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Article

A Framework for Assessment of the Influence of China's Urban Underground Space Developments on the Urban Microclimate

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Abstract: The paper aims to establish the framework for linking underground space projects and the urban microclimate, in order to construct an interdisciplinary research framework. Based on the combination of underground space, urban form and the urban microclimate, the impacts of underground space on urban microclimate factors above ground and underground are summarized and the internal mechanism is investigated. The above ground factor refers to the impact of a new urban form induced by the underground space planning on the urban microclimate. The underground factor refers to the impact of the control of the internal environment of underground space on the ground environment. This study mainly addresses two aspects. Firstly, to identify the influencing factors of urban underground space microclimate and define the research entry point and classify the indicator of the external space environment; secondly, to address the key issues of the research areas and their influence on the urban underground space project and the urban microclimate in the current phase and establish the direction of future research. The microclimate case of the Nanjing underground planning is provided to preliminarily analyze how underground space development improves the urban microclimate. By the comparative analysis of microclimate parameters, air quality parameters, and outdoor thermal environment parameters

(Mean Radiant Temperature, MRT), the influences and benefits of underground space projects on the urban microclimate is quantitatively explored.

Keywords: urban underground space; urban microclimate; urban planning; influence mechanism; research framework; case study

1. Introduction

Rapid urbanization has caused changes in land utilization and land cover, which, in return, impacts and alters the structure of the urban ecosystem and causes a raft of severe ecological and environmental issues, such as urban heat island effect, non-point source pollution, atmospheric contamination and decreasing biodiversity [1].Along with the accelerated urbanization process in the past two years, the urban environment in China has been gradually degraded by factors such as heavy air pollution[2,3], noise pollution [4,5], extreme lack of green space [6,7], nerve-wracking traffic congestion [8,9], long-term coexistence of pedestrians and vehicles [10], and undesirable community split [11].

A reasonable architectural design and layout is carried out to improve the urban environment, reduce the urban heat island effect and increase the index for urban microclimates. Meanwhile, the urban underlying surface property and architectural form is improved through efficient and aesthetic greening patterns, plant collocation and waterscape settings and the outdoor thermal environment is improved through conduction [12–18]. Globally, increasingly massive urban construction has caused the serious problem of insufficient land for urban development. Meanwhile, the saturated ground space capacity in cities, higher building density and plot ratio has aggravated the tension of urban land shortage. As urban open space and development land have become scarce resources, the method of increasing the greening rate through a change in the properties of land and improving the urban thermal environment through the reduction of the architectural density and plot ratio will be confronted with more restrictions.

From the beginning, the functional goal is to resolve the problem related to development and exploitation of urban underground space [19]. With the advantage of efficiently utilizing lands, expanding greening space and floor open space, underground space can reduce environmental contamination and improve the quality of the ground environment [20]. The use of its four principal resources (space, water, geothermal energy and geomaterials) can contribute significantly to the sustainable development of cities [21]. Developed countries have regarded the development and utilization of underground space as an important measure to handle urban resources and the environment crisis and as a crucial means to implement the intensive use of land and sustainable urban development [22].

In China, in order to solve the problems caused by rapid urbanization such as limited construction land, crowded living space, traffic congestion, ecological imbalance and environmental degradation, one must increase the quality of life of residents and, achieve the further development of the urban economy and society. The large-scale underground space which aims to solve the problems of urban traffic and environment has become a mainstream. Thus, underground space is increasingly utilized in China. Table 1 shows the amount of development and planning of underground space in major Chinese cities.

Table 1. The amount of development and planning of underground space in major Chinese cities.

	Beijng	**Shang hai**	**Guang zhou**	**Shen zhen**	**Nan jing**	**Hang zhou**	**Wu han**	**Tian jin**	**Jinan**	**Zheng zhou**	**Shen yang**	**Harbin**
Development scale of underground Space in 2013 (10,000 m^2)	3000	5600	1900	1350	2450	1224	950	910	380	580	1485	550
Urban built-up area in 2012 (km^2)	1261.1	998.8	1009.7	863.43	653	452.62	520.3	722.1	363.25	372.96	455	383.02
Urban green areain 2012 (km^2)	211.78	187.85	25.78	175.08	76.32	42.96	52.7	82.6	33.58	69.23	69	38.47
Planning and construction sites in 2020 (km^2)	1650	1800	1772	890	893	582	688	1113	410	450	698	458
Planning construction scale of underground Space in 2020 (10,000 m^2)	9000	12000	8500	7000	5200	3600	2000	1800	2580	980	5000	3100

2. Research Purpose

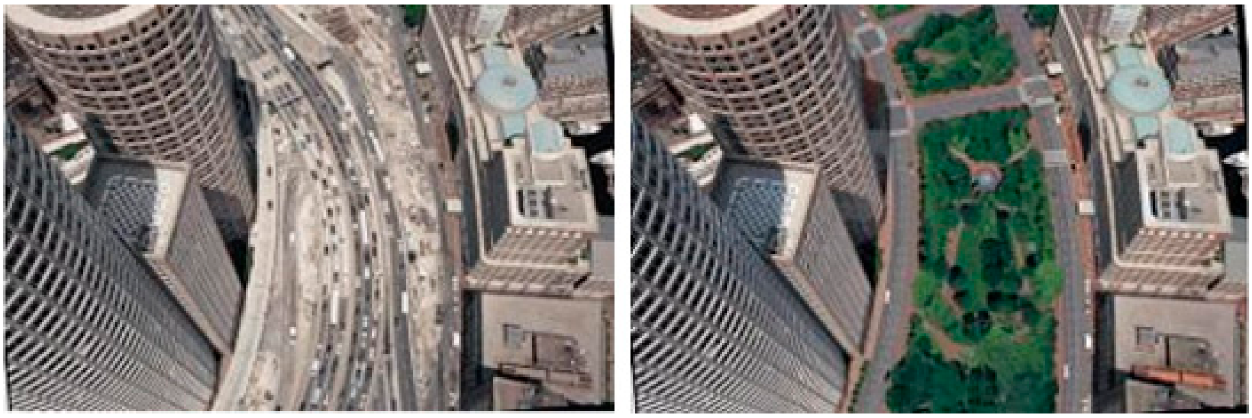
Overall, microclimatic factors are consistent with urban planning elements; urban microclimate factors mainly include spatial geometry factors (e.g., building layout, building density and building height) and underlying surface properties (e.g., paving way, green plants, water conditions), while anthropogenic heat factors mainly include air conditioning, refrigeration and traffic exhaust heat [23–28].

However, in the research on the urban thermal environment at the current stage, little attention has been paid to the influence on the urban microclimate in the process of developing and utilizing underground space. There are no well-targeted studies about the influencing mechanism, effect and rules of the underground space engineering development and utilization on urban microclimates. With respect to the research on underground space engineering, people place emphasis on the resolution of the problems related to urban planning and urban construction by underground space but neglect the issues pertaining to the urban microclimate.

In terms of effects of underground space on urban microclimates, there is still a lack of systematic and theoretical research around the world. According to the literature retrieved and collected, this field has so far focused mainly on the assessment and reporting of effects of underground road (especially tunnels) development on air quality. Since the 1970s, the United States has assessed the influence of the project "THE BIG" in Boston on the environment and published a series of environmental assessment project reports (Figure 1 shows the city environmental comparison before and after completion of CA/T).

The effects of its implementation on air quality, PM values, urban noise, carbon emissions, NO_X and CO emissions were given a systematic and comprehensive assessment by means of theoretical studies, simulations, wind tunnel tests and field measurement [29–35]. The Australian National Health and Medical Research Center (NHMRC) carried out experimental measurements on values of air quality and noise within and around the tunnels in Australia [36].

Figure 1. The city environmental comparison before and after completion of CA/T.



Whereas in China, Jiang Weimei conducted an experimental study and simulation analysis of the impacts of vehicle emissions in urban tunnels on environment, and monitored the effects exerted by vehicle emissions in Nanjing Gulou Tunnel on the environment; Wang Jun presented an analysis of the impact of emissions in urban large and long tunnels on the environment [37–41].

Summarizing the current research status, it can be found that, in terms of research on underground space, the research methods are mainly concentrated on experimental measurements and numerical simulation. The research objects focus on the impacts of tunnels (underground roads) on urban air quality; the results are not great in numbers and most of them are assessment reports. A systematic and comprehensive theoretical study of the effects of underground space on the urban microclimate from a professional perspective should be conducted.

Therefore, considering the blanks in this regard, it is of realistic significance to study the influencing mechanism and effect of underground space engineering on the urban thermal environment in the field of the underground space development and urban thermal environments.

China is in the stage of large-scale underground space development. The research on the effect of underground space projects on the urban environment will contribute to the green design and planning of urban underground space. This research focuses on the framework for linking underground space engineering and the urban microclimate. It constructs the interdisciplinary research framework and research methods that involve underground space, urban planning, urban environment, urban climate and building science. By sorting out the relationship between underground engineering, urban underlying surface and urban microclimate, this paper classifies the factors causing the influence of underground space engineering on the urban microclimate and defines the entry point for underground space engineering and urban microclimate. On the basis of analyzing the influencing mechanism of underground space engineering on the urban microclimate, it points out the problems that call for immediate solution at the current stage so as to determine the problems to be researched and the future direction. In the meantime, an underground parking construction in Nanjing as an example is analyzed. It offers a preliminary analysis of the influence of underground space development on the regional microclimate with quantitative data.

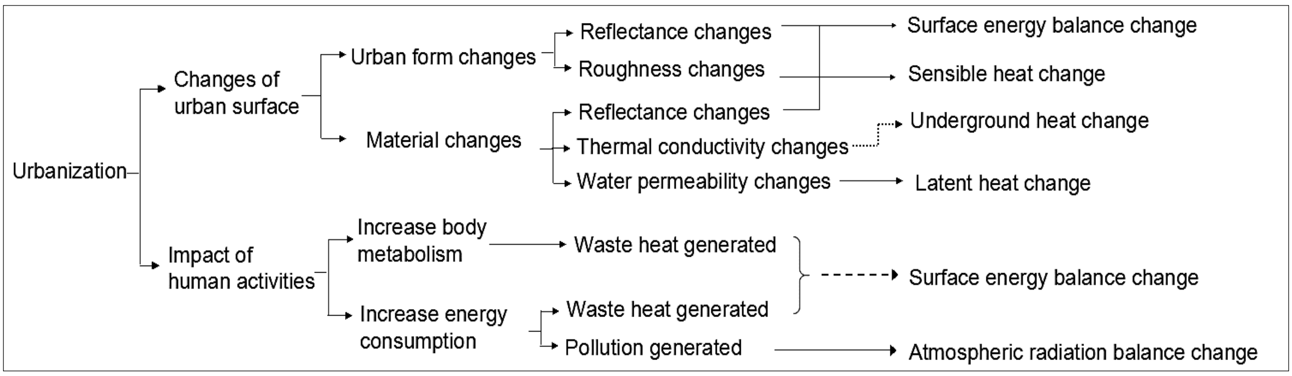
3. Two Framework Dimensions for Effects of Underground Space on Urban Microclimates

Recently, the urban microclimate research focus has shifted from urban areas to local ones, such as residential areas, commercial areas, university campuses and streets. The research objects are distributed over various climate zones. These researches gradually correlate urban layout and urban design elements. Frameworks between block size, building density, population, underlying surface layout and other influencing parameters are discussed. Through long-term observation and experiments, scientists have found many factors influencing the urban microclimate and the change mechanism [42–47]. The urban microclimate is most pronounced during calm and clear nights [48] and the main contributing factors include:

(1) changes in the physical characteristics of the land surface such as albedo, emissivity or thermal conductivity, brought about by the replacement of natural vegetation by impervious surfaces resulting in alterations in the surface energy balance;
(2) higher anthropogenic heat release (AHR);
(3) decreased surface evapotranspiration in urban areas;
(4) changes in the near-surface flow attributed to the complicated geometry of streets and tall buildings.

The relations diagram for the change mechanism of urban microclimate is listed as Figure 2. It shows that the urban microclimate is mainly influenced by the urban underlying surface and human activities.

Figure 2. The relations diagram for the change mechanism of urban microclimate.



The large-scale development of underground space breaks through the segments, restricts underground and ground spaces and allows a real three-dimensional integrated development of the urban elements and systems of these two spaces [49,50]. Three-dimensional integrated urban form has been formed and developed in many modern cities; the integrated, systematized, composite and socialized urban space has contributed to the growing links and increasingly blurred boundaries between ground space and underground space, as well as increasing mutual penetration and integration between them.

Therefore, the development of underground space and the formation of three-dimensional urban form change the spatial geometry factors and underlying surface properties in cities; the internal environment control of underground space forms new anthropogenic heat and emission factors, thereby affecting the urban outdoor environment.

3.1. Effects of Underground Space Development on Urban Underlying Surfaces

First of all, in terms of the urban three-dimensional integrated shape, a diversified, accessible and consistent urban spatial form is constructed in the urban underground space through the intensive and compound usage of urban space resources, thus extending the urban form featuring the ground as the basal plane to the three-dimensional basal plane form aboveground and underground, strengthening the opening degree of the urban space and changing the urban plot ratio, architectural density and the street canyon form.

As shown in Figure 3, when the integrated ground and underground project is developed, the ground urban functions can be transferred into the underground. With the increased size of underground space development, the construction area of urban ground will gradually reduce. The ground building size, building density, and building height decreased, while the urban form changed. Thus, this affects the reception of solar radiation in an urban environment, and changes the urban microclimate by radiant action.

As shown in Figure 4, when there is no development of underground space, ground buildings block the flow of the wind. When some urban functions are placed underground, a new ground pattern is formed. Wind continues to flow through the open urban form. Thereby, the urban wind environment changes.

Figure 3. Underground space changes the urban form.

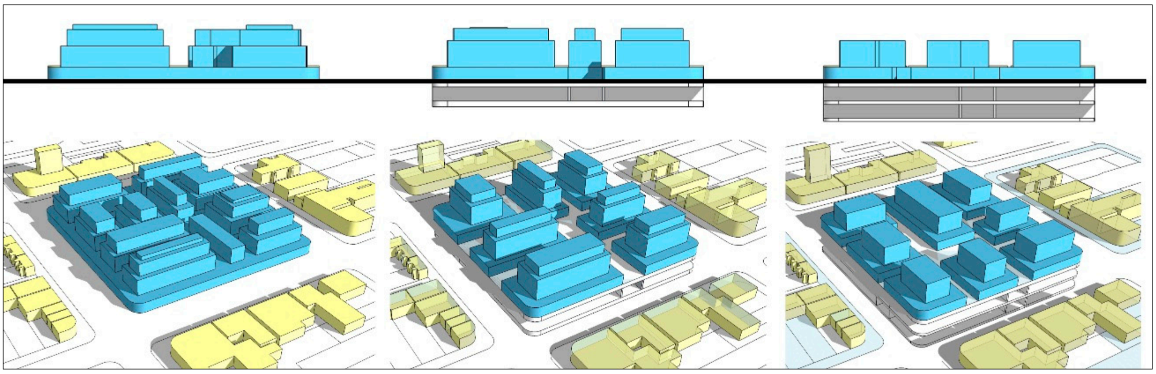
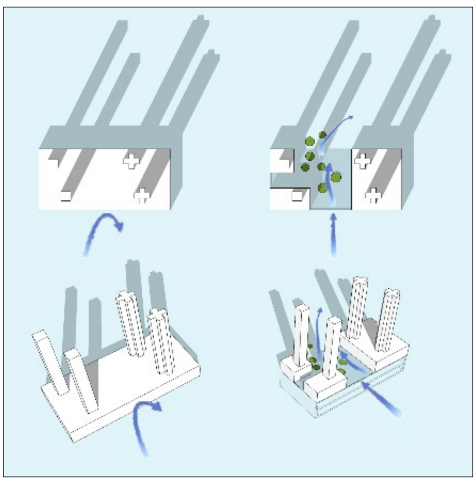


Figure 4. Underground space changes the urban wind environment.



For example, in the design of Shanghai Jing'an Temple Square (Figure 5), subway entrances and exits, urban squares, urban commerce and urban green land are combined with each other. Subway entrances and exits leverage the sunken space of urban squares, station hall base and sunken square integrated urban space.

Figure 5. Shanghai Jing'an Temple Square.

Secondly, the development of underground space enriches the city's green space hierarchy. This kind of development creates the unique three-dimensional urban greening and provides a more diverse urban greening layout space, allowing more diverse greening landscapes and more abundant hierarchies. Meanwhile, the development of underground space offers a variety of possibilities to the urban greening forms and provides effective means for an increase in urban greening capacity and improvement of the overall efficiency of the urban environment [51]. For example, in an urban center where land shortage is phenomenal, the functional spaces are put underground, while the ground is decorated with urban greening. Three-dimensional greening is an important feature of urban underground space.

The development of underground space engineering has saved aboveground land for landscape and greening construction and increased the greening capacity of cities. Abundant heat could be absorbed by the vegetation transpiration through latent heat, thus effectively reducing the temperature in the areas around the greenbelt [52–54]. Studies [55–57] show that an increase by 10% of the urban green in Manchester, UK, could amortize the predicted increase of the ambient temperature by 4 K over the next 80 years. Green roofs present a variety of advantages like storm water runoff management, increased roof materials' durability, decreased energy consumption, and possibly better air quality and noise reduction, as well as offering space for urban wildlife and increased mitigation of the urban heat island [58–73].

Thus, the development of underground space forms a three-dimensional urban form, facilitates the urban geometrical pattern in urban centers, and enriches the underlying surface compositions (such as green land and waters) of urban centers, which may exert a direct influence on the urban microclimate. Through the study of the mechanism and law of the effects of underground space on the urban microclimate, the urban microclimatic environment can be regulated by implementing space control, and adjusting the underlying surface form and optimizing landscape structure, especially the microclimatic environment of development zones in underground spaces.

3.2. Effects of Internal Environment Control within Underground Spaces on Outdoor Environments

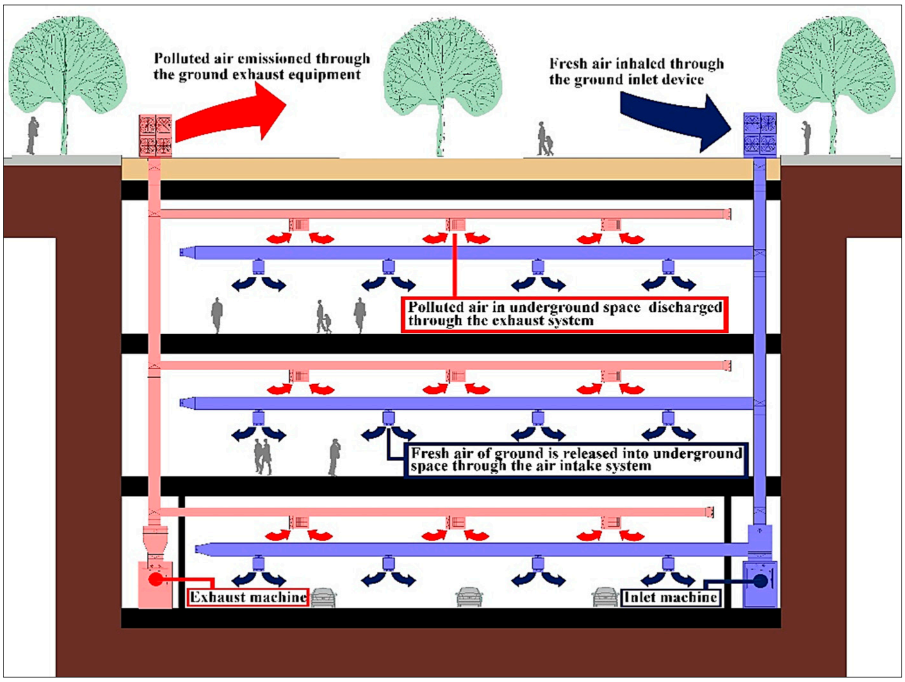
China's construction of underground spaces lacking in comparison with developed countries. The urban underground space system contains comprehensive functions such as underground infrastructure, underground public spaces, underground transportation facilities and underground disaster prevention facilities. At this stage, in order to meet the space and function needs of an urban development, the development of underground space in China is mainly in underground business (underground shopping malls, underground street, underground commercial complex) and underground transportation (subway, underground Guojietongdao, underground parking). As the urban commercial and transport functions are moved into underground space, there is a huge number of the population per day going into the underground space. For example, in Nanjing, the metro mileage is 180.2 kilometers in 2014 with 1.4 million passengers daily (Figure 6 shows the flow situation in a subway in the rush hour in Nanjing); the area of underground commercial space in the Nanjing Xinjiekou commercial center is 200,000 m^2 with 16.06 million passengers in 2013 [74].

Figure 6. The flow situation in a subway in the rush hour in Nanjing.

In order to create an environment that meets the requirements of human activities, the urban underground space environment should be controlled and improved by artificial means to a greater extent, including hydrothermal environment control, air quality control, sound and light environment control, psychological and visual environment control, and energy-saving control. Among these controls, the control over the hydrothermal environment and air quality should lie in ventilation and air conditioning systems, which have a direct impact on the indicators of urban hydrothermal environments and air quality.

As shown in Figure 7, underground space ventilation and air conditioning systems mainly consist of an intake and exhaust system. Through rational design of the organization of underground space airflow, the exhaust ventilation system sucks the air into the underground space through the exhaust pipe through the indoor air vents with the exhaust machine, then releases the polluted air through ground exhaust equipment. The intake system sucks the ground fresh air into the intake duct through the ground inlet device with inlet machine, then releases the fresh air into the underground space by vents. The circulation of air results in internal environment control.

Figure 7. The working principle of underground space ventilation and air conditioning systems.



3.2.1. Hydrothermal Environment Control in Underground Space

Heat dissipation of heat sources in underground spaces includes three major parts: heat dissipation of indoor process equipment, lighting heat dissipation and human body heat dissipation; the dissipation amount of equipment, lighting and human body heat accounts for a larger proportion of the air conditioning load. In the underground space, most people are in a state of motion, while the metabolic rate under the state of motion is twice that of the meditation state. The aggregation functions of underground traffic and underground business space create a higher occupant density. Because the mutual isothermal radiation effects between human, the external radiation heat is reduced. People will be more prone to discomfort. As a result, the indoor air temperature in the underground space should be designed to be a bit lower than the temperature set for the ground buildings. Only in this way can the comfort of the human body be achieved.

The higher content of water vapor, greater relative humidity and higher heat humidity ratio in the air of underground spaces are unfavorable for the creation of a good internal environment. Due to the wet dissipation on the surface of the enclosure structure and the absence of sunlight, the underground buildings are more humid than the ground ones. Sources of moisture in underground buildings mainly include the following aspects: construction water, fissure water, surface moisture, moisture in air, human body moisture and technology moisture. It is due to the particularity of the air environment in underground structures that "moisture protection and dehumidification" become a key aspect in the design of ventilation and air conditioning systems in underground buildings.

Consequently, ventilation and air conditioning systems of underground spaces may discharge excess heat into the ground environment, which exerts a direct influence on the hydrothermal environment of the development zones in urban underground space.

3.2.2. Air Quality Control in Underground Spaces

Influenced by rock, soil, enclosed space and other factors, the underground space has poor air conditions. For people in the underground space, it is necessary to improve the air quality of the underground space. The main factors that affect the air quality of underground space are as follows:

CO_2. In an indoor environment of underground space, human breath results in an elevated CO_2 concentration. In the underground space with a dense population, such as underground malls and underground railroads, the human body will discharge a large amount of emissions, represented by CO_2. Through fresh air provided by air conditioners, the CO_2 concentration in the air of most underground public buildings can be controlled within 0.15%.

CO. CO is a harmful gas. Generally speaking, no factors will lead to the increase in the concentration of CO, except for the air introduced from the outer space into the underground buildings in which CO content in the air does not exceed 10 mL/m^3. However, there is an exception: underground parking. Since vehicle exhaust gas has a higher concentration of CO, it will rise rapidly to the point at which great harm will be caused to human beings. Therefore, CO content should be controlled in the design and use of underground parking.

Dust and bacteria. Due to poor ventilation and high humidity of the underground environment, the microbial species and quantities of the underground space are higher than those of the ground space. Indoor microbial pollution mainly comes from the human body: breath, coughing, excrement and wounds on skin will all bring out bacteria or viruses. In the underground space, dust and bacterial contamination are extremely serious. The concentration of inhalable particles generally exceeds the allowable value (0.15 mg/m^3), even dozens of times of the standard value. By filtering of air, the dust and bacteria in the air of the underground space will spread to the ground environment through the ventilation and air conditioning systems.

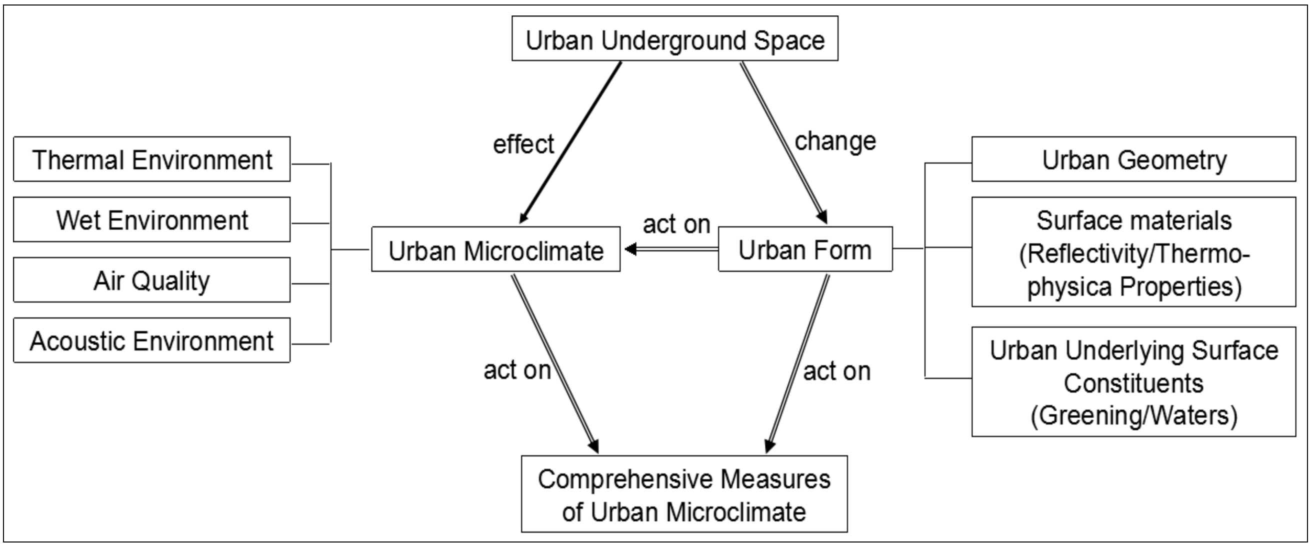
TVOC. In the past, people tended to pay attention to obvious indoor pollutants, but neglected many low-concentration volatile organic compounds (VOC). With the emergence of the concept of "molecular contamination", indoor air quality control extends to chemical pollution control from particulate pollution control. The concentration of the total volatile organic compounds (TVOC) in the air can be revealed in the oxygen consumption of organic matters. In addition, these compounds will also lead to symptoms like peculiar smell, dizziness, fatigue and irritability. As comprehensive air pollution indicators, they are not only related to and even significantly correlated with other indicators, but they have their own independence (the concentration of organic matter in the reaction chamber). The effects of indoor organic pollution on human health can be divided into: smell and other sensory effects; mucous membrane irritation, such as acetaldehydes, acrolein and naphthalene; genotoxicity and carcinogenicity, such as formaldehyde.

Radon pollution. In the underground structures, the actual distribution status of radon and its progeny is a very important parameter. The radon in the underground buildings mainly comes from 226 Ra in rock, soil and building materials. The radioactive effect in the underground buildings is generally greater than that in the ground buildings, and so is the radon pollution in the underground space. Radon ventilation in most of the existing underground works is made in accordance with the radon protection standards in the Environmental Health Criteria generally used in air defense projects. In this way, the radon pollutant in the underground space will be released into the ground environment. Through the dilution ventilation and displacement ventilation of ventilation and air conditioning systems, the indoor air quality of the underground space is improved to ensure that fresh air will be sent to the personal activity area and that the polluted air will be released to the urban environment, which directly affects the air quality parameters and pollutant levels.

3.3. Frameworks between Underground Space and Urban Microclimates

According to the analysis, two correlated objects exist in the framework of effects of underground space on urban microclimate: the urban form factors and the internal environment factors of underground space. These two correlated objects are closely related to the quality of microclimates. The frameworks between underground space and urban microclimate are as shown in Figure 8.

Figure 8. Frameworks between underground space and urban microclimate.



4. Instance and Quantitative Analyses of Influence of Underground Space Projects on the Urban Microclimate

We have conducted analyses on the influencing mechanism of urban underground space projects on the urban microclimate as well as their correlation in the former part. In this part, this paper includes a preliminary study of an underground parking development project in Nanjing, China. The development of underground parking mainly changes the urban underlying surface. This study adopts a "with-and-without method" to preliminarily analyze how an underground space project development changes the urban microclimate through urban underlying surface change. Through numerical calculation of the microclimate in residential areas under two schemes ("with underground space development" and "without underground space development"), this study compares the microclimate parameters of these two schemes, such as temperature, humidity, wind field and CO_2 concentration, so as to analyze the changes in the microclimate of the residential area before and after underground parking space development.

4.1. Case Study

The microclimates in different cities have different features and this research emphasizes the underground parking developments in the residential areas in Nanjing. Nanjing is a big city in the southeast of China and its total resident population has been more than 8,000,000 since 2010 according to the Sixth Nationwide Population Census. This is 28.31% more than that in 2000 and the urban population in Nanjing accounts for 78.5% of its total population. The rapid development in Nanjing aggravates the Heat Island Effect and worsens the environment.

Figure 9. The plan of the residential district.

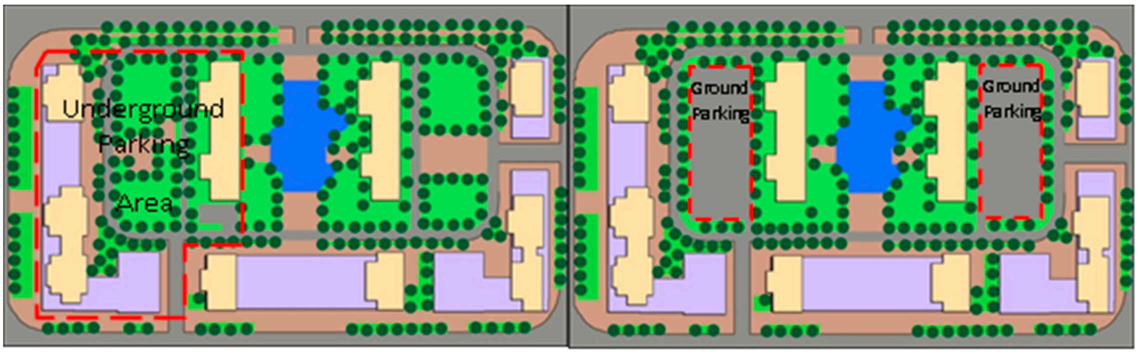
The target residential area is located in the southeast of Nanjing and its plane graph is shown in Figure 8. The planning land is about 45,000 m^2. The total building area covers about 133,000 m^2. The floor area ratio is 2.5. In the residential area, there are 12 small high-rise residential buildings, gathering around an ecological garden in the middle. In the community planning, the designers adopted the scheme of underground parking, which is concentrated under the greenbelt in the south (dashed region in Figure 9). In this community, there are 780 households and 680 parking lots for motor vehicles in all, among which 580 are under the ground. The underground parking garage covers an area of 10,000 m^2.

In this research, the microclimate simulation software Envi-met designed by the Institute of Geography of the University of Bochum is used to carry out a simulation analysis of the relationship between the underground parking garage and the environmental benefits in the urban residential area. The software applies mainly to the coupling calculation of windy, hot and wet environments in a mesoscale model microclimate. The Chinese scholars have done theoretical research, experimental check and sensitivity analysis of this software to verify its applicability in China, particularly in the areas with hot summers and cold winters, such as Nanjing. Therefore, this software is applicable to this research [75,76].

In order to facilitate the establishment of a digital map in Envi-met, the planning graph of this residential area needs to be simplified, with only six kinds of major underlying surface left, including buildings, roads, hardstand, greenbelt, trees and waters. The simplified planning graph is shown in Figure 10a (plan I).

In order to know what benefits the underground parking garage can bring to the microclimate in the community, we need to put forward another scheme without planning for underground parking lots, which can be used to contrast with Plan I. According to Standards and Guidelines of Construction of the Building's Equipped Parking-lot in Nanjing (2012 Amendments), the resident parking rate in the community should not be less than 10%, that is to say, the residential area in this research should have at least 78 parking spaces. According to Index of Standard Parking Construction for Motor Vehicles in Nanjing, the planning scheme of the residential areas which can provide the least number of parking lots and have no underground parking garages is shown in Figure 10b (plan II)

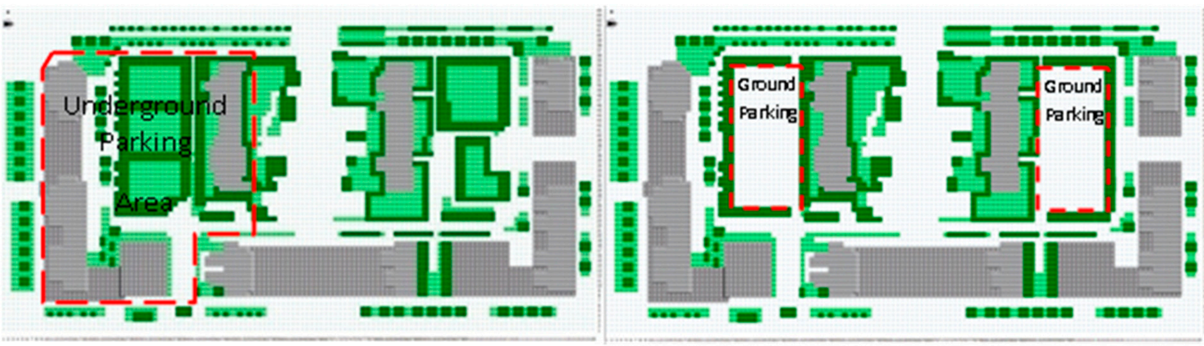
Figure 10. (**a**) Simplified plan of the residential district (Plan I); (**b**) Simplified plan of the residential district (Plan II).



(**a**) (**b**)

In accordance with the simplified planning graph, digital maps of two schemes in Envi-met can be seen respectively in Figure 11a,b. The attributes of the corresponding underlying surface in the digital maps are set based on the simplified graph.

Figure 11. (**a**) The digital map of Plan I; (**b**) The digital map of Plan II.



(**a**) (**b**)

The simulation meteorological parameters input to ENVI-met mainly include the initial simulation value, wind speed, wind direction, hourly solar radiation intensity, air temperature, relative humidity, soil temperature at various depths, *etc.* This research makes use of the meteorological data in Nanjing base station provided by Dedicated Meteorological Data Set for Building Thermal Environment Analysis in China. The geographic position is 32° north latitude, 118°48′ east longitude and 7.1 m above sea level. The input simulation parameters can be seen in Table 2.

Table 2. Inputs of simulation.

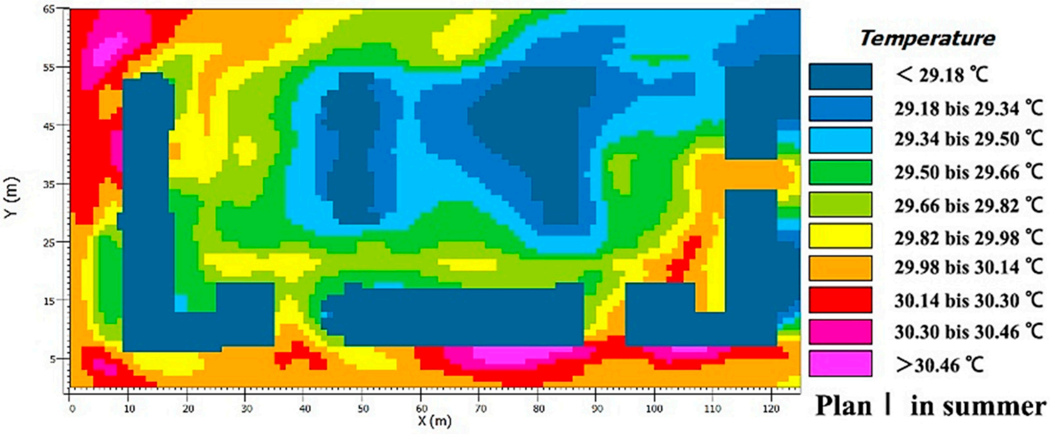
Initial value of simulation							
Typical Meteorological Day	**Initial atmospheric temperature (K)**	**Relative humidity**	**Wind velocity (m/s)**	**Wind direction (degree)**	**Outdoor atmospheric pressure (Pa)**	**initial time**	**Total simulation time (h)**
6.23 (Summer)	294.95	80%	2.4	157.5	100250	6:00	12
12.23 (Winter)	274.25	66%	3.2	67.5	102790		

4.2. Results and Analysis of the Case Study

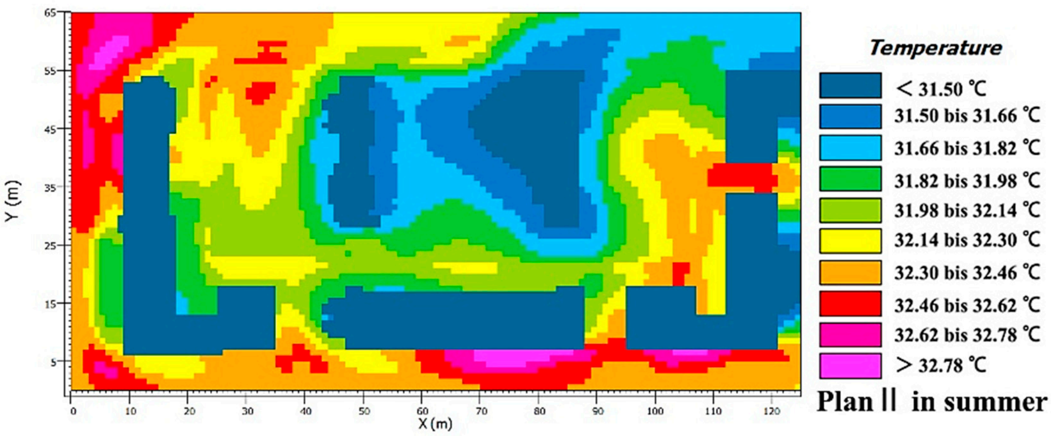
4.2.1. Comparative Analysis of Temperature Field

Figure 12 shows the temperature field cloud pictures 1.5 m above from the ground at 12:00 noon in the summer and winter of the two schemes. Figure 13a,b show the numerical simulation comparison of hourly air temperature curves (8:00–17:00) 1.5 m above from the ground in the summer and winter of the two schemes.

Figure 12. The temperature cloud atlas 1.5 m above the ground of Plan I and Plan II at 12:00.

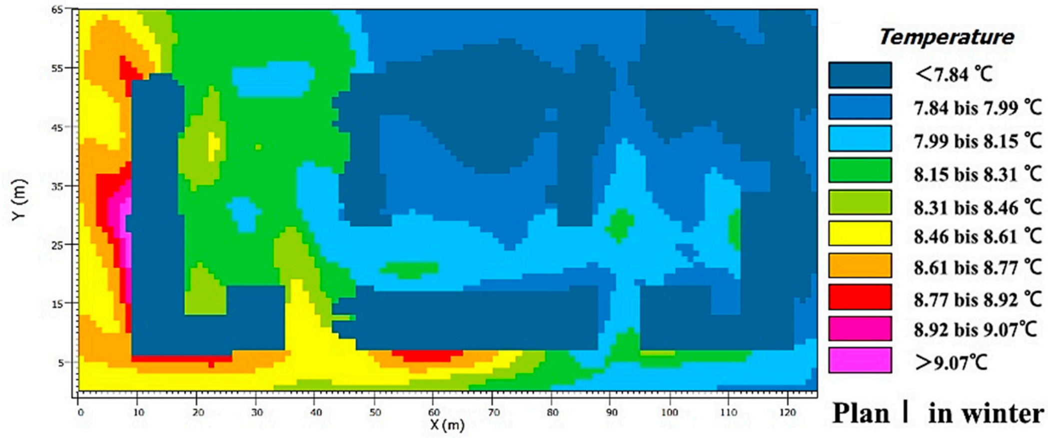


(**a**)



(**b**)

Figure 12. *Cont.*



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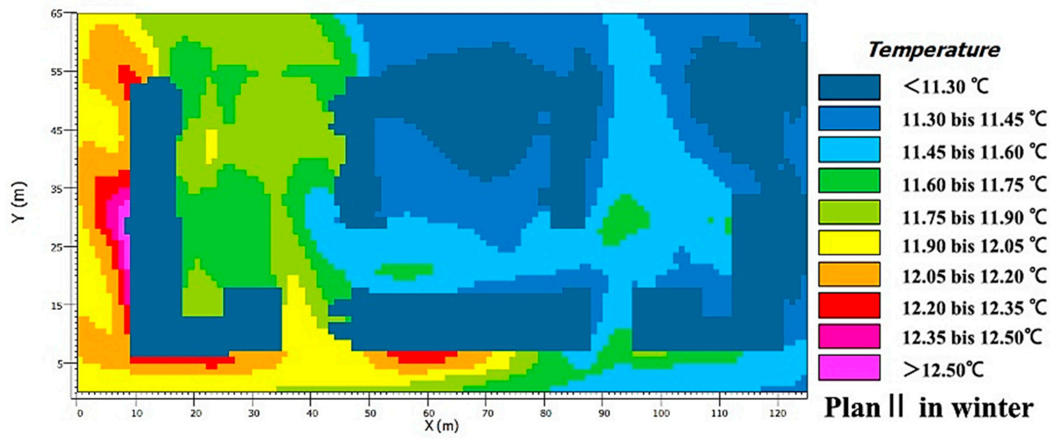
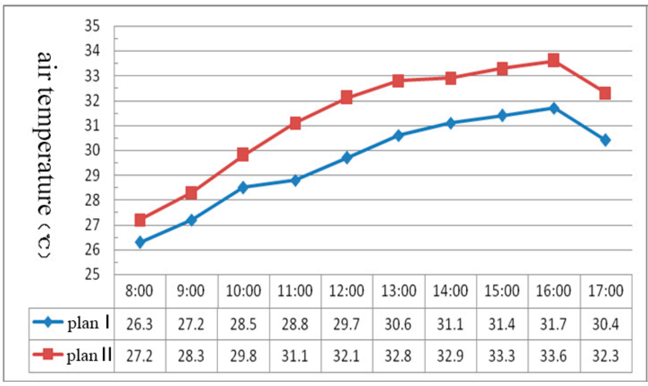
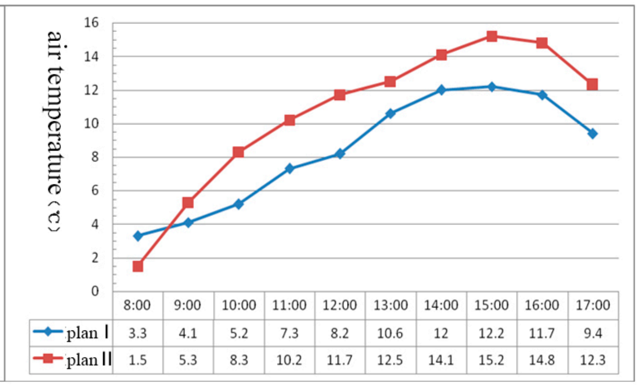


(**d**)

Figure 13. (**a**) Hourly air temperature curve comparison chart in summer; (**b**) Hourly air temperature curve comparison chart in winter.



(**a**)



(**b**)

We can see from the Figure13 that in summer, the average air temperature in Plan I is 1.7 °C lower than that in Plan II. The biggest temperature difference between the two schemes is 2.4 °C, which appears at 12:00 noon. From 11:00–14:00 when the temperature is high, all the hourly air temperatures in Plan I are more than 2 °C lower than those in Plan II. In winter, the average air temperature in Plan I is 2.1 °C lower than that in Plan II, however, the temperature variation in Plan II is larger than that in Plan I. The lowest air temperature in the simulation appears at 8:00 in Plan II.

It can be seen from the cloud pictures that the temperature of the ground parking lots in Plan II is evidently higher than that of the greenbelt at the same location in Plan I, which is also the main reason for the larger temperature variation in Plan II.

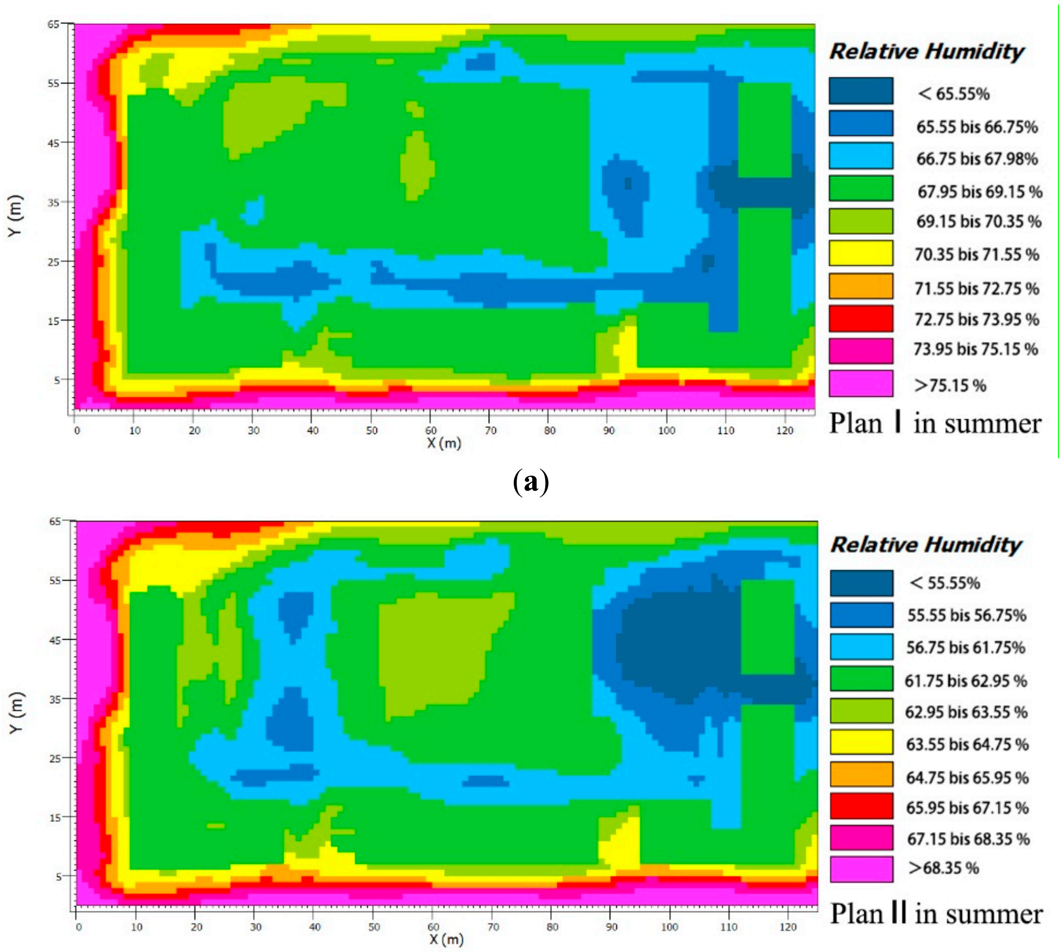
4.2.2. Comparative Analysis of Humidity Field

Figure 14 shows the humidity field cloud pictures 1.5 m above from the ground at 12:00 noon in the summer and winter of the two schemes. Figure 15a,b show the numerical simulation comparison of hourly relative humidity curves (8:00–17:00) 1.5 m above from the ground in the summer and winter of the two schemes.

We can see from the figures that the average humidity in Plan I is 2.3% higher than that in Plan II in summer and 4.6% higher in winter.

We can also see from the cloud pictures that the relative humidity of the ground parking lots in Plan II is lower than that of the greenbelt at the same location in Plan I. Besides, lower relative humidity is concentrated around the parking lots in the same cloud picture.

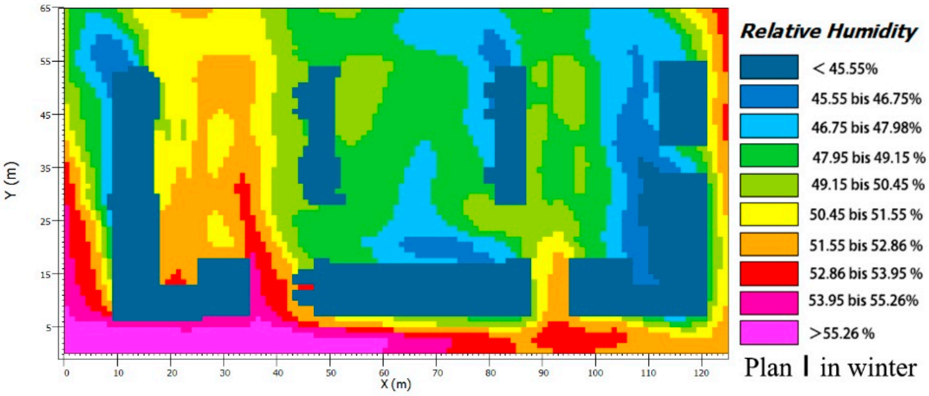
Figure 14. The relative humidity cloud atlas 1.5 m above the ground of Plan I and Plan II at 12:00.



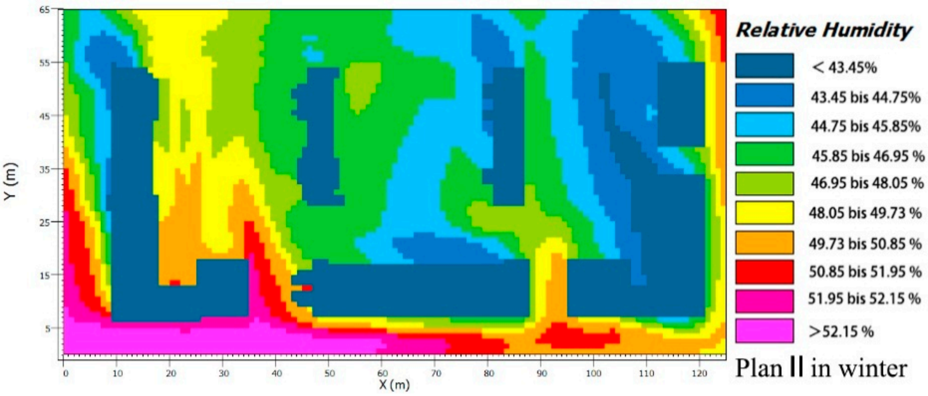
(**a**)

(**b**)

Figure 14. *Cont.*

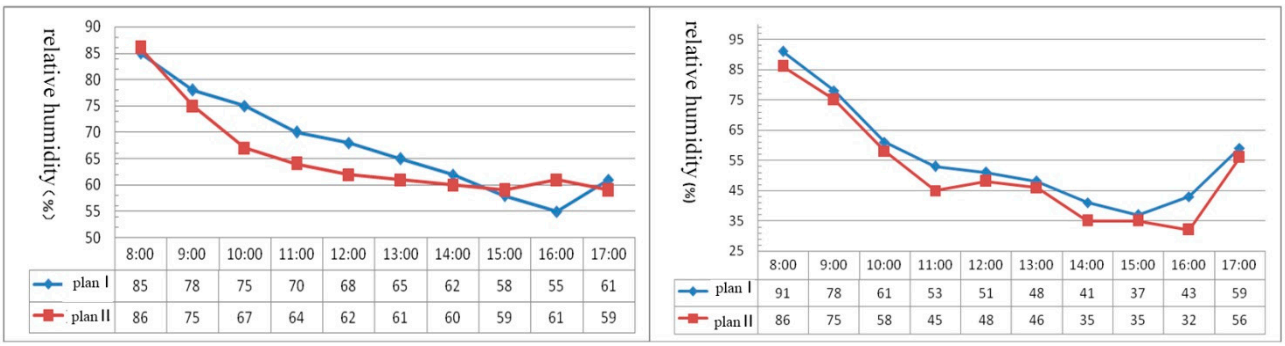


(**c**)



(**d**)

Figure 15. (**a**) Hourly relative humidity curve comparison chart in summer; (**b**) Hourly relative humidity curve comparison chart in winter.



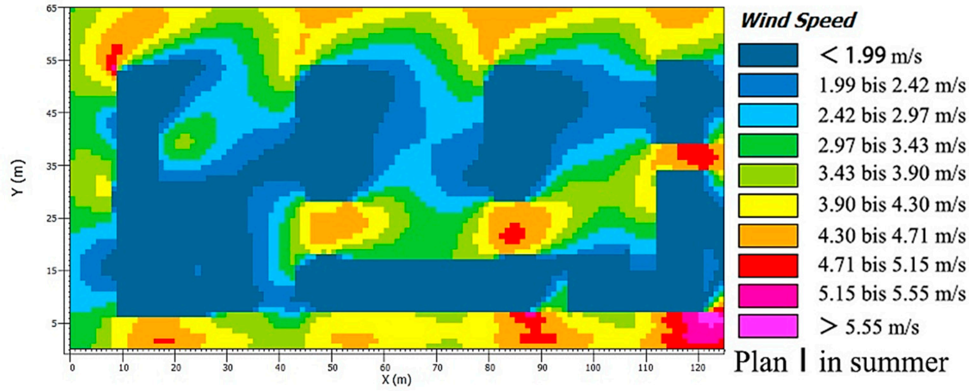
(**a**) (**b**)

4.2.3. Comparative Analysis of Wind Environment.

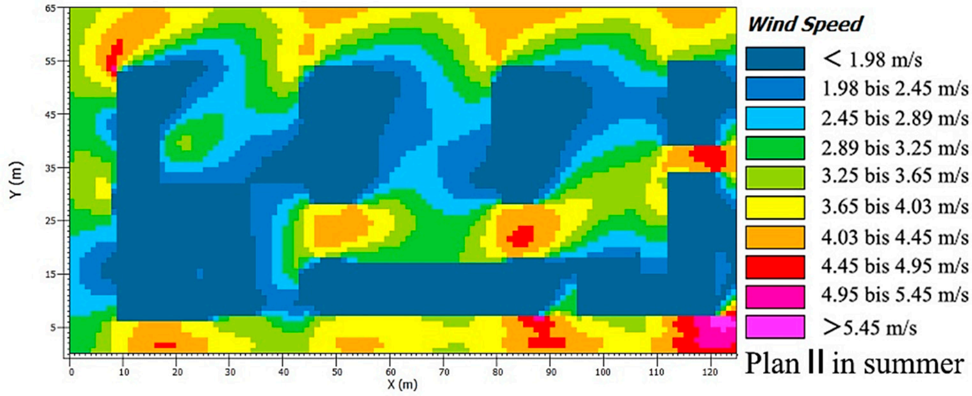
Figure 16 presents the cloud figures of wind speed 1.5 m above the ground at noon (12:00) in summer and winter in the two schemes. Figure 17a,b present the numerical simulation of hourly wind speed (8:00–17:00) 1.5 m above the ground in summer and winter in the two schemes.

Since the wind environment is co-determined by wind direction, wind speed and layout of residential buildings, Plan I and Plan II share very similar wind environment characteristics in summer and winter, and their cloud figure distribution and wind speed values are very close to each other.

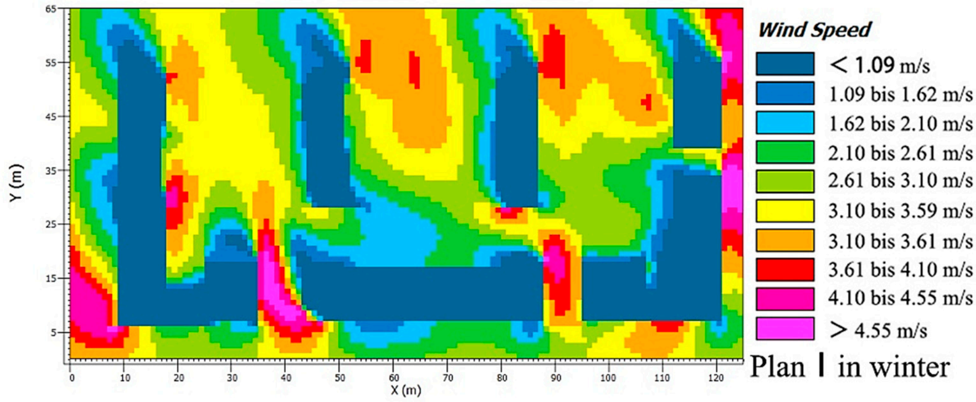
Figure 16. The wind velocity cloud atlas 1.5 m above the ground of Plan I and Plan II at 12:00.



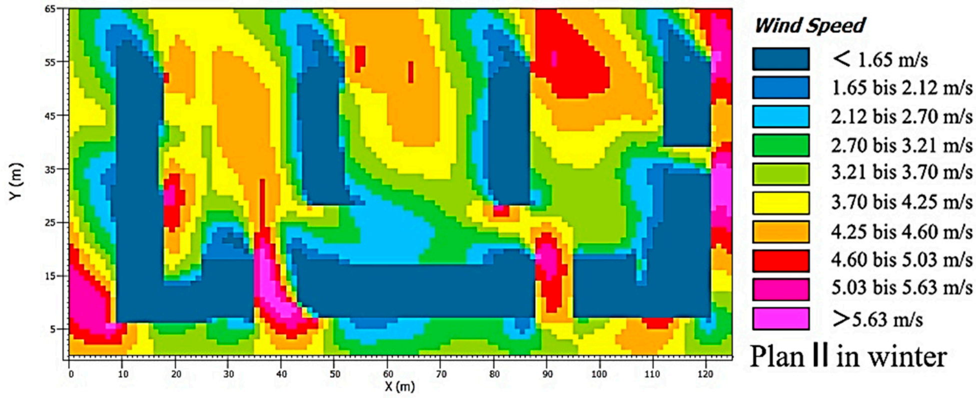
(**a**)



(**b**)

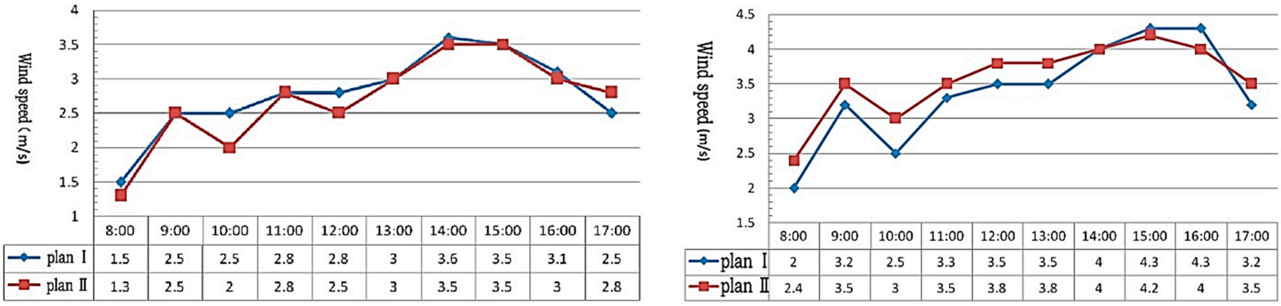


(**c**)



(**d**)

Figure 17. (**a**) Hourly wind velocity curve comparison chart in summer; (**b**) Hourly wind velocity curve comparison chart in winter.



(**a**) (**b**)

In summer, as the southeast wind is blocked by the building in the southeast corner, the wind speed within the residential area reduces and no area with high wind speed is formed, which is not conducive to ventilation and cooling of the residential area in summer. In winter, as there are entrances at the east and north sides, the northeast wind will enter the residential area and form a space with high wind speed at the entrance; besides, since the parking lot in Plan II directly connects to the entrance, a high wind speed space is also formed at the parking lot, leading to poor wind environment of the residential area in winter. Thus, it can be seen that the architectural layout of this residential area is not conducive to the formation of a good wind environment.

Wind speed values in Plan I and Plan II are slightly different. In summer, the average wind speed in Plan I is 0.09 m/s lower than that in Plan II. In winter, the average wind speed in Plan I is 0.19 m/s lower than that in Plan II. However, since a high wind speed space is formed at the parking lot in winter in Plan II, the wind environment in Plan II is poorer than that in Plan I.

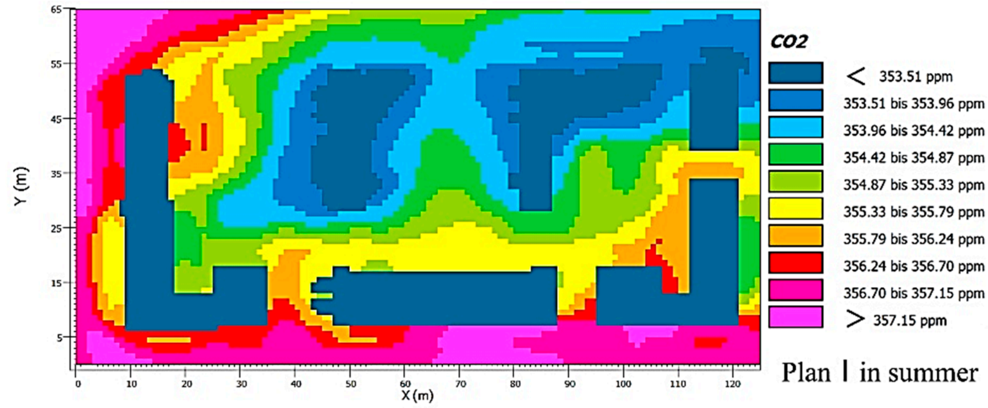
4.2.4. Comparative Analysis of CO_2 Concentration

Figure 18 presents the cloud figures of CO_2 concentration field 1.5 m above the ground at noon in summer and winter in the two schemes. Figure 19a,b present the numerical simulation of hourly CO_2 concentration (8:00–17:00) 1.5 m above the ground in summer and winter in the two schemes.

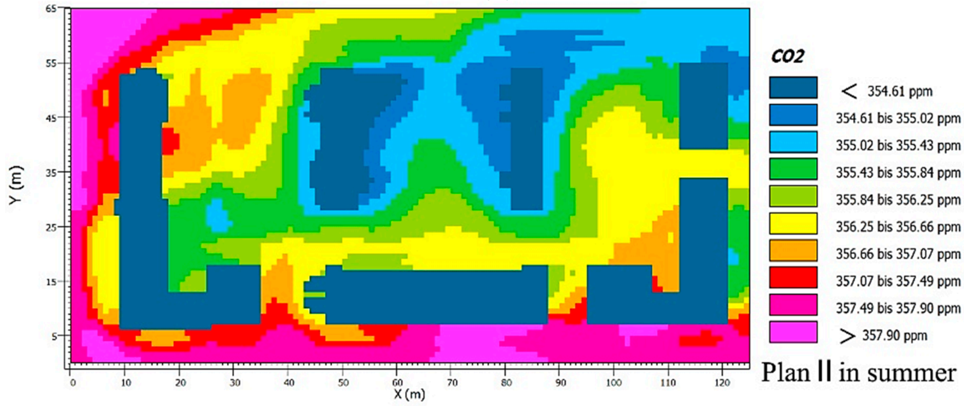
It can be seen from these figures that, in summer, the average CO_2 concentration in Plan I is 1.1 ppm lower than that in Plan II and the biggest difference is 2.9 ppm; in winter, the average CO_2 concentration in Plan I is 0.2 ppm lower than that in Plan II and the values are close. However, CO_2 concentration in Plan I is generally lower than that in Plan II.

The cloud figures show that, CO_2 concentration at ground parking lot in Plan II is higher than that at the same place in Plan I, and the areas with higher CO_2 concentration in the same cloud figure concentrate in the parking lot.

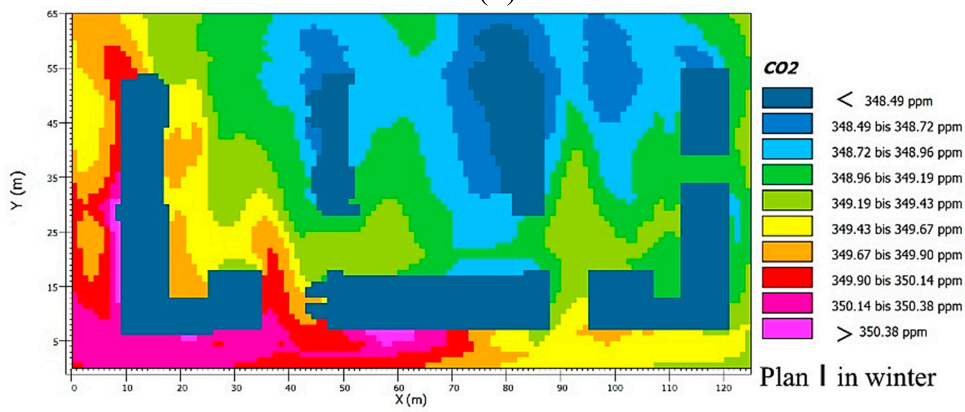
Figure 18. The CO_2 density cloud atlas 1.5 m above the ground of Plan I and Plan II at 12:00.



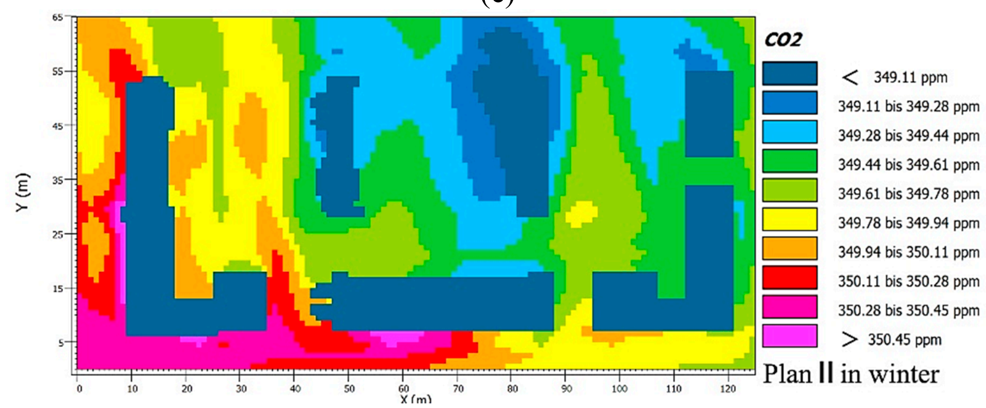
(**a**)



(**b**)

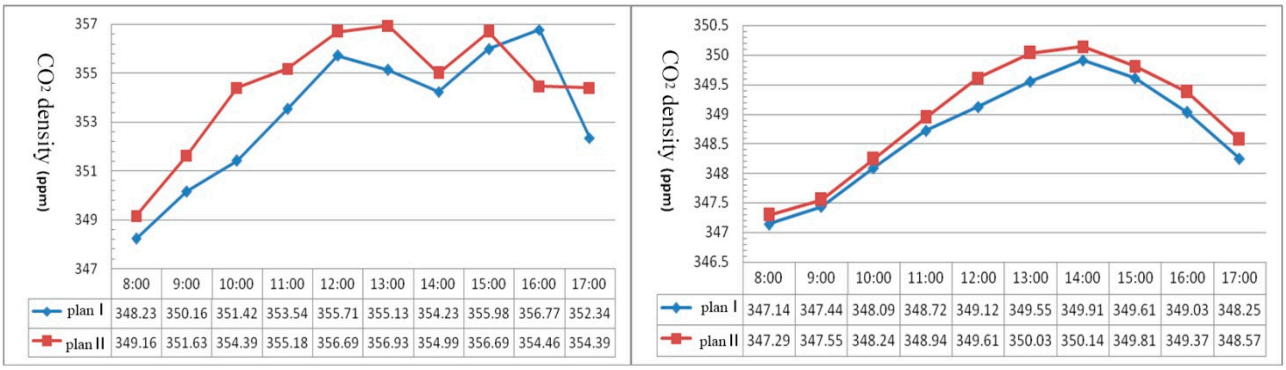


(**c**)



(**d**)

Figure 19. (**a**) Hourly CO_2 density curve comparison chart in summer; (**b**) Hourly CO_2 density curve comparison chart in winter.



(**a**) (**b**)

4.2.5. Comparative Analysis of Mean Radiant Temperature

One key factor to evaluate human outdoor comfort level is mean radiation temperature (MRT), which summarizes the short wave and long wave radiation flux that the human body absorbs. Under sunny day conditions, whatever kind of comfort indicator is used, MRT is the key variance in the evaluation of outdoor thermal sensation [77]. It represents the combined effects of air temperature, solar radiation and wind speed on the human body. It is one of the key factors in the study of human outdoor thermal comfort. MRT summed up the shortwave and long wave radiative flux absorbed by the body [78,79]. Through research of MRT, the relationships of underground space development indicators with a variety of radiation fluxes can be studied, the mechanism of underground space development action on the thermal environment can be analyzed. It is conducive to research the impact of underground space developments on outdoor thermal comfort. In this section, the paper includes a preliminary analysis of MRT.

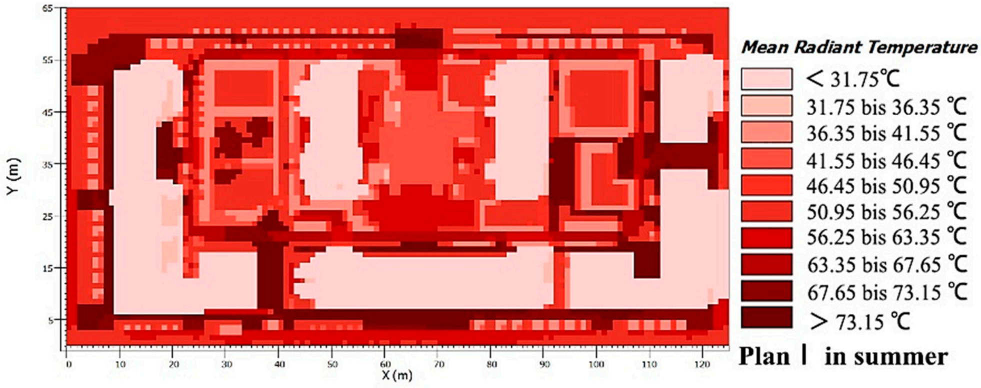
Figure 20 shows the cloud pictures of MRT 1.5 m above the ground at noon (12:00) in summer and winter in the two schemes. Figure 21a,b show the numerical simulation comparison of hourly MRT curves (8:00–17:00) 1.5 m above from the ground in summer and winter in the two schemes.

It can be seen from the figures that in summer, MRT in Plan I is 10.2 °C lower than that in Plan II. The gap between MRT in two schemes is large, with the largest difference of 15 °C at 12:00 noon. Most of the MRT in Plan II is above 50 °C and the highest temperature reaches 61 °C. All the MRTs in Plan I are below 40 °C before 12:00 and they are on the rise after 12:00. However, MRTs in Plan Ⅰ are quite different from those in Plan II and their down trend after 16:00 is also superior to that in Plan II.

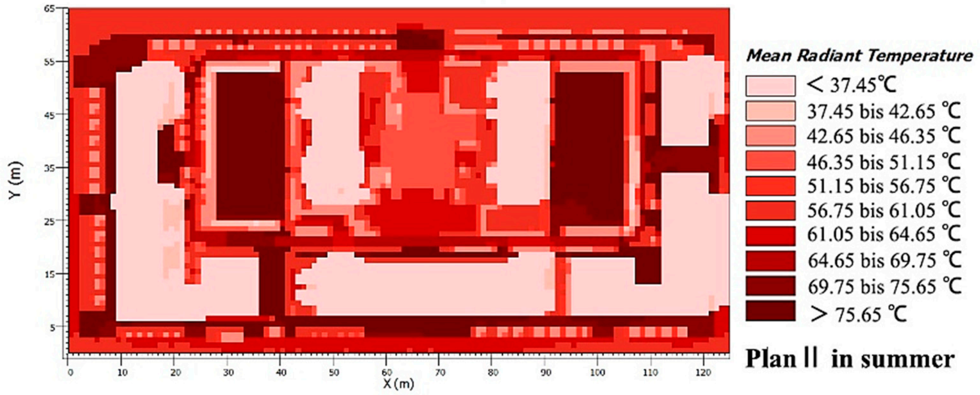
In winter, average MRT in Plan I is 1.7 °C lower than that in Plan II. The gap is small and MRT values are also similar.

We can see from the cloud pictures that in summer, MRT values of the ground parking lots in Plan II are obviously higher than those of ambient environment and those at the same location in Plan I, with a difference of over 10 °C. In winter the distributions and values in two schemes are similar, which is closely related not only to the relative position between the sun and the buildings but also to the position of the sun.

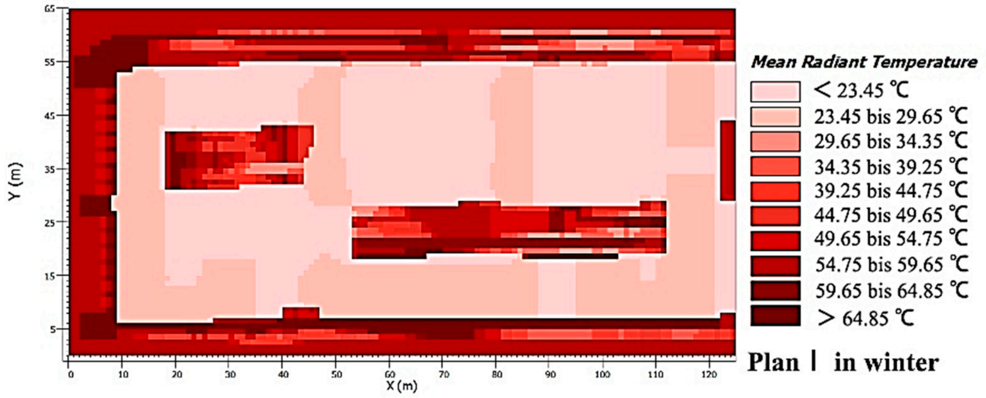
Figure 20. The mean radiation temperature (MRT) cloud atlas 1.5 m above the ground of Plan I and Plan II at 12:00.



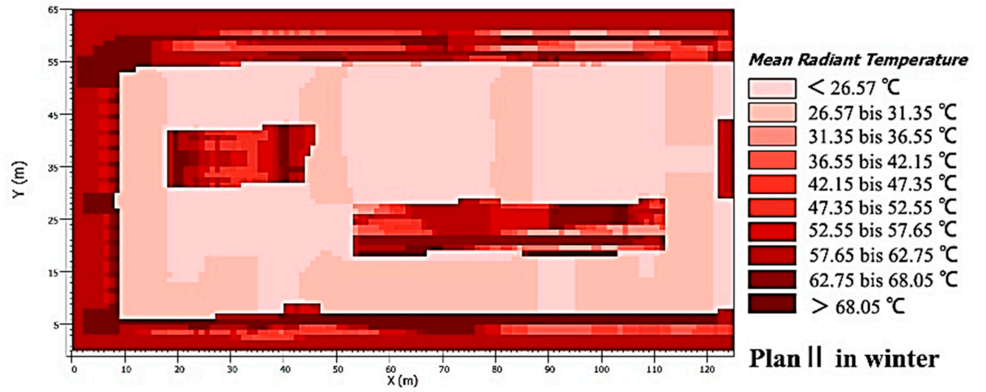
(**a**)



(**b**)

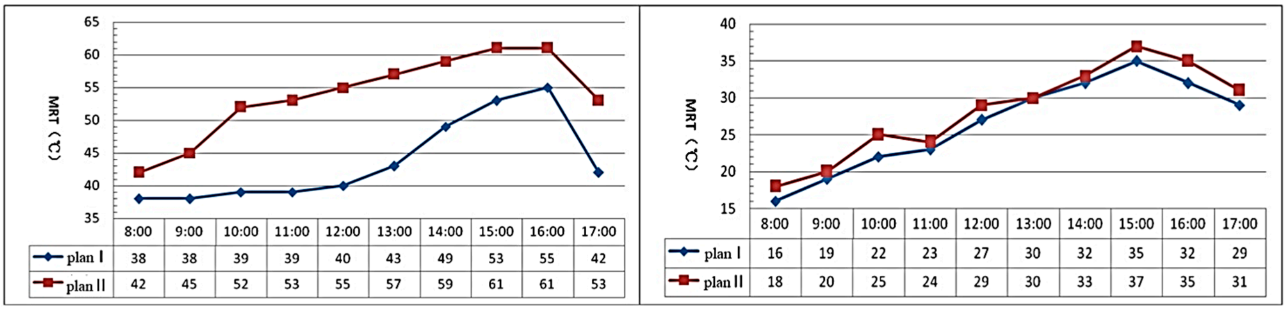


(**c**)



(**d**)

Figure 21. (**a**) Hourly mean radiant temperature (MRT) curve comparison chart in summer; (**b**) Hourly MRT curve comparison chart in winter.



(**a**) (**b**)

4.2.6. Summary of the Case Study

The comparative study of the microclimate effects of these two schemes suggests the underground parking development can change the underlying surface and has a significant effect on the improvement of the microclimate environment of urban residential areas. Compared with a ground parking development, an underground parking development can significantly reduce air temperature, provide better thermal environment and reduce CO_2 concentration in the air, leading to a more balanced distribution of ground microclimate parameters. In addition, the increase in ground green area can increase the residential landscape, which plays a positive role in creating an ecological urban environment.

However, this study only analyzed the change of underlying surface elements. Since there is no consideration of urban form and internal environment control within the underground space, it is incomprehensive in researching the influence of underground space developments on the urban microclimate. However, there has been limited progress due to the absence of advanced integrated three-dimensional integrated urban forms—internal environment control within underground spaces—and an urban microclimate environment modeling plat form capable of analyzing the behavior of complex, dynamic systems. Thus, systematic, complex and long-term research is necessary.

5. The Entry Point and Key for the Influence of Underground Space Engineering on the Urban Microclimate and the Establishment of the Research System

Through the analysis of the case, the improvement in the effect of the underground space engineering on the urban microclimate could be basically determined. However, it is worth noticing that the research in this field still exists at the initial stage but there is no established research system. For the in-depth and scientific research on the influence of underground space engineering on urban microclimates and their relevance, it is necessary to set up a system of research scope, research method, scientific indicators and research instruments with the aim of gaining a deep understanding of the research focus.

In the former section, the research objects are specified and two key correlated objects are put forward. The correlated objects are closely related to the microclimate quality. The research contents include: the frameworks between the integrated urban form of ground space and underground space, environment control factors of underground space, and urban microclimate indicators, as well as the influencing mechanism, which can be further subdivided into the following two key issues.

5.1. Research on Influencing Mechanism of Underground Space Developments on Urban Form and Urban Microclimates

From the perspective of integrated ground and underground spaces, this section discusses the influencing mechanism of underground space development on urban space form, ground texture, urban underlying surfaces and green plants, as well as the frameworks between its elements and urban microclimate, which include two major aspects:

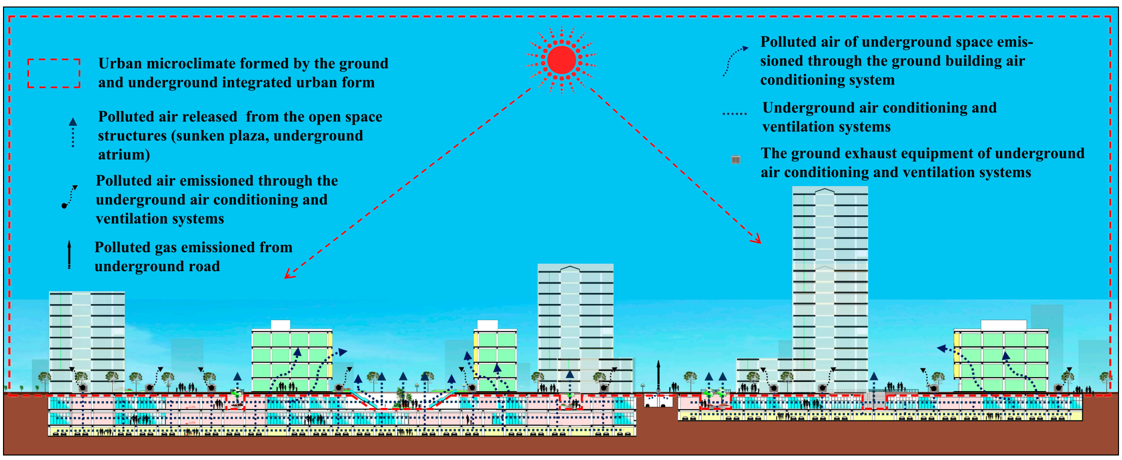
(1) According to the climate, topography, regional architecture and underground space form, the three-dimensional characteristics of urban space is analyzed. Based on the macroeconomic coordination and integration mechanism of multi-dimensional ground and underground spaces in different stages, the evolution model of integrated ground and underground spaces is studied, and the design pattern of the integrated ground and underground spaces and its influencing factors are determined.

(2) As the assessment on urban microclimate quality is not confined to the physical indicators, quantitative analyses of the relationships between urban center underground space geometry (such as area, perimeter and shape), urban underlying properties (type, vegetation cover degree and other greening parameters) and urban microclimate indicators are carried out. Various human comfort indicators are needed to be further specified to clarify the urban design elements (spatial geometric elements and underlying surface properties) that affect urban microclimate, and to define the entry point and scope of research on underground space discipline; Based on the above analyses, the framework factors between urban underground space and urban microclimate are determined.

5.2. Construction of Simulation Experiment Platform for Effects of Underground Space on Microclimate

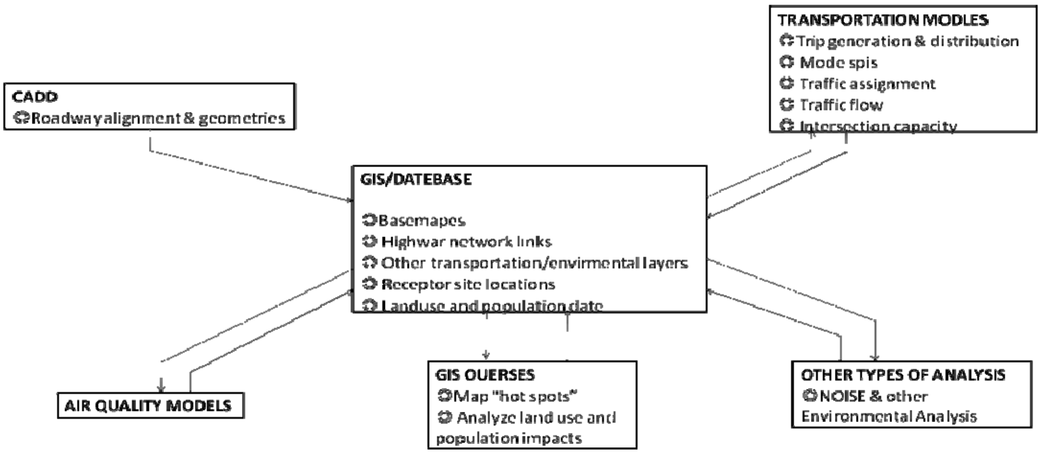
As analyzed in Section 4.2.6, an advanced modeling tool should be established for the research. According to Section 3, as shown in Figure 22, the influence of urban microclimate by underground development contains a number of factors, such as ground and underground integrated urban form, internal environment control of underground space, and emissions of underground roads. Each factor also contains a number of elements. Therefore, the platform requires various computational models and multiple data sources. These models and data should be integrated in the simulation platform.

Figure 22. The influence mechanism of underground space development on the urban microclimate.



In 1994, Medina *et al.* proposed a framework with a geographic information system (GIS) as a centerpiece to link Computed Aided Drawing and Design (CADD), GIS, and transportation and air quality models of underground road. The framework was to be applied to the evaluation of air quality impacts of several proposed river crossing alignments for the Boston Central Artery/Third Harbor Tunnel (CA/THT). The original framework involved the use of ArcCAD to integrate data from AutoCAD, Tran Plan, PC/Arc Info and Mobile5, as well as generating input files for CAL3QHC, a microcomputer-based model for predicting concentrations of carbon monoxide and other inert pollutants from motor vehicles at roadway intersections. The design is shown in Figure 23 [80].

Figure 23. Working framework for the Central Artery/Third Harbor Tunnel (CA/THT) project.

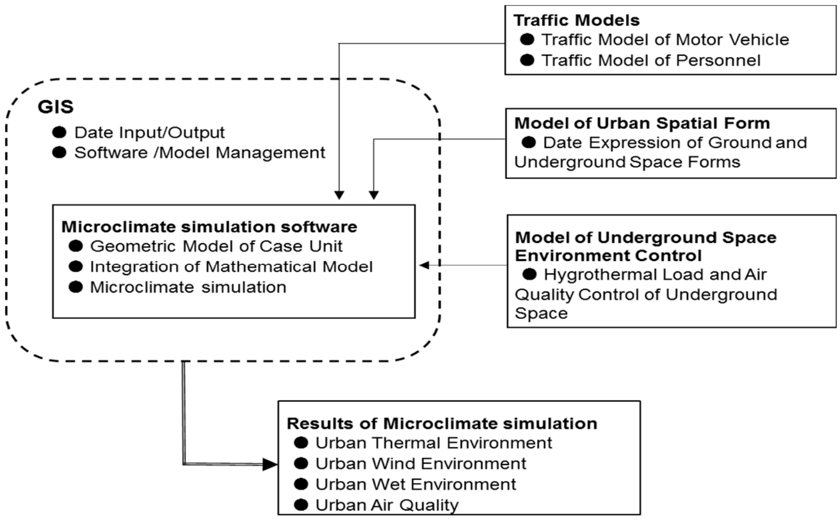


Whilst underground road air quality models have been available, they have not been integrated with land integrated urban form—internal environment control—urban microclimate models that analyze underground space development. This has been in part because of a lack of joint research teams considering the issue and in part due to the formidable task of combining the models integrated with land integrated urban form–internal environment control—urban microclimate models represent complex, dynamic systems with large data requirements and intensive computing tasks, and air shed models are even more demanding.

For future research, this paper proposes one original simulation experiment platform about the effects of underground space on the microclimate. The original platform design involved the following setup: (1) since the link urban geometry data was required as inputs to the modeling process, the GIS is needed to integrate the models' platform. The GIS component represents all mechanisms for managing data required by the other four components, including access to and conversion of input data, storage of intermediate and output data, provisions for report writing, charting, mapping and other analytical representations of data; (2) Traffic models reused to load the traffic configuration data of motor vehicles and personnel [81]. The roadway morphology links were to be generated using the GIS-base map and alignment designs as background; (3) The urban spatial form model has expressions of the ground and underground integrated spaces form, urban texture structure and spatial morphology. An urban space data expression model based on space data and property data should be established to provide data support for the integration of the integrated urban ground-underground multiple spaces into the geographic information system [82]; (4) The model of underground space environment control provides emission factors from hydrothermal load and air quality control of underground space; (5) GIS-based microclimate simulation software is used to integrate the various data and generate data input files of other models to analogy the thermal environment, wind environment, wet environment and air quality; (6) Results of GIS-based microclimate simulation from data outputs should be analyzed to research the effects of urban underground space on urban microclimate environment.

The construction and research ideas of the simulation experiment platform are as in Figure 24.

Figure 24. A simulation platform for analyses of effects of urban underground space on urban microclimate environments.



The above digitized methods are used to study the influencing law of underground space on urban microclimate. Based on the numerical simulation analysis of characteristics of microclimate, sub-item analyses are carried out, such as the relationship between urban underground form and thermal environment, the relationships between urban three-dimensional greening, the underlying surface properties and the thermal environment. Then, the mathematical prediction model on the effects of the underground space planning and environment control elements on microclimate indicators, based on the urban ground–underground space integration, is established. Besides, starting from human thermal comfort under the urban environment, indicators for the underground space planning and design elements are examined for urban thermal comfort optimization.

6. Conclusions

Both the changes in urban space form and underlying surfaces caused by underground space and the environment control of underground space directly affect the formation of an urban microclimate. There are three points to be considered.

First of all, in the relationships between underground space and urban microclimate, urban space form and texture form are the most direct and important elements, which need to be studied from the perspective of integrated ground and underground spaces.

Secondly, in terms of the environment control of underground space, many careful experiments and comprehensive data analyses should be carried out, among which the study of the effects on urban air quality is a focus.

Most importantly, reasonable thresholds of underground space planning and design parameters determined by the research provide a crucial basis for the establishment of design principles and the guidance of underground space construction.

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Author Contributions

Xiaobin Yang made substantial contributions to the design of the study, acquisition, analysis and interpretation of data, and drafting and revising the article; Hao Cai and Linjian Ma both helped to analyze the result and provided good advice throughout the paper; Zhilong Chen helped to revise the manuscript, and produced the final approval of the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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