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Research on the Planning Method and Strategy of Urban Wind and Heat Environment Optimization—Taking Shenzhen, a Sub-Tropical Megacity in Southern China, as an Example

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Abstract: The planning techniques and strategies for optimizing the urban wind and heat environment are important means for cities to adapt to climate change at the source. This study used Shenzhen, a sub-tropical megacity in southern China, as an example for evaluating the climate environment, heat island intensity, and urban form, and then for analyzing the relationships between them. The results revealed a high-quality climate area located southeast of Shenzhen that can provide a high wind speed and low temperature. Low-quality climate areas were located in the central and western regions and were less comfortable. The relationship between surface ventilation potential and urban form was analyzed using linear regression and the Pearson correlation coefficient, showing that there was a significant correlation between a surface urban heat island (SUHI) and building density (BD) as well as the sky view factor (*SVF*), and that there was also a correlation between the ventilation potential coefficient (*VPC*) and other factors, such as the surface's roughness length (RL) and building height (BH). The results showed that ventilation capacity deteriorated as BH and RL increased. An environmentally sensitive thermal area was identified from the surface urban heat island intensity, which was always in a strong heat island (SHI) or sub-strong heat island (SSHI) year-round. It was recommended that seven level one corridors and nine level two corridors be formed. Additionally, thermal and wind environment optimization strategies and protective suggestions were proposed for the city's overall development.

Keywords: heat island; ventilation; urban form; planning strategy

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1. Introduction

High-density urban buildings can cause significant changes in a local climate, resulting in lower wind speeds in urban blocks and exacerbating heat island effects and air pollution [1]. Hu et al. noted that the density (total building area) of an urban area is a decisive parameter affecting the urban heat island (UHI) intensity of that area; the higher the density is, the lower the *SVF* value is, which causes higher UHI intensity [2]. The research of Peng Wang et al. (2021) showed that urbanization significantly increases the frequency of hot extremes occurring in the summer, and that upward trends in human-perceived temperature (HPT) and actual near-surface air temperature (T) are more prominent in areas with higher urbanization levels and denser populations [3]. Liu (2021) explored the influence of the urban spatial morphology layout on urban heat islands and noted that spatial morphological parameters have become a more important driver of UHI changes than land surface parameters are [4].

In the past several decades, since Shenzhen was established as a special economic zone in 1980, its permanent population has increased from 330,000 to more than 13 million, and it has become one of the 37 megacities in the world with a population of over 10 million.

Shenzhen's GDP has also increased rapidly, from RMB 196 million to RMB 3066.485 billion, with an average annual growth rate of about 22%, placing its economic aggregate rate among the top five cities in Asia. Furthermore, the urban built-up area rapidly increased from 3.8 km^2 to 960 km^2, and there are nearly 300 high-rise buildings over 150 m tall in Shenzhen, ranking it first in China. The speed of its urbanization is rare. However, due to the low mountains and hills in the territory, the land resources that can be developed and utilized are very scarce. Thus, it is necessary to adopt a relatively high-density development and construction model, which means more buildings and stronger heat emissions per unit area. The research shows that the average annual temperature increase in Shenzhen from 1968 to 2013 was about 1.68 ± 0.18 °C and that the temperature increase rate is about 0.35 ± 0.04/10 a, which are both much higher than the increases of 0.47 ± 0.20 °C and 0.1 ± 0.04/10 a in Hong Kong. The contribution of urbanization to the temperature rise exceeds 80%, which leads to a series of climate and environmental problems, such as decreased environmental comfort, increased energy consumption, increased difficulty with water resource management, frequent occurrences of waterlogging, and deterioration of the ecological environment [5].

Therefore, research on planning methods and strategies for optimizing the urban wind and heat environment is necessary and important for cities in order to begin adapting to climate change. Giridharan proposed that energy-efficient designs can be achieved by manipulating the surface albedo, sky view factor, and total height-to-floor area ratio (building mass) while maximizing cross-ventilation, which reduces energy consumption and mitigates the heat island effect in Hong Kong [6,7]. Kubota performed wind tunnel tests on 22 residential neighborhoods selected from actual Japanese cities, and the results showed that there is a strong relationship between the gross building coverage ratio and mean wind velocity ratio. Next, the wind environment evaluation for case study areas was performed using the wind tunnel results and the climatic conditions of several major Japanese cities. Finally, the development method of guidelines for realizing an acceptable wind environment in residential neighborhoods using the gross building coverage ratio was proposed [8]. Yuan Leiconducted a quantitative study on the relationship between morphology and environment in the Nanshan District, Shenzhen. They identified the impact of different elements on a city environment and other problems, proposed planning suggestions of a green system and a ventilation system, and provided a reference for sustainable ecological city development [9]. In Zheng Yingsheng's study, they first simulated the ventilation conditions of the Tai Po Market in summer using a fluid dynamics simulation software and identified areas with poor ventilation. Second, on the premise of ensuring the existing functional composition and construction density of the Tai Po Market, the block shape and building group layout were adjusted. Next, the sky view factor and wind speed at pedestrian level were compared to verify the possibility of wind environment improvement through urban morphology optimization under the same density. They proved that the urban ventilation strategies proposed in their paper can improve an urban microclimate and enhance human thermal comfort [10]. However, most of the research to date has focused on using wind tunnel tests or fluid mechanics methods to simulate the local microclimate characteristics of residential quarters with high floor area ratios, and researchers have not yet developed a detailed standard for the quality assessment of the wind and thermal environment in the entire urban environment.

For a high-density city like Shenzhen, the problem is how to optimize the urban form to reasonably use the remaining open space and increase green land in the process of urban renewal within the currently developed high-density built-up environment in order to revitalize the stock space by focusing on adjusting the structures, improving quality, and mitigating the heat island effect, as well as improving human comfort. This is a fundamental requirement in order to improve the living environment, and it is also an necessity for building an ecologically civilized city and developing it sustainably. Therefore, this study considered the characteristics of wind and thermal environments combined with the overall shape of the urban layout in Shenzhen, which is long and narrow in the

east–west direction and short in the north–south direction, and classified climate quality, identified climate-sensitive areas, and analyzed the relationship between the urban form and heat island and ventilation. The whole city of Shenzhen is urbanized, in the context of limited open space resources and a large population. Using climate statistics, remote sensing inversion, and GIS spatial calculation to propose planning and control strategies, such as urban ventilation corridors and locally zoned land layout based on suggestions according to wind and heat environment comfort, can be useful for providing technical support for urban planning and for improving the quality of urban living.

2. Data and Methods

2.1. Study Area

Shenzhen is located at 113°43′ to 114°38′ east longitude and 22°24′ to 22°52′ north latitude. It is located on the Pearl River Delta and adjacent to Hong Kong and Macao. It is a demonstration area of socialism with Chinese characteristics and also the core of the Guangdong–Hong Kong–Macao Greater Bay Area. The sub-tropical oceanic climate gives Shenzhen hot, long summers and warm, short winters. The average temperature in summer is 27.5 °C, and the relative humidity is about 80%. High temperature and hot extremes in summer have a significant impact on human comfort. The focal area of this study includes the entire city of Shenzhen, with 10 administrative districts and a total area of 1996.85 km^2. Figure 1 shows the geographical location and elevation distribution of the study area.

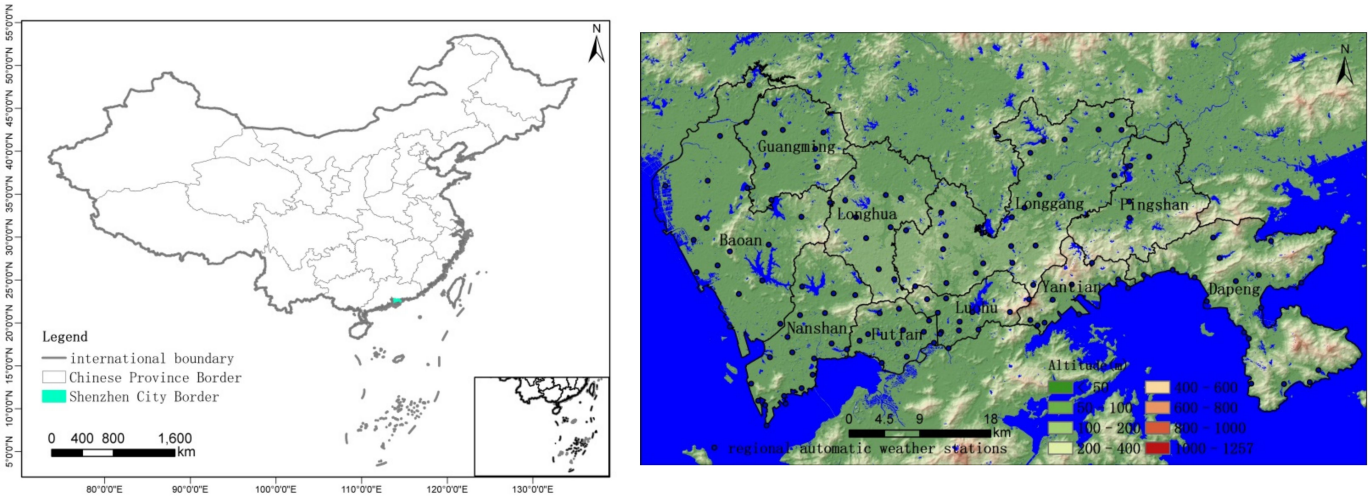


Figure 1. Geographical location and elevation distribution of Shenzhen.

2.2. Data Acquisition

The meteorological data used in this paper are hour-by-hour data taken from 133 automatic weather stations (AWS) in Shenzhen from 2016 to 2018, including temperature, wind speed, and wind direction. These meteorological data were obtained from the Shenzhen Meteorological Bureau and were subject to quality control. The geographic information data were taken from the Bureau of Planning, Land, and Resources of Shenzhen Municipality, including the administrative divisions and 1:2000 topographic map of the city's residential land and buildings of 2018. Satellite images of the clear sky on 7 October 2009, 9 August 2013, and 22 July 2018 were chosen from Landsat-8 OLI, which captured images at a resolution of 30 m, mainly obtained from the Geospatial Data Cloud website (http://www.gscloud.cn/sources, accessed on 26 July 2022).

2.3. Methods

2.3.1. Climate Statistics and Spatial Analysis

Using the observation data from the national weather station in Shenzhen, the wind direction frequency and wind speed from 1981 to 2018 were statistically analyzed, and the wind rose chart was applied to determine the dominant and sub-dominant winds in different seasons and throughout the year. The IDW interpolation method was selected to study the spatial distribution characteristics of air temperature and wind speed based on the observation data of regional automatic weather stations. Meanwhile, the wind direction frequency of soft light wind at a wind force scale of 1 and 2 [11], which is wind speed between 0.3 and 3.3 m/s, from 2016 to 2018 was calculated in order to grasp the characteristics of the local wind environment.

When considering human thermal comfort as the evaluation standard, if an area has higher wind speed and lower summer temperature than other areas, it can be considered to have relatively better climate comfort [12]. Based on this, the study area was divided into two parts: high-climate quality area (HCQA) and low-climate quality area (LCQA). Specifically for Shenzhen, we defined wind speed greater than grade 1, that is, above 1.5 m/s, and air temperature lower than 28 °C as HCQA, while we defined wind speed less than or equal to 1.5 m/s and air temperature higher than 28 °C as LCQA [13].

2.3.2. Heat Island Intensity Calculation

The land surface temperature was retrieved using the single-channel inversion method proposed by Jimenez-Munoz and Sobrino [14]. The surface urban heat island (SUHI) was calculated based on the urban–rural surface temperature difference [15], and the heat island intensity was divided into seven levels, as shown in Table 1.

Table 1. Levels and implications of different SUHI values.

Levels	SUHI (°C)	Significance
1	≤−7.0	SCI
2	−7.0 to −5.0	SSCI
3	−5.0 to −3.0	WCI
4	−3.0 to 3.0	NHI
5	3.0 to 5.0	WHI
6	5.0 to 7.0	SSHI
7	>7.0	SHI

SCI, strong cold island; SSCI, sub-strong cold island; WCI, weak cold island; NHI, no heat island; WHI, weak heat island; SSHI, sub-strong heat island; SHI, strong heat island.

2.3.3. Calculation of Urban Form Parameters

Urban form refers to the geometric morphological characteristics of the underlying urban surface. In this study, several parameters were selected to describe the urban form: the land use, building height (BH), building density (BD), sky view factor (*SVF*), and surface roughness length (RL) [16,17].

The land use classification method is based on three indices: the normalized difference vegetation index (NDVI), modified normalized difference water index (MNDWI), and normalized difference built-up index (NDBI). The classification and regression tree method, combined with the spectral characteristics and image information, was used to determine the threshold value and build a decision tree model for the classification of land use types. As shown in Figure 2, the land surface was divided into four types: vegetation, buildings, water, and bare land. According to the 10% confidence requirement, the NDVI threshold value is defined as 0.43, MNDWI is defined as 0.9, and NDBI is defined as −0.5 [18].

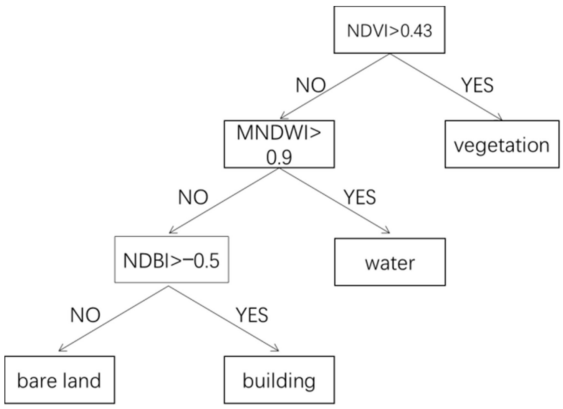


Figure 2. Land use classification and regression.

Using the 1:2000 topographic map of Shenzhen's residential land and buildings in 2018, the building density and building height were obtained, and the blocks were numbered according to the administrative divisions, as shown in Table 2. The building density was the percentage of building area in the space unit (%), the building height was the average number of the floors of all grid buildings in the space unit, and the building height (m) was extrapolated according to an estimate of 3 m per floor, calculated as the number of floors multiplied by 3.

Table 2. Block names and administrative numbers in Shenzhen.

Block Number	Block Name	Jurisdiction	Block Number	Block Name	Jurisdiction
1	Xinan	Baoan district	38	Yuanshan	Longgang district
2	Shiyan	Baoan district	39	Longcheng	Longgang district
3	Fuyong	Baoan district	40	Pingdi	Longgang district
4	Songgang	Baoan district	41	Minzhi	Longhua district
5	Xinqiao	Baoan district	42	Guanlan	Longhua district
6	Hangcheng	Baoan district	43	Longhua	Longhua district
7	Shajing	Baoan district	44	Fucheng	Longhua district
8	Yanluo	Baoan district	45	Guanhu	Longhua district
9	Fuhai	Baoan district	46	Dalang	Longhua district
10	Xixiang	Baoan district	47	Nanhu	Luohu district
11	Dapeng	Dapeng district	48	Dongmen	Luohu district
12	Kuiyong	Dapeng district	49	Guiyuan	Luohu district
13	Nanao	Dapeng district	50	Sungang	Luohu district
14	Huaqiangbei	Futian district	51	Qingshuihe	Luohu district
15	Yuanling	Futian district	52	Dongxiao	Luohu district
16	Huafu	Futian district	53	Cuizhu	Luohu district
17	Lianhua	Futian district	54	Huangbei	Luohu district
18	Meilin	Futian district	55	Liantang	Luohu district
19	Fubao	Futian district	56	Donghu	Luohu district
20	Futian	Futian district	57	Yuehai	Nanshan district
21	Nanyuan	Futian district	58	Xili	Nanshan district
22	Shatou	Futian district	59	Shekou	Nanshan district
23	Xiangmihu	Futian district	60	Nanshan	Nanshan district
24	Xinhu	Guangming district	61	Shahe	Nanshan district
25	Matian	Guangming district	62	Nantou	Nanshan district

Table 2. *Cont.*

Block Number	Block Name	Jurisdiction	Block Number	Block Name	Jurisdiction
26	Gongming	Guangming district	63	Zhaoshang	Nanshan district
27	Fenghuang	Guangming district	64	Taoyuan	Nanshan district
28	Yutang	Guangming district	65	Biling	Pingshan district
29	Guangming	Guangming district	66	Maluan	Pingshan district
30	Baolong	Longgang district	67	Shijing	Pingshan district
31	Longgang	Longgang district	68	Kengzi	Pingshan district
32	Jihua	Longgang district	69	Pingshan	Pingshan district
33	Bantian	Longgang district	70	Longtian	Pingshan district
34	Buji	Longgang district	71	Shatoujiao	Yantian district
35	Nanwan	Longgang district	72	Haishan	Yantian district
36	Pinghu	Longgang district	73	Yantian	Yantian district
37	Henggang	Longgang district	74	Meisha	Yantian district

RL reflects the morphology of rough elements (primarily buildings) and their effect on air circulation in the atmospheric boundary layer, which is estimated according to the morphological model. For the specific calculation steps, please refer to the literature [19,20]. The sky view factor (*SVF*) is commonly used as an indicator to describe urban geometry; it indicates the ratio of the radiation received (or emitted) by a planar surface from the sky to the radiation emitted (or received) from the entire hemispheric radiating environment. According to the research of Klemen Zakšek [21] and Liang Chen [22], n = 36 for the azimuth (expressed in intervals of 10°) and R = 20 for the influential sphere radius (radius of influence is 20 × 5 = 100 m around) were chosen as the input parameters to calculate the *SVF* with 25 m resolution.

2.3.4. Correlation Analysis between Urban Form and Wind and Thermal Environment

Studies have shown that in high-density cities, the intensity of heat islands depends on the urban form [23]; the openness of urban blocks is closely related to the urban heat island effect, and the smaller the *SVF* is, the greater the probability and intensity of the urban heat island effect [6]. In order to determine the relationship between urban form and heat island, the environmentally sensitive thermal area was selected. The average value of urban form parameters was used as an independent variable to characterize the urban form, and the mean SUHI value was used as the dependent variable to characterize urban heat island intensity. Pearson correlation coefficient analyses were used to analyze the relationship between the heat island intensity and urban form [4,24].

The correlation coefficient mainly studied the degree of linear correlation between variables. The value of the Pearson correlation coefficient is [−1, 1]. The closer the value is to 1 (or −1), the stronger that the linear positive correlation (negative correlation) between the two variables is and the closer the value is to 0, indicating that the correlation between the two variables is weaker. The significance is mainly tested by the p-value. In general, if the p-value is less than 0.05, the correlation between the two variables is significant. The Pearson correlation coefficient is calculated as Formula (1) [25]:

$$R = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum (x_i - x)^2 \sum (y_i - y)^2}} \quad (1)$$

where R is the correlation coefficient value between the two variables, n is the number of samples, $\overline{x}$ is the average value of the x variable, and $\overline{y}$ is the average value of the y variable. In this study, x_i is the spatial morphological parameter for constructing urban form, and y_i

is the mean SUHI value. Through this calculation, we can know the degree of correlation between spatial morphological parameters and urban heat island intensity.

According to Matzarakis [26], the primary indicator of good air circulation capacity of a ventilation corridor is an aerodynamic rough length less than 0.5 m. Therefore, 0.5 m is regarded as the upper limit of the higher ventilation potential, and 1.0 m as the prescribed minimum. Chen et al. [27], studying the *SVF* of Hong Kong city, found that the upper limit of the effective range of *SVF* in the relationship between *SVF* and heat island intensity was 0.76. Since Shenzhen is adjacent to Hong Kong and has similar climatic characteristics, the prescribed minimum *SVF* for Shenzhen with its higher ventilation potential is defined as 0.75, which is similar to Hong Kong. The calculation results of the ventilation potential are classified according to the principles shown in Table 3. The ventilation potential levels and their significance were used to identify areas with greater ventilation potential under the existing built-up area conditions.

Table 3. Ventilation potential levels and their significance.

Level	Significance	Roughness Length (Z_0)	*SVF* (*F*)
1	None or poor	$Z_0 > 1.0$	—
2	Relatively poor	$0.5 < Z_0 \leq 1.0$	$F < 0.75$
3	General	$0.5 < Z_0 \leq 1.0$	$F \geq 0.75$
4	Relatively high	$Z_0 \leq 0.5$	$F < 0.75$
5	High	$Z_0 \leq 0.5$	$F \geq 0.75$

In order to analyze the relationship between the spatial morphological parameters and ventilation ability, the ventilation potential coefficient (*VPC*) was used for quantitative estimation [20] in order to evaluate the ventilation status of the city. The calculation method is shown as Formula (2):

$$VPC = \frac{Z_0}{SVF} \quad (2)$$

where *VPC* is the ventilation potential coefficient, and the larger its value is, the lower the surface ventilation potential is; Z_0 is the roughness length; and *SVF* is the sky view factor. The *VPC* calculation results were classified according to the principles shown in Table 4. Based on the above, the average values of BH and RL were used as independent variables to characterize the urban form, and the average *VPC* was used as the dependent variable to characterize the ventilation ability. The relationship between the surface ventilation potential and urban form was analyzed by linear regression and a Pearson correlation coefficient analysis.

Table 4. Ventilation potential coefficient levels and their significance.

Level	*VPC*	Significance
1	>1.5	None or poor
2	1.0–1.5	Relatively poor
3	0.5–1.0	General
4	0.1–0.5	Relatively high
5	<0.1	High

3. Results and Analysis

3.1. Climatic Environmental Analysis

3.1.1. Wind Environment Analysis

Figure 3 shows the spatial distribution of average annual wind speed and dominant wind direction in summer (June, July, and August), based on the observation data from regional automatic weather stations' hourly data of 10-min wind speeds and 10-min wind directions from 2016 to 2018. The results show that in the northern plain area, northern winds prevail; the main urban area is dominated by northern and northeastern winds, and

northeastern winds prevail in the southeast area of Shenzhen. As for wind speed, it is generally higher in the east than the west and higher in coastal areas than inland areas. The light wind speed zones (below 1.5 m/s) are generally concentrated in the western and northern inland areas, mainly in the Longhua, Guangming, and Futian Districts, as well as the western part of Longgang District and the northern part of Nanshan District. The southeastern mountainous area has relatively high wind speeds.

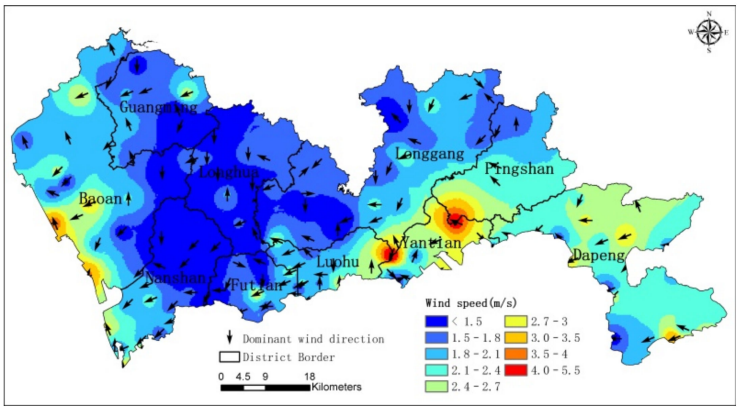


Figure 3. Spatial distribution of the annual average wind speed and dominant wind direction from 2016 to 2018.

3.1.2. Thermal Environment Analysis

Figure 4 shows the spatial distribution of the average temperature in summer based on the observation data of regional automatic weather stations in Shenzhen from 2016 to 2018. The results show that the summer temperature was high in the west and low in the east, with high-temperature centers located in the coastal areas of the Nanshan and Bao'an Districts, as well as parts of the Longhua and Luohu Districts. In these areas, the highest temperature can reach 28.5–29 °C. The low-temperature centers are located in Maluan Mountain, Wutong Mountain, Xikeng Reservoir, and Lianhuashan Park, which are about 23–24 °C throughout the year, or 3–4 °C lower than the surrounding areas. The reason is that these are ecological green sources such as forest land, park green spaces, and water bodies, which play a significant role in cooling the air temperature.

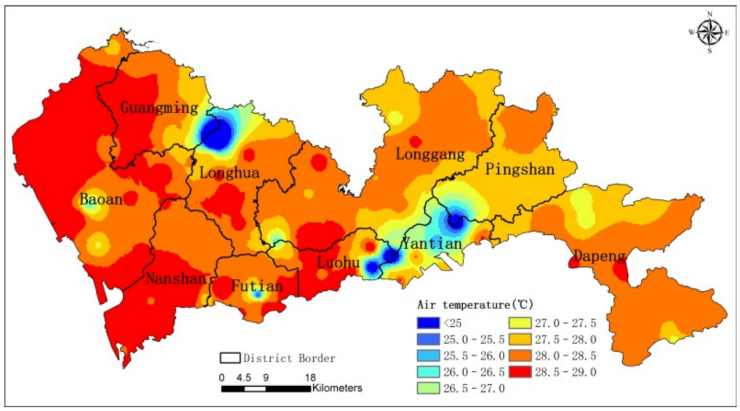


Figure 4. Spatial distribution of the average temperature in June, July, and August from 2016 to 2018.

3.1.3. Spatial Distribution of Climate Quality

According to the definition in Section 2.3.1, the spatial distribution of the climate quality in Shenzhen was obtained, as shown in Figure 5. The results show that HCQAs are located in the southeast, mainly in the Yantian, Pingshan, and Dapeng Districts. They are distributed with mountainous forest land, a large ecological source where fresh cold air

is generated. An ecological source can provide high wind speed and low temperature for good climate compensation in both wind and thermal environments for more comfort and easy ventilation. LCQAs are located in the southern part of Longhua District, the western part of Longgang District, and the northern part of Nanshan District. These are inland areas, where the wind speed is lower than it is in the western and southern coastal areas and the temperature is higher. This is consistent with the results of LAI Xin's research (2020) [28], showing that the area with the most comfortable climate in Shenzhen is the eastern part, which has the best ecological environmental protection, and that the further inland one goes, the less comfortable the environment feels.

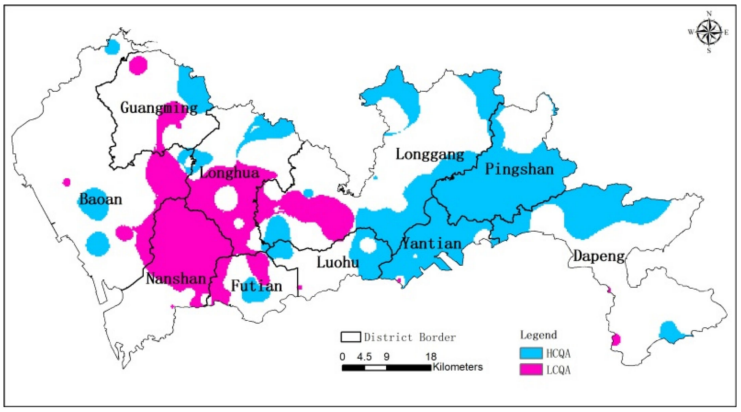


Figure 5. Spatial distribution of climate quality in Shenzhen.

3.2. Urban Heat Island Intensity Distribution

According to the SUHI calculation, the spatial distribution of SUHI in Shenzhen on 7 October 2009, 9 August 2013, and 22 July 2018 was obtained, as shown in Figures 6–8. The figures show that the heat island in Shenzhen was generally strong in the west and weak in the east. The surface temperature of the harbors in the Yantian and Nanshan Districts was obviously high, and the main urban areas in the Futian and Luohu Districts were in the heat island range every year. This indicates that the heat absorption effect of roads and sheet metal is high. From 2009 to 2018, the total heat island area in Shenzhen increased from 191.8 to 463.6 km^2, and the percentage of heat island area increased from 9.8 to 23.7%. The areas with different SUHI levels each year were counted separately, and the results show that the proportion of SSHI (5 °C $\leq$ SUHI $\leq$ 7 °C) increased from 6.2 to 25.6%, and the proportion of SHI (SUHI $\geq$ 7 °C) increased from 0.7 to 5.7%, showing that the heat island effect of Shenzhen indeed increased and expanded.

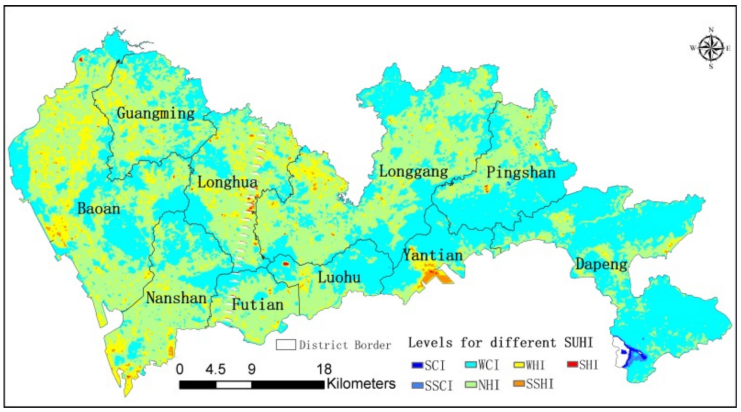


Figure 6. SUHI grades on 7 October 2009.

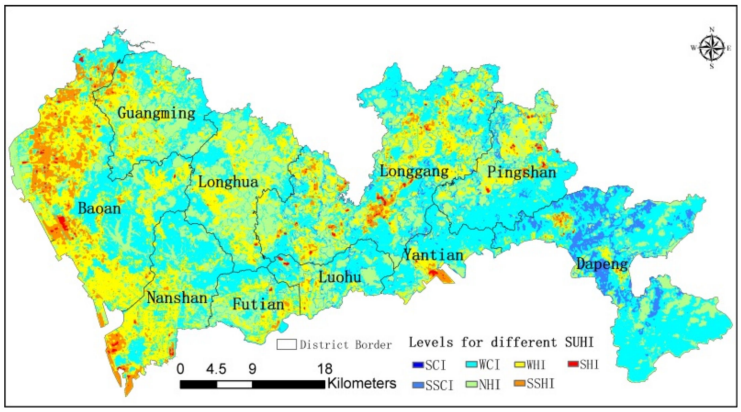


Figure 7. SUHI grades on 9 August 2013.

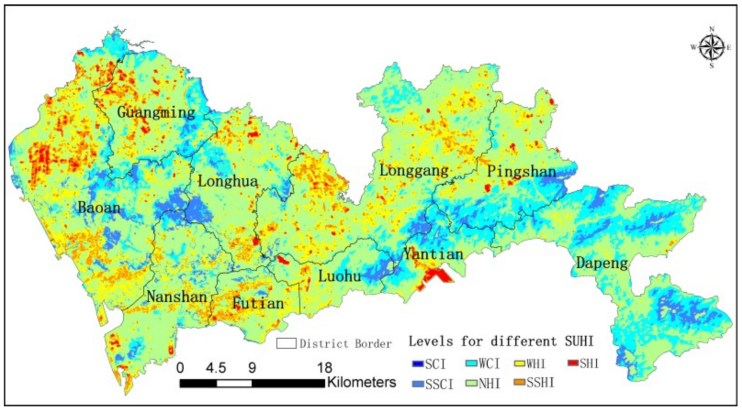


Figure 8. SUHI grades on 22 July 2018.

3.3. Analysis of Urban Spatial Morphological Characteristics

According to the decision tree model mentioned in Section 2.3.3, the spatial distribution of the land use types in Shenzhen was obtained, as shown in Figure 9. The results show that the overall shape of the urban layout in Shenzhen is long and narrow in the east–west direction and short in the north–south direction. The Yantian, Pingshan, and Dapeng Districts have high vegetation coverage. In these areas, the wind speed is generally high, and the temperature is low throughout the year, as shown in Figures 3 and 4. The valley winds formed there are conducive to improving the air circulation in the surrounding areas, and they can serve as an important source of fresh air to provide good climate compensation for the city. The Guangming and Longhua Districts and the northern part of Longgang District are the areas upstream of the dominant wind direction. In these areas, the wind speed is low and the temperature is high, which is disadvantageous to the transportation of climatic resources, and the east–west expansion easily forms a barrier against the dominant wind. The main urban areas, mainly in the Futian, Luohu, and Nanshan Districts, are dominated by northern and northeastern winds; however, there is a large proportion of buildings and less open space along the dominant wind directions.

Based on the residential land and building layer in Shenzhen, the building height and building density were obtained, as shown in Figures 10 and 11. It can be seen from the figures that high-rise buildings are generally distributed in the central and southern regions, mainly in areas 47, 48, and 49, where there are many office and residential buildings. In addition, the building height in areas 14 and 20 is high, because it encompasses a business center, a convention and exhibition center, and a financial center. Fortunately, the open space area is large. The high building density is mainly concentrated in areas 47, 48, and 49, and areas with building density more than 60% account for a large population, overlapping with the distribution of high-rise buildings. This indicates that these areas are indeed

high-density, high-rise developments. A building area percentage of more than 50% is also common in areas 43 and 50, but since most of the buildings in those areas are multi-story (4–6 floors), the tall buildings are rare and scattered.

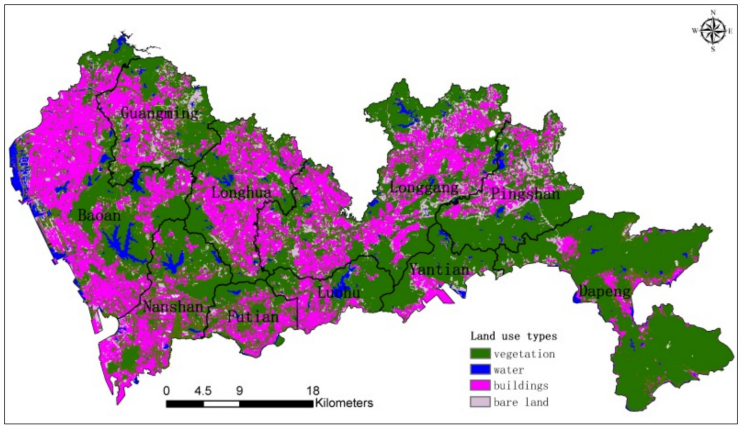


Figure 9. Land use types in Shenzhen.

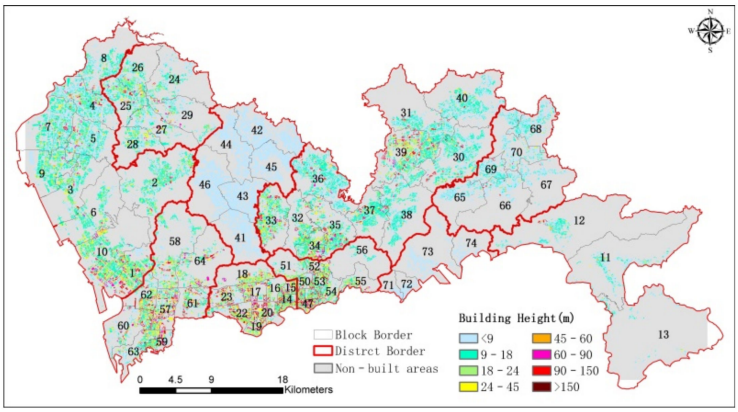


Figure 10. Building height distribution in Shenzhen.

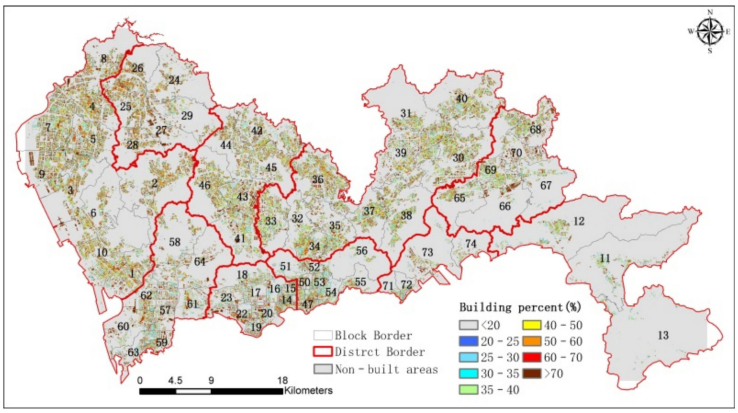


Figure 11. Building density distribution in Shenzhen.

Figures 12 and 13 show the spatial distribution of RL and *SVF*, respectively. The results show that in areas 14, 20, 47, 49, 57, and 59, the RL values are significantly higher than they are in other regions, reaching more than 2.0 m. Generally, RL $\geq$ 1.0 m is bad for urban ventilation. Thus, it can be seen that there are large areas of urban ventilation obstacles in Shenzhen. In areas 1, 10, 14, 20, 21, 22, 47, 48, 49, 59, and 62, the *SVF* is generally below 0.50, which means openness to the sky in these areas is severely occluded, and there are large

areas of high-rise buildings with BH over 45 m and BD over 30%, indicating that areas with taller buildings and higher building density have a low *SVF*. The *SVF* values gradually increase from the main urban areas to the surrounding areas. *SVF* values are between 0.5 and 0.8 in Longhua District and the northern part of Nanshan District, whereas in parks, on riverbanks, and in mountainous forestland, the values are above 0.8.

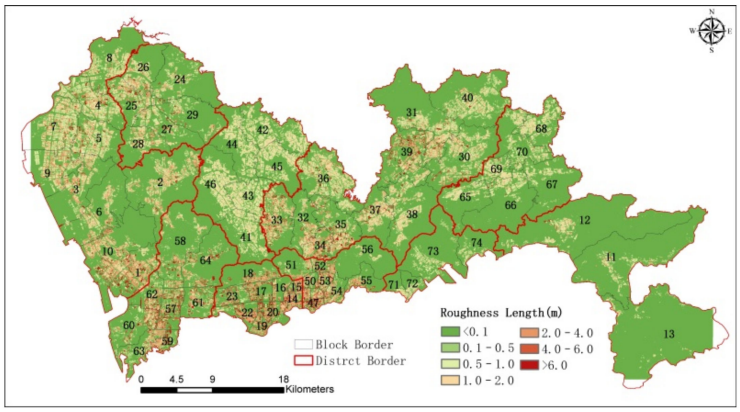


Figure 12. Roughness length distribution in Shenzhen.

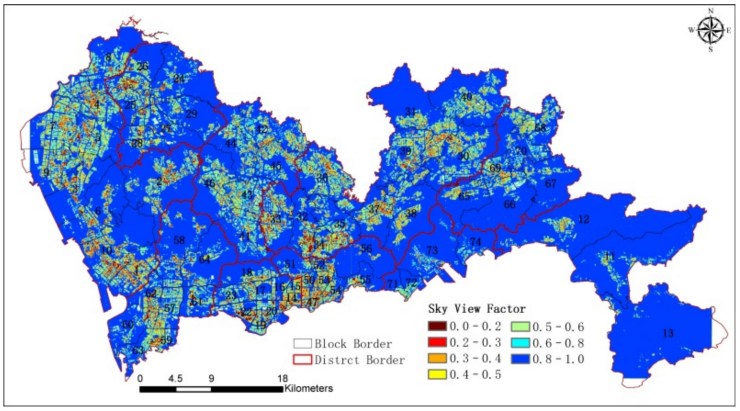


Figure 13. *SVF* distribution in Shenzhen.

3.4. Analysis of the Relationship between Urban Form and Heat Island

Based on the spatial distribution of SUHI in each year, we can figure out areas that are always in SSHI or SHI all year round, as shown in the red zone in Figure 14. Thus, the western part of Luohu District and the eastern part of Futian District were chosen as climate sensitive areas. Figure 14 also shows their location. Using the general principles of civil building design, we defined civil buildings taller than 24 m as high-rise buildings [29]. The proportion of high-rise buildings in the sensitive areas is about 23.8%, which is the largest distribution of high-density buildings in Shenzhen. The heat island area accounts for about 40% every year, and SSHI or SHI accounts for about 11%. Indeed, it is sensitive and vulnerable to the thermal environment and urgently needs improvement. This is representative of the typical spatial unit for analyzing the relationship between the urban form and heat island.

Table 5 shows the Pearson correlation between SUHI and spatial morphological parameters. The results show that BD has a significant positive correlation with SUHI, and the correlation coefficient is 0.646. That is, SUHI increases with building density. As the building density increases, heat is not easily dissipated, causing the temperature to rise and the impervious surface area to increase. Since the impervious surface area has less evaporation and does not cool easily, heat is released into the air, causing the air temperature to rise. Meanwhile, most of the impervious surface area has a higher sunlight

absorption rate than that of the natural surface area, which also leads to an increase in temperature [4].

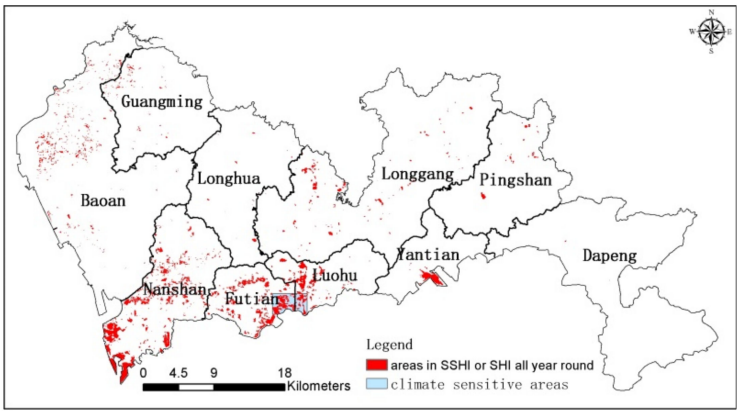


Figure 14. Climatic sensitive areas in Shenzhen.

Table 5. Pearson correlation between SUHI and spatial morphological parameters.

Spatial Morphological Parameters	*R* Value	*p* Value
BD	0.646	4.397×10^{-14}
BH	0.06	2.567×10^{-15}
RL	−0.113	1.106×10^{-16}
SVF	−0.553	6.17×10^{-18}

SVF has a significantly negative correlation with SUHI, with a correlation coefficient of −0.553. It clearly shows that the degree of SUHI decreases with the increase of *SVF*. Yuan Chao [23] noted that for every 10% increase in the average value of the *SVF*, the average air temperature in the area decreased by about 0.16 °C. Thus, they proposed that on the premise of maintaining land use efficiency, building density should be controlled, and building height should be adjusted to mitigate the heat island effect in high-density cities.

3.5. Analysis of the Relationship between Urban Space Form and Ventilation

Figure 15 shows the spatial distribution of the ventilation potential coefficient in Shenzhen. The results show that areas with *VPC* > 4.0 are mainly located in the central and southwestern coastal areas, such as Futian District and the western part of Luohu District, and in the southern part of Nanshan District. Combined with the spatial distribution of building height and building density, there are generally many high-rise and super-high-rise buildings in these areas, and the building density is high, which leads to difficulty with air flow and air exchange, causing the surface ventilation environment to be poor. There are large areas with *VPC* < 1.5 in the eastern part of Shenzhen, including the Pingshan, Yantian, and Dapeng Districts, as well as the northern part of Nanshan District, the central part of Baoan District, and the northeastern part of Longgang District. Since these areas are distributed with green space and forestland, they have a good ventilation environment. In Longhua District, the northern part of Bao'an District, and the central part of Longgang District, the *VPC* is between 1.5 and 4.0. In these areas, since the streets are wide and the buildings are relatively low and scattered, the surface ventilation potential is high, and the ventilation environment may be less affected by urban construction.

Table 6 shows the Pearson correlation between *VPC* and spatial morphological parameters; the results show that BH and RL have correlation coefficients of 0.535 and 0.545, respectively, with *VPC*. As BH increases, RL increases, and the drag of the airflow also increases, leading to a poorer ventilation environment.

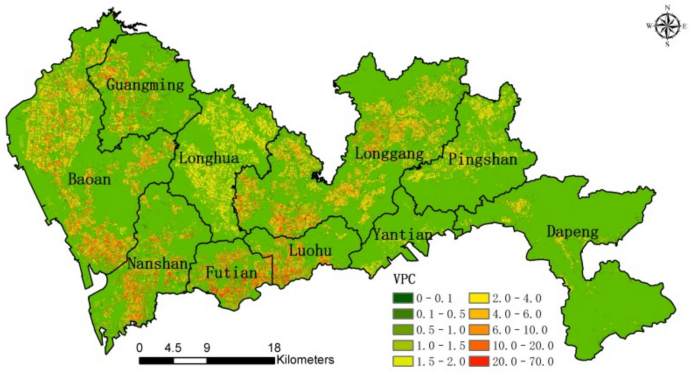


Figure 15. Spatial distribution of the ventilation potential coefficient in Shenzhen.

Table 6. Pearson correlation between *VPC* and spatial morphological parameters.

Spatial Morphological Parameters	*R* Value	*p* Value
BD	0.343	3.149×10^{-17}
BH	0.535	5.668×10^{-13}
RL	0.545	0.026761822
SVF	−0.325	6.732×10^{-17}

4. Urban Spatial Wind and Thermal Environment Optimization Strategy

4.1. Thermal Environment Optimization Strategy

We used a new method of categorizing urban climatic zones, called "Climatopes", based on the research of Yonghong Liu et al. [17]. Taking into account the background wind environments and the *VPC* and SUHI indexes, Climatopes can further divide spaces into four classes of "sensitivity", the climate environment, and the spatial distribution characteristics of SUHI. Suggestions for the thermal environment are given in Figure 16.

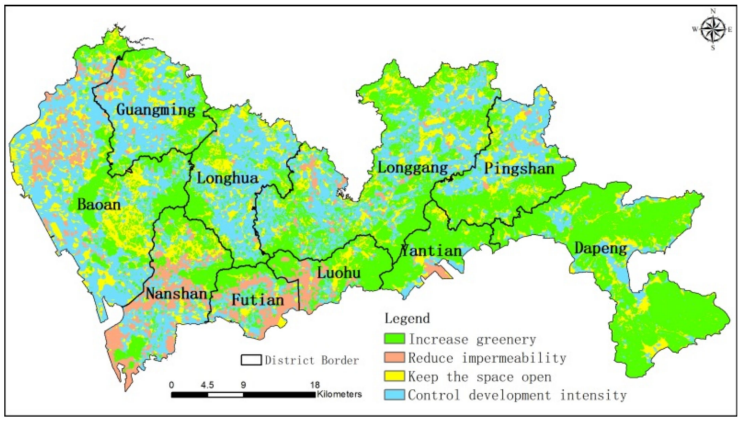


Figure 16. Urban climate analysis map of the thermal environment in Shenzhen.

The green areas are those that need to increase the proportion of green land to ensure vegetation coverage. Since forest land is a low-temperature center throughout the year, it is the place where fresh and cold air is generated, and its climate quality is generally high. Either the wind or thermal environment can provide good compensation to nearby areas. If the vegetation coverage of the forest land is low, it cannot have a significant cooling effect on the surroundings. Therefore, based on the terrain slope and vegetation coverage, the areas that need to increase the proportion of green land were extracted. If the slope was greater than 5 and the vegetation coverage was less than 0.6, we regarded that area as the corresponding layer.

The red areas are those that need to reduce the impervious surface ratio, mainly for climate sensitive areas, and we believe it necessary to reduce the impervious ratio for expansion within 100 m of sensitive areas.

The yellow areas are where high-density buildings are prohibited. We recommend avoiding large building components or tall trees and keeping the space open.

The blue areas are where urban development intensity needs to be slowed down; generally, new buildings within 300 m of areas close to ecological green sources need to be strictly controlled to avoid hindering climate resources.

4.2. Wind Environment Optimization Strategy

Good natural ventilation requires greater ventilation potential and that the wind passes through as easily as possible. Considering the distribution of ventilation potential in Shenzhen (Figure 15), combined with the background wind environment (Figure 3), we outlined seven level one corridors and nine level two corridors (Figure 17), along with suggestions on planning and control.

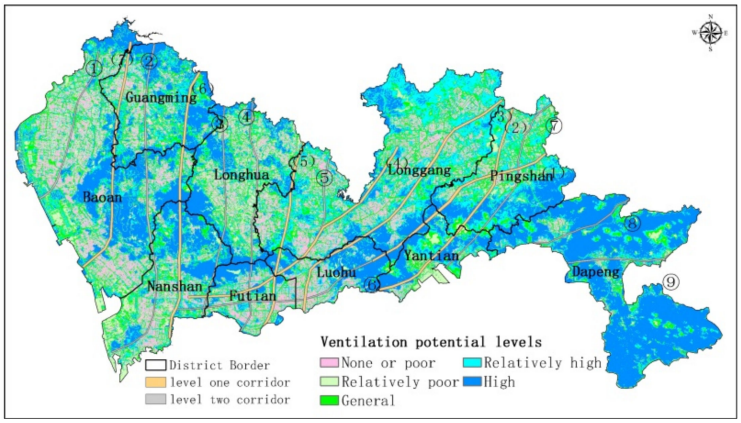


Figure 17. Recommended ventilation plan for Shenzhen.

Since wind in the northern area is dominated by northerly wind, the direction of the corridor is mainly north–south. We recommend that development should mainly focus on the north–south direction in order to avoid hindering dominant winds in the vertical direction.

In Longgang and Pingshan Districts, we recommend building level one corridors in open areas with high ventilation potential in the suburbs. Full use should be made of the Bijiashan, Honghu, Weiling, and OCT Wetland Parks and other green spaces as climate compensation, as well as Shenzhen River, Xili Reservoir, Dasha River, and other fresh and cool air sources. The green areas and vegetation coverage of open spaces should be maintained, and level one and two corridors should be better connected with each other to guide air flow direction and allow fresh air to transfer to climate-sensitive and urban-barrier areas in order to improve the ventilation environment.

Since the southern part of Longhua District, the western part of Longgang District, and the northern part of Nanshan District are located in the LCQA, we recommend that in LVQA zones, more ventilation corridors should be set up to increase the penetration of the dominant wind and achieve good air circulation.

The development intensity should be limited in HCQA and potential high-ventilation areas as ecological conservation areas, in order to protect land with high ecological value so that it can easily and continuously provide fresh and cool air to the main urban areas.

5. Conclusions and Limitation

5.1. Conclusions

(1) The Yantian, Pingshan, and Dapeng Districts have high wind speed and low temperature, which makes these areas more comfortable and easily ventilated. The climate quality is high. The southern part of Longhua District, the western part of Longgang District, and the northern part of Nanshan District have low wind speed and high temperature, and the climate quality is low. Judging from the spatial distribution of heat island intensity over the years, we saw that the heat island effect of Shenzhen has increased and expanded. The overall shape of the urban layout in Shenzhen is long and narrow in the east–west direction and short in the north–south direction, which can easily hinder the dominant wind, and is not conducive to the downstream transport of climate resources.

(2) Research on the correlation between urban form and SUHI in Shenzhen shows that the building density parameter has a significant positive correlation with SUHI, with a correlation coefficient of 0.446. In addition, *SVF* has a significant negative correlation with SUHI, with a correlation coefficient of -0.553, and BH and RL have correlation coefficients of 0.535 and 0.545, respectively, with *VPC*.

(3) Combining the background wind environment, surface ventilation potential distribution, and heat island intensity assessment, we provided strategies and suggestions for optimizing the thermal and ventilation environment. Seven level one corridors and nine level two corridors will help mitigate the heat island effect and enhance air circulation.

5.2. Limitation

(1) The wind and heat environment of high-density cities is affected by the urban climate, urban space form, greening environment, and other factors. This study only discussed the planning method and strategy of urban wind and heat environment optimization from the perspective of urban space form, which has certain limitations.

(2) For studying the relationship between urban space form and heat island, we selected a climate-sensitive area, and we used the linear regression method to analyze the relationship between several spatial morphological parameters and SUHI. The results only show the qualitative relationship and lack a quantification study, which is an issue that needs to be further discussed in follow-up research.

(3) Since the urban spatial wind and thermal environment optimization strategy proposed in this study is mainly a guidance strategy, lacking quantitative control indicators, more in-depth research and exploration are still needed.

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