Revealing the Multi-dimensional Impacts of Urban form and Land Use on Microclimate: A Case Study based on Nanjing

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Abstract. Urban microclimates are closely related to the indoor living environment of residents. Factors affecting microclimate are diverse, including building design, urban form, urban heat island effect, and climate change. However, most study ignored the interaction of multiple factors and only considered the role of a single dimension. How 2D and 3D characteristics of building and land use interact to influence microclimate was yet unknown. In this study, the impact of urban form and land use are quantified on microclimate under the joint action of two dimensions. And we combined five typical building groups in Nanjing with six land types to form 30 building group models, simulated the microclimate of building group models by Envi-met, and explored the impact on microclimate by linear regression models. The results showed that the effect of urban form on wind speed, temperature and relative humidity varies significantly across land types. These findings provide theoretical support for urban planners and researchers to improve urban microclimates from land use and urban form perspectives.

Keywords: ENVI-met; multi-dimensional; urban form; land use; microclimate.

1 INTRODUCTION

The microclimate of the building is closely related to the indoor environment, the health of residents, and living comfort. Understanding the influencing factors and effects on microclimate can make good use of these factors to improve the living environment for residents. The existing factors influencing microclimate include architectural design, urban form, urban heat island effect, climate change, etc. However, most of the current studies only consider the influence of a single dimension, ignoring the possible interaction of influencing factors of different dimensions [1,2]. It have been progressed and confirmed to some extent the nonlinear effects and complex interactions of 2D and 3D urban landscape metrics on land surface temperatures. However, how the interactions between 2D/3D urban landscape metrics affecting microclimates has not been demonstrated. Even if the green space is widely distributed or the building is surrounded by good wind conditions, the positive impact of the land type on the microclimate can be

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reduced due to the improper building layout [3]. How the influences of different dimensions factors interact to affect the microclimate is unclear. Previous studies have analyzed the effects of 2D/3D single-dimensional metrics on microclimate, but how their complex interactions affect microclimate has not been explained. This study attempts to provide the field with a better understanding of the seasonally disparate responses of the microclimate to 2D and 3D urban form indicators. Therefore, this study will explore the impact of urban form and land use on microclimate. Specifically, 30 models of building groups were formed by combining five typical building groups in Nanjing and combining six land types. Then Envi-met was used to simulate the microclimate characteristics of these building models, and finally the linear regression model was used to analyze the influence of urban form on the microclimate under different land types. The study provides a theoretical basis for urban planners to improve the microclimate of buildings from the point of land use and urban form.

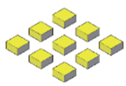
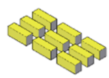
2 DATA & METHODOLOGY

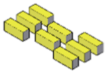
The object of the study is 30 building complex scenarios composed of five building models under 6 land types. We simulated the 24-hour microclimate of the winter solstice and the summer solstice under 30 building complex scenarios. Then we used the linear regression method to analyze the influence of urban form on the microclimate. Finally, we compared the differences in the effect of urban form on the microclimate under different land types.

2.1 Architectural Model

In this paper, the architectural complexes of Nanjing are taken as the research object (**Table 1**) [4]. These 5 groups of building models are established according to the typical morphological characteristics of 114 residential district samples in Nanjing. Therefore, the research results are representative and referential.

Table 1. Five typical building groups in Nanjing.

		
Building size East-West spacing South-North spacing	15×15×9m 15m 15m	15×15×9m 12m 3m
		
Building size East-West spacing South-North spacing	18×18×18m 18m 18m	36×12×18m 6m 18m

		
Building size East-West spacing South-North spacing	36×12×30m 9m 12m	

2.2 Architectural Microclimate, Land Use, Architectural Form

The study used wind speed, temperature and relative humidity as dependent variables. The independent variables include land use and urban form (**Table 2**) [5].

Table 2. Urban form variables.

Independent variable	Formula
Floor area ratio (FAR)	Ratio of the total floor area of a building to the land area it occupies
Volume-to-area ratio (VAR)	The ratio of the volume of the building to the floor area
Surface area ratio (SAR)	The ratio of the total surface of the given particles to the surface area of cells
Site coverage (SC)	Higher SAR results in a relatively large surface area of the building
Site segmentation (SSD)	The total length of the building's footprint/site area
Sky View Factor (SVF)	The ratio of the visible sky area of a point in space to the total sky area.
The reciprocal of the open space ratio (rOSR)	The difference between the total area of the building divided by the area of the site and the floor area of the building
The average height of the building	The average height of the building

The relevant parameters of the architectural forms of different architectural complexes are shown in Table 3. About land use, Type A is composed of dense and tall woods, with many tall trees and lush vegetation. Type B is composed of fewer sparse trees, normal number of trees on the land, normal vegetation. Type C is composed of shrubs and meadows, where the land is made up of low trees, bushes and meadows. Type D is composed of land grassland, where the land is all grassland. Type E is composed of land bare rocks, with few plants, mostly bare. Type F is composed of bare bare soil, desert, and concrete roads.

Table 3. Urban form parameters of the five building models.

	FAR	rOSR	VAR	SAR
Model1	0.71	0.93	2.14	1.57
Model2	0.52	0.63	1.56	1.42
Model3	1.47	1.96	4.41	1.98
Model4	1.9	2.78	5.69	2.26
Model5	1.43	1.67	4.29	1.95
	SC	**SSD**	**SVF**	**Building height**
Model1	0.24	14.05	0.53	9

Model2	0.17	10.22	0.56	9
Model3	0.25	12.55	0.4	18
Model4	0.32	15.65	0.29	18
Model5	0.14	7.49	0.35	30

2.3 linear Regression

Linear regression analysis and stepwise regression are important statistical methods, which examines the relationship between a metric-scaled dependent variable (also called endogenous, explained, response, or predicted variable) and one or more metric-scaled independent variables (also called exogenous, explanatory, control, or predictor variable). They have been widely used in the study of the influence mechanism of urban form, landscape characteristics on microclimate and land surface temperature. Linear regression includes single linear regression and multiple linear regression. The study utilized single linear regression in exploring the effect on wind speed, multiple regression in exploring the effect on humidity, and stepwise regression in exploring the effect on temperature, respectively.

Univariate linear regression refers to a situation where there is only one independent variable and one dependent variable. The linear relationship between the independent variable and the dependent variable is a regression model of a one-time function. The general form of multiple linear regression is as follows (Equation 1) [6]:

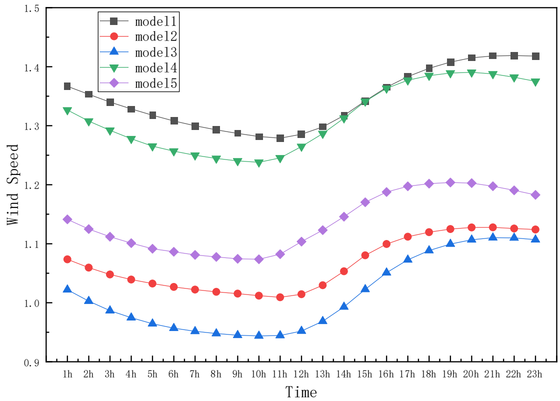
$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_k X_{ki} + \mu_i \tag{1}$$

Where k is the number of explanatory variables and β_k is the regression coefficient.

A stepwise regression has been implemented to select the optimal number of predictors to be included in each multiple regression model [7].

3 RESULTS

3.1 Microclimate Change



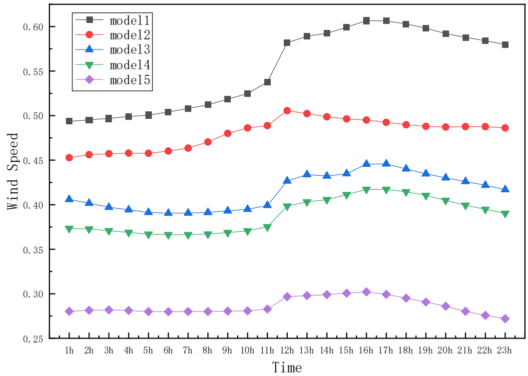


Fig. 1. Wind speed changes in summer solstice and winter solstice.

On the summer solstice, the wind speed increases with the time of day **(Fig.1.)**. The wind speed of model 1 and model 2 is generally larger, while the wind speed of model 5 is the lowest. On the winter solstice, the wind speed of model 1 and 4 is higher, while model 3 is always at a lower level of wind speed.

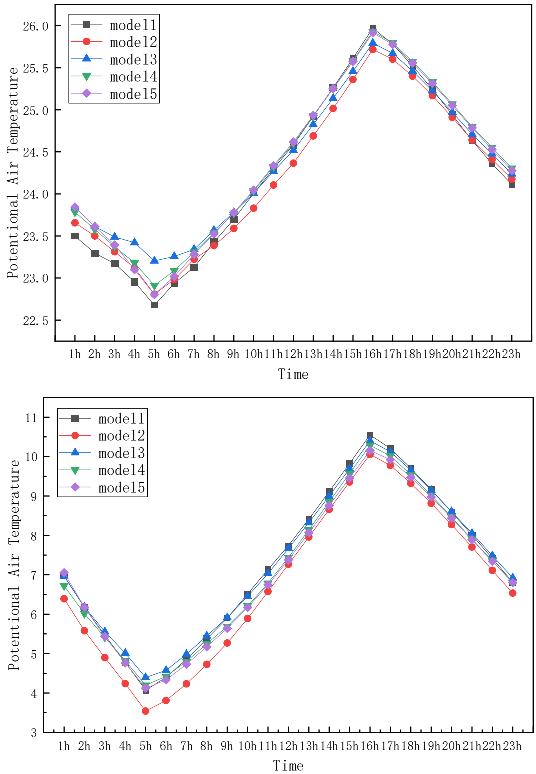


Fig. 2. Temperature change in summer solstice and winter solstice.

On the summer solstice, the temperature decreases on 1-5 o'clock and 16-23 o'clock, and increases on 5-23 o'clock. And the difference between the models is not significant **(Fig.2.)**. On the winter solstice, the temperature showed a downward trend 1-5 o'clock and 5-23 o'clock. And it increased on 5-16 o'clock.

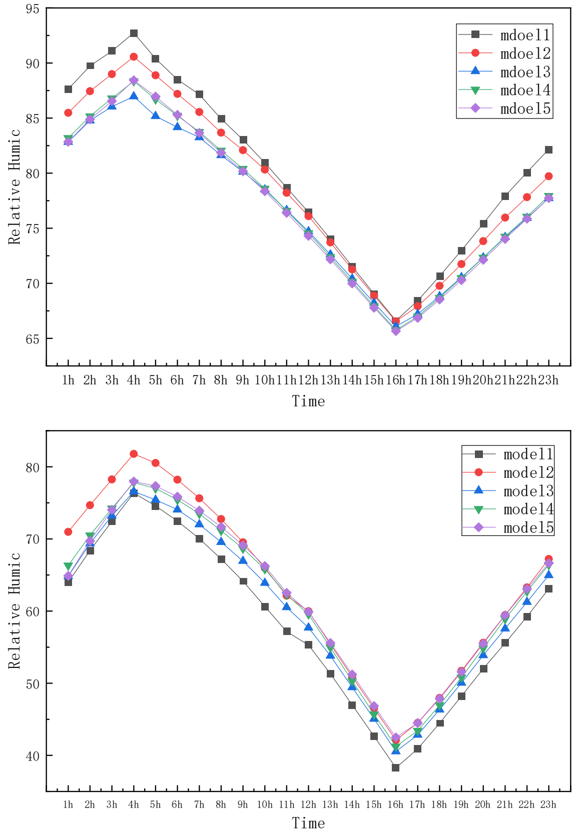


Fig. 3. Relative humidity changes in summer solstice and winter solstice.

On the summer solstice, the relative humidity increases on 1-4 and 16-23 o'clock. It decreases on 4-16 o'clock. The magnitude of change in relative humidity was greater for model 1 than for the other models. Moreover, it should be noted that the relative humidity increases on 1- 4 o'clock and 16-23 o'clock on the winter solstice. It decreases on 4-16 o'clock. Model 1 and 2 were consistently at higher relative humidity levels **(Fig.3.)**.

3.2 Influence of Urban Form and Land Type on Microclimate

Effect on Wind Speed.

In general, the higher the FAR, the denser the building. In the case of building type

A, the denser the woods, the lower the wind speed. For the C land type, the denser the wind speed, the wind speed increases (Table 4). This could be due to the fact that the dense building complex may form a barrier against the wind, causing the wind speed to be blocked and reduced.

Table 4. Influence of urban form on wind speed under different land types.

	A	B	C
FAR	-0.189*		0.364
VAR	-0.063*		0.122
SAR	-0.319*		0.609
SC		0.692**	0.197*
SSD		0.022*	
SVF	0.93*		-0.503
rOSR	-0.121*		0.238
Building height	-0.01*	-0.007*	0.018
	D	**E**	**F**
FAR			
VAR			
SAR			
SC	0.164*	0.118**	-0.438
SSD	0.027*	0.135**	0.074
SVF	-0.284**		-0.621**
rOSR			
Building height			0.031

Note: *p < 0.10, **p < 0.05, ***p < 0.01.

The effect of VAR on wind speed, which is negative in type A buildings, indicating that the wind speed decreases as the surface increases. The larger the surface area increases the building's resistance to the wind, resulting in a decrease in wind speed. Friction and drag effects on the surface of a building can prevent wind from flowing smoothly, reducing the surrounding wind speed.

In the A land type, the effect of SVF is positive. Large SVF means that the sky view around the building is more open, reducing the local obstruction of the building to the surrounding wind flow. It helps the wind to pass through the space around the building more easily, forming a smoother ventilation channel. However, in type D and type F, the effect of SVF is negative. This may be due to the fact that buildings on D and F land area are relatively densely, which impedes the surrounding wind flow. It's not conducive to the formation of ventilation corridors.

The effect of average height of buildings is negative in land types A and B. The blocking effect is enhanced due to dense vegetation, and taller buildings may form a stronger blocking effect, which makes the wind flow more obstructed.

Effect on Temperature.

The effect of the surface area ratio on temperature in AB land type is negative (Table 5). The reason may be that higher SAR will lead to a relatively large surface area of the building, resulting in a shading effect. In addition, the large surface area of the building may produce more shadows, providing a certain degree of shading for the surrounding area, and reducing direct sunlight exposure.

Table 5. Influence of urban form on temperature under different land types.

	AB	CD	EF
FAR			
VAR			
SAR	-3.078***		
SC		-0.806***	
SSD	-0.551***		
SVF		2.943***	
rOSR	3.571***	3.269***	
Building height		0.254	0.15***

Note: *p < 0.10, **p < 0.05, ***p < 0.01.

SVF is positive in CD type land, with more openness between buildings and more visible areas in the sky due to shading and heating absorption. In this case, sunlight is more likely to hit the surface directly, causing the surface temperature to rise.

The average building height is positive in the EF land type. This could be due to the fact that the higher the height, the closer it is to the sun, the more solar radiation it receives.

Effect on Relative Humidity.

In the C land type, the SSD is negative (Table 6). It can be concluded that the relative humidity will be lower with the higher the total length/site area of the building footprint. Green spaces and water bodies have the role of water storage and evaporation, helping to keep the environment moist. However, larger SSDs cannot be fully affected by the effective effects of green spaces and water bodies, resulting in lower humidity. Therefore, more water bodies and green areas should be built.

In the F type cement floor, the SSD is positive, which may be due to the shading effect. Large buildings avoid direct sunlight on the ground by shading, which reduces water evaporation and lowers humidity.

Table 6. Influence of urban form on relative humidity under different land types.

	A	B	C	D	E	F
FAR						
VAR						
SAR						
SC						
SSD			-0.581*			0.437*
SVF						
rOSR						
Building height						-0.232*

Note: *p < 0.10, **p < 0.05, ***p < 0.01.

In building height, F land type is negative, as taller buildings usually mean more surface area directly exposed to sunlight. In a high-temperature environment, a larger surface area helps in heating and evaporation, which makes it easier for moisture to evaporate from the surface and reduce humidity.

4 CONCLUSION

The study explored the impact of urban form and land use on microclimate. We found that for areas with high green space rate and dense vegetation, the larger the site coverage and site segmentation, the greater the wind speed. The greater the surface area ratio, the lower the wind speed. Therefore, for heavily vegetated areas, planners can regulate wind speeds by improving metrics such as site coverage, surface area ratio, etc. For areas with low green space rate and large impervious area, the larger the reciprocal of the floor area ratio, site segmentation, and open space ratio, the increase in the average height of the building, wind speed, temperature, and relative humidity. Therefore, for areas with high green space and dense vegetation, the government should pay attention to the site coverage and surface area ratio of buildings within a reasonable range, while for areas with large impervious areas, in order to create a suitable microclimate environment for buildings, urban planners should focus on regulating the design of the building's floor area ratio, site segmentation, and open space ratio. In this study, only typical building groups are selected for Nanjing buildings, and more building types can be included in the future to enrich the results of the article. In addition, the urban morphology indexes in this study are not comprehensive enough, and the future study can include more dimensional form indexes and building physical indexes to explore the impact on building microclimate, such as the greening rate of building facades and the materials used in the building walls.

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