPs and SLUCM_DEF is small (Figure 13a). The building heights in region 2 are relatively small, so the heating effect of walls decreases. Due to the lack of the heat from walls, the air temperature of SLUCM_UCPs is lower than that of SLUCM_DEF in region 2 (Figure 13b). In addition, the SLUCM_UCPs cases adopted the frontal area index accounting for the drag effect of buildings on wind in all directions, which significantly improves the simulation of wind speed in urban areas.

5.2. Multilayer Urban Canopy Schemes (BEP, BEP + BEM)

BEP and BEP + BEM consider the effects of vertical (walls) and horizontal (streets and roofs) surfaces on momentum, TKE, and potential temperature on each level within the urban canopy. The real UCPs could provide accurate vertical surfaces and horizontal surfaces so that WRF could better describe the effect of buildings on drag force and heat exchange.

The presence of horizontal surfaces such as roofs or canyon floors induces a frictional force with consequent loss of momentum. And the presence of buildings in urban induces pressure and viscous drag forces on the flow (Martilli et al., 2002). The probability distribution of building height determines the area of horizontal surface and vertical surface at different height. It plays a very important role in the calculation of momentum within the urban canopy. However, the assumption of probability distribution of building height in WRF is inappropriate for most cities in China. The default building height probability distribution of BEP and BEP + BEM is: 10 m–20%, 15 m–60%, and 20 m–20% (without considering buildings above 20 m). It underestimates both low-rise and high-rise buildings in Nanjing.

Figure 14 shows the spatial distribution of the average difference in wind speed from 0800 LST on July 31, 2017 to 0800 LST on August 1, 2017 (BEP_UCPs-BEP_DEF, m/s).

![Figure 14](image_url)
heat exchange, buildings also affect the radiation process within the urban canopy. Figure 15 shows the spatial distribution of the difference in 2-m surface air temperatures between BEP_UCPs and BEP_DEF at 1400 LST July 31, 2017. The simulated 2-m surface air temperature of BEP_UCPs increased in most areas in Nanjing compared with BEP_DEF, and the increase is more obvious in the city center (more than 1.5°C). This result is mainly caused by the difference in the probability distribution of building height. BEP_DEF only considers buildings below 20 m, while the maximum height of the building is set to 75 m in BEP_UCPs, which enhances the radiation trap effect. The city center area absorbs more solar radiation due to the increase in the complete building surface, so the increase in temperature in the city center is larger. In the area where the complete building surface is decreasing, the radiation absorbed by buildings decreases. The decreasing absorption of radiation weakens the warming effect caused by radiation traps.

On the basis of BEP, the BEP + BEM scheme accounts for the generation of heat due to occupants and equipment and the heat from AC. Therefore, the BEM_UCPs can simulate the high air temperature in the city center during the daytime (the heating effect of waste heat generated by AC). The internal temperature of the buildings is kept constant in BEP + BEM, and the heat emitted from buildings to the atmosphere is positively related to the volume of the building. The influence of urban morphological parameters on the simulation of temperature is determined by the volume of buildings (in areas with larger building volumes, ACs emits more waste heat, contributing to a higher temperature). The impact of urban morphological parameters on the wind speed of BEP + BEM is the same as that of BEP, so it will not be described in detail here.

6. Summary and Discussion

In this study, we developed the first data set of high-resolution urban morphological parameters using vector-format building data for the main Chinese cities. By analyzing the characteristics of urban morphological parameters of different cities, the distribution characteristics of cities in China were summarized. The new suitable UCPs for different regions of China were also summarized based on the real UCPs of Chinese cities. The sensitivity of existing urban canopy parameterization schemes to urban morphological parameters was investigated and the applicability of the data set developed here was preliminarily confirmed. The conclusions are described as follows:

1. The distribution of urban morphology in China shows certain regional characteristics, and the mean height of buildings in southern cities is larger than that in northern cities. The high-rise buildings account for a small proportion in China, which is slightly larger in southern cities than in northern cities.
2. The urban morphology of Chinese cities can be broadly divided into two types: single-peak and double-peak. The number of low-rise buildings in single-peak cities is much larger than that of double-peak cities, which contributes to the difference between the two types of cities.
3. The default parameters of urban canopy parameterization schemes in WRF are not representative in China, which seriously underestimates street width and overestimates building width. The fixed values of WRF cannot represent the diversities of urban morphologies of Chinese cities. Based on the data set, the new suitable UCPs for different regions of China were summarized in this study.
4. WRF is sensitive to high-resolution urban morphological parameters, and different urban canopy schemes have different responses to these parameters, which is mainly dependent on the simplification of urban areas. Urban morphology has a significant impact on the urban energy budget, and the urban morphological parameters greatly improve the simulation of wind speed in urban areas and the spatial distribution of temperature.
Existing researches about urban morphology in China are only for several particular cities or limited area and these studies lacked the discussion of the physical mechanism of the impacts of UCPs. The research in this study shows that the real UCPs could enhance the performance of WRF in urban areas. The influence of urban morphology on the radiation progress includes: trapping of radiation, shadowing of the buildings and building heat storage. The three processes have a complex competitive relationship and the overall effect depends on the specific urban morphology. It is very necessary to apply real UCPs in WRF simulations. The urban morphological parameter data set developed in this study can fill the gap of the missing UCPs for main Chinese cities. But there are more than 160 cities with a population over one million in China, it is very hard to produce a data set covering the whole Chinese cities. Based on the analysis of the spatial distribution of UCP features of the existing cities, the urban morphology has obvious regional characteristics in China. For those cities without the gridded UCPs, we also give a set of urban morphological parameters for different regions. In future work, we will expand the data set to whole China based on the existing UCPs data, combined with remote sensing, social and economic data using more complicated methods such as machine learning.

At present, only Nanjing was taken as the testbed city to investigate the impact of UCPs on the WRF simulation. The result showed that the UCPs have obvious influences on the temperature and wind in urban areas. The impacts of UCPs on radiation progress and wind field may change with cities. More simulations with large-scale and long-time need to be conducted. The UCPs data set is essential for urban climate research. Researchers should apply the high-resolution UCPs when they conduct research on urban climate or urban air quality.

Data Availability Statement

The detailed vector-format building data of 60 main cities in China are available at http://www.resdc.cn/data.aspx?DATAID=270. The data sets produced in this study are available at https://box.nju.edu.cn/published/chinaucpv1.0 and https://doi.org/10.7910/DVN/VZH1QY. It can be downloaded freely for noncommercial use with referencing. The FROM-GLC10 data are described in this study: (Gong et al., 2019).

Acknowledgments

This study is supported by the National Natural Science Foundation of China (Grant No. 41975006) and the Chinese National Key Research and Development Program (Grant No. 2016YFA0600303).

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